THERMOSPHERIC VARIABILITY DURING 7 MARTIAN YEARS.

F. González-Galindo, M.A. López-Valverde, *Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain***, E. Millour, F. Forget,** *Laboratoire de Météorologie Dynamique, CNRS, Paris, France***.**

Introduction

The temperatures in the thermosphere are an important parameter that influences many different physical processes, from the rates of different chemical reactions to the thermal escape rate (Chaufray et al., 2012) and the density structure in that region. This in turn affects the drag experienced by a spacecraft during aerobraking maneouvers. The Martian thermosphere has been studied by different observational strategies and by different spacecrafts (e.g. Keating et al., 1998, 2003; Forbes et al., 2008; Forget et al., 2009). Information about the neutral upper atmosphere can also be gained from ionospheric observations (e.g. Bougher et al., 2001). All these observations together have unveiled the complexity of the thermosphere, influenced both by the radiation coming from the Sun and from the state of the lower atmosphere.

Theoretical works using state-of-the-art GCMs (e.g. Bougher et al., 1999, 2009; González-Galindo et al., 2009a) have shown that thermospheric temperatures are governed by the balance between the heating produced by the absorption of UV solar radiation and the cooling provided by the thermal conduction and by CO_2 15 μm emissions. The adiabatic heating/cooling linked to dynamics introduces important departures of this situation. It has also been shown that variations in the dust load in the lower atmosphere can also affect temperatures at high altitude, at least in the lower thermosphere (Bell et al., 2007).

Bougher et al. (2009) studied the effects of the 11-year solar cycle over the thermospheric temperatures by using GCM simulations at equinox and at solstice and a range of different solar activities (given by different F10.7 values). They concluded that the global winds could play a significant role in modulating the solar cycle variability of the temperatures. Similarly, González-Galindo et al. (2009a) used simulations for a full Martian year using three different solar activities (constant during each year) to evaluate the variability of the temperatures produced by the 11-year solar cycle. A good agreement with the solar cycle variability measured by Forbes et al. (2008) was found, although the seasonal variability of the temperatures was overestimated by the model.

However, the use of a constant UV solar flux during a given period of time can be an oversimplification if that period is not sufficiently short. It is well known that the EUV solar flux presents medium and short-term variations due to solar rotation and to transient phenomena such as solar flares. This variability has been shown to affect the upper atmosphere of Mars. Different observations have revealed solar rotation effects in the measured electronic concentration at about 140 km (Withers and Mendillo, 2005; Nielsen et al., 2006). Forbes et al. (2006) have also shown that the densities at 390 km derived by an MGS precise orbit determination present oscillations due to solar rotation. During a Martian year (that spans almost two terrestrial years and thus a non-negligible fraction of a solar cycle) the solar EUV flux will also be modified by the 11-year solar cycle. It is thus expected that this variability will modify the seasonal response of the thermospheric temperatures.

In this work we aim to overcome the limitation of using a constant UV solar flux to model the upper atmosphere. We have simulated the thermospheric temperatures with a state-of-the-art General Circulation Model of the Martian atmosphere, the LMD-MGCM. The model is forced by a day-to-day variable UV solar flux and dust load. Here we focus on the interannual variability produced by differences in the solar activity and the dust load, on the modification of the seasonal variability produced by the solar variability during a given year, and on the effects of the solar rotation.

The GCM modeling

The LMD-MGCM was used in this work. This model considers all the relevant processes that we think affect the atmosphere from the surface to the exobase (González-Galindo et al. 2009). Focusing on the upper atmosphere, this model has been used, among other studies, to interpret the longitudinal variability of the densities measured during MGS aerobraking (Angelats i Coll et al., 2004), to study the thermospheric polar warming (González-Galindo et al. 2009b), to compare with observations of CO_2 mesospheric clouds (González-Galindo et al., 2011) and for the study of the NO nightglow (Gagné et al., 2013).

