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ATMOSPHERE ASSESSMENT FOR MARS SCIENCE LABORATORY ENTRY, DESCENT AND LANDING OPERATIONS

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On August 6, 2012, the Mars Science Laboratory rover, Curiosity, successfully landed on the surface of Mars. The Entry, Descent and Landing (EDL) sequence was designed using atmospheric conditions estimated from mesoscale numerical models. The models, developed by two independent organizations (Oregon State University and the Southwest Research Institute), were validated against observations at Mars from three prior years. In the weeks and days before entry, the MSL "Council of Atmospheres" (CoA), a group of atmospheric scientists and modelers, instrument experts and EDL simulation engineers, evaluated the latest Mars data from orbiting assets including the Mars Reconnaissance Orbiter's Mars Color Imager (MARCI) and Mars Climate Sounder (MCS), as well as Mars Odyssey's Thermal Emission Imaging System (THEMIS). The observations were compared to the mesoscale models developed for EDL performance simulation to determine if a spacecraft parameter update was necessary prior to entry. This paper summarizes the daily atmosphere observations and comparison to the performance simulation atmosphere models. Options to modify the atmosphere model in the simulation to compensate for atmosphere effects are also presented. Finally, a summary of the CoA decisions and recommendations to the MSL project in the days leading up to EDL is provided.

INTRODUCTION

Since the timing of EDL events depends on the density profile of the atmosphere, accurate characterization of the conditions at Mars during Entry, Descent and Landing (EDL) is critical to successful landing. The Mars Science Laboratory (MSL) mission was able to take advantage of

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daily observations from orbiting assets at the planet including Mars Reconnaissance Orbiter's Mars Color Imager (MARCI) and Mars Climate Sounder (MCS), as well as Mars Odyssey's Thermal Emission Imaging System (THEMIS) to characterize the entry environment. Additionally, the engineers and atmosphere scientists were able to take advantage of the past three Mars years of observations from the instruments. The MSL EDL sequence was designed using a performance simulation with atmospheric conditions calculated from mesoscale numerical models developed by two independent organizations (Oregon State University and the Southwest Research Institute). In the weeks prior to EDL, the project was able to compare observations to models to determine if any spacecraft parameter updates were necessary to compensate for unexpected entry conditions.

Early in the design phase, the project assembled a group of atmospheric scientists and mesoscale model developers, instrument experts and EDL simulation engineers known collectively as the MSL "Council of Atmospheres" (CoA). They were responsible for determining the atmosphere conditions to be modeled for MSL EDL. The CoA model developers were responsible for developing atmosphere models to be used in the EDL performance simulation. In preparation for EDL, the CoA performed comparisons of observations to the simulation models. The CoA began meeting to evaluate available data two months prior to EDL. The meeting frequency is provided in Table 1.

Table 1. CoA Pre-EDL Meeting Schedule.

Date From Entry (E)	Meeting Frequency
E-8 weeks to E-4 weeks	Every other week
E-4 weeks to E-2 weeks	Every week
E-2 weeks to E-7 days	Two times per week
E-7 days to E+0 days	Daily

The team acknowledged that the conditions of the atmosphere two months prior to EDL were not necessarily indicative of the conditions to be expected at landing. However, holding the meetings before the critical entry operations phase allowed the team to become familiar with available data sets, streamline the data analysis, discuss potential model modification options, generate sample presentations, and formulate recommendations. The process was continually refined until the day of entry.

The outcome of the CoA analysis was to provide the project managers with a recommendation. The CoA, comparing the observations to the models, determined if the difference was sufficient to warrant an update to the spacecraft entry parameter update (EPU) file. Particular parameters that might be affected included the guidance and sequencing parameters. Opportunities to upload parameters to the spacecraft occurred daily. The final opportunity to deliver parameter update was two hours prior to entry.

The processes and analyses that informed the CoA recommendation are discussed in the following sections. The first will review, in detail, the specific data products from orbiting assets that were available prior to entry. The second summarizes the mesoscale models used in the performance simulation. Finally, a summary of the daily process that the CoA used during MSL EDL operations to formulate a recommendation is provided.

INSTRUMENTS AND PREFLIGHT ATMOSPHERE OBSERVATIONS

The MARCI, MCS, and THEMIS instruments provided the daily observations used to characterize the MSL entry environment. A description of each data set is provided below. Since the last update to the spacecraft could be made just hours before entry, the data and analysis assessment provided herein corresponds to the last set of observed data available prior to entry.

Mars Color Imager (MARCI)

The MARCI instrument is a framing camera that provides full color images of the planet. Due to the MRO orbit, a complete global mosaic is obtained every day through accumulation of individual swaths that are taken approximately two hours apart. This is an important factor to keep in mind when using the images to track local weather events. The time laps can skew the size, shape and movement of a disturbance or miss them all together. The mosaic depicts clouds and dust storms at a ~1 km resolution. Regional local conditions are inferred by noting the location and movement of weather systems. The complete global image of the Mars atmosphere available on the day before the MSL entry (taken ~ 45 hours prior to EDL) is shown in Figure 1. The white circle at ~135° E longitude shows the landing site location in Gale Crater. Also annotated are the location of water ice clouds (bluish-white) in the region of the landing site and a regional dust storm near the southern polar cap in the Hellas Basin, approximately 3860 km southwest of the landing site. Based on this and prior MARCI images, a direction and rate of translation of this storm was not identifiable. However based on knowledge of speed and direction of prior storms in this region and at this season, it posed no threat to the Gale region in the 45 hours until MSL entry.

