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# Preliminary results of a Mesoscale Model for MARS(*)

K. De Sanctis([1])(**), R. Ferretti([2])([1]) and G. Visconti([1])([2])

([1]) *Center for the Forecast of Severe Weather by Remote Sensing and Numerical Modelling (CETEMPS), Università di L'Aquila - L'Aquila, Italy*
([2]) *Dipartimento di Fisica, Università di L'Aquila - L'Aquila, Italy*

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**Summary.** — The Earth atmospheric circulation has been studied for long time using both GCM (General Circulation Models) and Mesoscale Models or LAM (Limited Area Models). The latter have been widely applied to study local circulation at high resolution and for weather forecasting. In the last years, the Martian atmosphere arouse the interest of the scientific community, both for supporting the landing of Beagle 2 lander and for studying and assessing similarities/differences with the Earth atmosphere. To this aim, GCM have been successfully used. Recently, also Earth LAMs have been changed to simulate the Mars atmosphere, showing good results. The scarce availability of observations did not allowed for validating these models. In this work an attempt is made to validate the newly developed MARS-MM5 against GCM. The model simulation produced using a data base on the basis of output from multi-annual integration of two CGM (see Lewis S. R. *et al.*, *J. Geophys. Res.*, **104** (E10) (1999) 177) is used for statistically evaluates MARS-MM5. The preliminary results suggest that MARS-MM5 is able to correctly reproduce the Mars atmosphere, indeed either the horizontal and the vertical structure of temperature produced by MARS-MM5 is in good agreement with the ones produced by GCM. A few discrepancies are found in the PBL, probably produced by a different parameterization.

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## 1. – Introduction

Since middle sixties the interest for the Mars planet has driven the scientific community to plan missions which would allow for collecting information on this planet. Mars was the most interesting planet of our galaxy because of the large similarities with the

(*) The authors of this paper have agreed to not receive the proofs for correction.
(**) E-mail: klaide.desanctis@aquila.infn.it

Earth. Mariner 4 was the first mission to make it successfully to Mars: it reached the Mars atmosphere on July 14, 1965. The following missions Mariner 4, 6, 7, and 9 had great success in returning images of Mars. In the mean time, the availability of some information on the Mars atmosphere triggered the interest of the Earth atmospheric scientific community in understanding the Mars physics and dynamics. To this aim the Earth atmosphere General Circulation Models were changed to correctly reproduce the Mars atmosphere. Forget *et al.* [1] successfully developed a general circulation model which was used to produce a climate data base for Mars [2]. More recently, to better reproduce local features Toigo and Richardson [3] adapted the MM5 model from the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR), used for reproducing mesoscale feature of the Earth atmosphere, to the Mars atmosphere. In their work the authors showed model simulations for a few cases of the Mars atmosphere. Similarly, in this paper a newly developed Martian Mesoscale Model (MARS-MM5) based on the Pennsylvania State University (PSU)/National Centre for Atmosphere Research (NCAR) Mesoscale Model Version 5 [4,5] is presented. The new aspect of this work is the use of observation for adapting the model to Mars. The Mars Orbital Laser Altimeter (MOLA) [6,7] data has been used to describe the topography in to the model; whereas the albedo and thermal capacity are derived by the Thermal Emission Spectrometer experiments (TES) [8]. The MARS-MM5 results are compared with the GCM developed by [2] and the Climate Mars data base is used to this aim. The comparison allowed for correctly design the PBL, which is one of the most important parameterizations for the Mars atmosphere. Afterwards, it will be illustrated that to correctly reproduce the Planetary Boundary Layer (PBL) dynamics, the support conditions are:

– Differential heating of the surface.

– Wind presence that generates a turbulent rise, very important on Mars.

– Very irregular orography.

Also the radiative scheme plays a major role because of the difference in the atmospheric constituents: the radiative effects through the Martian atmosphere may be conditioned by a massive presence of carbon dioxide, dust and a minor presence of water vapor and ozone.

The paper is organized as follows: the model modifications and the experiment are presented in sect. **2** and **3**, respectively. The results are discussed in sect. **4**. The conclusions are drawn in sect. **5**.