For this work, we have used the lattest version of the model, described in Millour et al. (2012) and González-Galindo et al. (2013). In the upper atmosphere, this version includes several improvements with respect to previous versions. First, an improved, more physically consistent parameterization for the Non-LTE 15 μm cooling by CO_2 has been included, that provides temperatures at the upper mesosphere and lower thermosphere in better agreement with SPICAM observations (López-Valverde et al., 2011). Second, an improved description of the molecular diffusion has been implemented, solving pre-

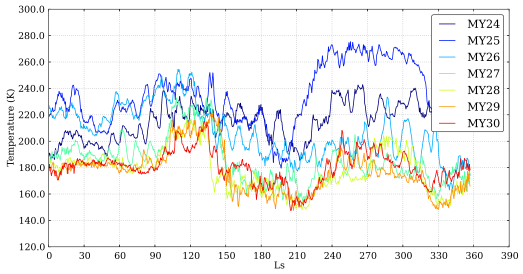

Figure 1: Equatorial temperature at 160 km of altitude and LT=12 as a function of L$_s$, simulated for 7 consecutive Martian Years

vious problems with the vertical profiles of H and H$_2$ (Chaufray et al., 2014). Third, an extended thermospheric photochemical scheme that includes Nitrogen species and ionospheric chemistry has been developed (González-Galindo et al., 2013). And fourth, a new parameterization of the absorption of the EUV solar radiation has been implemented, that includes realistic day-to-day variability of the EUV solar flux (González-Galindo et al., 2013)

Selection of results

The model has been run to simulate the variation of thermospheric temperatures during 7 Martian Years (MYs 24 to 30, from about mid 1999 to mid 2011, encompasing a full solar cycle) using as inputs the observed day-to-day variability of the EUV solar flux as given by the semi-empirical model SIP (Tobiska et al., 2006) and the observed day-to-day variable dust load in the lower atmosphere (Montabone et al., 2012). For comparison purposes, a second set of simulations using the observed variability of the dust load, but a fixed solar flux appropriate for solar average conditions (see González-Galindo et al., 2013) have also been performed. The comparison between these two sets of simulations will allow to separate the contribution of the solar variability from the dust variability. Some preliminary results are summarized below.

Fig. 1 shows the temporal evolution of the equatorial temperatures at a constant altitude level of 160 km and constant Local Time LT=12, for the 7 simulated Martian years. There is a significant year-to-year variability in the simulated temperatures, with MY25 (a Martian year for which the Sun was at its maximum of activity during the last cycle) being the warmest year and MY28, MY29 and MY30 the coldest ones. These are the Martian years corresponding to the long recent period of minimum solar activity. This interannual variability ranges from about 40 K at the beginning of the year to about 100 K during the perihelion season.

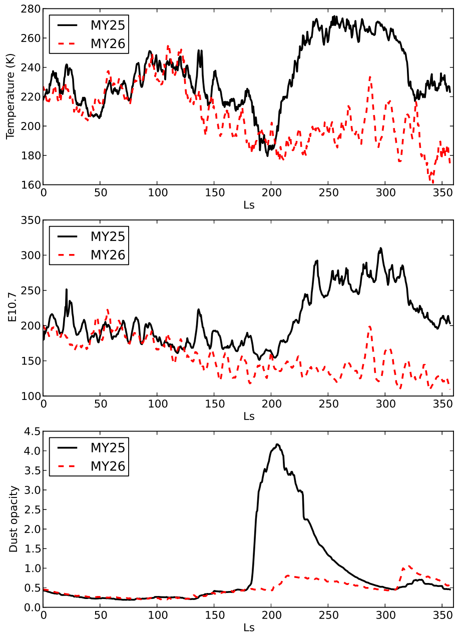

Figure 2: Upper panel: seasonal variability of the equatorial temperature at 160 km of altitude and LT=12 simulated. Central panel: Seasonal variability of the E10.7 solar proxy index. Lower panel: Seasonal variability of the dust opacity. The black solid lines show the variation of these parameters during MY25 and the red dashed lines for MY26

The seasonal variability of the temperatures is also different in every Martian Year, due to the peculiar temporal evolution of the solar activity within each MY. So, for MY25 there is a significant increase of the temperatures after L$_s$ $\approx$200, not present at other years, due to the particular increase of the solar activity around that date. This can be better appreciated in Fig. 2 where the seasonal variability of the equatorial temperatures at LT 12 is shown together with the seasonal variability of the E10.7 solar proxy index and of the dust load of the lower atmosphere for MY25 and MY26. For MY25, the increase in the thermospheric temperatures after L$_s$=200 corresponds to a similar increase in the solar activity. Note also that the increase in the dust load corresponding to the global dust storm between L$_s$=180 and 200 seems to produce a decline in the thermospheric temperatures. For MY26, a year coincident with the declining phase of the solar cycle, the temperatures decrease with increasing time, due to a similar decrease of the solar activity.