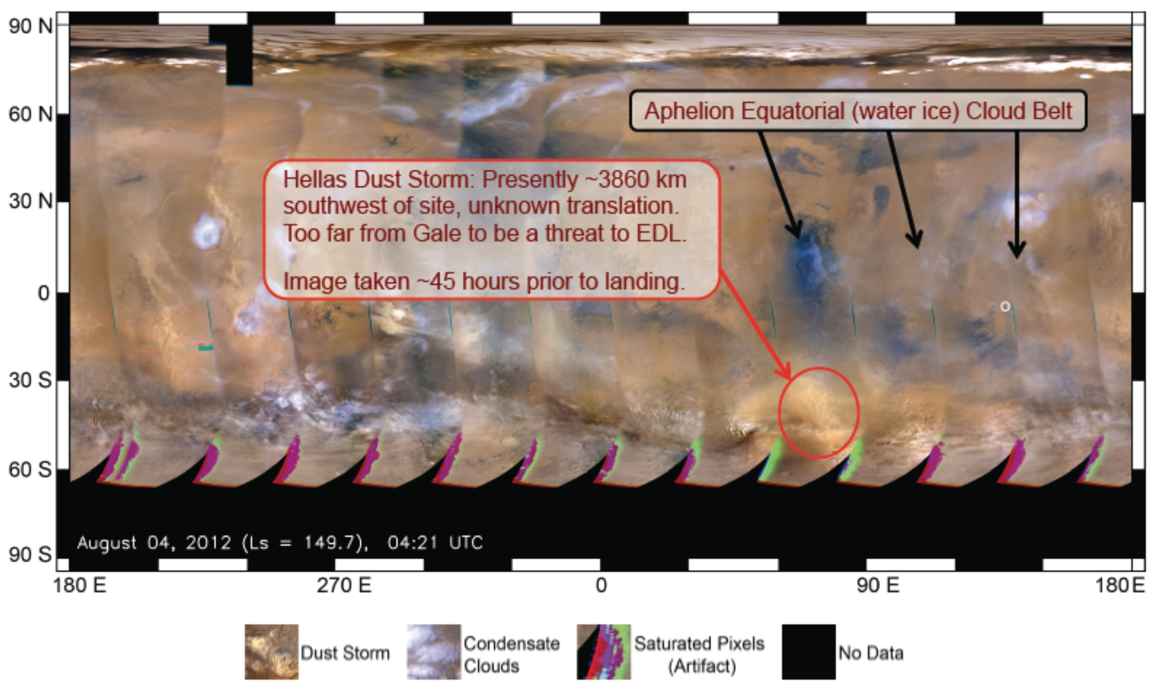

Figure 1. MARCI daily global map, generated from images taken on 13 consecutive orbital passes two days prior to MSL EDL. Map is simple cylindrically projected at 6 km/pixel.

Mars Climate Sounder (MCS)

The MCS instrument measures profiles of temperature, water ice and dust content of the Mars atmosphere.[1] MCS team members at the Jet Propulsion Laboratory provided derived vertical profiles of these quantities versus pressure for MCS observations nearest to the landing site each day.[2,3] Due to the cold and low-dust atmosphere near Gale Crater on the days prior to entry, only a few MCS retrievals were obtained through water ice clouds that were opaque along the MCS line of sight. Most of the successfully retrieved profiles did not extend to the lower atmosphere. Figure 2 illustrates the locations of the MCS retrievals relative to the landing site for the week prior to landing. The red diamond in the center represents the landing site location. The box denotes the range (approximately 20° in latitude and longitude from the landing site) for which data was considered for comparison to the models. The four red points along the right side of the box correspond to location of the retrievals closest to the landing site the day prior to entry. They were retrieved August 5, 2012 at 03:01 hours (Local Mars time 15:26:38). The asterisks correspond to profiles generated using the standard MCS data processing techniques (v3.1) while the plus signs denote profiles processed using an updated v3.1.1. The four selected profiles have a mean distance of 1260 km from the landing site and are further east of the landing site than any of the other profiles considered during the week prior to entry. It is noted that these four profiles only extend to approximately 28 km above the surface due to the amount of water ice in the atmosphere. The temperature, dust and water ice retrieved at the four selected points are shown in Figure 3, 4, and 5.

