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Technical note:
Mars weather forecast for the Exomars 2016 EDL

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1. Executive summary and recommendations

We assess the possibility to forecast the atmospheric environment in Meridiani Planum 7 days before the entry of the Exomars 2016 EDL Descent Module (EDM) to possibly modify some parameters for the EDL operations.

The primary sources of uncertainty in the atmospheric environment for the 2016 EDL are the local, regional and global-scale dust storms which affect the thermal structure, the density and the winds. We review the existing observation relevant for the EDM landing site and provide first estimates of the probability of dust loading changes based on a statistical analysis of these observations.

We also review all the observations that could be available in October 2016 to monitor the Martian atmosphere at the time of the landing. Several datasets can be useful. We recommend to use at least:

- The Mars Reconnaissance Orbiter Mars Climate Sounder (MCD) and Mars Color Imager (MARCI) data, which benefit from a regular sun-synchronous low orbit allowing a complete daily mapping of Mars. To favour the collaboration with the MRO team, a formal agreement with NASA would be desirable.

- The ESA Mars Express/PFS retrievals of temperature profiles and dust opacities.

- In parallel, through another NASA agreement, we should use the daily dust opacity measurements from Opportunity (if it is still operative in October 2016) located near the Exomars EDM landing site in Meridiani.

- Finally, a telescope campaign involving amateur astronomers from all around the world would very well complement the spacecraft observations (at high resolution but fixed local times) by helping to detect the onset of dust storms using synoptic images of the Mars disc, while providing an opportunity for public outreach of the Exomars 2016 project.

On the basis of these datasets, we discuss the possibilities of forecasting dust conditions a few days ahead (up to 10 days). Two levels of forecast can be proposed:

1. A minimum objective is to identify, 7 days before EDL, if the atmosphere is nominally dusty or if a high opacity global-scale dust storm is ongoing. If a global-scale storm is already active and recognized as such, past observations show that the evolution of the storm is slow and highly predictable. The level of dust loading then remains globally high or very high.

2. If no global-scale dust storm is ongoing, a more ambitious objective is to attempt "weather forecasting" in order to estimate if a global or regional dust storm will affect the EDL. With regard to global-scale storms, past observations show that they can fully develop within a few days period (starting from a nominal atmospheric state for a given season). However, the probability of having the initiation of a global-scale storm during a given week is low (<1%, but see caveats detailed in Section 6). With regard to regional or local storms, the probability to be affected at the Meridiani landing site appears to be relatively moderate at the particular season of landing and in comparison to other areas on Mars, but is far from being negligible.

For this second objective, our analysis indicates that the best way of approaching a reliable forecast could be to entrust a dedicated pool of “Martian meteorologists” with the task of coordinating the collection of available data and analyse the evolution of the meteorological state, possibly being assisted by available model and/or data assimilation simulations. This task should be informed by a specific study aiming at identifying the weather patterns preceding dust storm events at the season of the EDM 2016 landing.
2. Introduction

2.1. Objective of the report.

The objective of this report is to assess the possibility to forecast the atmospheric environment before the release of the Exomars 2016 EDL Descent Module (EDM) from the Trace Gas Orbiter (TGO). The advantage would be to adapt to the actual atmospheric conditions and possibly modify some parameters for the EDL operations.

In practice the separation of EDM from TGO occurs 3 days before Entry Interface Point (EIP), but the relevant Trajectory Correction Manoeuvre (TCM’s) are performed 30 days before EIP (for fine targeting of the entry point) and 5 days before EIP as latest opportunity for final targeting and trimming. The duration of the "forecast" should be on the order of 7 days, considering that the navigation is shut-down 2 days before the last TCM, and the decision for correction manoeuvres takes 2 days in order to upload any possible fine correction (S. Portigliotti, TASI, personal communication).

The key environmental parameters affecting EDL are the atmospheric density below 60 km and the horizontal winds between 0 and 10 km. At the season of the planned landing in 2016 (Ls ~240°-250°), the meteorological variability is controlled by the content of dust in the atmosphere (background dust loading and local-, regional-, global-scale dust storms) through its impact on the radiative properties of the atmosphere and, consequently, on the thermal and wind structures.

2.2. Summary of our previous studies on the possibility of dust storms affecting the 2016 EDL:

Previous studies conducted within the “Exomars Environmental Atmospheric Support Analysis” contracts with TAS-I (see EXM-MS-TNO-LMD-0063, 09/2012) have highlighted that, given the specific season and location of Exomars 2016 EDM landing:

- Planetary-encircling dust storms constitute the major source of environmental uncertainty to EDL operations, because of the intensity of such global events, the large spam of solar longitudes they affect, and their sudden (and therefore mostly unpredictable) occurrence. To date, "solstitial" storms seem more frequent than "equinoctial" storms (5 to 2), posing higher risk for Exomars landing.

- Regional storms can pose hazards even at large distances from the location where they have their original onset, due to possible advection by large-scale winds and to their effects on the overall background dust opacity. A particular type of regional dust storms, so-called “cross-equatorial” or “flushing” storms, can originate in the northern plains at high latitudes in autumn-winter time, move southward, increase in size and strongly affect the tropical and equatorial latitudes. They are known to have affected Meridiani in several occasions (almost every Martian year) with different degrees of impact, depending on their specific trajectory, but no regional storm has been recorded in Meridiani from MY 24 to MY 31 within 15° solar longitude from Exomars’ nominal landing time (Ls ~245°). The statistical significant reduction of observed flushing storms in a range of solar longitude Ls ~[230°, 290°] has been linked to the reduction in the amplitudes of the atmospheric baroclinic waves in the first scale-height above the ground (i.e. about 0–15 km altitude) around winter solstices, both in the northern and in the southern hemisphere. Recent studies (Lewis et al., 2015, Mulholland et al., 2015) put the basis for a systematic cause-effect explanation. However, the risk reduction due to the solstitial pause in flushing storm occurrence does not eliminate the risk of other types of dust storms (local, regional or planetary-encircling), which might be generated by specific weather conditions not related to high latitude northern baroclinic waves.
Local dust storms are extremely frequent on Mars, and they can occur at almost any time of the year and almost any location on the planet (except for ice-covered regions far from the ice edge). They are also short time-scale events, in the sense that they can develop and rapidly decay in a few hours. A complete statistics of local dust storms in Meridiani shows that it is likely to have the development of a minor storm close to Exomars’ landing location and time (at least within ±5° or ±10° solar longitude from L$_s$ = 245°).

