MAJOR CHALLENGES IN MARS CLIMATE MODELING: DUST, CLOUDS AND WAVES.

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Introduction: The Mars atmosphere Global Climate Model (GCM) developed at the Laboratoire de Météorologie Dynamique in collaboration with several teams in Europe (LATMOS, the Instituto de Astrofisica de Andalucia University of Oxford, The Open University), and with the support of ESA and CNES is currently used for many kind of applications. Our primary objective is to predict all details of the Mars Climate system, including the dust, water, CO_2 and photochemical cycles from the surface to the exobase, yet only on the basis of universal equations.

For such a project, the core of the modelling effort has to be on the accurate simulation of temperatures and winds, themselves directly influenced by the dust distribution and ice clouds. While the GCM is now able to predict temperature observations with an error better than 10 K at most location and time, we have found that to improve the accuracy of the GCM it is necessary to update our representation of several physical processes at work in the Martian atmosphere.

1. The **vertical distribution of the dust**, which has been shown by the Mars Climate Sounder to be characterized by detached layers around 20 to 30 km, and by large day-night variations (*McCleese et al., 2010; Heavens et al., 2011a,b,c, Navarro et al. 2014a*). These characteristics are not spontaneously predicted by our GCM (e.g. *Madeleine et al.* 2011).
2. The **spatial and temporal distribution of clouds**, which have been shown to strongly impact the thermal structure and circulation of the atmosphere. The GCM does an acceptable job of predicting clouds and water vapor (*Navarro et al.* 2014b), but it is still a challenge to reach a good accuracy and represent well the radiative impacts of clouds.
3. The effect of **gravity waves** (orographic and/or non-orographic) which have been found to have a small, but significant impact on the temperatures of the atmosphere below 80 km (and much more above). See *Gilli et al.*, this issue.
4. Ultimately a process shown to be incorrectly represented in the GCM is the **phasing of the thermal tide wave** in the vertical. This incorrect behavior is probably resulting from the incorrect representation of the three processes mentioned above.

During the workshop, we will discuss these challenges and what we are doing to address them in the LMD GCM.

Dust vertical distribution. Various physical processes have been proposed to explain the formation of dust detached layers in the Martian atmosphere and their diurnal variations: scavenging by water ice clouds (estimated to be negligible by *Navarro et al.* 2014b); solar induced convective motions in local and regional dust storms ("Rocket dust storms" in *Spiga et al.* 2013), or injection by slope winds above mountain tops (e.g. *Rafkin et al.,* 2002).

We have developed a parametrisation of the "Rocket dust storm" processes. Such convective storms inevitably occur in mesoscale simulations with a few kilometers resolution (*Spiga et al. 2013),* but not in GCM with ~200 km resolution. To account for the small scale processes, when dust is lifted in the model, we represent the dust storm as clouds of dust only filling a fraction of the GCM mesh. The radiative transfer is computed twice, so that we can estimate the radiative heating and cooling inside and outside the subgrid scale dust storm. On the basis of our analysis of the Meso-scale simulations, we then assume that the extra radiative heating (due to absorption of sunlight by the storm dust during daytime) is instantaneously converted into a vertical motion that results in an adiabatic cooling equal to the extra heating. We compute the corresponding vertical transport of the storm dust in a subgrid column, as well as its progressive "detrainment" and mixing with the background dust that fills the entire grid mesh.

Figure 1 illustrates the typical behaviour of such a rocket dust storm in the GCM, induced by a local dust storm around Ls=154°. In comparison with observations, the actual evolution of the dust field agrees much better with the MCS observations than in the traditional GCM, as shown on Figure 2. However, this is only true when dust storms are active, i.e. during the dusty seasons. During the clear season, when dust lifting in storms is negligible, we found that detached dust layers cannot be maintained in the GCM simulations, whereas they are osbserved in reality.