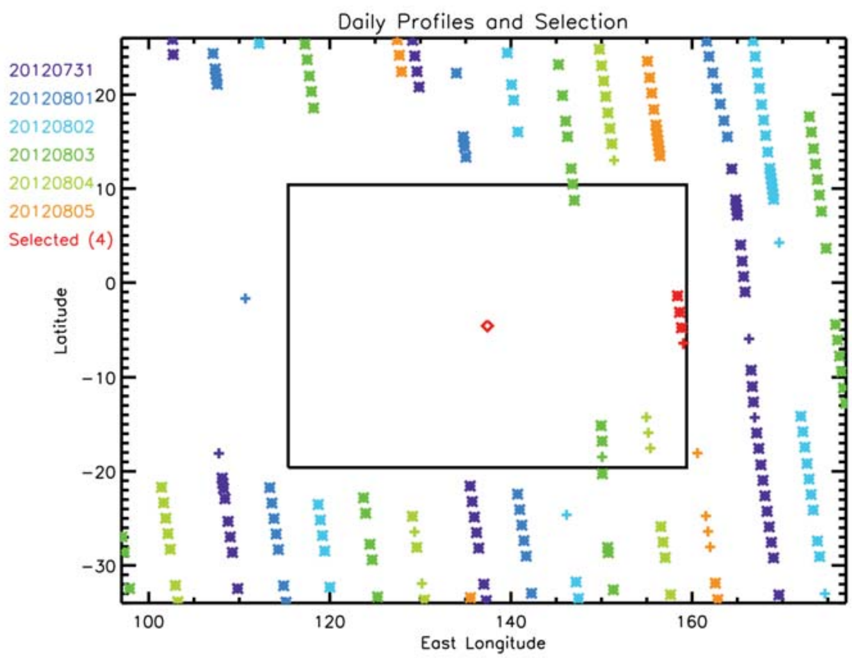

Figure 2. Locations of the MCS retrievals taken the week prior to MSL EDL. The inner box denotes the region near the landing site for which profiles are considered.

Figure 3 shows the temperatures for each of the four profiles. The blue line corresponds to the southern most of the four profiles, and the colors change from blue to green to orange for each successive northward profile. All four profiles have similar temperature structure as a function of pressure and the structure varies a bit from the seasonal mean of the Mars Year 28 data (see the red solid line (mean) and dotted line (1 sigma)).

Figure 4 shows the dust opacities of the same four retrievals. Dashed lines of constant opacity are shown for reference. Due to lack of information in the lower atmosphere the dust opacity at the lowest altitude is held constant and extrapolated to the surface. Figure 5 shows a similar plot for water ice opacity of the four retrievals. The profiles all extend to the maximum ice opacity limit of 3 indicating that the profiles are likely cut off due to significant ice in the atmosphere, a trend that has persisted throughout the week. The lack of retrievals nearer to Gale and the large water ice opacities values observed over the past week, which are typical of the aphelion season, indicate that MSL will likely encounter a very cold atmosphere for entry should conditions persist for the next 24 hours.

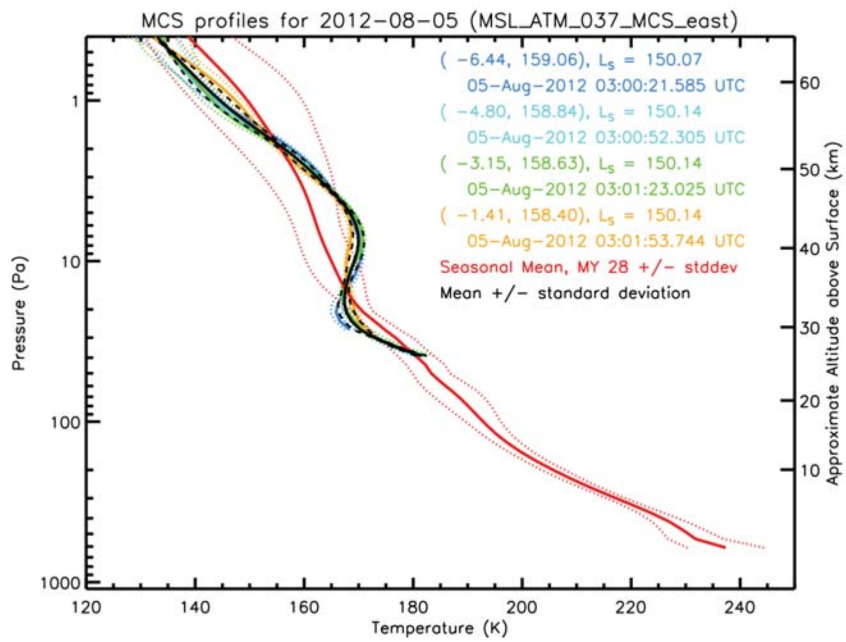

Figure 3. MCS Temperature retrievals taken the day prior to MSL EDL. The red profile is from three Mars Years prior to MSL EDL and was used for reference.

