THE CHALLENGE OF ATMOSPHERIC DATA ASSIMILATION: ILLUSTRATION WITH THE LMD GCM, MCS OBSERVATIONS AND A KALMAN FILTER METHOD

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Introduction:

The ever-growing number of missions to Mars gives us an unprecedented amount of datasets, with a continuous coverage of the monitoring of the Martian atmosphere. This trend is not expected to slow down, as more and more countries are interested in the scientific exploration of Mars (Figure 1). Therefore, Mars science is turning from the one of a distant astronomical object to the one of a frequently observed physical system for which we have an increasing number of datasets of climatology, such as Earth is.

In this context of observational data deluge, the need to make sense of observations is a new challenge for Martian atmospheric science. Data assimilation is an ideal approach to tackle this issue [1,2], which consists of the extrapolation of observations with the use of a global climate model.

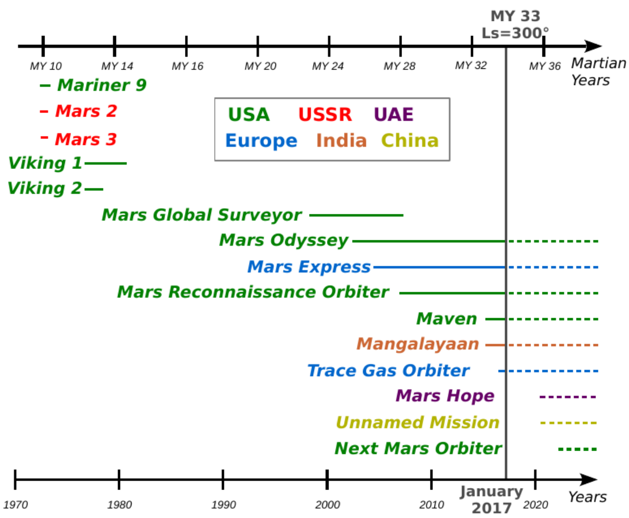

Figure 1: All Mars scientific missions that successfully went into orbit or are planned to. An increasing number of missions occurs now and is expected in the near future.

Data Assimilation:

Data assimilation is a technique widely used in geophysical sciences, especially meteorology and weather forecast. It optimally reconstructs a best estimate of the atmospheric state by combining instrumental observations and an *a priori* (or *background*) provided by a numerical model.

Usually, atmospheric observations are more reliable than the result of a global climate model. However, they are scattered or with a limited spatial and time coverage, and restricted to observable variables only, such as winds or temperature for instance. The advantage of a model, in contrast, is the possibility to have access to any physical variable at any location. As illustrated in Figure 2, the aim of data assimilation is to extrapolate in space and time the observations with the means of a model in order to recover the state of the atmosphere as complete and as accurate as possible, given the two sources of information that are observations and our knowledge of the physics put in a numerical model.

Mars in the context of assimilation:

Historically, assimilation was developed for the purpose of weather forecast on Earth. However, when compared to Earth, Mars has a very low atmospheric density and a shorter typical radiative timescale [3,4]. As a consequence, the Martian atmospheric variability is dominated by the diurnal cycle on its surface.

Also, oceans on Earth are huge thermal reservoirs with timescales orders of magnitude larger than the atmospheric ones. They damp atmospheric diurnal variations, at least locally. The lack of oceans, or any such energy reservoir in close interaction with the Martian atmosphere, prevents the attenuation of the Martian diurnal cycle as on Earth. All these elements give Mars a strong direct solar radiative forcing at the surface, giving the planet a “hypercontinental” climate.

In theory, this confers Mars a very predictable weather, but that does not go without consequences for atmospheric data assimilation. For a large portion of the year, instabilities in the Martian atmosphere do not grow [5,6], a situation that never occurs on Earth, where the atmosphere is intrinsically more chaotic. Paradoxically, this makes assimilation of Martian data more difficult, because the main source of disagreement between model and observations are biases (whether these are model or observational biases), rather than flow instabilities [3].

Observations - Mars Climate Sounder data:

The Mars Climate Sounder (MCS) is a limb-viewing spectrometer on board the sun-synchronous spacecraft Mars Reconnaissance Orbiter [7]. It has provided vertical profiles of atmospheric temperatures, dust and water ice opacities since MY 28. Its high density of data, with a new acquisition every 30 seconds in nominal mode, makes it ideal for assimilation.

LMD Global Climate Model (GCM):

The LMD GCM [8] is a finite-difference model, with equations of the hydrodynamics and parameterization of the physics that includes the radiative transfer of CO_2 gas and aerosols (dust and water ice); the condensation of CO_2; the lifting and transport of dust for which the total column opacity is prescribed by a scenario; a water cycle with microphysics of ice clouds that interact with dust; etc… It is used with a resolution of 64 longitudes by 48 latitudes points, and 36 vertical levels (up to approximately 150 km).