Although not very clear in Fig. 2, the temperatures at 160 km present oscillations with a typical period of

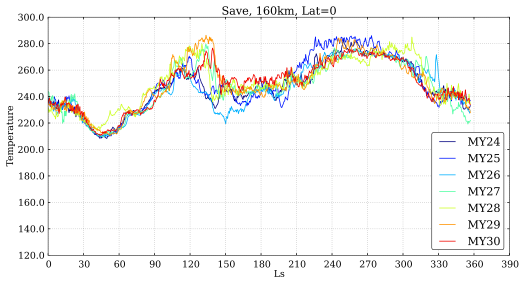

Figure 3: Equatorial temperature at 160 km of altitude and constante LT=12 simulated for 7 different Martian Years when the same constant EUV solar flux is used as an input, as a function of L$_S$

around 27 days, which correlate very well with similar oscillations in the E10.7 solar proxy index, and which are due to the solar rotation. These temperature oscillations have amplitudes of around 20 K, showing that it is important to take into account the day-to-day solar variability to properly reproduce the thermospheric temperatures at this degree of detail. The amplitude of these oscillations decrease with decreasing altitude, so that at 120 km (the approximate altitude of the mesopause) they are negligible.

Fig. 3 is similar to Fig. 1, but it is obtained from the simulations using a constant EUV solar flux (the same for every MY) but the dust load observed for every MY. In this case, the interannual variability of the simulated temperatures remains most of the time lower than 20 k. This indicates that the main source of interannual variability in the thermosphere is the interannual variation of the EUV solar flux, while the interannual variation of the dust load in the lower atmosphere has a more modest effect, at least in the case of the 7 Mars years studied here. However, the effect of major dust events, such as the big dust storms of MY25 and MY28 can still be felt in the temperatures at 160 km: temperatures around L$_s$=200 and L$_s$=240 are significantly higher for MY25, a year where a global dust storm developed around those dates. Similarly, temperatures between L$_s$=280 and L$_s$=320 are higher for MY28, simultaneously to the presence of another global dust storm.

Summary

We have used the LMD-MGCM to evaluate the effects of temporal variations in the EUV solar flux over the thermospheric temperatures. The preliminary analysis of the results shows that the variability of the solar flux induces a strong interannual variability of the temperatures and modifies its seasonal behavior. The solar rotation is also a source of variability in shorter temporal scales.

We think this work is relevant for the preparation and the analysis of data from the future MAVEN mission. This mission will measure for the first time on Mars simultaneously the state of the upper atmosphere (including the temperature) and the UV solar flux, its main forcing.

References

Angelats i Coll, M., F. Forget, M. A. López-Valverde, P. L. Read, and S. Lewis (2004). Upper atmosphere of Mars up to 120 km: Mars Global Surveyor data analysis with the LMD general circulation model, J. Geophys. Res., 109, E01011.

Bell, J. M., S. W. Bougher, and J. R. Murphy (2007), Vertical dust mixing and the interannual variations in the Mars thermosphere, J. Geophys. Res., 112, E12002.

Bougher, S. W., S. Engel, R. G. Roble, and B. Foster (1999). Comparative terrestrial planet thermospheres 2. Solar cycle variation of global structure and winds at equinox, J. Geophys. Res., 104, 16,591-16,611.

Bougher, S. W., S. Engel, D. P. Hinson, and J. M. Forbes (2001). Mars Global Surveyor radio science electron density profiles: Neutral atmosphere implications, Geophys. Res. Lett., 28, 3091-3094.

Bougher, S. W., T. M. McDunn, K. A. Zoldak, and J. M. Forbes (2009). Solar cycle variability of Mars dayside exospheric temperatures: Model evaluation of underlying thermal balances, Geophys. Res. Lett., 36, L05201.

Chaufray, J.-Y. et al. (2012). Current state of Mars exospheric studies, paper presented at the 39th COSPAR Scientific Assembly. Held 14-22 July 2012, in Mysore, India. Abstract C2.2-52-12, p.321.

Chaufray, J.-Y., F. Leblanc, R. Modolo, S. Hess, F. González-Galindo, M. López-Valverde and F. Forget (2014). 3D simulations of the Hydrogen Escape on Mars, paper presented at the 5th Mars Atmosphere Modeling and Observations Workshop, Oxford.