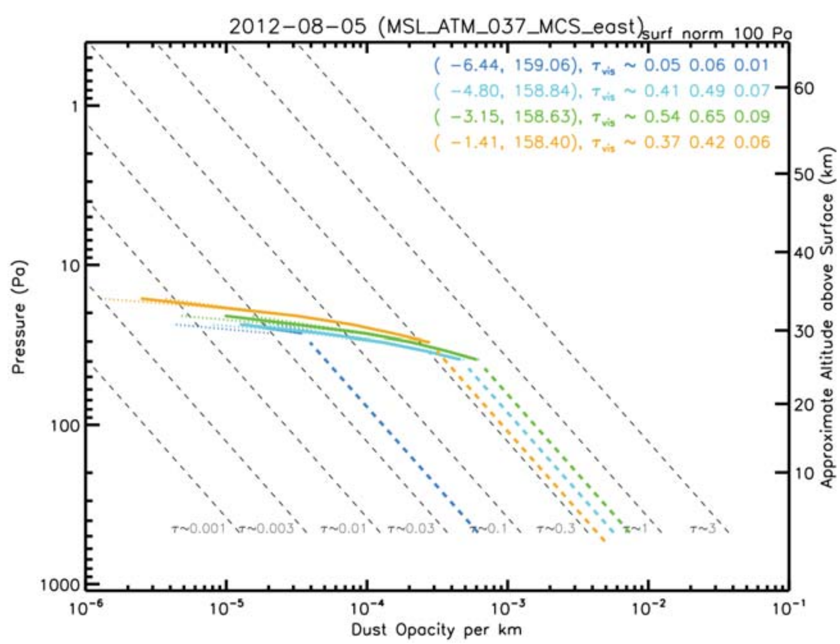

Figure 4. MCS dust opacity retrievals taken the day prior to MSL EDL.

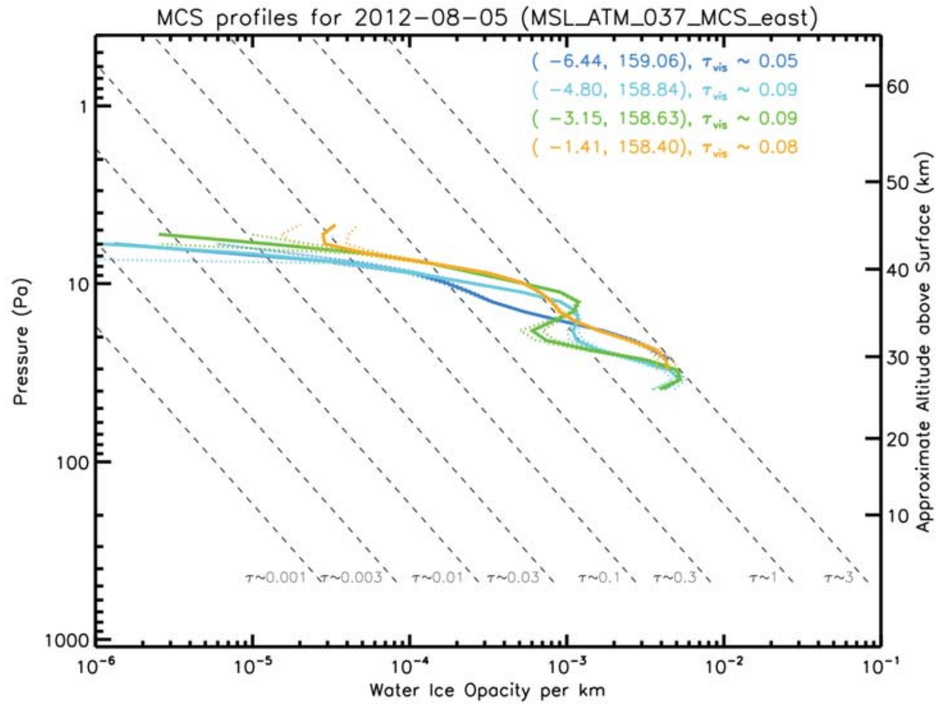

Figure 5. MCS water ice retrievals taken the day prior to MSL EDL.

Additionally, global MCS temperature information was used to correlate with MARCI images. Figure 6 shows the global mean temperature at 136 Pa (approximately 15 km). Additional global maps of MCS data were provided at 50 Pa and 30 Pa (approximately 25-30 km). The additional maps were partly to compensate for the difficulty in retrieving the temperature in the lowest atmosphere. Thus the higher-pressure level (136 Pa) often had less complete maps due to the lack of retrievals at lower altitudes. Daily trends in the global temperatures were also tracked each day. An example of global temperatures at 136 Pa for four consecutive days is shown in Figure 7. Warmer colors show regions of higher temperatures; however, due to the lack of data near the cold southern pole, any disturbance from the regional storm near Hellas shown in Figure 1 does not appear in the MCS data at this pressure level. In fact, as the days progressed, the higher temperatures at this pressure level seem to be settling.

To summarize the local weather near Gale based on MCS observations, the landing site weather one day before EDL appeared to be seasonal (compared to MCS data from Mars Years 28 and 30). There appeared to be a slight warming trend in the temperature in the middle atmosphere. All of the MCS temperature profiles obtained the week prior to entry (shown in Figure 9) trend warmer. It is likely due to either a spatial (longitudinal) or seasonal trend and is not a concern for EDL. There were also no indications that any activity near the site would cause rapid warming in the next 24 hours. Globally, there are no major events seen or ongoing and there are no indications of middle atmosphere dust activity or warming associated with disturbances.