The values of atmospheric dust optical depth at a particular time and location on Mars, including Meridiani, are obviously linked to the kind of dust storms that occurred before and/or are occurring at that particular time. On the basis of past observations of column dust optical depth from MY 24 to MY 31 using three different instruments onboard three spacecraft (Mars Global Surveyor, Mars Odyssey and Mars Reconnaissance Orbiter), Montabone et al. (2015) make the statistical prediction that the absorption IR (9.3 μm) column dust optical depth normalized to 610 Pa is likely to be moderate ($\tau_{\text{IR}} = 0.38 \pm 0.12$) in a solar longitude range L$_s$=[240°, 250°]. This value is equivalent to $\tau_{\text{VIS}} = 1.09 \pm 0.34$ at average visible wavelengths in extinction, if one uses the factors 1.3 for the extinction/absorption conversion (Smith, 2004), and 2.2 for the visible/IR conversion at late solar longitudes (Wolff et al., 2006, Lemmon et al., 2015). In this value, the decay of the MY 25 planet-encircling storm is taken into account, but the possibility of high dust loading induced by a solstitial planet-encircling dust storm - which did not occur so far in the range considered - cannot be ruled out.

3. Available data

We review here the data from various sources that could be used to constrain the dust conditions in October 2016 before the EDM release, and discuss their availability in "near-real time".

**General comments:** for most spacecraft orbiting Mars, the data rate between Mars and the Earth should be excellent in October 2016, only a few months after the minimum Mars-Earth distance (Mars opposition is on May 22, 2016).

**3.1. Mars Reconnaissance Orbiter (NASA)**

Our contact: R. Zurek, Chief scientist, JPL Mars Exploration Program Office, MRO project scientist.

The MRO spacecraft reached Mars on March 10, 2006, and is currently in its “extended mission 3” phase. It is very likely that it will still be operative in 2016. For science mapping, the orbiter operates in a near-polar orbit around Mars with a periapsis of 255 km above the south pole and an apoapsis of 320 km above the north pole. The orbit is also sun-synchronous: the orbiter always monitors the same time of day (around 3am on the night side and 3pm on the day side). The spacecraft completes 12 orbits per day, with an orbit-to-orbit longitudinal drift of ~27°, enabling a good planet-wide coverage. We contacted Richard Zurek who informally agreed that there should not be any specific problem to use MRO data for EDM, although priority will be given to the beginning of the Insight mission (arrival on Mars on September 28, 2006), but this should last only a few days and thus should not be problematic.

Observation from two instruments could be used:

- **MARCI:** (Our contact: B. Cantor, Malin Space Science Systems, Co-I of MARCI, in charge of atmospheric observations). The Mars Color Imager (MARCI) is a wide-angle, relatively low-
resolution camera that views the surface of Mars in five visible and two ultraviolet bands. Each day, MARCI collects about 84 images and produces a global map with pixel resolutions of 1 to 10 km. These are used to provide “near real-time” weekly weather reports for the general public (see e.g. http://www.msss.com/msss_images/latest_weather.html). Obtaining processed data within a short time-scale (a few Earth days) is possible. The team receives data 3 times per day and can do a full mosaic in real time without effort “unless the data rate is low” (B. Cantor) which should not be the case in October 2016, as explained above.

- **MCS**: *(Our contact: David Kass, JPL, MCS team).* The Mars Climate Sounder (MCS) is an infrared thermal emission radiometer which observes the Martian surface and atmosphere with eight infrared spectral channels and one visible/near-infrared channel. From the channels' simultaneous measurements, vertical profiles of atmospheric temperature, dust and water ice opacities can be retrieved up to ~80 km altitude, with a ~5km vertical resolution. Obtaining processed data within a short time-scale (a few Earth days) is possible. Real-time processing can be carried out if the data rate is sufficient, but the MCS team cannot commit to better than 48 hours delay because that is the commitment from the Deep Space Network (DSN) to deliver to the team.

### 3.2. Mars Express

*Contact: Dimitry Titov, Mars Express project scientist (ESA, ESTEC)*

Mars Express is in orbit since December 2003 and has been approved to function in fall 2016. It operates in a polar orbit with about 3 orbits per day. Observations are carried out around the satellite periapsis, whose latitude and local time slowly vary with time. In October 2016, the latitude of Mars Express periapsis will be around 60°N, which will enable a large scale view of the equatorial region (TBC).

In theory, observations from several instruments could be used:

- **PFS**: *(Our contact: Marco Giuranna, INAF, PI of PFS).* The Planetary Fourier Spectrometer is capable of measuring the distribution of the major gaseous components of the atmosphere, the vertical distribution of atmospheric temperature, as well as detecting the presence of airborne dust. PFS measurements have a spatial resolution ranging from 7 to 12 kilometres when Mars is observed from an altitude of 250 kilometres at apoapsis. In practice, the observations could be available 4 days after acquisition (2 to 3 days are usually needed to get the data from Mars Express through the ground segment, and the PFS team could perform the retrieval in one night).

- **MARS**: *(Our contact: Martin Pätzold, University of Cologne, PI of MARS).* The Mars Express Radio Science experiment can obtain high resolution accurate temperature profile between the surface and about 40 km altitude. Such temperature profiles could be used to monitor the thermal structure, but only locally, where the Mars Express spacecraft traverses the atmospheric limb as seen from the Earth. This only occurs during "occultation periods" that last roughly 4 months, about every 10 months. It turns out that October 2016 corresponds to one of such periods. However, the latitude which will be monitored is likely to be very high. We have contacted the MARS team but have not received any reply yet.

- **OMEGA**: The Mars Express Imaging spectrometer has been used to monitor dust and clouds. In particular the visible camera could be used to monitor dust storms. However this requires significant treatment and the coverage is not as good as what can be provided by, for instance, the MARCI camera on MRO.
• **SPICAM**: The near-infrared / UV spectrometer can also monitor dust in the atmosphere. However the UV channel is not functioning anymore. The 1-1.7 µm NIR channel could be used in theory but, with such a narrow wavelength range, aerosol retrieval is difficult.

### 3.3. MAVEN

*Our contact*: Franck Lefèvre (LATMOS, France), IUVS co-I in charge of ozone mapping

The MAVEN spacecraft has been in orbit around Mars since September 2014. The only remote sensing instrument able to monitor the lower atmosphere is the Imaging UltraViolet Spectrograph (IUVS) which is notably used to map Ozone from apoapies. The Ozone retrieval includes an estimation of the UV dust opacity which could be used. The coverage depends on the illumination of the planet which varies with time (we do not know yet what will be geometry in October 2016, but this could be asked). The delay between data acquisition and the provision of dust maps should be of the order or 48h to 72h, "mainly depending on the time taken by Lockheed-Martin to provide the geometry data".

### 3.4. Surface measurements

*Our contact*: Mark Lemmon (Texas A&M University, College Station, TX, USA), in charge of dust opacity measurements on most US rovers and landers.

The cameras on Opportunity, Curiosity, Insight (which will land on Mars on September 28, 2016) are used to monitor dust opacities through Solar imaging or by measuring sky radiance at different elevation angles. Such data would be available from Mark Lemmon, who would nevertheless appreciate a formal agreement with NASA.