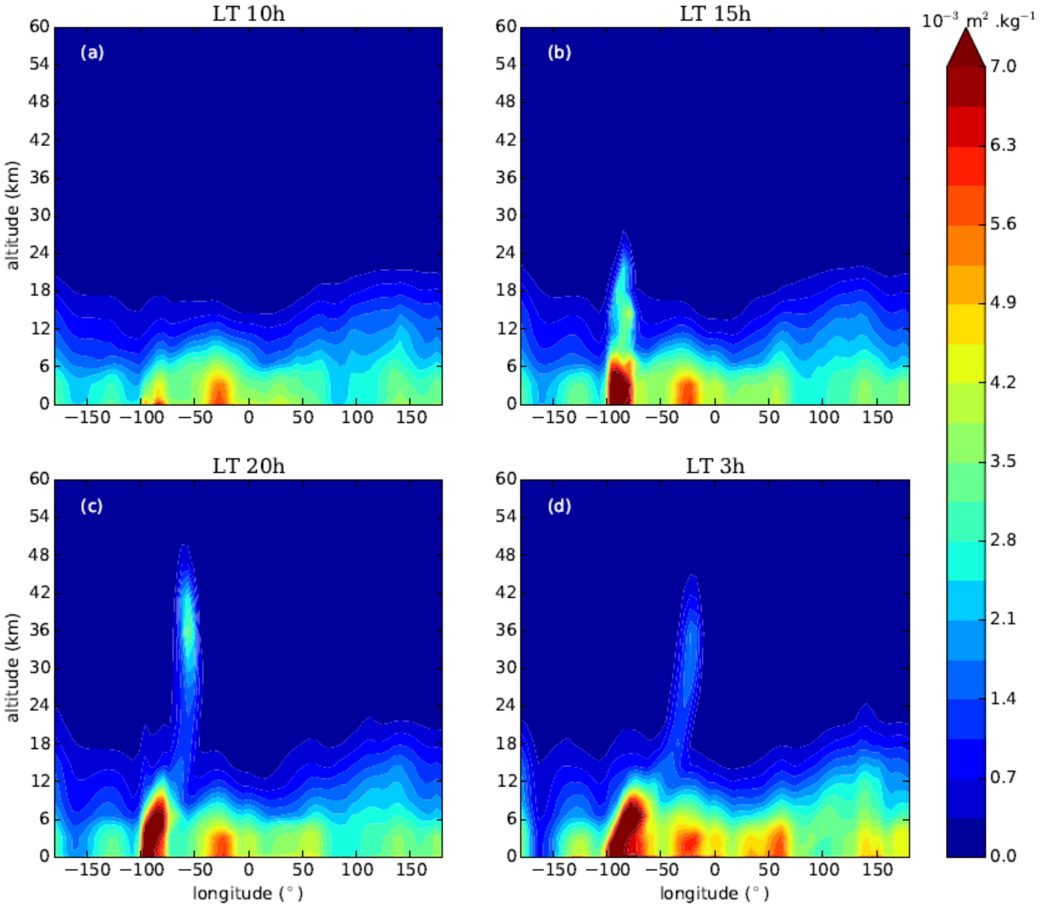

Figure 1. An exemple of simulated rocket dust storm. Cross-sections of the dust visible density-scaled opacity (DSO) at lat=56.25°N at various local times. Season is late northern summer (Ls = 153.8-154.4°). From *Wang et al.* (in preparation for JGR, 2017)

To improve the modeling of the clear seasons, we are including a second parametrisation designed to represent another sub-grid scale process: the injection of the near-surface atmospheric dust into the atmosphere at 20-30 km by the thermal circulation above mountain tops as in *Rafkin et al.* (2002). Our scheme includes a map of the summit tops and their scales in each GCM mesh, and an estimation of the daytime upward wind profile above these tops calculated on the basis of atmospheric physic principles. As in the rocket dust storm parametrisation described above, dust vertical transport is performed in a subgrid-scale column in which the radiative heating is calculated separately, so that the "rocket dust storm" convective effect can play a role in the dust injection to high altitude during daytime. Preliminary simulations yield promising results, with the formation of detached dust layer at the right seasons (Figure 3). However more work is required to tune the scheme and match the observations all year long.