## 2. – From Earth MM5 to MARS-MM5

The MM5V3 version 5 from PSU/NCAR by [4,5] has been adapted to Mars planet. The original MM5 is a non-hydrostatic model at the primitive equations using the sigma vertical coordinate which is a terrain following one. The horizontal grid uses an Arakawa B-staggering for the velocity variables with respect to the scalars: the scalars ($T, q$, etc.) are defined at the centre of the grid square, while the eastward ($u$) and northward ($v$) velocity components are collocated at the corner. The model may use three different types of map projection: Lambert Conformal is suitable for mid-latitude, Polar Stereographic for high latitude and Mercator for low latitude. The MM5 model has the feasibility of several physical parameterizations for the PBL, the cumulus convection and the radiative transfer scheme. The MARS-MM5 retains most of these characteristics, but the conversion to a Mars atmosphere required several modifications, the most important ones involving:

– Geography and topography characteristics.

– Thermodynamics.

– PBL parameterization.

– Radiative parameterization.

**2**˙1. *Geophysics modifications.* – In order to obtain a correct representation of soil characteristics, the surface data topography derived from Mars Orbital Laser Altimeter (MOLA) [6,7] is used, while albedo and thermal inertia are provided by Thermal Emission Spectrometer experiment (TES) [8]. Typical geophysics features, such as gravitational constant, planetary mean radius, seasonal cycles, orbital eccentricity, solar constant, albedo, planetary rotation have necessarily been changed and adapted for the characteristics of Mars. The MM5 model uses a set of land-use categorization that is assigned along with elevations for the characterization of each grid cell: for Mars a representative single type of the soil characterization is sufficient.

**2**˙2. *Thermodynamics modifications.* – The composition of the Mars atmosphere is based mainly on a massive presence of $CO_2$ (95.3%) and a series of other minor gases: $N_2$ (2.7%), Ar (1.7%), $O_2$ (0.1%), $H_2O$ (0.03%). Since composition is largely different from the Earth atmospheric one, specific heat and constant $R$ of gases are changed in order to make the model suitable for a different concentration of chemical elements.

**2**˙3. *PBL changes.* – An accurate description of near-surface conditions is required for correctly reproducing the Martian atmosphere. The planetary boundary layer is in general very important since here there are exchange and transport from the surface to the atmosphere and vice-versa, atmospheric mass momentum and energy. These processes are critical especially for the Mars atmosphere because the temperature gradients produced by the diurnal cycle are much larger than the ones on the Earth, and those are the most efficient mechanisms for turbulent motions transporting vertical flows at every scale. The Mars PBL offers a significant variability of these conditions, for example, a night time PBL from 100 meters extends to few kilometres during diurnal hours having a pure convective characteristic. The Earth PBL scheme adapted to Mars is based on Mellor-Yamada unstationary 2.5-level scheme [9]. This scheme predicts TKE (Turbulent Kinetic Energy) and has local vertical mixing using an equation for the energy $E$. TKE is a three-dimensional prognostic variable which computes vertical diffusion of $T, Qv, U, V$. The empiric coefficients related to the calculation of surface temperature and heat fluxes are changed in order to correctly reproduce the Mars PBL. The coefficients are chosen in according to [1].

**2**˙4. *Radiative scheme.* – The Rapid Radiative Transfer Model (RRTM) calculates fluxes and cooling rates for long-wave spectral regions (10–3000 $\mathrm{cm}^{-1}$) of an arbitrary atmosphere. The molecular species treated in the model are water vapor, carbon dioxide, ozone and methane. This long-wave scheme is based on the model developed by Mlawer *et al.* [10], it is highly accurate and represents an efficient method provided by Atmospheric and Environmental Research (AER): the Rapid Radiative Transfer Model (RRTM) uses a correlated-k model to represent the effects of the detailed absorption spectrum. The RRTM model calculates the upward fluxes, downward fluxes, and heating rates for an arbitrary clear atmosphere and permits to obtain an accurate description of fluxes and heating rates into an inhomogeneous atmosphere. The Martian atmosphere is supposed to be mainly composed by carbon dioxide while water vapor, ozone and methane are considered minor gases. Therefore, to adapt the RRTM Earth model to Mars the standard atmospheric profile has been given a different value: a fixed amount of $CO_2$ and $H_2O$ while $N_2$, Ar, and $O_2$ are absent.

