GRAVITY WAVE-INDUCED HIGH ALTITUDE ICE CLOUDS ON MARS.

Erdal Yiğit, *Department of Physics and Astronomy, George Mason University, Fairfax, VA, USA (eyigit@gmu.edu)*, **Alexanders S. Medvedev,** *Max Planck Institute for Solar System Research, Göttingen, Germany*, **Paul Hartogh,** *Max Planck Institute for Solar System Research, Göttingen, Germany*, **Takeshi Kuroda,** *National Institute of Information and Communications Technology, Tokyo, Japan*, **David E. Siskind,** *Naval Research Laboratory, Washington, DC, USA*.

Introduction

Internal gravity waves (GWs) play a significant role for the energy and momentum budget of Earth's upper atmosphere [*Yiğit and Medvedev*, 2015]. Their importance is increasingly acknowledged in the Martian upper atmosphere as well. GWs are generated in the lower atmosphere, propagate upward growing in amplitude and produce substantial body forces at higher altitudes. GW dissipation in the upper atmosphere and the resulting dynamical and thermal effects are a manifestation of *vertical coupling* on Mars. Recent modeling studies have demonstrated appreciable dynamical [*Medvedev et al.*, 2013] and thermal effects [*Medvedev and Yiğit*, 2012] on the Martian middle and upper atmosphere.

Carbon Dioxide ice clouds have routinely been observed in the Martian mesosphere in the last 20 years by a number of authors [*Clancy and Sandor*, 1998; *Montmessin et al.*, 2007; *Sefton-Nash et al.*, 2013; *Määttänen et al.*, 2013; *McConnochie et al.*, 2010]. Previous global modeling studies of the Martian atmosphere have not been able to produce the necessary very cold mesospheric temperatures, which the detected occurrence of these clouds in the mesosphere imply. Though, for example the mesoscale modeling study of *Spiga et al.* [2012] have indicated a possible role of GW effects on the formation of ice clouds. Previous studies have emphasized the dynamical coupling between the lower atmosphere and terrestrial polar mesospheric clouds [*Siskind et al.*, 2011]. On Mars, A comprehensive modeling study of the role of GWs on the formation of clouds is yet to be undertaken. In this work, we report on our recent research activity on the general circulation modeling study of the role of small-scale GWs in forming CO_2 ice clouds [*Yiğit et al.*, 2015a]. We use the Max Planck Institute Martian General Circulation Model (MPI-MGCM), incorporating the whole atmosphere GW parameterization of *Yiğit et al.* [2008], in order to assess the dynamical and thermal role of GWs of lower atmospheric origin on the formation of CO_2 ice clouds. In the next sections we describe the GW scheme, the MGCM and our results on the analysis of wave effects on the high-altitude CO_2 ice clouds.

The Martian General Circulation Model

The Max Planck Institute Martian General Circulation Model (MPI-MGCM) is a first-principle time-dependent general circulation model that solves the basics conservation laws of energy, momentum, and mass from the surface up to the lower thermosphere ($\sim 150-160$ km). Its most recent version is discussed in the work by *Medvedev et al.* [2016]. The topography is described by the Mars digital elevation model derived from the Mars Orbiter Laser Altimeter (MOLA) profiles [*Delacourt et al.*, 2003]. The standard version of the model has 67 hybrid vertical levels, which are terrain-following in the lower atmosphere and pressure-based in the upper atmosphere, and T21 horizontal spectral truncation (36×64 longitude$\times$latitude grid points). The model includes all the relevant physics and chemistry for the lower and upper atmosphere. We have radiative schemes, which account for absorption by dust [*Nakajima and Tanaka*, 1986] and CO_2 in IR and visible, for non-LTE CO_2 effects in the middle atmosphere [*Gusev and Kutepov*, 2003], UV and EUV in the upper atmosphere, eddy and molecular diffusion, CO_2 condensation/sublimation scheme, and energy processes on the surface. The effects of the subgrid-scale GWs are incorporated via the *Yiğit et al.* [2008] extended scheme.