In practice, the shared product would be the same one provided to the project for internal use. This is generally a quick-look product and subject to later revision, but useful for science or engineering operations. The reasons for later revision could include: the product may be based on 'thumbnail' data, and a full data product becomes available later; or the calibration is updated, for instance by correcting for time-varying dust on the optics. In any case, these corrections should be small for our purpose, as they are usually small compared to variability between days or sites.

**Opportunity** would provide the most interesting measurements since its location is close to the EDL landing site. However, it is not certain that it will still be operating in October 2016. At least one measurement is done nearly every day, and the data are automatically processed and available internally for the team within 30 minutes of image receipt at JPL. The data are usually accessible outside the flight firewall within another hour, although automatically emailed updates could be easily arranged. For example:

http://www.lpl.arizona.edu/~lemmon/mars-tau-b.html

http://gemelli.colorado.edu/~wolff/MER/pancam/tau/00_B_TAU_880.TAB

**Curiosity** is less relevant than Opportunity since it is located on the other side of the planet. Data are taken closer to weekly, but Mark Lemmon thinks they could be done at a higher frequency for a couple of weeks prior to the EDM EDL. Moreover, the treatment requires a longer delay for manual processing, at this time, up to potentially several days. However this might be automated by 2016. Project approval would be required for sharing, but it is expected that this would be just a formality. A paper describing the MSL process and results to date is nearing submission.
InSight is also located on the other side of the planet. At that time in the mission, daily measurements should be possible. The process is planned as fully automated for a result in less than 60 minutes from data receipt; given permissions, automatically emailed results could be possible. However, at the beginning of the mission (hence also in October 2016), given the very different measurement technique (using sky brightness rather than solar imaging), the process may still be manual.

3.5. Indian Mars Orbiter Mission (MOM, or Mangalyaan):

Our contact: Anil Bhardwaj, PI of the MENCA instrument onboard Mangalyaan, director of Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum.

Successful orbit insertion of Mangalyaan occurred on September 24, 2014. Two instruments, MCC (Mars Colour Camera) and TIS (Thermal Infra-red Imaging Spectrometer) might be useful to obtain information on the state of the atmosphere. Note that MOM has a very elliptical orbit (apoapsis of 80000km and periapsis of 370km) with a period of ~76.73 hours. The nominal length of the mission was of 6 (Earth) months, but has been extended. In principle the mission should still be ongoing by the time the ExoMars 2016 EDL occurs. Contact with ISRO (Anil Bhardwaj) confirmed that indeed “it might be possible with support from MCC (Mars Colour Camera), quite fast, and probably TIS (Thermal Infrared Spectrometer)”.

3.6. Terrestrial observations

In October 2016, Mars will be easily observable from the Earth with an apparent angle declining from 8.77″ (arcseconds) on October 1 to 7.9″ on October 21 (to be compared with 18.6″ at opposition on May 22, 2016). Mars weather, and in particular Mars regional- and global-scale dust storm events could be constantly monitored from the Earth using synoptic images of the Mars disc by various means:

- Professional telescopes. Mid-size professional telescopes such as the 1-m planetary telescope at Pic du Midi in France (which provided the best possible Mars telescopic images before the Hubble Space Telescope) would be very suitable for such a monitoring. The managers of this telescope (Our contact: Francois Colas, IMCCE, Paris, France) would be interested in supporting Exomars 2016 within this context, and could employ amateur astronomer.

- Networks of amateur astronomers could do an excellent job in monitoring the onset and evolution of dust storms from all around the world, allowing continuous monitoring. Several organized networks exist, and have contributed to similar projects in the past. Such a project could notably be announced during the European Planetary Science Congress 2015 (Nantes, France, 27 September – 02 October 2015), which includes an “Amateur Astronomy” session suitable to initiate such a project.

- Radio Telescope interferometer operating in the submillimeter wavelength range could do a good job to monitor the atmospheric temperature profiles and their variations. Observation time could be asked to ESO to use the Atacama Large Millimeter Array (ALMA) in Chile within the context of a ”Target or opportunity proposal”, or to the IRAM interferometer (with a proposal in March 2016). However, especially in the case of ALMA, it would be necessary to prepare the retrieval procedure (which can be tricky when using interferometers data) and to validate the results within a preparatory campaign well in advance.
3.7. Conclusions

The most promising datasets are from

- The Mars Reconnaissance Orbiter MCS and MARCI data, which benefit from a regular sun-synchronous low orbit allowing a complete daily mapping of Mars. To favour the collaboration with the MRO team, a formal agreement with NASA would be desirable.

- This should be combined with the ESA Mars Express/PFS measurements.

- In parallel, through another NASA agreement, we should at least use the daily dust opacity measurements from Opportunity (if it is still operative) located near the Exomars EDM landing site.

- Finally, a telescope campaign involving amateur astronomers from all around the world would very well complement the spacecraft observations by helping to detect the onset of dust storms, while enhancing the public outreach of the Exomars 2016 project.

4. Will the atmosphere dust loading change in ~10 days?

4.1. Introduction

The onset of local dust storms on Mars can happen very suddenly, and the development into large regional or even planetary-encircling storms can be rapid and rather unpredictable, taken into account the current knowledge of dust lifting mechanisms and meteorological feedback.

Although operative dust storm forecast currently presents significant challenges (see Section 5), a forecast based on the statistics of past information is more readily achievable, thanks to the plethora of dust optical depth observations available since the Mariner era. In particular, Montabone et al. (2015) have reconstructed the atmospheric dust climatology at all locations on the planet from MY 24 through MY 31 using observations from the Mars Global Surveyor/TES, the Mars Odyssey/THEMIS, and the Mars Reconnaissance Orbiter/MCS. The multiannual dataset of daily gridded maps of retrieved IR absorption column dust optical depth (CDOD) they have produced can serve to the purpose of statistically forecasting the dust loading at selected seasons and locations on the planet. Specifically to Meridiani Planum and Gusev Crater, moreover, the MERs ‘Opportunity’ and ‘Spirit’ have continuously collected near-IR (880 nm wavelength) and visible (440 nm wavelength) CDOD data from about $L_s \sim 330^\circ$ in MY 26, as retrieved by Lemmon et al. (2015) using the onboard PanCam camera observations. Opportunity is still collecting data as of May 2015, while Spirit collected data through $L_s \sim 67^\circ$, MY 29.

In this section, we use the MER ‘Opportunity’ near-IR dataset (Lemmon et al., 2015) and the reconstructed IR absorption dust climatology dataset (Montabone et al., 2015) to estimate the atmospheric CDOD expected in Meridiani at the season of the EDM’s landing, and to examine how much the atmospheric dust loading can change (in statistical terms) over a time period of 10 sols. In other words, we want to estimate the probability $Y\%$ that the CDOD changes by more than $X\%$ after 10 sols, for all sol within EDM’s extended landing window ($L_s = [220^\circ-270^\circ]$) in the Meridiani Planum area.