## 3. – MM5 Model set-up and statistics

The selected MARS-MM5 configuration (horizontal domain, vertical layers and horizontal resolution) is based on CGM configuration. The model domain is $35 \times 40$ degrees and has a resolution of 300 km ($\sim 5$ martian degrees) into solar longitude intervals between 30–60 degrees. Since this area is on the equatorial region, the Mercator projection is used for the simulations. According to GCM configuration, 20 vertical sigma layers are used from 6 Pa (surface pressure) to 0.01 Pa ($\sim 50$ km) at the top. The newly upgraded version of both the Mellor-Yamada [9] and RRTM parameterization [10] are applied for respectively the planetary boundary layer and radiative transfer; a simple parameterization is used to describe the explicit moisture and hydrometeor scheme. No cumulus convection parameterization is used because this effect is negligible. The initial and boundary conditions are provided by the MCD (http://www-mars.lmd.jussieu.fr/) for 30–60 degrees of solar longitude (LS). It has to be noticed that MARS-MM5 is initialized using climate data and the same data base at different hours is used for the validation: in particular, mean data containing 12 seasonal mean values, corresponding to 12 solar times of day with 2 hours time step, are used. Consequently, the MARS-MM5 results are not exactly climatological values, hence differences are expected between the GCM and MARS-MM5.

**3·1.** *Statistical parameters*. – To the aim of validating MARS-MM5 the GCM results are used as reference. The statistical approach will permit to objectively compare MARS-MM5 and GCM results by means of the RMS for temperature $T$ for each level. The correlation coefficient for each vertical level ($k = 1,\ldots,$ number of vertical levels) is defined as

$$r_k = \frac{\sum_{\alpha=1}^{i\cdot j}(x_{\alpha k} - \overline{x_k})(y_{\alpha k} - \overline{y_k})}{\sqrt{{\sigma_x}^2 {\sigma_y}^2}}\,, \tag{1}$$

where $\overline{x_k}$ and $\overline{y_k}$ are the horizontal mean temperatures of two models, while $i$ and $j$ are horizontal grid dimensions. The value of $r$ lies between $-1$ and 1, inclusive. It takes on a value of 1, termed "complete positive correlation", when the data points lie on a perfect straight line with positive slope, with $x$ and $y$ increasing together. The value 1 holds independently of the magnitude of the slope. If the data points lie on a perfect straight line with negative slope, $y$ decreasing as $x$ increases, then $r$ has the value $-1$: this is called "complete negative correlation". A value of $r$ near zero indicates that the variables $x$ and $y$ are *uncorrelated*. In this study, $x_j$ assumes the MARS-MM5 model's data while $y_j$ assumes the GCM data.

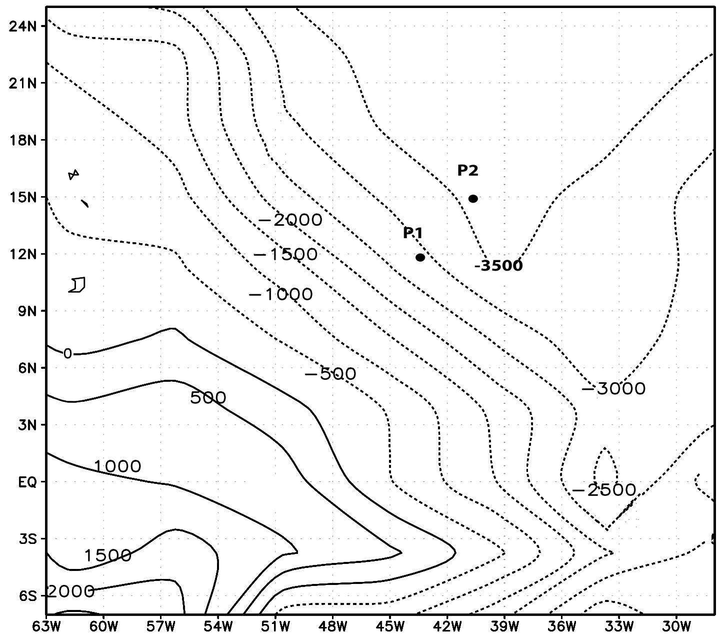


Fig. 1. – Model topography for MM5 domain and points $P_i$ = (latitude, longitude): $P_1 = (12°, -43°)$ and $P_2 = (15°, -39°)$.

## 4. – Results

The comparison between the horizontal and vertical temperature field produced by MARS-MM5 and CGM is performed for two local times: at 0600LT and 0800LT. For the horizontal comparison four levels are selected: the first at surface, the second and the third into PLB, respectively at 200 meters and 7 kilometers and finally the fourth at 14.2 kilometers from the surface. The levels are chosen in order to eventually highlight discrepancies at the lower and upper levels. For the vertical comparison, vertical temperature profiles for MARS-MM5 and GCM at the two locations Points 1 and 2 (fig. 1) will be presented. The following analysis will be performed for 48hours and the comparison with GCM is carried out at +6 hours and +8 hours, since the differences between MARS-MM5 and GCM became negligible at the following steps.