Accounting for subgrid-scale clouds. In 2010-2014, several key improvements were included in our representation of water ice clouds to account for their radiative effects (*Madeleine et al.* 2012) and better calculate their microphysics (*Navarro et al.*, 2014b). These developments allowed to better account for the influence of clouds on the temperature and control their formation. However, the GCM remained highly sensitive to poorly known parameters, and was not able to quantitatively simulate the water vapor and cloud content (polar hood) in the polar regions simultaneously with the right water vapor and cloud content (aphelion belt) in the equatorial region (*Navarro et al.*, 2014b). To further improve our representation of the Martian cloudiness, we now include an effect which is of key importance in Earth GCMs, and usually neglected in Martian models: the fact that clouds can be much smaller than a GCM grid mesh, so that they usually only form and cover a fraction of the meshes. For this purpose, we assume that within a grid mesh, the atmospheric temperature exhibits subgrid-scale variations of the order of a few Kelvins (this "ΔT" is the key parameter of the parametrisation). Therefore, at a given timestep it often happens that only a fraction of the mesh undergoes water vapor saturation and condensation. In practice we assume that cloud formation only occurs in this fraction of the mesh. We use the mean temperature in this fraction to compute the cloud microphysics (ice nucleation and growth), and separately compute the radiative transfer in the fraction of the mesh occupied by the clouds and in the rest of the mesh ("clear-sky" fraction). Preliminary results indicate that the behaviour of the GCM is improved when using this simulations, notably because the clouds induce less destabilizing threshold effects when they form. Furthermore, we find that this scheme yield to a better representation of the seasonal water vapor and cloud cycle, as illustrated in Figure 4.

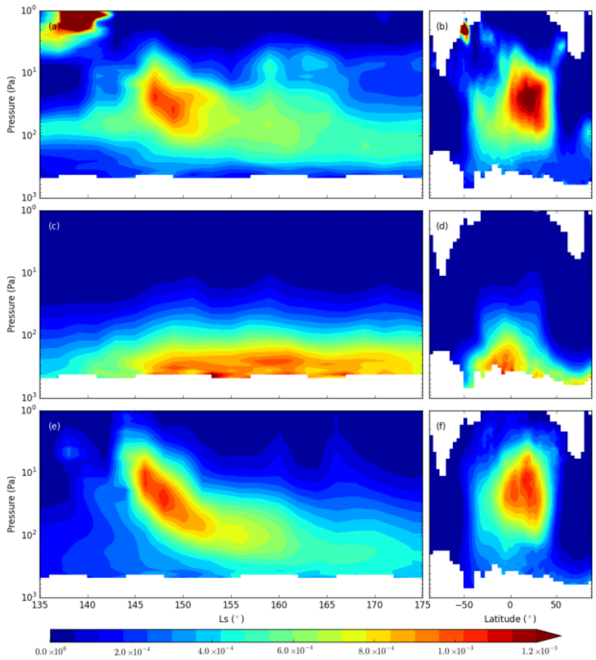

Figure 2. The nighttime Dust Scale Opacity (DSO) from the MCS observation (*McCleese et al*. 2010) on Martian year 29 (a, b), simulations by our traditional GCM (c, d) and by the GCM with the rocket dust storm parameterization (e, f). All data are binned in Ls (every 5°). In the left column, dust DSO averaged over latitude from 10°S to 10°N and all longitudes are plotted. In the right column, zonal mean of dust DSO from Ls = 145° to 150° are displayed.