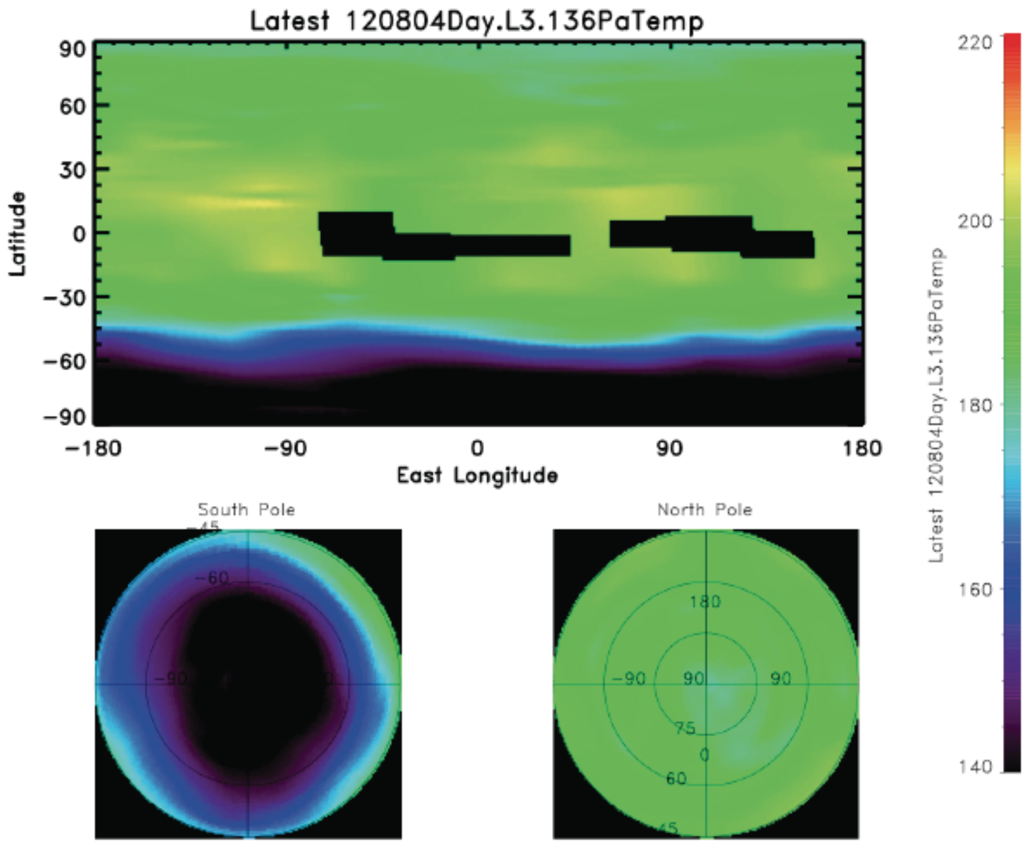

Figure 6. MCS Global map at 136 Pa for August 4, 2012, the day prior to MSL EDL.

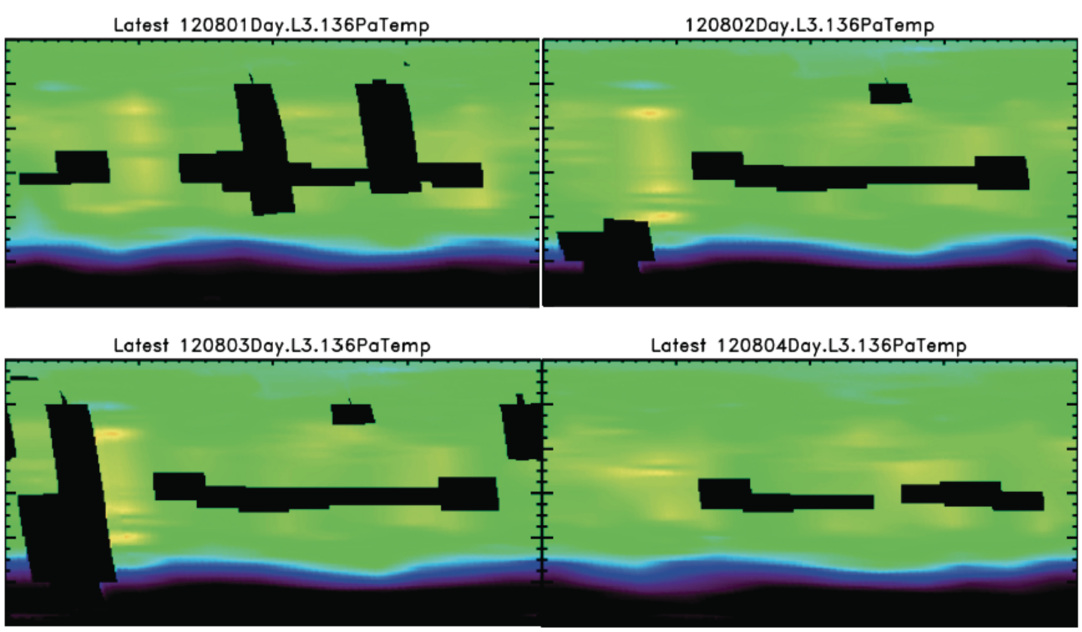

Figure 7. Global MCS maps at 136 Pa for the four days prior to MSL EDL. The maps use the same color scale as Figure 6.

THEMIS

The THEMIS instrument can measure the spectral signs of minerals on the surface and dust in the atmosphere using both visible and infrared portions of the spectrum. In the days leading up to MSL landing, THEMIS provided smoothed and interpolated maps of dust opacity derived from individual images of a small percentage of the surface. Figure 8 shows the interpolated THEMIS results from August 2 to August 4, 2012. Despite the light blue color indicating slightly elevated dust in the region of Gale Crater, relative to the scale, there is actually very little dust in the landing region, which agrees with both the MARCI image and the MCS data.

