Nighttime Convection by Water-Ice Clouds on Mars

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Background

Martian water ice clouds are ubiquitous and were one of the first atmospheric phenomena to be observed on Mars[1]. Although the absolute quantity of water vapor is much smaller than on the Earth (a few precipitable microns, 1 pr-μm = 1000 kg m^{-2}), the low pressure and temperature of the Martian atmosphere cause the relative humidity to often reach saturation conditions[2,3], although the possibility for super-saturation has been evidenced recently on Mars[4]. The morphology of those clouds show considerable variety, from cirrus-like to puffy appearance[5,6,7,8]. The negligible latent heat release during the formation of Martian water ice clouds suggested thus far that they were devoid of the deep convective motions encountered in terrestrial cumulus clouds. Water ice clouds on Mars exhibit seasonal variability, with the formation of the aphelion cloud belt and summertime polar hoods[9,10]. Clouds play a major role in the volatile cycle on Mars by modulating the flux of water vapor from one hemisphere to the other[9,11] and forming nuclei for heterogeneous chemistry[12].

Recently, Martian water ice clouds have been acknowledged to play an even more central role in Mars' meteorology and climate. Their infrared absorption and emission overwhelm their diffusive and absorbing role in the visible[13], thereby warming the daytime upper troposphere of Mars[14] and most significantly cooling the atmosphere and warming the surface in the night (up to $+25$ K)[15]. This causes the strong temperature inversions in radio-occultation profiles obtained on board Mars Global Surveyor[16]. Global Climate Modeling showed that the radiative effect of clouds plays an essential role in the global thermal structure and dynamics of the Martian atmosphere[17,18,19].

Observations

Radio-occultation measurements performed recently with the Mars Reconnaissance Orbiter confirmed the nighttime temperature inversions caused by the radiative effect of water ice clouds[20]. However, a surprising discovery was made when recasting the profiles in potential temperature θ (temperature corrected for adiabatic effects) demonstrated that the temperature inversions are so pronounced that the resulting layers are convectively neutral ($\partial\theta/\partial z = 0$), hinting at mixing processes occurring over a $\sim$ 8 km-deep layer. Those mixing layers occuring at 2-3AM local time were found to be independent of the mixing layers caused by the daytime convective boundary layer, which disappear a few hours after sunset[20,21]. A renewed analysis of the Mars Global Surveyor profiles[16] shows that nighttime mixed layers in the Martian troposphere are almost systematically found in the aphelion belt regions where water ice clouds are found (Figure 1, to be compared to Figure 3 bottom in reference 15). Nevertheless, gravity wave activity, which might produce mixed layers when breaking occur, is also significant in regions where water ice clouds are found[22]. Those regions are also associated with strong atmospheric disturbances by the large-scale thermal tides[23], which control the thermal structure and diurnal variability of the water ice clouds[16], although the possibility that tides would cause mixed layers so low in the atmosphere would imply wave breaking or saturation much lower than expected from modeling and observations[24,25].

Mesoscale simulations

To unambiguously demonstrate the direct link between water-ice clouds and nighttime mixed layers, we carried out three-dimensional numerical modeling of the Martian atmosphere in the aphelion belt season (solar longitude $L_s = 140°$) with a mesoscale model[26] which resolves the atmospheric circulations and clouds at high spatial resolution (20 km in the horizontal and 1 km the vertical) in a specific region of interest including Tharsis Planitia and Amazonis Planitia. While the impact of radiatively active clouds on the global large-scale circulations on Mars has been examined in detail[14,17,18,19], their impact on smaller-scale circulations has never been addressed thus far. The mesoscale simulations carried out here feature the condensation and sedimentation of radiatively-active water-ice clouds[17], and interaction thereof with dust particles[28] through a microphysics scheme allowing for super-saturation to potentially occur[27]. Both dust and water-ice particles are transported interactively at each dynamical iteration as a tracer in the model. The forcing used at the boundaries of the limited domain of interest is provided by Martian Global Climate Modeling using the exact same sub-grid

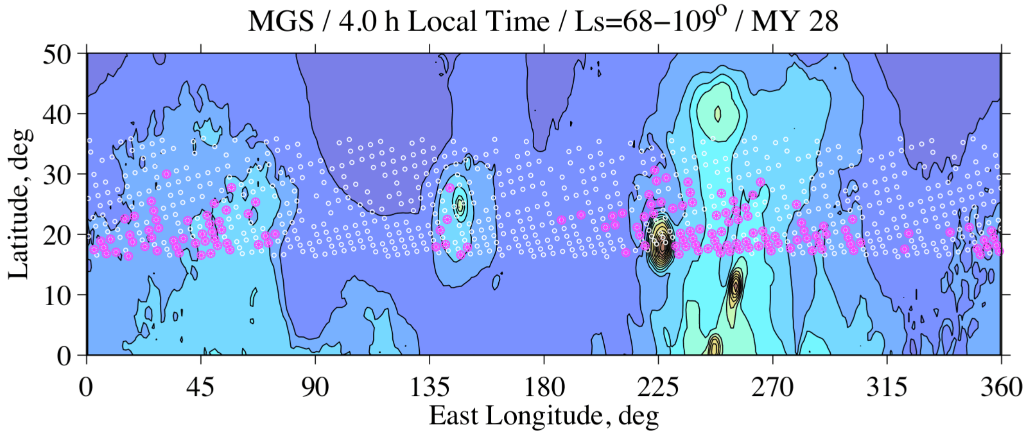

Figure 1: Regional variability of nighttime mixed layers detected in Mars Global Surveyor's radio-occultations in the aphelion cloud belt season. Each square represents one radio-occultation profile; the square is colored in pink of a neighttime mixed layer is found in the profile. This figure complements the observational study published in reference 20.