The Extended Gravity Wave Parameterization

The gravity wave parameterization developed by *Yiğit et al.* [2008] is the first GW scheme that calculates GW effects in the whole atmosphere system. It is suitable for use in all planetary atmosphere GCMs in order to represent the subgrid-scale GW effects. Attenuation of GWs in the lower and middle atmosphere as well as in the thermosphere-ionosphere are calculated by taking into account nonlinear diffusive damping β^j_{non}, turbulent viscosity β^j_{eddy}, molecular diffusion and thermal conduction β^j_{mol}, ion drag β^j_{ion}, and radiative damping β^j_{rad} as follows

$$\beta^j_{tot} = \beta^j_{non} + \beta^j_{mol} + \beta^j_{ion} + \beta^j_{rad} + \beta^j_{eddy} \qquad (1)$$

The scheme assumes a distribution of GW activity at a given source level in the lower atmosphere and the interaction of these waves with the atmosphere and with other waves (i.e., $\beta^j_{tot} > 0$) in the spectrum are

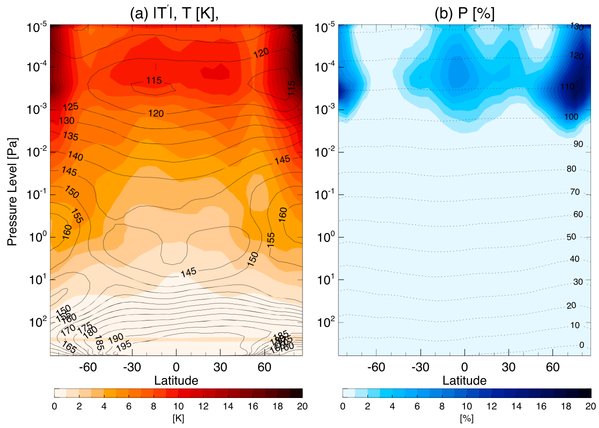

Figure 1: *Pressure-latitude cross sections of the simulated 40-sol mean zonal mean (a) gravity wave induced temperature fluctuations $|T'|$ (red shading) and the neutral temperature in K (contour); (b) probability P in percentage of CO_2 ice cloud formation. The mean geopotential height in km is plotted in panel b [Yiğit et al., 2015a, Figure 1].*

evaluated iteratively for every model grid point and vertical level. For each model time step, the scheme produces the amount of acceleration/deceleration (drag), heating/cooling, and mixing, which are accounted for in the conservation of momentum, energy, and continuity in the MGCM. Most recently, the scheme has been used in order to interpret MAVEN observation of thermospheric GW activity [*Yiğit et al.*, 2015b].

Model Experiment Design

The model was run for 40 sols in a day-stepping mode, approximately corresponding to $L_s = 0 - 20°$, that is, for a northern hemisphere spring equinox. The low-dust optical depth ($\tau = 0.2$ in visible) appropriate for this season, and constant low-solar flux of $F_{10.7} = 80 \times 10^{-22}$ W m^{-2} Hz^{-1} were used throughout the simulations. Model mean fields to be shown have been calculated as 40-sol averaged fields.

Linking Gravity Wave Activity and Cloud Formation

For each model grid point and time step the *Yiğit et al.* [2008] scheme calculates the vertical profiles the amplitude of the wave-induced horizontal velocity fluctuations, u_i', for each harmonic in the spectrum. The root-mean-square fluctuations include the contributions from all harmonics and describes the net GW induced fluctuations $|u'|$. Assuming that the GW kinetics and the potential energies are equal, we have

$$E_k = E_p = \frac{1}{2}|u'| = \frac{1}{2}\left(\frac{g}{N}\right)^2 \frac{|T'^2|}{T^2}, \qquad (2)$$

where $g = 3.72$ m s^{-2} is the acceleration of gravity on the Martian surface, N is the Brunt-Väisälä frequency, and T is the neutral temperature resolved by the model, the total wave-induced RMS temperature perturbations $|T'|$ can be computed from $|u'|$, where $|T'|$ does not include any information about phases of the waves. Individual wave-induced temperature fluctuations in each point are, thus, bound by $|T'|$: $-|T'| \leq T' \leq |T'|$.

