NUMERICAL SIMULATION OF THE WINTER POLAR WAVE CLOUDS OBSERVED BY MARS GLOBAL SURVEYOR MARS ORBITER LASER ALTIMETER.

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Introduction

Since 1998, the Mars Orbiter Laser Altimeter (MOLA) aboard the Mars Global Surveyor (MGS) orbiter has observed optically thick clouds above the winter north and south polar cap (Zuber *et al*. 1998). The fact that they are only present during the winter polar night suggests that they are constituted of CO_2 ice particles (Ivanov and Muhleman 2001). These clouds have high vertical extension and look tilted against the dominant winds. Some of them are isolated while others present quasi periodic successive patterns. These observations suggest that they are produced by mountain waves and that their periodic patterns can be due to the presence of trapped lee waves (Pettengill and Ford 2000, Zuber *et al*. 1998). The fact that these clouds are triggered by the orography is supported by that the topography on Mars presents large mesoscales irregularities near the Poles. The north polar ice cap is elevated above its surrounding with a 3km maximum elevation near the Pole (Zuber *et al*. 1998). It is sculpted by spiral troughs, whose typical depth and half-depth width are around 0.5km and 7km (Ivanov 2000), respectively.

Although the existence of polar CO_2 ice clouds during the polar night had been intuited for a long time (Gierash and Goody 1968, Pollack *et al*. 1990, Forget *et al*. 1995), the observation by MOLA is the first direct evidence of their presence. The clouds optical properties can explain the low brightness temperature areas observed on the winter polar cap (Kieffer *et al*. 1977, Forget *et al*. 1995, Titus *et al.* 2001). So they may play a key role in the Martian climate, which greatly depends on the condensation of CO_2 in polar night conditions. Accordingly, these clouds may need to be parametrized in General Circulation Models, and a better understanding of their life cycle is essential for this purpose.

The objective of the present paper is to give further evidence that the organized structures, seen in the MOLA echoes, are produced by CO_2 ice clouds triggered by orographic gravity waves. For this purpose, we developed a model that couples a 2D dynamical stratified flow model with a cloud model. The dynamical model solves the anelastic equations of motion (Lipps and Hemler 1991), and has been used for the Earth atmosphere to study mountain waves (Lott 1998, Georgelin and Lott 2001). The cloud model includes CO_2 ice microphysics, sedimentation and wind advection. In the present study, we present numerical simulations of CO_2 ice clouds in meteorological conditions representative of the Martian winter north polar cap. We consider mean state background flows for the north polar winter consistent with both the LMD Martian GCM simulations (Forget *et al*. 1999) and the available MGS observations. We examine the generation of gravity waves by a single orographic trough in a non condensing north polar winter atmosphere as well as the impact of the release of latent due to CO_2 condensation. We examine to which extent the regular structure can be related to resonant trapped waves, and to which extent their dynamics is affected by the CO_2 ice condensation. Numerical simulations with simple cloud physics and realistic north polar cap topographies have been performed. In order to compare with the MOLA clouds echoes observation, we reconstruct from the model outputs the echoes the simulated clouds produce.

Results

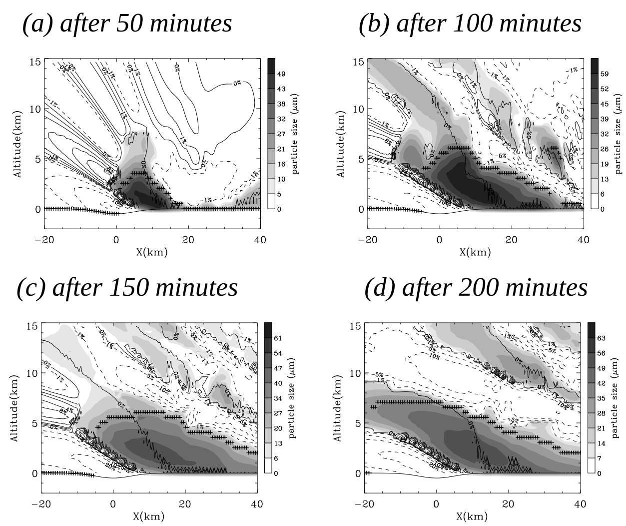

Figure 1: Different stages of the wave clouds formation. These simulations were performed with a constant wind profile U_0=10m.s^{-1} and the T_0 temperature profile,$N_{part} = 10^7$ kg^{-1}, for s_{nucl}= 10%. Shaded contours represent CO_2 ice particles radius (μm). Contour plots represent supersaturation and subsaturation (plane and dashed line). Black crosses are simulated clouds MOLA echoes. The wind blows from the left to the right.