Ensemble Kalman Filter:

The Local Ensemble Transform Kalman Filter (LETKF) developed by the University of Maryland [9,10] is the method used here for assimilation. As a Kalman filter, the LETKF estimates both the physical state of the Martian atmosphere and its uncertainty as function of time. The uncertainty of the model is assessed by an ensemble of GCM simulations (Figure 2) to map all the possible trajectories taken by the atmospheric system, and compared to MCS errors in order to construct an *analysis*, which is the optimal combination of the MCS data and the LMD GCM, from the *background* of the model.

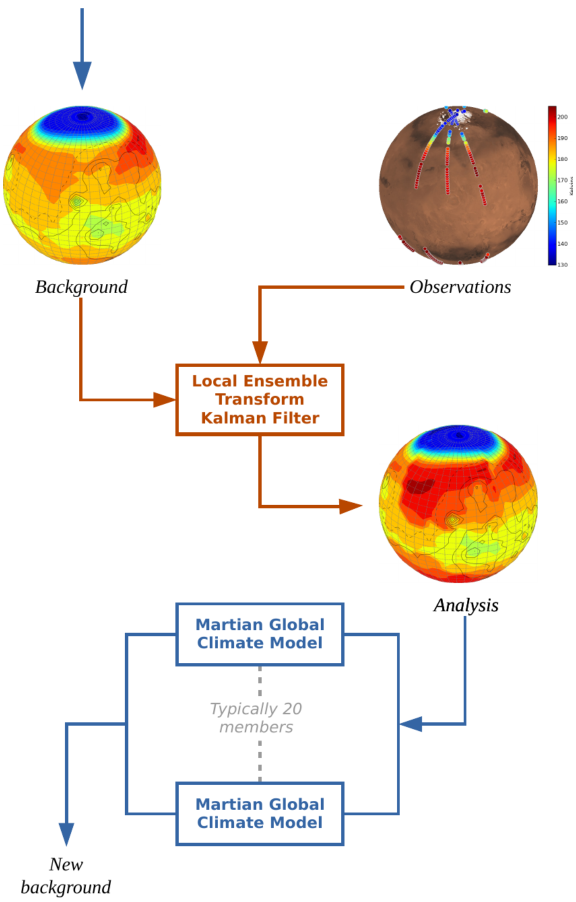

Figure 2: Illustration of a cycle of data assimilation. A new cycle, and a new analysis, occur every 6 hours.