Forbes, J. M., S. L. Bruinsma, and F. G. Lemoine (2006), Solar rotation effects in the thermospheres of Mars and Earth, Science, 312, 1366-1368.

Forbes, J. M., F. G. Lemoine, S. L. Bruinsma, M. D. Smith, and X. Zhang (2008). Solar flux variability of Mars' exosphere densities and temperatures, Geophys. Res. Lett., 35, L01201.

Forget, F., F. Montmessin, J.-L. Bertaux, F. González-Galindo, S. Lebonnois, E. Quémerais, A. Reberac, E. Dimarells, and M. A. López-Valverde (2009). Density and temperatures of the upper Martian atmosphere measured by stellar occultations with Mars Express SPICAM, J. Geophys. Res., 114, E01004.

Gagné, M.-E., J.-L. Bertaux, F. González-Galindo, S. M. L. Melo, F. Montmessin, and K. Strong (2013). New nitric oxide (NO) nightglow measurements with SPICAM/MEx as a tracer of Mars upper atmosphere circulation and comparison with LMD-MGCM model prediction: Evidence for asymmetric hemispheres, J. Geophys. Res. Planets, 118.

González-Galindo, F., F. Forget, M. A. López-Valverde, M. Angelats i Coll, and E. Millour (2009a). A ground-to-exosphere Martian general circulation model: 1. Seasonal, diurnal, and solar cycle variation of thermospheric temperatures, J. Geophys. Res., 114, E04001.

González-Galindo, F., F. Forget, M. A. López-Valverde, and M. Angelats i Coll (2009b), A ground-to-exosphere Martian general circulation model: 2. Atmosphere during solstice conditions. Thermospheric polar warming, J. Geophys. Res., 114, E08004.

González-Galindo, F., A. Määttänen, F. Forget, and A. Spiga (2011). The Martian mesosphere as revealed by CO2 clouds observations and general circulation modeling, Icarus, 216, 10â^22.

González-Galindo, F., J.-Y. Chaufray, M. A. López-Valverde, G. Gilli, F. Forget, F. Leblanc, R. Modolo, S. Hess, and M. Yagi (2013). Three-dimensional Martian ionosphere model: I. The photochemical ionosphere below 180 km, J. Geophys. Res. Planets, 118.

Keating, G., et al. (1998). The structure of the upper atmosphere of Mars: In situ accelerometer measurements from Mars Global Surveyor, Science, 279, 1672-1676.

Keating, G., M. Theriot, R. Tolson, S. Bougher, F. Forget, and J. Forbes (2003). Brief review on the results obtained with the MGS and Mars Odyssey 2001 accelerometer experiments, paper presented at Mars Atmosphere: Modelling and Observations Workshop, Eur. Space Agency, Granada, Spain, 13-15 Jan.

López-Valverde, M. A., F. González-Galindo, and M. López-Puertas (2011). Revisiting the radiative balance of the mesosphere of Mars, in Proceedings of the Mars Atmosphere: Modelling and Observation, edited by F. Forget, and E. Millour, pp. 359-362, Paris, France.

Millour, E. et al. (2012). The latest improvements in the LMD Global Climate Model and derived Mars Climate Database (version 5), paper presented at the 39th COSPAR Scientific Assembly. Held 14-22 July 2012, in Mysore, India. Abstract C3.2-33-12, p.1239

Montabone, L., E. Millour, F. Forget, and S.R. Lewis (2012). Seven-Year Climatology of Dust Opacity on Mars, paper presented at the European Planetary Science Congress 2012, held 23-28 September, 2012 in Madrid, Spain. http://meetings.copernicus.org/epsc2012, id. EPSC2012-773

Nielsen, E., H. Zou, D. A. Gurnett, D. L. Kirchner, D. D. Morgan, R. Huff, R. Orosei, A. Safaeinili, J. J. Plaut, and G. Picardi (2006). Observations of vertical reflections from the topside Martian ionosphere, Space Sci. Rev., 126, 373-388.

Tobiska, W. K., and S. D. Bouwer (2006), New developments in SOLAR2000 for space research and operations, Adv. Space Res., 37, 347â^358.

Withers, P., and M. Mendillo (2005). Response of peak electron densities in the Martian ionosphere to day-to-day changes in solar flux due to solar rotation, Planet. Space Sci., 53, 1401-1418.