4˙1. *Horizontal comparison MM5-GCM*. – At glance (fig. 2), there clearly appears a very good agreement between MARS-MM5 and GCM temperatures at 0600LT, both for absolute values and for spatial distribution. A few discrepancies are detected at lower levels, whereas a better agreement is already over 10 km. Small discrepancies are found at the surface (fig. 2a,b) mostly at the edges of the domain, as the correlation confirms $r = 0.611$. At both 200 m and 7 km (fig. 2c,d,e,f) remarkable differences are found confirmed by $r = 0.183$ and $r = 0.118$. These large differences are associated to a strong temperature gradient produced by MARS-MM5 (fig. 2c between 60 W and 50 W), which is probably caused by the sharp topography variation (fig. 1). This discrepancy between MARS-MM5 and GCM is not surprising because climatological values are expected to be smoother than daily values, as MARS-MM5 produces. A similar temperature gradient is

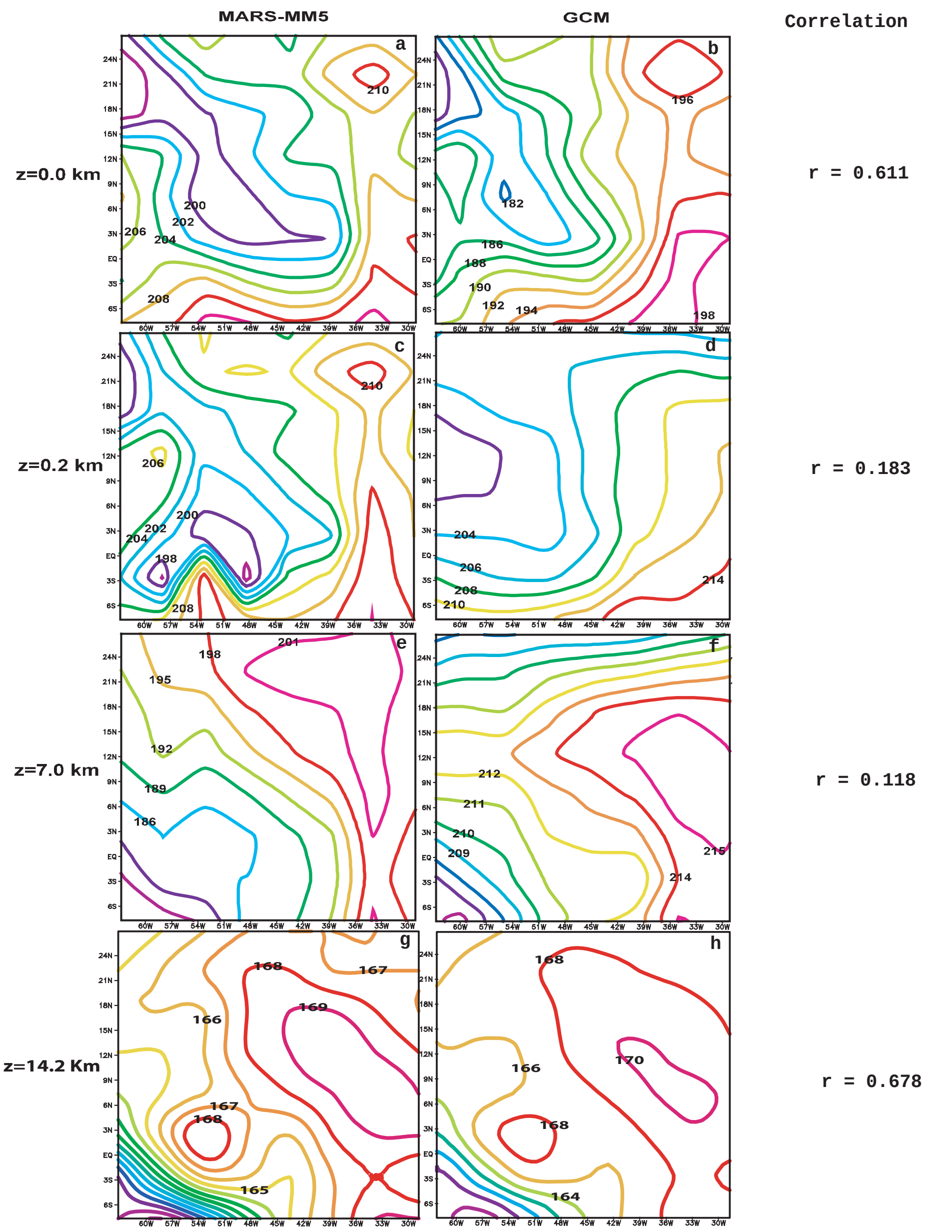


Fig. 2. – Temperature (K) for MARS-MM5 (first column) and CGM (second column) at 0600LT (30–60 LS) at four different levels: at the surface on the first line, at 200 m on the second line, at 7 km on the third line and at 14.2 km on the fourth line. In the last column the correlation between MARS-MM5 and GCM at the same levels is shown.