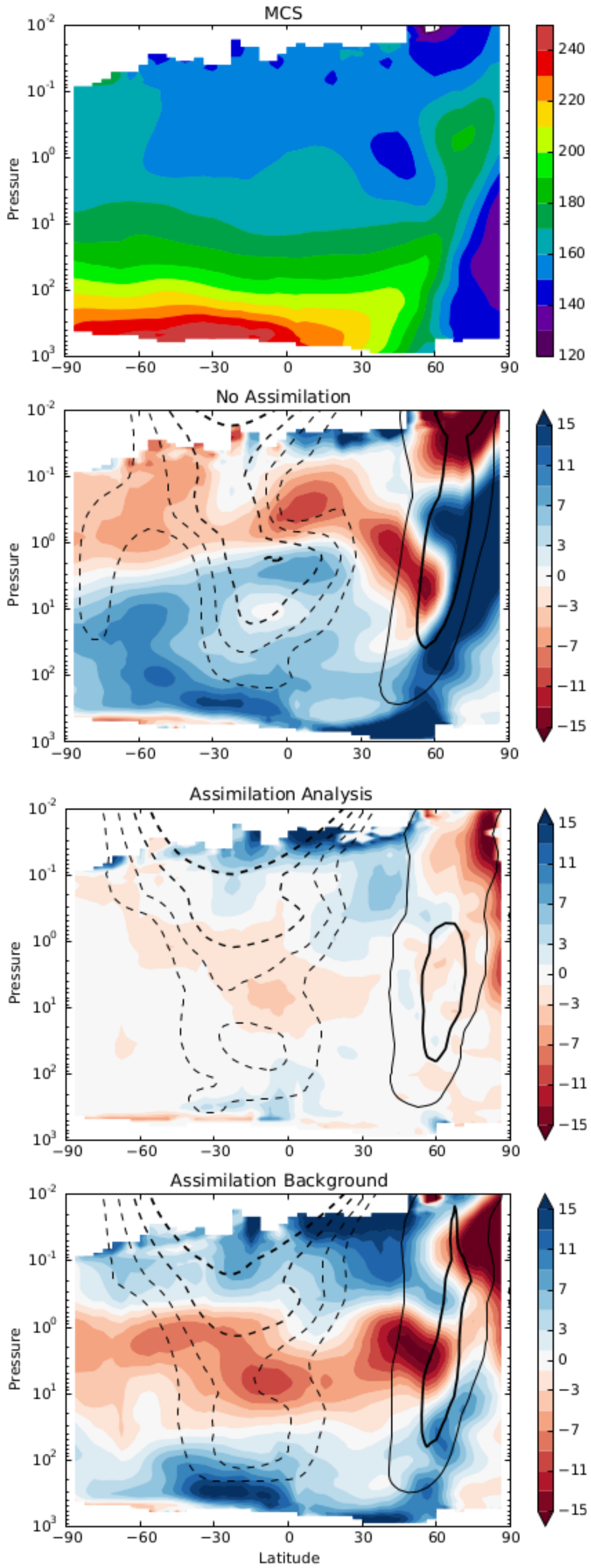

Figure 3: Zonal average of dayside temperatures at M29, Ls=300° - 305° for MCS, and its difference with the model for a case without assimilation and one with (background and analysis). Red (blue) indicates that the model is warmer (colder) than observations. Zonal winds are indicated in contours.

Assimilation of temperature:

Here are presented results of an assimilation of temperature alone for the second half of MY29. In Figure 3, there is a difference that can exceed 15 K between MCS and the GCM without assimilation, reduced to 3 K in the analysis of the assimilation. However, the background of the assimilation exhibits differences with values in line with the case without assimilation, meaning that 6 hours after the information has been provided by the observations, the performance of the atmospheric state in the model is nearly the same as the one without assimilation. Zonal winds are changed by the assimilation of temperature, and stay changed in the background, but are not sufficient to hold the good comparison with observations obtained with the analysis.

The reason for this behavior is due to the shift of the thermal tide (Figure 4). Without assimilation, significant differences exist between the model and MCS, but the structure of the thermal tide is in good comparison with MCS. The assimilation tends to get model temperatures closer to MCS, but disrupts the thermal tide, which is the reason why the background evolves towards an atmospheric away from the analysis.