The effect of gravity waves. Further discrepancies between the GCM and the MCS observations have been revealed, notably when performing data assimilation (see *Navarro et al.*, this issue). We are including a new parametrisation of the non-orographic gravity waves on the circulation which is found to significantly improve the model-observation agreement. This is discussed in details in *Gilli et al.* (This issue)

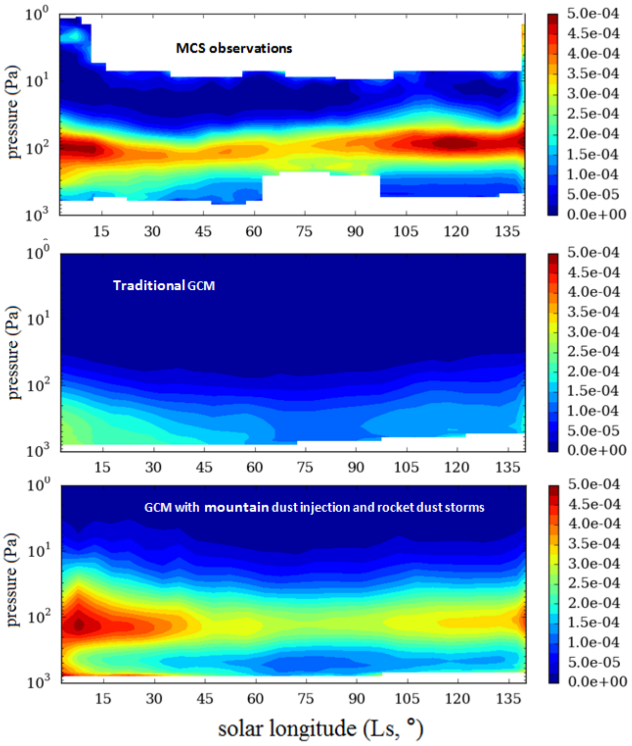

Figure 3. **Top:** Equatorial nighttime Dust Scale Opacity (DSO) observed by MCS (*McCleese et al.* 2010) on Martian year 29. **Middle** simulations by our traditional GCM **Bottom**. GCM simulation including the upward transport of near-surface atmospheric dust by the thermal circulation above mountain top (*Wang et al.*, in preparation).

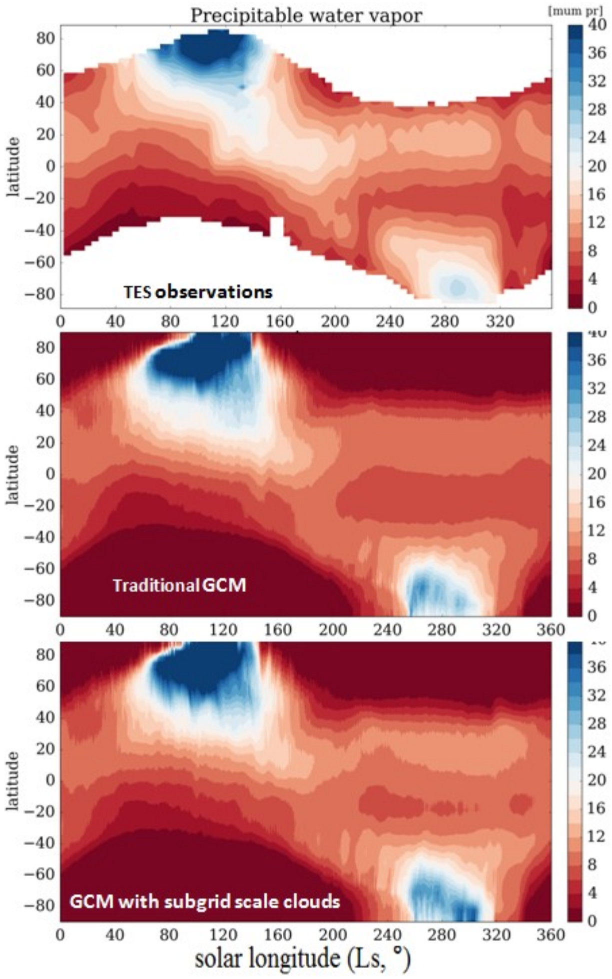

Figure 4. The daytime sonal-mean water vapor seasonal evolution observed by TES (*Smith et al.* 2002) compared to simulations performed with the "traditionnal "LMD GCM described in *Navarro et al.* (2014b) and with the same GCM including a new parametrization of subgrid-scale clouds with ΔT=3K (see text). Figure from Alizee Pottier PhD thesis.

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