In order to simplify the tasks of using the results presented in this section and comparing to MER Opportunity PanCam, the calculated values obtained at IR wavelengths in absorption using Montabone et al. (2015) dataset are henceforth converted to equivalent visible and presented as such in
the following graphs and tables. The conversion is operated by multiplying by the factor 2.86, which is the combination of the factor 1.3 for the extinction/absorption conversion (Smith, 2004), and the factor 2.2 for the visible/IR conversion at late solar longitudes (Wolff et al., 2006, Lemmon et al., 2015).

4.2. The dust loading context in Meridiani

In order to put our statistical dust loading forecast (section 4.3) into the general context of the dust distribution in the Meridiani area, Fig. 1 shows the time series of near-IR (880 nm wavelength) CDOD from Opportunity for all available Martian years (MY 26-32, but only a few sols in late MY 26 and only the first part of MY 32), normalized to the reference pressure of 610 Pa. The time series in the visible (440 nm wavelength) are equivalent, and do not present significant differences. The first 250 sols of each year (until about $L_s \approx 120^\circ$) exhibit very little or no interannual variability and decreasing or stationary low values of CDOD (see upper panel). Montabone et al. (2015) included a discussion on the reliability of such low CDOD values at this time of the year. After sol 250, both the values of CDOD and the interannual variability strongly increase. The three equatorial phases described in Montabone et al. (2015)—the early one ($L_s \approx 130^\circ$-$160^\circ$), the middle one ($L_s \approx 220^\circ$-$245^\circ$), and the late one ($L_s \approx 310^\circ$-$330^\circ$)—produce distinctive but repeatable peaks from year to year, if one excludes the signal from the MY 28 planet-encircling dust storm. Focusing on the period $L_s \approx 220^\circ$-$270^\circ$ (Fig. 1, lower panel), which includes the EDM landing window ($L_s \approx 240^\circ$-$250^\circ$), data from Opportunity in Meridiani show two large peaks of dust loading before sol-of-year 470 ($L_s \approx 241^\circ$), originating from regional storms in MY 27 and 29. The atmospheric dust loading after sol-of-year 481 ($L_s \approx 248^\circ$) steadily decreases every year, while approaching the climax of the “solstitial pause” of northern baroclinic wave activity around $L_s \approx 270^\circ$ (Lewis et al., 2015, Mulholland et al., 2015). The sudden dramatic increase in Meridiani from sol-of-year 507 in MY 28 ($L_s \approx 265^\circ$), due to the onset of a planet-encircling dust storm, does not obviously follow the same statistics, but it rather follows the statistics of extreme events.

From the Opportunity time series in the lower panel of Fig. 1 we can plot an histogram of the CDOD normalised to 610 Pa within the range $L_s=[220^\circ$-$270^\circ]$ (sol-of-year=[438-515]), shown in Fig. 2. We have added in the same figure an histogram of the values limited to the landing window $L_s=[240^\circ$-$250^\circ]$ (sol-of-year=[469-485]). These histograms may represent an estimate of the likely dust loading the EDM could encounter during its descent, based on ground observations in Meridiani over the past 5 Martian years. The distributions are rather skewed, therefore the most likely values of CDOD depend on which measure of central tendency one decides to consider. These values are summarized in Table 1 considering the mode, median and mean as different measures of central tendency.

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1 See also the sol-based Mars calendar in Montabone et al., 2015.
Figure 1: Time series of near-IR (880 nm) column dust optical depths as retrieved by Lemmon et al. (2015) from MER 'Opportunity' PanCam at Meridiani Planum (longitude ~5.5°W, latitude ~2.0°S) over 7 Mars years (data are plotted until L_s~50° in MY 32, although Opportunity is still collecting observations as of May 2015). The dashed vertical lines in the upper panel indicate the time range considered in the lower panel and in the subsequent analysis. The values are normalised to the 610 Pa reference pressure. Differences between values retrieved from PanCam at 880 nm (near-IR) and those at 440 nm (visible) are not significant, therefore no factor is needed to convert from near-IR to equivalent visible. The grey envelopes show the daily standard deviation (root mean squared deviation), i.e. the variability within each sol.
Figure 2: Histograms of column dust optical depth retrieved from MER ‘Opportunity’ PanCAM within the solar longitude ranges $L_s=[220^\circ-270^\circ]$ and $L_s=[240^\circ-250^\circ]$, corresponding to the time series in the lower panel of Fig. 1.

The values provided by the analysis of Opportunity observations are also compared in Table 1 to the corresponding values calculated by using the reconstructed dust climatology\(^2\) of Montabone et al. (2015) over an extended area centred in Meridiani (longitude $[21^\circ W, 9^\circ E]$, latitude $[15^\circ S, 10^\circ N]$), from MY 24 through MY 31 (values calculated using only MY 27 through 31 are also provided, for better comparison with Opportunity data). In Figures 3 and 4 we also show the corresponding time series and histograms over the extended solar longitude range $L_s=[220^\circ-270^\circ]$ and the EDL time window $L_s=[240^\circ-250^\circ]$.

There are specific differences between the two datasets (e.g. the peak of CDOD in MY 29 at sol-of-year 461, $L_s\sim235^\circ$, is observed by Opportunity but not reliably present in the reconstructed climatology, and data in the reconstructed climatology is quite noisy when only THEMIS observations are available, as in most of MY 27 and part of MY 28), but overall the statistical information agree

\(^2\) Data extracted from the Montabone et al. (2015) gridded climatology (http://www.mars.lmd.jussieu.fr/mars/dust_climatology/index.html) are filtered to allow only those grid points with: 1) a number of averaged observations $\geq 5$, 2) a time window $\leq 5$ sols, 3) a reliability value $\geq 0.6$. Furthermore, the value of daily column dust optical depth associated to the $[21^\circ W, 9^\circ E]$ lon $\times [15^\circ S, 10^\circ N]$ lat area is calculated using a weighted average with weights provided by the reliability values included in the Montabone et al. (2015) climatology, and is provided for a specific sol only if at least 25% of the grid points in the area are valid.
quite well in pointing toward a likely moderate dust loading during the EDL time window as well as in the extended solar longitude range considered. The inter-annual variability over several Martian years (two of them including the decay or onset of a planetary-scale dust storm in the extended solar longitude range) allows also the reliable estimate of the dispersion around the measures of central tendency, reported in Table 1. We stress again here that planetary-scale dust storms do not follow the statistics of “typical” dust storm seasons; therefore values in Table 1 might underestimate the impact of such storms, particularly if one attained the peak in dust opacity during the EDL window.