Simulations with an isolated idealized trough The four pictures on Fig. 1 present successive phases (t= 50, 100, 150 and 200 minutes) of clouds development. In all figures, the black crosses represent the altitude of the expected MOLA echoes. These four successive pictures show that the wave perturbations increase in amplitude aloft the trough with time. However this increase is rapidly limited by the development of the clouds. After t=50mn (Fig. 1a), the wave perturbations has propagated upward and the supersaturation reached the critical nucleation supersaturation s_{nucl} between 1 and 3 kilometers aloft the trough. At that time (Fig. 1a), a small cloud has already formed. Where the ice particles nucleate, supersaturation decreases, except in narrow bands very near the windward side of the cloud. In these bands, supersaturation stays quite high to allow the further growth of the ice particles. The supersaturation in the cloud rapidly falls to $\simeq$0%. The ice particles stop to grow, and they are just advected by the wind and fall down. The ice particles sublimate downstream where s<0%, which limits the horizontal extension of the cloud. Before starting to sublimate, ice particles within the clouds reach about 60μm radius. After 100 minutes (Fig. 1b), a large cloud is formed. Above this primary cloud, other clouds start to form. Because they are made of smaller particle and because the number density of particles decreases with altitude, they remain undetectable. Only the main extended cloud aloft the trough is detectable by MOLA. Thereafter this large cloud keep growing (Fig. 1c) and, at t=200mn (Fig. 1d), we obtain model cloud echoes similar to MOLA echoes of isolated observed clouds (Pettengill and Ford, 2000) : the vertical extension of the cloud echoes ve_{cloud} is above 5km, and the slope of the echoes δ_{cloud} is near 8-12°. It is noteworthy that the model clouds echoes do not necessarily correspond to the clouds top but to a region within the clouds where the ice particles are large and dense enough to backscatter the Laser pulse at a level detectable by MOLA. Nevertheless, the shape of the echoes backscatters is directly related to the clouds shape, which is itself related to the waves pattern. We test the sensitivity of our results to the model parameters (background conditions (U_0, T_0), microphysical parameters (s_{nucl}, N_{part}, growth rate limiting process ($R_h \ll R_k$ or $R_h \gg R_k$).

Our model results show that isolated clouds are tilted against the wind direction. They formed just aloft a trough. The echoes slope corresponds to the clouds slope but does not necessarily correspond to the top of the clouds. Our findings are not really sensitive to the background flow profiles above 10km and to the critical nucleation supersaturation s_{nucl} value. The temperature anomalies induced by a 10m.s^{-1} wind over a 0.5 km depth trough in an atmosphere close to the frost point of CO_2 is large enough to create CO_2 ice wave clouds at low altitude (below 20km).

Simulations with realistic topographies We consider three topography profiles that correspond roughly to the three MOLA observations: Passes 207, 260 (Pettengill and Ford 2000) and 222 (Ivanov 2000). The global direction of the wind which corresponds to the three MOLA observations can be estimated from the shape of the cloud (assumed to be tilted against the wind). The wind direction corresponds to a large scale upslope air motion for Pass 222 (Fig. 4) and to a large scale downslope air motion for Pass 207 (Fig. 3). Large scale cooling and warming will be induced by these large scale upslope and downslope air motion, respectively (Forget *et al*. 1998). Like in the isolated trough case, we performed sensitivity tests. These simulations show that polar cap orography induces both small-scale and large-scale dynamical cooling and warming. When the wind is directed upslope of the polar cap (Pass 222, Fig. 4), air condenses globally. A large-scale cloud is then created, but it is modulated by smaller-scale waves motion. In this case, nevertheless, the large scale cloud makes that a large amount of ice particles precipitate to the ground. On the other hand, when the wind blows downslope, air is globally warmed. Small-scale topography variations generate small cooling areas, and ice particles nucleation can occur above 3-5 km only. In this case, the large-scale downslope warming sublimate all the ice particles before they reach the ground, and the sloping clouds are between 5 and 10 km only.