Figure 1 presents (a) the mean zonal mean neutral temperature and the GW-wave induced temperature fluctuations $|T'|$; (b) the resulting probability P of CO_2 ice cloud formation in percentage. Gravity waves produce the largest temperature fluctuations around the mesopause region and in the lower thermosphere, exceeding 20 K at high-latitudes. In the coldest regions, GWs produce the largest thermal effects. As a consequence, the peak probability of cloud formation of up to 20% is encountered in the regions of largest GW activity around 95–120 km. These results predict cloud formation that are higher in altitude than the previous observations of clouds.

So what are the possible geographical variations in the ice clouds? Figure 2 demonstrates 40-sol mean latitude-longitude distributions of $|T'|$ (in panels a and b) and the cloud formation probability P (in panels c and d) in the upper mesosphere at $p = 10^{-3}$ Pa (a and c) and around the mesopause at 10^{-4} Pa (b and d), where also topographic features are indicated in panel (d). Significant amount of spatial variability in GW temperature fluctuations are seen. $|T'|$ values reach from 4-12 K in the upper mesosphere to values exceeding 20 K in the mesopause region. The simulated cloud probability distribution demonstrate significant spatial correlation with the GW thermal activity. Peak probabilities are seen around the equator and at high-latitudes around 60°W-120°W and 60°E-120°E, where GW activity typically peaks. The geographical regions partially agree with the findings of *Spiga et al.* [2012].

Results suggest that GW effects constitute an important physical mechanism contributing to cloud formation. GW effects are expected to demonstrate local time variations as well due to the dependence of the wave propagation and dissipation on the background atmosphere. So, to what extend is cloud formation a function of the local time variations of GWs? Figure 3 presents the geographical distributions of $|T'|$ and P (a) at local night 0200 LT and (b) during day 1400 LT. Significant GW activity and cloud formation are seen at night demonstrating a large geographical correlation. At around 60°W-120°W and 60°E-120°E, large cloud fomatin probability of more than 30% coincides with strong GW-induced temperature fluctuations of up to 20 K.