Figure 3: Time series of equivalent visible column dust optical depths calculated using Montabone et al. (2015) in an area of longitude [21°W, 9°E], latitude [15°S, 10°N] over 8 Mars years. The dashed vertical lines in the upper panel indicate the time range considered in the lower panel and in the subsequent analysis. The values are normalised to the 610 Pa reference pressure and converted to equivalent visible in extinction from the original IR in absorption. The grey envelopes show the daily standard deviation (combined root mean squared deviations over the given area), i.e. the combined variability within each sol over the given area in Meridiani Planum.
Figure 4: Histograms of column dust optical depth calculated from Montabone et al. (2015) within the solar longitude ranges $L_s=[220^\circ-270^\circ]$ and $L_s=[240^\circ-250^\circ]$ and using either MY 27 through 31, or MY 24 through 31, in an area of longitude $[21^\circ W, 9^\circ E]$, latitude $[15^\circ S, 10^\circ N]$. The values plotted in the histograms correspond to the time series in the lower panel of Fig. 3.
Table 1: Mode, median and mean for histograms in Fig. 2 (near-IR 880 nm column dust optical depth observations from Opportunity/PanCam around longitude 5.5°W, latitude 2.0°S) and for histograms in Fig. 4 (equivalent-visible column dust optical depth reconstructed by using Montabone et al. (2015) in an area of longitude [21°W, 9°E], latitude [15°S, 10°N]). Two solar longitude ranges are provided. Associated uncertainties are calculated as mean absolute deviation for the mode, mean absolute deviation for the median, and root mean squared deviation for the mean. We remind that the mean absolute deviation is minimised by the median, and that the root mean squared deviation is minimised by the mean.

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<tr>
<td>Opportunity MY27-31</td>
<td>[0.80, 0.85] ±0.14</td>
<td>0.88±0.13</td>
<td>0.94±0.23</td>
<td>[0.95, 1.00] ±0.08</td>
<td>0.97±0.08</td>
<td>0.96±0.10</td>
</tr>
<tr>
<td>Montabone et al. (2015) MY 27-31</td>
<td>[0.86, 1.00] ±0.14</td>
<td>0.89±0.14</td>
<td>0.92±0.26</td>
<td>[0.86, 1.00] ±0.11</td>
<td>0.94±0.11</td>
<td>1.00±0.17</td>
</tr>
<tr>
<td>Montabone et al. (2015) MY 24-31</td>
<td>[0.72, 0.86] ±0.29</td>
<td>0.89±0.26</td>
<td>1.03±0.49</td>
<td>[0.86, 1.00] ±0.23</td>
<td>0.97±0.23</td>
<td>1.06±0.34</td>
</tr>
</tbody>
</table>

4.3. Statistical 10-day forecast of dust loading changes

As seen in the lower panels of Fig. 1 and 3, the dust loading decreases with time after sol-of-year 475, Ls~245°. Using the Montabone et al. (2015) dust climatology dataset (opportunely filtered as explained in footnote 2), we have calculated the relative difference in dust loading (i.e. column dust optical depth) between each sol in the solar longitude range [220°-270°] and 10 sols ahead in the future, over three different areas of the planet:

1) within a box centred on Meridiani Planum (longitude [21°W, 9°E], latitude [15°S, 10°N]);
2) In a tropical band (latitude [20°S, 20°N]);
3) In an extended extra-tropical band (latitude [60°S, 60°N]).

The all-year histograms in Fig. 5 clearly show the signature of the decrease in dust loading after Ls~245° (see the significant negative bias in the mean value), despite regional dust storms occurring in MY 24 and 27, a planet-encircling dust storm decaying in MY 25, and another planet-encircling dust storm developing in MY 28 within the considered solar longitude range (see also the lower panel of Fig. 3).

When looking at the specificity of Meridiani Planum during the considered season, the middle and right panel of Fig. 5 show that it is rather representative of the global situation. The histograms are obviously smoother (more grid points are taken into account), but the bias in the mean value due to the general decrease of the dust loading after sol-of-year 475 is still present.

Once again, the global decrease in dust loading after Ls~245° can be linked to the solstitial pause in baroclinic wave activity (Lewis et al., 2015, Mulholland et al., 2015), which reduces dust lifting in the northern regions. This has the consequence of reducing also the probability of large regional cross-equatorial storms, which are one of the main sources of dust loading at this season.
Using the Montabone et al. (2015) multiannual dust climatology dataset, we have calculated the relative difference in dust loading (i.e. column dust optical depth) between each sol in the solar longitude range [220°-270°] and 10 sols ahead in the future, within a box centred on Meridiani Planum (longitude [21°W, 9°E], latitude [15°S, 10°N]), or in a tropical band (latitude [20°S, 20°N]), or in an extended extra-tropical band (latitude [60°S, 60°N]). This figure shows the histogram of this relative difference.

The histograms in Fig. 5 are the intermediate step toward the evaluation of the probability of dust loading changes. In order to statistically estimate the probability Y % that the CDOD changes by more than X % after 10 sols, for all sol within EDM’s extended landing window (Ls=[220°-270°]) in the Meridiani Planum area, we need to consider the cumulative histograms in Fig. 6. They are provided for the same regions as in Fig. 5, with the left panel corresponding to Meridiani. If one makes the assumption that, statistically speaking, for the large number of grid points considered in each histograms (at least 10k grid points), the relative frequency tends to the probability, then the Y values of the cumulative histograms estimate the probability that the column dust optical depth changes by more than the corresponding X value 10 sols in the future. A summary table of values is provided in Table 2.
| Lon=\([21^\circ \text{S}, 9^\circ \text{N}]\), Lat=\([15^\circ \text{S}, 10^\circ \text{N}]\) | All longitudes, Lat=[20°S, 20°N] | All longitudes, Lat=[60°S, 60°N] |
| Change ≥ 10% | Prob. = 49 % | Prob. = 52 % | Prob. = 58 % |
| Change ≥ 20% | Prob. = 14 % | Prob. = 16 % | Prob. = 25 % |
| Change ≥ 30% | Prob. = 6 % | Prob. = 7 % | Prob. = 11 % |
| Change ≥ 40% | Prob. = 3 % | Prob. = 4 % | Prob. = 6 % |
| Change ≥ 50% | Prob. = 2 % | Prob. = 2 % | Prob. = 3 % |

Table 2 : Estimate of the probability that the column dust optical depth changes by more than the value in the left-most column 10 sols ahead in the future, if considering all sols within \(Ls=\)[220°-270°] in three different areas on the planet. Data corresponds to the values marked by dotted lines in Fig. 6.

5. Forecasting atmospheric dust loading and dust storms

5.1. Introduction:

Weather forecasting on Mars is very different from that on the Earth. When compared to Earth, the specificities of the Martian atmosphere (low atmospheric density, water in trace quantities, absence of oceans) provide Mars with a very predictable weather. For a large portion of the year, flow instabilities in the Martian atmosphere do not grow [Newman et al. 2004, Greybush et al. 2013]. On the contrary, this situation never occurs on Earth, where the atmosphere is intrinsically more chaotic. Paradoxically, this makes the prediction of the state of the Martian atmosphere with models more problematic in a certain sense, because the main source of disagreement between model and observations are possibly unknown biases (whether model or observational biases), rather than more or less known flow instabilities [Rogberg et al. 2010].