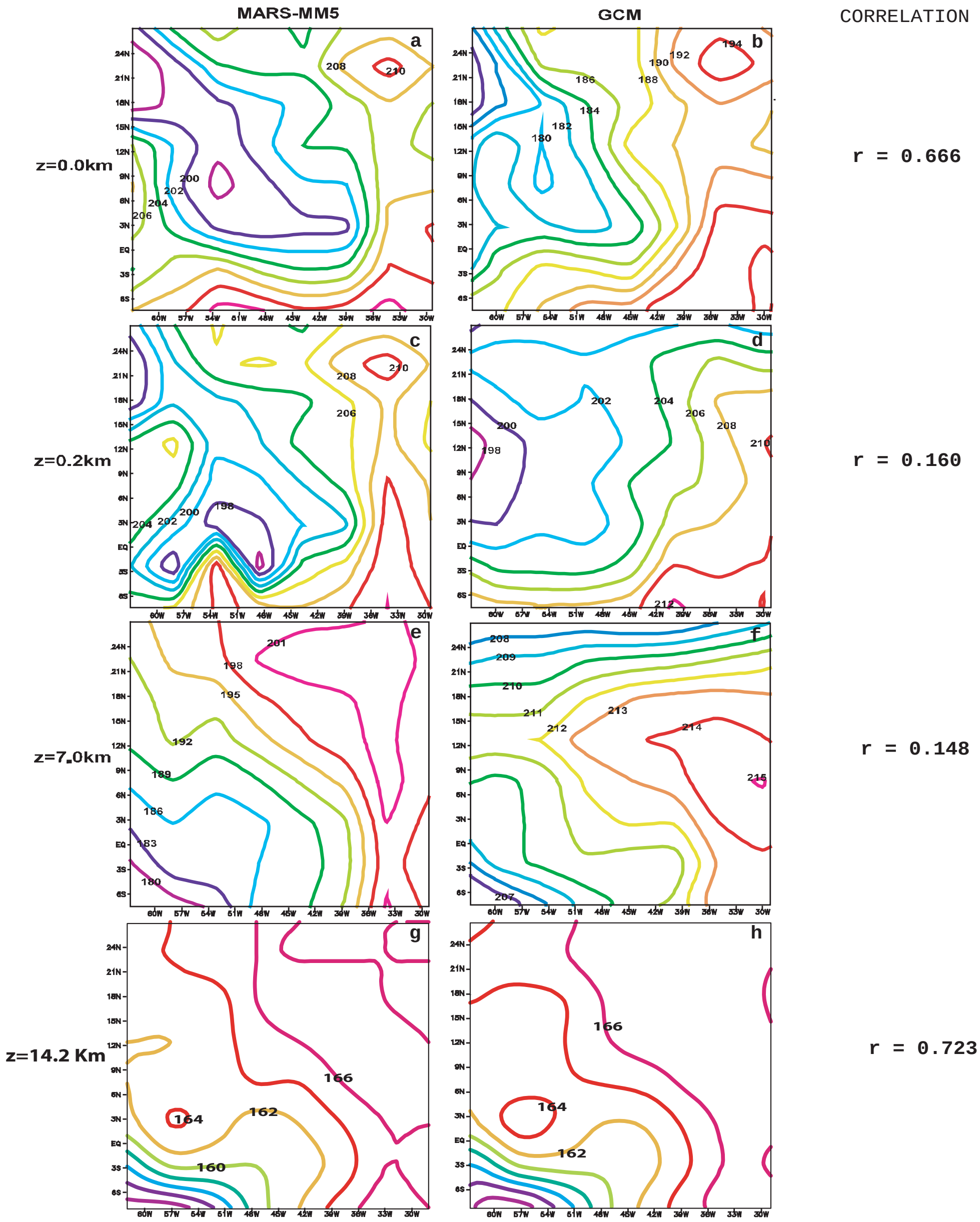


Fig. 3. – Temperature (K) for MARS-MM5 (first column) and CGM (second column) at 0800LT (30–60 LS) at four different levels: at the surface on the first line, at 200 m on the second line, at 7 km on the third line and at 14.2 km on the fourth line. In the last column the correlation between MARS-MM5 and GCM at the same levels is shown.