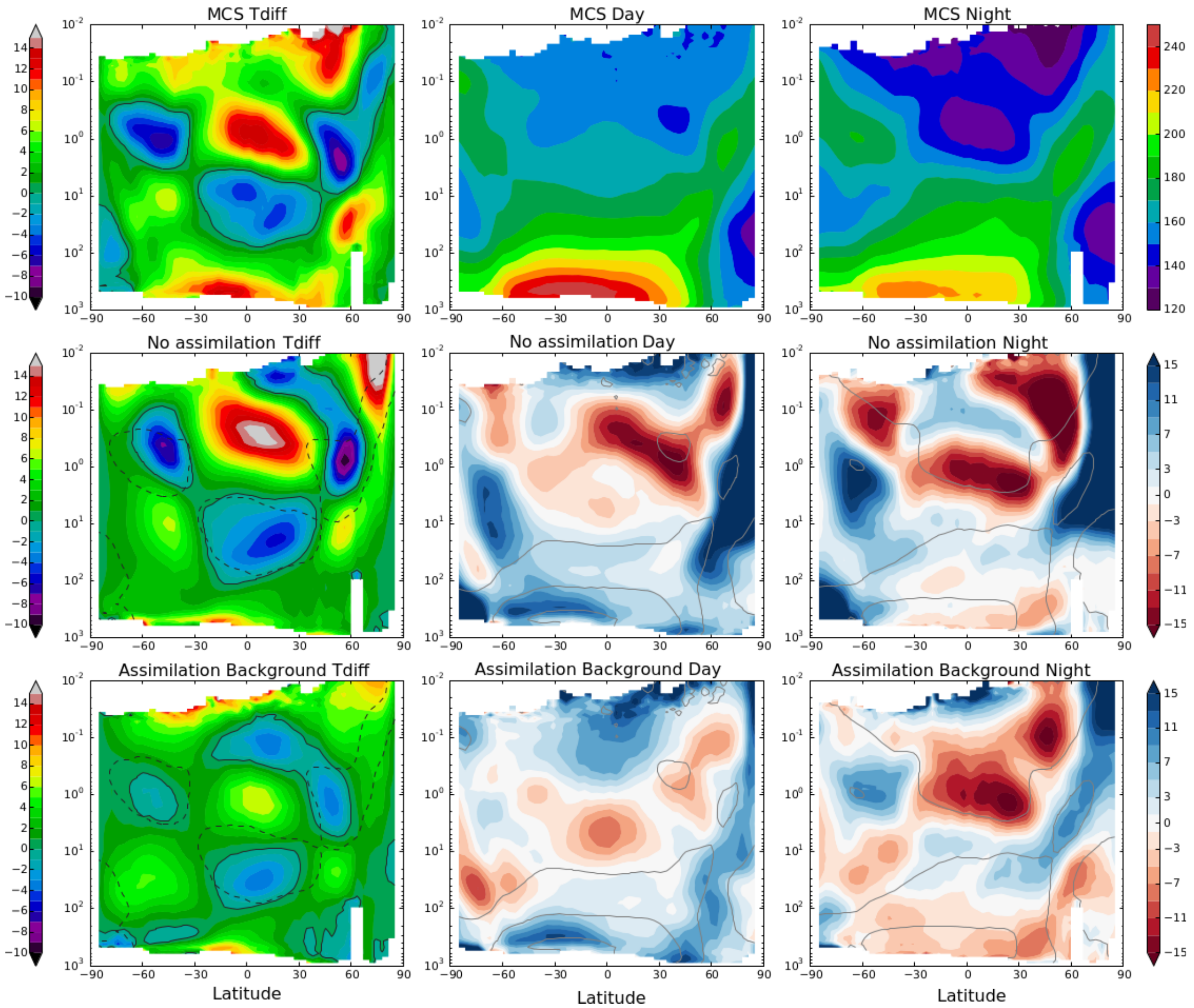

Figure 4: Zonal average of MCS dayside and nightside temperatures for MY29, Ls=200-210°, and their difference, that shows the structure of the thermal tide in the tropics and its opposite mode at greater latitudes. As in figure 3, temperature is compared for a case without assimilation and with assimilation of temperature, for the background.

Assimilation of aerosols:

To take into account the correct structure of the thermal tide, we assimilated MCS observations of aerosols along with temperature. Unfortunately, the effect on this thermal tide shows little improvement over the case where temperature only is assimilated.

Although not fully satisfying, the assimilation of aerosols gives us the possibility to locally predict the evolution of the Martian atmosphere for a few days in the favorable case of a regional dust storm, as shown in Figure 5, a great improvement over the case where temperature only is assimilated, but for those particular case only.

The assimilation of water ice is extremely challenging, as it depends to a great extent on the accuracy of temperature. In order to assimilate water ice with temperature, the addition or removal of water ice or vapor in the analysis state is done in line with its temperature increments so that the analysis state shows coherence between temperature and ice, i.e. there is no vapor in excess of saturation or ice without vapor saturation before the ensemble of model simulations is started again. In the resulting assimilation, the ice field is generally not in agreement with the observations, both because the temperature reaches an unrealistic equilibrium (as explained above) and because vapor is not transported to places where a water ice cloud should occur according to MCS.

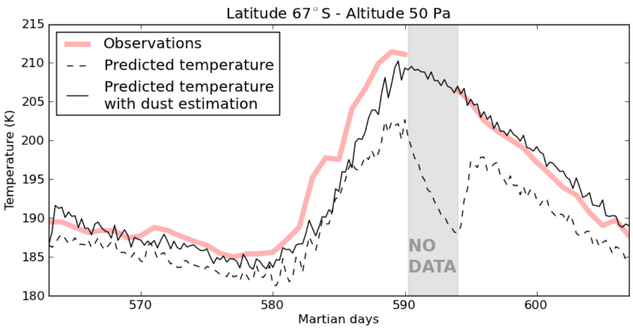

Figure 5: Evolution of temperature as a function of time in a case with assimilation of temperature only (dashed), and with assimilation of temperature and aerosols (plain) for MY29 during a regional dust storm. There is an absence of measurements between sols 590 and 593.

Conclusion:

Even though a good agreement exists between LMD GCM and MCS temperatures, a slight model bias, such as the amplitude and phasing of the thermal tide shown here, leads to an adverse effect in the assimilation of temperature that cannot be overcome. Even when assimilating aerosols, that are great forcings on the atmospheric dynamics, the issue still prevails, partly because of the feedbacks between the aerosols, their radiative effects, and the atmospheric dynamics, but also because of a lack of observations at all local times that, for instance, leave unanswered the puzzling behavior of dust vertical motions between days and night [11].

The fundamental cause for this difficulty in the assimilation lies in the lack of variability of the Martian atmosphere, where a few K of difference cannot be accounted for the synoptic variability, as it is done for Earth atmospheric assimilation. A possible direction for future improvement of Martian assimilation is to take into account the model biases by assimilating a set of relevant model parameters [12] that have an impact on the structure of dynamical features to match MCS observations to an unprecedented level of realism needed to do a proper assimilation of temperature.

One major purpose of the Martian assimilation appears then to be the necessary improvement of models in order to make sense of observations.

References:

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