While forecasting the atmospheric state (i.e temperatures and winds) when the atmosphere is clear of dust is an achievable task in a large part of the atmosphere and at most times, it becomes a much more difficult enterprise when dust storms occur. The main reason comes from the fact that, at the current state of knowledge on the Martian dust cycle, the prediction of the onset of dust storms is not yet reliable. Several factors contribute to make this prediction as such:

- The lack of deep understanding of the mechanisms of dust lifting, including the effects of dynamical thresholds (Mulholland et al., 2013), electric fields, sand-dust interaction, vertical fluxes;
- The lack of knowledge on the time-variable reservoirs of surface dust available to be lifted (including the possibility of differentiating between “fresh dust” and compacted layers);
- The approximate knowledge of the dust particle sizes injected in the turbulent boundary layer and beyond.
- The approximate understanding of the radiative/dynamical feedback that make a local storm transform into a regional one, and ultimately into a planetary-scale storm, within a short time-scale (usually just a few sols).

Once dust is airborne, the transport and sedimentation processes are much better constrained than lifting and atmospheric injection. Furthermore, the radiative impact of dust has been the object of several recent improvements (e.g. Wolff et al., 2009, Madeleine et al., 2011). Provided the size distribution of the airborne dust is known within reasonable uncertainties, models can forecast the
distribution of dust particles and the feedback on the thermal and wind structure. Paradoxically, it would therefore be easier to forecast the evolution of a dust storm that initiated a few sols before EDL than to forecast the possible onset of a storm that presented no signs in the sols preceding the EDL.

There are two cases when the prediction of the onset of a dust storm is facilitated on one extreme, and hardened on the other extreme (at the current state of knowledge). The cross-equatorial or “flushing” storms, mentioned in Section 2.2 and 4.3, belong to the former, while the planetary-scale (also called global-scale or planetary-encircling) storms belong to the latter and are the subject of Section 6.

5.2. Weather forecasting using data assimilation as on Earth

Data assimilation consists in combining all available information to reconstruct a best estimate of the state of the atmosphere. The information comes from two sources of data: observations by instrument(s) and results from a numerical model of the considered system. Thus, assimilation can be seen as an (optimal) extrapolation or interpolation of observations in space and time using a numerical model.

The basic concepts of data assimilation appeared about 60 years ago, when forecasters intended for the first time to use a numerical model to predict the weather to be a few days in advance. Since then, data assimilation has been a flourishing field tackling the issue of the reconstruction of many different geophysical systems, e.g. the Earth atmosphere, oceans, glaciers, oil reservoirs, as well as the Mars atmosphere.

The philosophy of data assimilation is to combine the best of observations (that are usually very precise, but limited in coverage) and model (usually less precise than observations, but with global coverage and access to any geophysical variable). Three families of schemes exist in the literature:

- Nudging, which consist in relaxing the state of the atmosphere in a numerical model towards observations,
- Variational approach, where the best estimate of the atmospheric state is the solution of the minimization of the model with respect to variables (geophysical or model parameters) under the constraint of observations.
- Ensemble Kalman filtering, which relies on the estimation of both the average and the uncertainty of the state of the atmosphere. The spread of this state is computed using an ensemble of numerical simulations (typically 20), run in parallel with slightly different initial states.

The current research in assimilation for Mars’ atmosphere has focused on nudging and ensemble Kalman filtering. A reason why a variational approach has never been developed for Mars could be that such a solution requires the development of an adjoint of the model, a huge task that needs extra effort to take into account any modification in constantly updated and improved models. In Europe, two assimilation schemes exist to possibly forecast weather in advance on Mars:

1) The ACS (Analysis Correction Scheme) (Lorenc et al., 1991) is a nudging scheme derived from the British Meteorological Office that has been used to assimilate TES data (temperature profiles and column dust optical depths) within the UK version of the LMD model (Lewis et al., 1997, 2007, Montabone et al., 2006, 2014). The predictability of this scheme has been addressed in Rogberg et al. (2010), showing that once temperature observations stop being assimilated, the relaxation time towards the model climatology is
a few hours when the atmosphere is dynamically active (e.g. during highly variable dust loading or intense baroclinic wave activity), preventing a reliable forecast beyond this time frame. The reason is that the aerosols distributions (i.e. airborne dust and water ice) used in the version of the model by Rogberg et al. (2010) were not realistic enough. More recently, the assimilation of retrieved vertical profiles of dust and ice from MCS (Steele et al., 2014, Ruan et al., 2014) should go in the direction of improving predictability.

2) The LETKF (Local Ensemble Transform Kalman Filter, Hunt et al., 2006) is an ensemble Kalman filtering scheme developed at the University of Maryland, which is used to assimilate MCS data with the LMD model. When compared to nudging, the asset of using an ensemble of simulations is that the scheme can use model-based correlations between variables that are observed (e.g. temperature) and non-observed (e.g. winds) in space and time, in order to estimate the uncertainties. In Navarro et al. (2014), the use of temperature observations could permit the reconstruction of the dust field in the atmosphere, allowing the possibility to forecast the evolution of a regional dust storm days in advance, although not its onset.

All in all, the ACS and LETKF schemes are still in development and they are not mature enough yet to be used for the purpose of predictability of dust storms. Promising results using the assimilation of temperature and aerosol observations could lead to prediction of the evolution of dust days in advance, once it has already been lifted, injected and observed in the atmosphere. This is made possible by the capability of a numerical model to efficiently simulate the horizontal and vertical transport of dust on a global scale. However, the complexity of dust lifting and atmospheric injection mechanisms (see e.g. Mulholland et al. 2013, Spiga et al. 2013), which induces a lack of understanding of the onset of dust storms - particularly in the models - are the reasons why it is quite unlikely to have soon an assimilation tool that is fully able to predict the occurrence of a dust storm.

5.3. Weather forecasting using weather patterns and teleconnections

We discuss here the possibility of forecasting the possible onset of large dust storms by identifying typical pre-storm patterns already observed in previous years.