Conclusion

Whatever topography profiles and passes we consider, we obtain extended clouds, whose slope corresponds almost to that induced by upward freely propagating gravity waves, trapped waves do not seem to play an important role. Clouds location and size are dependent on topography profiles, but not their slope. The slope of clouds echoes depends on the microphysical parameters. According to our model, we conclude that the observed clouds are quasi-stationary clouds made of moving ice particles (R_{max}=50-100μm) that grow and sublimate successively by crossing cooling and warming area induced by the succession of polar cap troughs. The nucleation of ice particles occurs in the upstream side of the clouds. A portion of the ice particles precipitates to the ground. The release and absorption of latent heat damp the waves perturbation and prevent resonant trapped wave mode to take place. The apparent periodicity of the observed clouds feature is linked to the periodicity of the north polar cap troughs succession. The particular structure of polar night atmosphere is responsible of the clouds slope and high vertical extension. The slope of observed echoes is related to the slope of the clouds, but do not correspond necessarily with the top of clouds.

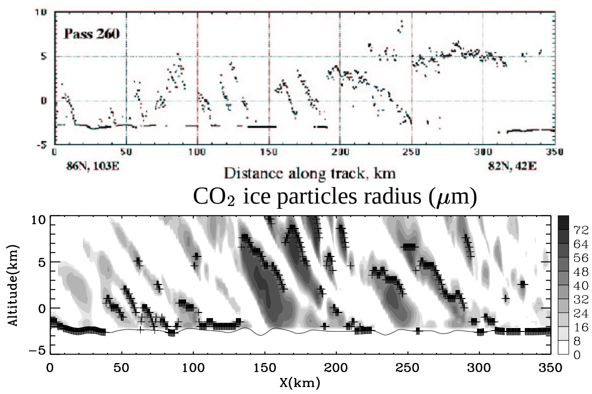

Figure 2: Comparison between MOLA observations (Pass 260, Pettengill and Ford 2000)(top) and wave clouds simulation (bottom) with a large scale flat topography. The simulation is performed with the following background conditions: U_0=10m.s^{-1}, T=T_{cond} (T_0) and microphysical parameters: N_{part}=10^7 kg^{-1}, s_{nucl}=10%, Rh$\gg$Rk, after 2 hours evolution. Shaded contours represent CO_2 ice particles radius (μm). Black crosses are clouds MOLA echoes.

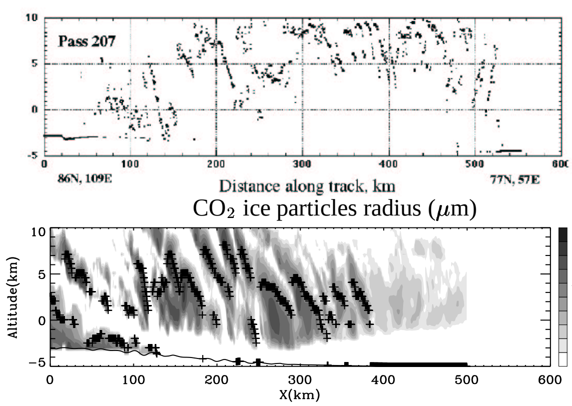

Figure 3: Comparison between MOLA observations (Pass 207, Pettengill and Ford 2000)(top) and wave clouds simulation (bottom) with a large scale downslope topography. The simulation is performed with the following background conditions: U_0=10m.s^{-1}, T=T_{cond} and microphysical parameters: N_{part}=5.10^7 kg^{-1}, s_{nucl}= 10%, Rh$\gg$Rk, after 5 hours evolution.

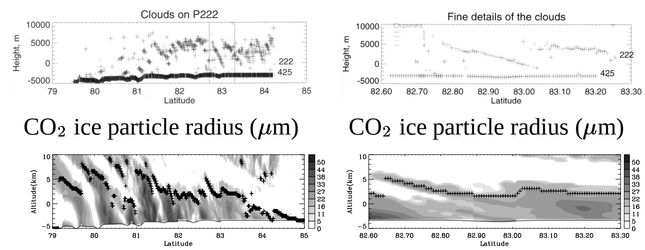

Figure 4: Comparison between MOLA observations (Pass 222, Ivanov 2000) (top) and wave clouds simulation (bottom) with a large scale upslope topography. Topography is taken from Pass 425, which was not obscured by clouds and lies adjacent to the track 222. The simulation is performed with the following background conditions: U_0=10m.s^{-1}, T=T_{cond} and microphysical parameters: N_{part}=5.10^{7}kg^{-1}, s_{nucl}=35%,R_h $\gg$$R_k$, after 4 hours evolution. The right graphs show a fine detail of the left graphs.