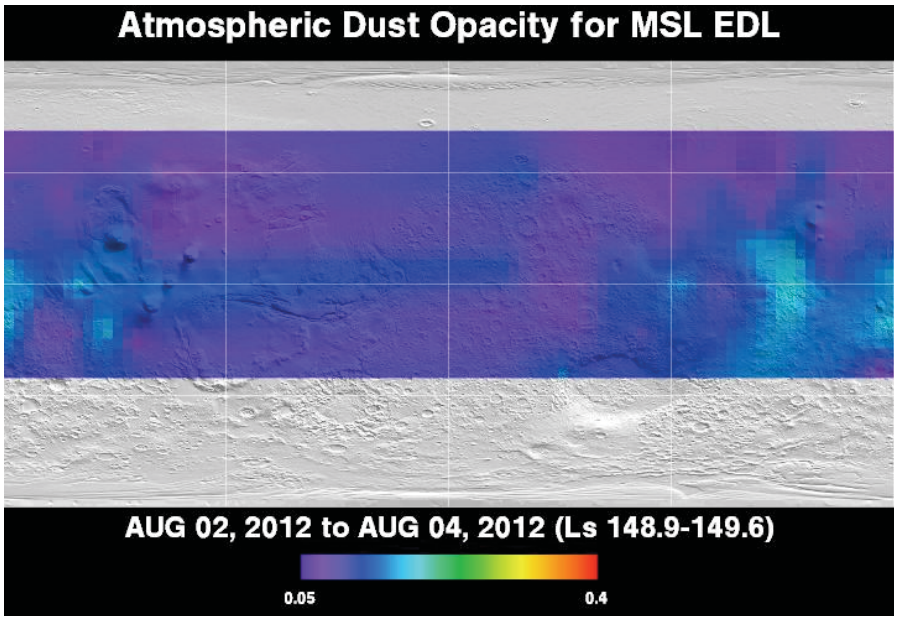

Figure 8. Global THEMIS maps two to four days prior to MSL EDL.

MESOSCALE MODELS IN THE PERFORMANCE SIMULATION

Because MSL flew a lifting trajectory that had several hundreds of kilometers of horizontal flight at low altitudes (~10 km above the surface), and the capability to land in regions of highly varied terrain, a different approach to atmosphere modeling was used from that of past Mars EDL missions. To capture the terrain affects, MSL decided to utilize high-resolution mesoscale modeling. Two models were used. One, called Mars Mesoscale Model v5 (MMM5) was developed at Oregon State University (OSU);[4,5] the second is the Mars Regional Atmosphere Model System (MRAMS) developed at the Southwest Research Institute (SwRI).[6,7] While detailed description of how the models were implemented for MSL is provided elsewhere,[8] a summary is provided here.

The mesoscale model in the performance simulation is based on MMM5 and MRAMS mesoscale model results $\pm$10 days and $\pm$2.5 hours from the expected MSL entry date and time. The duration allows for the calculation of the mean and standard deviation of atmosphere parameters including density, temperature, pressure and winds. It was observed that the densities of two models began to diverge above 15 km. See Figure 9. Therefore, the project, seeking to increase robustness for EDL atmosphere modeling, decided to create a combination (Combo) model. The Combo model mean would be the mean of the means of each MMM5 and MRAMS atmosphere parameters. The standard deviation of the Combo model became the extremes of each individual model's standard deviation. Therefore, the Combo 3 sigma high density became the maximum of the 3 sigma high values from the two models at each altitude. Likewise, the minimum of the 3 sigma low values from each model became the Combo “3 sigma low” density. A comparison of the 3 sigma densities normalized to the Combination model is shown in Figure 9. Finally, to include additional performance margin, an additional 10% was added to the Combo 3 sigma bounds (not shown in Figure 9).

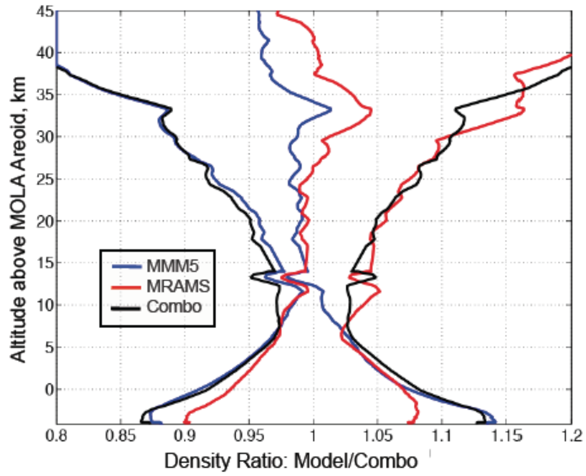

Figure 9. Normalized 3 sigma density limits for both mesoscale models MMM5 and MRAMS with the circumscribed bounds of the Combo Model.