Cross-equatorial storms. As mentioned in the introduction to Section 4, there is a particular case of dust storms, called “cross-equatorial” or “flushing” storms, which originate in specific areas – the northern plains – and follow specific southward trajectories, crossing the equator – hence their name – and generally expanding to regional scale once in the southern hemisphere. The onset of these storms is dynamically linked to strong surface winds induced by the passage of low-high pressure systems and fronts in the northern plains in autumn, winter, and early spring. Such weather systems are the manifestation of high latitude baroclinic waves, which contribute to create “storm zones” analogue to the ones originated by Rossby waves on the Earth. Hollingsworth et al. (1996) first recognised the importance of the northern lowlands orography in setting up Martian storm zones, as a counterpart of the Terrestrial surface thermal contrasts. Hollingsworth et al. (1997) then studied the seasonal variations of such storm zones, to recognise that during northern autumn, winter and spring seasons, localized “storm zones” can occur which are particularly strong within the lowlands of Arcadia, Acidalia and Utopia planitia. During early northern spring, the baroclinic wave activity is stronger than that found during any other season. In more recent studies, Wang et al. (2003, 2005), Wang
(2007) and Wang and Richardson (2015) have followed the onset and development of flushing storms from the northern plains to their expansion in southern hemisphere in years observed by spacecraft cameras, i.e. MOC onboard MGS (MY 24, 25, 26) and MARCI onboard MRO (MY 28 through 30). The link between baroclinic waves and flushing storms has been established, and the roles of thermal tides and western boundary currents have been identified as likely mechanisms for the southward cross-equatorial trajectories. Wang and Richardson (2015) in particular is a good source as a catalogue of large (i.e. regional-scale) dust storm origination areas and routes, providing typical trajectories and development styles of specific typologies of regional-scale storms, including the cross-equatorial ones.

**Transient teleconnection event.** Another type of “pattern” related to weather events has been recognised on Mars. Dust storms produce strong localised heating of the atmosphere, which in turns can interfere with the typical patterns of thermal tides and other Martian waves sensitive to heat fluxes. Such interference can originate transient modifications of the wave patterns, which tend to induce temporary alterations of the thermal and wind structures. The net effect is what Montabone et al. (2008) and Martinez-Alvarado et al. (2009) identified as “transient teleconnection event”. In contrast with teleconnection patterns, which can be thought as vast atmospheric regions dynamically coupled over long time scales, a transient teleconnection event couples distant regions over much shorter time scales, through the propagation of some kind of mediating signal.

The signature of a transient teleconnection event, for instance, has been identified in a data assimilation dataset of the Martian atmosphere (which includes observations from the Mars Global Surveyor/TES instrument) during the onset of the 2001 (MY 25) planet-encircling dust storm. Montabone et al. (2008) and Martinez-Alvarado et al. (2009) have identified a long-range radiative-dynamical coupling between the site where a regional dust storm (about a thousand kilometres across) had its explosive growth, near the Hellas Planitia basin, and the area where subsequent storms appeared in the Tharsis region, on the opposite side of the planet. In this specific case, the mediating signal that allowed the teleconnection has been identified in the interference of the diurnal and “Kelvin” components of the thermal tides.

In another study, Montabone et al. (2015b) describe another possible transient teleconnection event, coupling the northern and southern hemispheres rather than the eastern and western ones. This event originates from the development of a large regional dust storm (analogously to the previously mentioned one) occurring in late MY 26, which seems to induce a radiative-dynamical coupling between the two hemispheres. This event had as consequences a strong enhancement of the northern polar warming and significant modifications of the structure and intensity of the northern polar vortex.

**Conclusions.** Storm zones, teleconnection events, and generally speaking “weather patterns” are, therefore, coherent and usually repetitive manifestations of weather phenomena that might help to forecast future events. On Earth, indexes are usually associated to long-term teleconnection patterns, which help to assess seasonal and monthly weather forecasts. A well-known example is the manifestation of *El Niño* (or the opposite phase, *La Niña*) in the central and east-central equatorial Pacific Ocean, which induces strong effects in several parts of the world (e.g. rise in surface pressure over the Indian Ocean, Indonesia, Australia, weakening of trade winds in the south Pacific, rains in the northern Peruvian deserts, etc.). A “warm phase” index is associated to *El Niño* Southern Oscillation, while a “cold phase” index is associated to *La Niña* counterpart.

On Mars, although several studies have identified weather patterns and possible teleconnections (at least short-term ones), there is currently no systematic study available on the identification and
indexing of patterns specifically related to dust storms onset and/or development, beyond the statistics of past events.

This study (or at least minor components of such a major study) could be provided on the basis of a specific preparative work for the EDM’s EDL.

6. The extreme case: Observations of global-scale dust storm onset

The minimum objective of Mars weather forecast for the Exomars 2016 EDL is to identify if a high opacity global-scale dust storm will be active during EDL. If the storm is already active 7 days before EDL, past observations show that the evolution of the storm is slow and highly predictable. However, what do such past observations tell us about the onset of these dust storms on a weekly time scale?

If forecasting the onset of a local or regional dust storm is difficult, forecasting the onset of a dust storm that attains a global (or planetary) scale – i.e. encircles all longitudes within a large latitudinal band– is even more difficult at the current state of the knowledge. **Planetary-encircling dust storms develop suddenly, rapidly, most of the times as a combination of multiple regional storms.** The atmospheric dust loading usually increases explosively by more than 5-fold within 10 sols, reaches a peak within 30–40 sols before dust lifting is shut down, then decays slowly over a long period of time (even longer than 150 sols, depending on the peak value) after sedimentation prevails, to eventually attain typical background values again. All these phases can be clearly recognised in Fig. 7, where we plot the time series of the MY 25 and MY 28 column dust optical depth in an area included in Meridiani Planum, using data extracted from the Montabone et al. (2015) dust climatology. At the end of June/early July 2001 (MY 25, sol-of-year~384, L~186°) one of the four best observed planet-encircling dust storms developed, followed by a storm at the end of June 2007 (MY 28, sol-of-year~505, L~264°). The former – an equinoctial storm – was observed by instruments onboard the Mars Global Surveyor (mainly the MOC camera and the TES spectrometer), while the latter – a solstitial storm – was captured by instruments on board the Mars Reconnaissance Orbiter (mainly the MARCI camera and the MCS radiometer) as well as on board the Mars Express spacecraft (mainly the PFS spectrometer). Before these most recent global-scale storms, instruments onboard the Viking orbiters and landers had the chance to observe and measure the development of two planet-encircling storms in 1977, one late equinoctial storm in February (MY 12, L~204°) and one solstitial storm in late May (MY 12, L~268°).