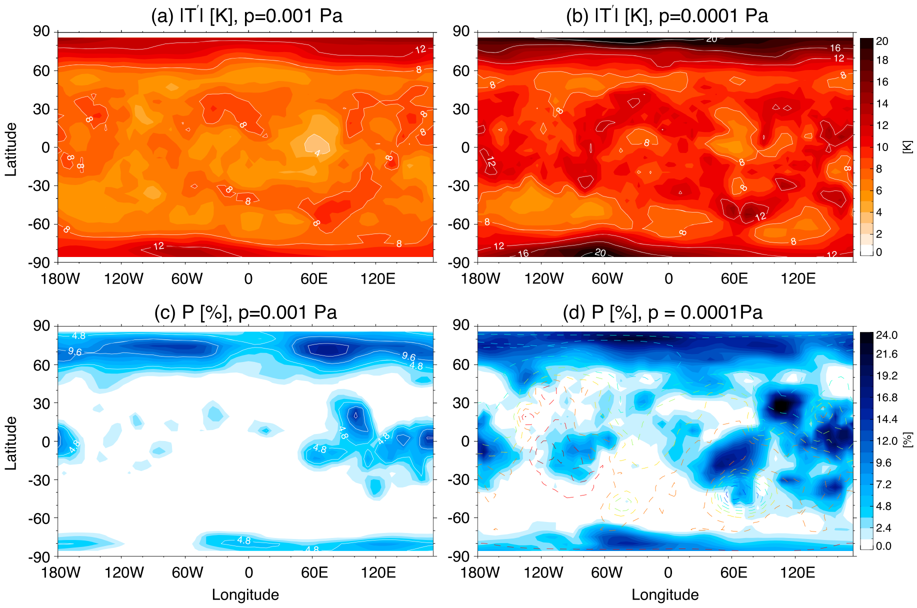

Figure 2: *Gravity wave induced temperature fluctuations (upper panels) and the probability of cloud formation (lower panels) at around the upper mesosphere ($p = 0.001 Pa$) and the mesopause/lower thermosphere ($p = 0.0001$ Pa) region [Yiğit et al., 2015a, Figure 2].*

Summary

Using a Martian General Circulation Model extending from the surface to the lower thermosphere, including a state-of-the-art subgrid-scale gravity wave parameterization [*Yiğit et al.*, 2008], we have presented the first global-scale investigation of the effects of small-scale GWs on the formation of Martian high-altitude Carbon Dioxide ice clouds, specifically focusing on the mesopause and lower thermosphere region. We have undertaken model simulations for the northern hemisphere spring equinox conditions $L_s = 0 - 20°$ and at low solar activity and presented the associated mean GW effects on cloud formation. The main inferences of our study are as follows:

- GWs propagate into the upper mesosphere and thermosphere with significant amplitudes.
- GW-induced temperature fluctuations peak at high-latitudes in the mesosphere and lower thermosphere with amplitudes reaching 20 K.
- Small-scale GW activity in the Martian mesosphere and lower thermosphere facilitate CO_2 ice cloud formation. Without accounting for the effects of GWs, the models cannot produce sufficiently low temperatures and clouds are not formed.
- The geographical distribution of GW activity and the probability of cloud formation demonstrate appreciable spatial variability. Overall, clouds have high chances of forming in the regions of peak wave activity.
- The predicted cloud formation probabilities peak at night locally exceeding 30% as a result of cold background temperatures and enhanced GW activity.
- More clouds are predicted at higher altitudes than what the Martian observations have indicated so far. Further studies are needed in order to investigate the nature of high-altitude clouds and techniques of better observing their characteristics.

Overall, our studies have demonstrated that GW thermal effects produce global cooling in the Martian atmosphere [*Medvedev and Yiğit*, 2012; *Medvedev et al.*, 2015], as was previously demonstrated in the case of the terrestrial thermosphere [*Yiğit and Medvedev*, 2009], in addition to the local temperature fluctuations, and should be accounted for in the studies of Martian high-altitude cloud formation and variability.

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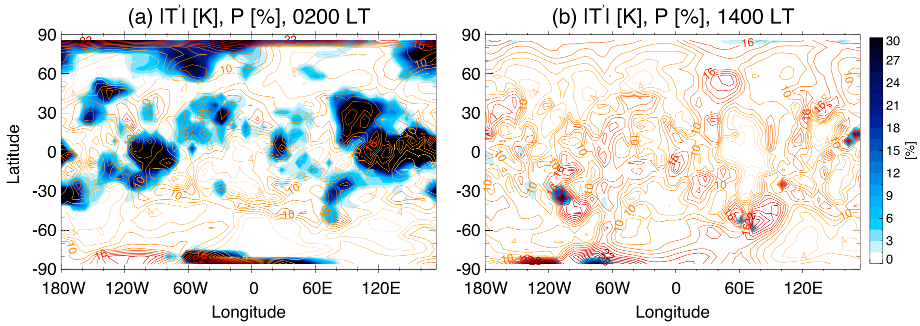

Figure 3: *Mean gravity wave induced temperature fluctuations (red contour lines) and the probability of cloud formation (blue shading) at local night (0200 LT, panel a) and local afternoon (1400 LT, panel b) [Yiğit et al., 2015a, Figure 3].*

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