For the engineers designing the MSL entry trajectory, the primary atmosphere parameter of concern is the density profile as a function of altitude. Atmosphere density affects many aspects of the entry including the entry heating environment, the parachute deploy loads, guidance initiations, event triggers, etc., so it is imperative to accurately model density. However, none of the instruments currently orbiting Mars provide a direct calculation of density as a function of altitude. MCS provides temperature versus pressure that can be converted to density, but without a ground based pressure measurement to anchor the pressure to an altitude, there is approximately 5% error on the density when calculated from MCS data.

The challenge of comparing observed temperature and pressure data to the mesoscale model density versus altitude curves from the performance simulation remains. A straightforward solution was to convert the Combo model density to a temperature assuming constant surface pressure for comparison with the MCS observations. The Combo model 3 sigma +10% limits, or the performance bounds in the simulation, are converted to temperature and pressure space and are shown in the black dashed lines in Figure 10. For additional comparison, the 3 sigma pressure and temperature vertical profiles directly from MMM5 and MRAMS mesoscale models are also plotted in blue and gray dashed lines respectively. The three performance simulation models can now be compared directly to the MCS observations.

Figure 10 also includes the MCS profiles observed near the site in the 10 days prior to entry, with each successive day colored in shades from blue to red. The blue profiles from earlier in the week extend to lower altitudes due to slightly warmer temperatures, less water ice clouds or perhaps surface effects at those particular retrieval locations. As the week progresses, more water ice clouds prevent low altitude retrievals. But the key point is that all of the MCS retrievals remain well within the Combo 3 sigma +10% limits and compare well to the individual model calculated 3 sigma bounds with the exception of 30-Jul_2012 profiles that have slightly cooler temperatures between 100 and 200 Pa (10 to 15 km).

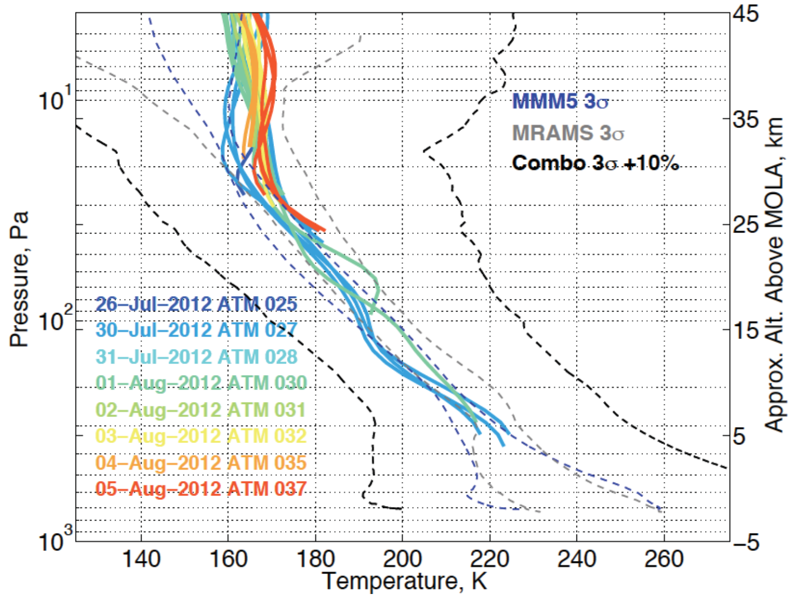

Figure 10. Comparison of pressure vs. temperature for the MCS retrievals and the mesoscale model 3 sigma bounds as well as the simulation combo model 3 sigma +10% limits.

For comparison, the current MCS profiles are also compared to MCS profiles obtained in the same season from Mars Years 28, 29 and 30I . The dust storm in Mars Year 29 results in higher temperatures and dust levels during this season compared to other years. Also, trends in the data considered for MSL EDL tend to be more in family with the observations in Mars Years 28 and 30.

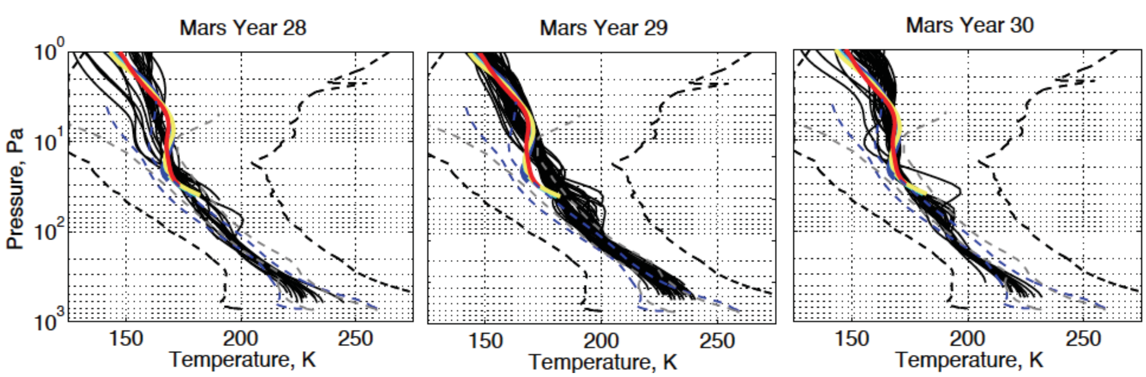

Figure 11. MCS retrievals from August 5, 2012 (colored profiles) compared to MCS retrievals (solid black profiles) during the same season in the past 3 Mars Years. Dashed lines denote performance simulation and mesoscale model 3 sigma bounds.