Five confirmed global dust storms have been observed by instruments either in Mars orbit or on the Martian surface—one in 1971 (MY 9; Mariner 9), two in 1977 (MY 12; Viking), one in 2001 (MY 25; MGS), and one in 2007 (MY 28; ODY/MRO/MEX). One additional storm, in 1982 (MY 15) was identified from VL1 pressure observations and two more confirmed storms—one in 1956 (MY 1) and one in 1973 (MY 10)—are well documented in the ground-based telescopic record (See also EXMS-TNO-LMD-0063 for a detailed report of all known global-scale storms to date). On this basis, a very rough estimation of the probability of the onset of a global-scale dust storm within a given week (7 sols) during the ~250 sols dust storm season (L~180°-330°) over Martian years 1-32 yields a probability of the order of 1% [i.e. 8 storms /(32 Martian years * (250 sols/7 sols)) = 0.7% < 1%]. It must be stressed that this very general and roughly calculated value of probability does not take into account the increase or decrease of probability depending on the specific season and location, nor it takes into account the fact that the probability distribution of global-scale dust storms likely follows that of extreme episodic events rather than a classic Gaussian probability, therefore inferring probability values from past frequencies might not be a valid approach, as much as it is not valid, for instance, in the cases of the stock market and earthquake forecast.
Figure 7: Time series of equivalent visible column dust optical depths calculated using Montabone et al. (2015) in an area of longitude \([21°W, 9°E]\), latitude \([15°S, 10°N]\) within Meridiani Planum for Martian years 25 and 28, when the 2001 and 2007 planet-encircling dust storms occurred, respectively. The dashed vertical line in the upper panel indicates the limit of the time range considered in the lower panel (i.e. \(L_s=[180°-360°]\)). The values are normalised to the 610 Pa reference pressure and converted to equivalent visible in extinction from the original IR in absorption. The grey envelopes show the daily standard deviation (combined root mean squared deviations over the given area), i.e. the combined variability within each sol over the given area in Meridiani Planum.

The main difficulties in forecasting the onset of what can become a planet-encircling dust storm are:

- These kind of storms can start as a local or regional-scale storm with no apparent preferential location within an extended band of latitudes (excluding the high latitudes);

- They do not have preferential solar longitudes (see e.g. Fig. 4 of Montabone, 2012 report), although they seem to cluster around northern hemisphere autumn equinox (equinoctial storms) and winter solstice (solstitial storms);

- They do not seemingly have a preferential time interval between two consecutive occurrences (e.g. two of such storms occurred in MY 12, but three Martian years passed between the one in MY 25 and the one in MY 28, and none occurred for the last 4 years);

- The dust loading background in the sols preceding the onset of a planet-encircling dust storm may look very similar to the one present at the same season in years without global-scale storms. The simple monitoring of dust opacity, therefore, might not be sufficient if it is not associated to the monitoring of dynamical variables such as temperature, pressure, or (possibly derived) winds.

As an illustration of the variability among the two best observed global-scale storms, we summarise here the events that characterised their respective initiations.
2001 storm (MY 25). Strausberg et al. (2005) is one of the studies that describe the onset of the 2001 storm. They use MOC wide-angle images and TES temperature and aerosol opacities retrievals. According to their analysis, the initiation of the storm “began along the northwestern rim of the Hellas basin just before southern spring solstice. The storm was initiated as several local dust storms propagated into Hellas from the seasonal ice cap edge to the south. Seasonal cap edge dust storm activity prior to $L_n = 177°$ was little different in 2001 to that in the previous Martian year. However, between $L_n = 177°$ and $178°$, the area of local cap edge storm activity dramatically increased over that of the previous year, with this increase due almost completely to increased activity in the vicinity of Hellas, with area of lofted dust exceeding that in 1999 by over a factor of two thereafter. (…) Expansion of the storm out of the Hellas basin initially occurred to the north and to the east. No sustained transport to the west was observed, although ‘pulses’ of dust to the west were. (…) For five days following $L_n = 182°$, the storm persisted as a regional event spilling north and east of Hellas, but without significant net growth. After $L_n = 185°$, the dust storm rapidly broke out of the Hellas region, with large amounts of dust spilling across Hesperia. The highly asymmetric dust spreading, to the east and not to the west, does not appear to be a ready consequence of winds predicted by numerical models, which do not show such mono-directionality. (…) At the same time as the eastward expansion, dust began spreading to the south, across the southern cap. The main dust cloud reached the edge of Tharsis just before $L_n = 190°$. At this point, distinct secondary dust lifting events occurred on the Tharsis plateau to the south of the ridge volcanoes, in Solis/Syria and Daedalia. Three degrees of $L_n$ after the activation of the Solis/Syria/Daedalia lifting center, the storm had become fully global.”

2007 storm (MY 28). Wang and Richardson (2015) describe the onset of the 2007 storm (MY 28) using MARCI Mars Daily Global Maps (MDGM): “While the 2001 global storm was unambiguously triggered in the mid-southern latitudes, the origin of the 2007 storm was less obvious. The major growth of the 2007 storm was at southern mid-latitudes between Hellas and Noachis. However, a confined (‘flushing’) dust storm was observed moving southwards from Chryse to Margaritifer Terra prior to the onset of subsequent major dust lifting. This raises the possibility that the Chryse storm in some way triggered or merged with the southern mid-latitude dust storm. (…) Ambiguity in this association, however, arises from the nature of the data coverage. The remainder of the 2007 global dust storm initiation played out directly from the Noachis dust storm. The MDGM sequence shows the lifting in Noachis to strengthen over the next 3 sols with very little lateral motion. A threshold appears to have been dramatically crossed between Day 6 and 7, as the storm explosively grew during Day 7. Multiple secondary dust lifting centers appear to have become involved as early as Day 8 or 9 in the MDGM sequence. By the 10th day, the storm is well on its way toward planet-encircling scale.”

It should be reported here that a most recently study from Shirley (2015) claims a “statistically significant” correlation between the occurrence (and non-occurrence) of global-scale dust storms and the changes of Mars’ orbital angular momentum with respect to the Solar System barycentre. This study uses their claimed correlation as a necessary-but-not-sufficient condition to forecast the presence or absence of global-scale storms in the next seven Mars years. Could indeed this study help to forecast the onset of a global storm in the future? The main limits of the study, clearly recognized by the author, are that 1) there is no hypothesis made on the physical mechanism(s) that would favour the onset of a global-scale dust storm when changes on the Mars’ orbital angular momentum occur, and 2) even if an (arguably significant) correlation meant that there was an underlying physical mechanism(s), the scale of the forcing could be far too small compared to other necessary conditions - e.g. the availability of dust to be lifted - to have an appreciable impact. At the current state of knowledge, it is our opinion that the forecast presented in this study cannot be reliably used unless future work establishes the underlying physical mechanisms validating the claimed correlation, and assesses the scale of the related forcing. For completeness, though, we report here the forecast included in Shirley (2015) for MY 32 and MY 33. For MY 32, “as there appears to be no strong preponderance of evidence in favor of either alternative (global-scale storm or no global-scale storm), we are unable to provide an evidence-based forecast for this season.” For MY 33, “if no global-scale storm occurs in the 2014–2015 dust storm season, then a mid-season GSFS event is likely to occur in the 2016 perihelion season.” As far as Exomars EDM landing is concerned, therefore, since no global-scale storm occurred in MY 32, the forecast included in Shirley (2015) warns of a likely solstitial
storm event in MY 33. It must be stressed, though, that the forecast is so vague (no measure of probability provided, no indication of likely time and/or location of initiation, no indication of peak dust optical depth, etc.) that it has effectively no practical usefulness.

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