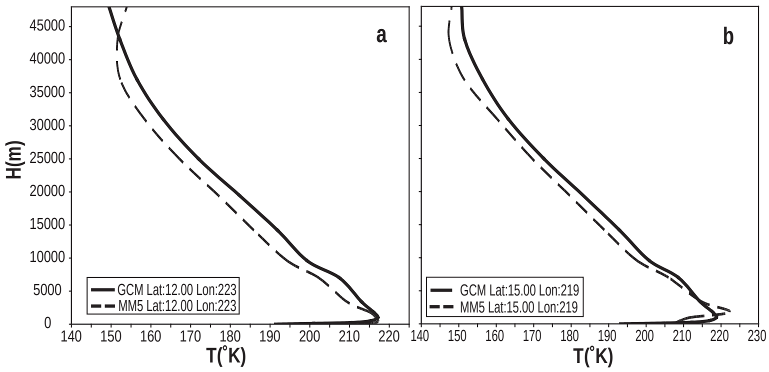


Fig. 4. – The temperature vertical profiles for MARS-MM5 (black solid line) and CGM (black dashed line) for the 2 points in fig. 1: a) point P1; b) point P2.

found at the same place for all LT (fig. 2c,e, 3c,e and 2d,f, 3d,f), supporting the previous hypothesis. Above the PBL the agreement is much larger than in the previous cases, indeed smaller differences are detected at 14 km (fig. 2g,h). The correlation coefficient is $r = 0.678$ and takes on high values up to the top level. The temperatures at 40 km are similar for both models and do not show differences (not shown). The comparison at 0800LT (fig. 3) shows results similar to the ones at the previous step: a good agreement is found (fig. 3a,b) at the lower level, thus the correlation coefficient shows a value equal to 0.666. Also in the PBL the results are similar to the previous LT. The correlation offers values equal to $r = 0.160$ for 200 m and $r = 0.148$ for 7 km (fig. 3c,d,e,f). Similarly to the previous time step, the compatibility between the two models temperature field distribution (fig. 3g,h) is very high at upper level, with $r = 0.723$. It has to be noticed that MARS-MM5 overestimates the temperature at low level while it underestimates the temperature at high level: this is reasonable because MARS-MM5 parametrization does not include dust presence yet (under development). In summary the previous results show discrepancies between the two models in reproducing the PBL.

**4**˙2. *Vertical comparison MM5-GCM*. – The comparison between the vertical temperature profiles for MARS-MM5 and GCM at the two locations (P1 and P2 on fig. 1) is now presented. The vertical temperature profiles for MARS-MM5 (dashed line) and GCM (continuous line) show a generally good agreement between MARS-MM5 and GCM, suggesting that the newly developed MARS-MM5 is able to reproduce the Mars atmosphere. Moreover, MARS-MM5 shows a small cold bias with respect to GCM up to 38 km (fig. 4a). At higher altitude the bias in inverted. Noteworthy, the MARS-MM5 lapse rate is in very good agreement with the GCM one.

## 5. – Conclusions

A newly developed mesoscale model for the Martian atmosphere adapting MM5V3 from PSU/NCAR is presented. Several changes are applied to the Earth MM5 to correctly reproduce the Martian atmosphere. Both the PBL model, concerning the calculation of surface temperature and heat fluxes, and the RRTM model for radiative transfer are modified. To validate the newly developed MARS-MM5 the results are verified against a CGM. Both the horizontal and vertical structures of temperature field are used to verify MARS-MM5. The comparison between the MARS-MM5 and GCM temperature field at four different levels suggest a good agreement between the two models. Moreover, the correlation coefficient computed for MARS-MM5 and GCM allows to assess a few discrepancies in the PBL, probably produced by a different parameterization and different ability in dealing with the topography for the two models. The comparison between the vertical temperature profiles obtained from MARS-MM5 and GCM shows a good agreement assessing the MARS-MM5 ability in reproducing both the horizontal and vertical structure of the MARS atmosphere. These preliminary results are encouraging and they suggest for further improving MARS-MM5. Moreover, they support the need of having a mesoscale model for the Martian atmosphere. Unfortunately, the lack of experimental data does not allow for a statistical analysis which would infer a better understanding of the behavior of MARS-MM5 within the PBL.

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