DAILY ANALYSIS PROCESSES FOR OPERATIONS

Meetings commenced with a summary of the health of the spacecraft and the maneuver and spacecraft upload opportunities available in the next 24 hours. The team then considered the latest MARCI images, like that shown in Figure 1, identifying any regional weather activity and comparing it to the previous weeks images to determine the movement and dissipation of each disturbance. The global MARCI image was also compared to historical MARCI images for the same season (solar longitude) in Mars Year 28, 29 and 30. The team also considered single-track MARCI images nearest to the landing site for an alternate view that also showed clouds and dust in the region of the landing site. Next, the locations of the most recent MCS retrievals were shown and compared to the location of the Gale landing site, as depicted in Figure 2. Individual profiles of temperature, water ice and dust were considered and compared to historical data. Global maps of the MCS data at three pressure levels (30, 50, and 136 Pa) were presented (similar to Figure 6). The current day's maps were compared with the previous 3 days of data to identify the trends in temperature like those shown in Figure 7. By considering the daily progression of weather systems, patterns are identified. THEMIS maps were also presented and attempts were made to correlate the MCS and THEMIS data with the MARCI images. Regional weather systems were identified and tracked to determine the potential future impact to the Gale landing site.

After all observation data were reviewed, the latest MCS temperature data were compared to the mesoscale and combo model bounds. The colored lines in Figure 10 show how the atmosphere profiles near the site change in the 10 days prior to landing. The MCS profiles were also compared to retrievals obtained near Gale during the same season in the previous 3 Mars Years. It is noted that Mars Years 28 and 30 did not experience large dust activity near the MSL entry season and the profiles more closely match the observations made in the months and weeks preceding MSL entry. Mars Year 29, which experienced more dust activity and had higher temperatures, offered an alternative atmosphere for comparison.

Figure 10 shows that the profiles obtained early in the week before EDL were slightly outside the 3 sigma bound of the mesoscale model near 10 km altitude but well within the performance margin allowance identified by the black dashed Combo 3 sigma + 10%. In fact, as the entry date approaches, the trends in the MCS data from the middle atmosphere match the models quite closely. The lack of retrievals in the lower atmosphere indicate that the atmosphere, if conditions remain the same, will be cold for entry, a situation that is welcome and planned for by trajectory designers.

Based on all the data available, the CoA makes a recommendation to the project as to whether an atmosphere model update in the performance simulation is required to more accurately represent the observed atmosphere. A summary report of the observations, model comparisons and recommendation to was prepared and presented at the planning meeting later in the day.

Model Recommendations

As mentioned previously, the challenge for comparing observations to models is that in situ measurements cannot provide a direct measurement of density as a function of altitude that the EDL engineers model and affects the timing of events during entry. Despite this, the CoA evaluated the observed atmosphere conditions, focusing on the altitude region between 10 and 20 km (determined to be the most critical altitude range for a successful landing). The CoA had to determine if the observed parameters differed sufficiently from the models to warrant recommending an atmosphere model update in the flight performance simulation. Had the atmosphere model been updated, the results of the simulation may suggest an update to a parameter in the EPU file that could be uploaded each day.

The CoA and simulation teams established the following guidelines to determine if additional off line analysis and flight performance simulation was needed. If the difference in density, calculated from observed MCS temperature profiles assuming constant pressure, was less than 5% different from the model mean, then no change to the models was recommended and no additional analysis was performed. If the density difference was between 5 and 10% or trending toward 10%, then the CoA might consider additional analysis to be run off-line using the performance simulation to assess the effect of the changing atmosphere on the entry performance. Though no immediate changes would be recommend to the project, the results would be presented for consideration at the next CoA meeting for a final decision. Finally, if the difference in observations and models was or appeared to be trending greater than 10%, specific set of analyses would be outlined and initiated in the performance simulation. The mesoscale atmosphere might be scaled to more closely match observations or dispersions might be increased in a Monte Carlo analysis to evaluate the effect the difference would have on entry parameters. Had any parameter updates seemed necessary, the CoA would have carried that recommendation forward to the project in the daily parameter update decision meetings.

In the week leading up to MSL EDL, no regional weather systems that substantially effected density moved into the Gale region and all CoA recommendations to the project were to continue to use the nominal atmosphere and dispersions in EDL planning efforts.

CONCLUSION

After weeks of observing the weather at Mars prior to MSL EDL, the conditions at Mars closely matched the model predictions and no changes were made to the atmosphere models in the performance simulation. The observations agreed well with the model predictions generated a year prior to entry. Additionally, the post flight reconstructed entry profile agreed well with the observations and models. [9]

Given the correlation between the observations and the models at Gale, two questions emerge: was MSL fortunate due to the landing site selected, and would the observations at the other 'finalist' landing sites, with higher landing elevations and latitudes, and higher probabilities of dust storms have fared as well? Future analysis to evaluate the MCS data at the other MSL candidate sites may provide indications to the robustness of this approach to atmosphere analysis for entry operations that worked well at Gale.

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