scale physical parameterizations (radiative transfer, dust scheme, cloud scheme) as the mesoscale model. Model simulations were performed with and without the radiative effect of clouds to unambiguously evidence the impact of those clouds. The water-ice cloud spatial coverage and opacities reproduced by both the Martian Global Climate Model and mesoscale model are compliant with observations[15,29] (and do not vary significantly if the models are run with or without the radiative effect of clouds). Mesoscale simulations are capable to resolve the propagation of gravity waves and correctly replicate the mountain wave associated to Martian volcanoes in the Tharsis region[26,30].

The mesoscale simulations reproduce nighttime mixed layers in agreement with those found in radio-occultations[20]. The model predicts correctly both the observed mixed layer's extent and altitude in Tharsis Planitia where water ice clouds are present at atitudes 10-12 km, and the lack thereof in Amazonis Planitia where no water ice cloud is present (Figure 2). Figure 3 shows simulation results with and without the radiative effects of clouds and further demonstrates that the radiative effect of water-ice clouds strongly affects the thermal structure within and below the cloud and causes the observed deep nighttime mixed layers. Simulations run without the radiative effect of water-ice clouds do not show any mixed layer at the altitudes indicated by observations. Gravity waves resolved by our mesoscale simulations with or without the radiatively-active water ice clouds do produce mixed layers, but their vertical extent is much thinner, their altitude of occurrence is higher, and their region of occurrence is mostly above volcanoes, making the gravity waves source unlikely to produce the nighttime mixed layers. The simulations also rule out the possibility that thermal tides may directly cause the convectively-unstable nighttime mixed layers[31]; however, they are indirectly important as a strong global control on the thermal structure and the regions in which water-ice clouds appear. This remains consistent with the longitudinal variability of the thermal tide signature being correlated to the variability of the mixed layers in Figure 1.

Convective mixing associated with water-ice clouds is driven in a much different fashion than, e.g., daytime convection in the Planetary Boundary Layer. Air parcels become negatively buoyant because the cloud layer is cooling radiatively, especially close to the top, which explains why the mixed layers appear mostly below the water-ice cloud. The model indicates that the radiative cooling rate from thermal infrared emission caused by water ice clouds reach 4 K per hour (Figure 4), which means it takes only a few hours for the atmosphere to reach convective instability. (This would also suggest that mixed layers are late night occurences, although the local-time coverage of the occultations does not permit to verify this claim). Given that the water-ice cloud is destabilized at its summit, this shall give rise to penetrative convection, somewhat analogous to the putative mechanism for convective motions within Venus' sulfuric acid clouds[32], although the Venusian cloud layer is actually destabilized from below by incoming infrared radiation and stabilized above by the absorption of incoming sunlight by cloud particles[33]. The analogy with marine boundary layer clouds on Earth[34] destabilized by radiative cooling is more relevant, although the destabilization does not result in mixing layers as deep as is the case on Martian nighttime water-ice clouds.

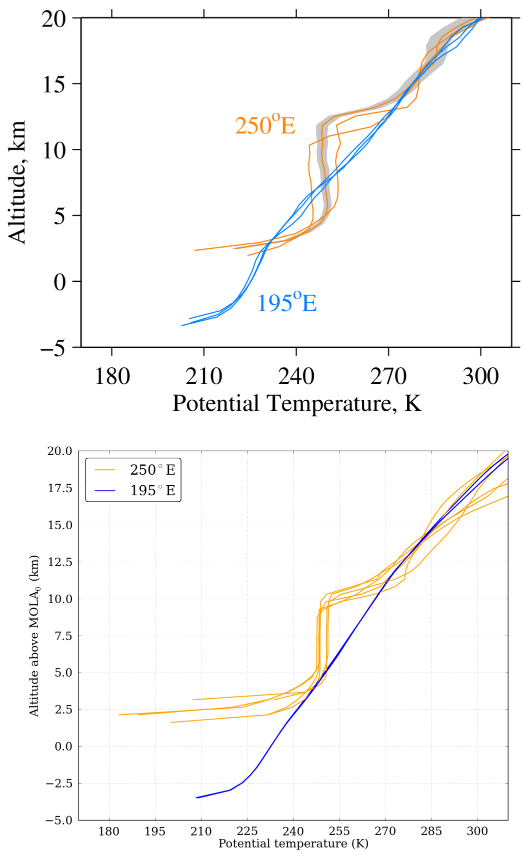

Figure 2: [Top] Observed potential temperature profiles in Mars Global Surveyor radio-occultations in Tharsis Planitia (orange) and Amazonis Planitia (blue) at $L_s = 140°$. [Bottom] Potential temperature profiles at the same season and location, as is simulated by the mesoscale model[26] with radiatively-active water-ice clouds[17,27].

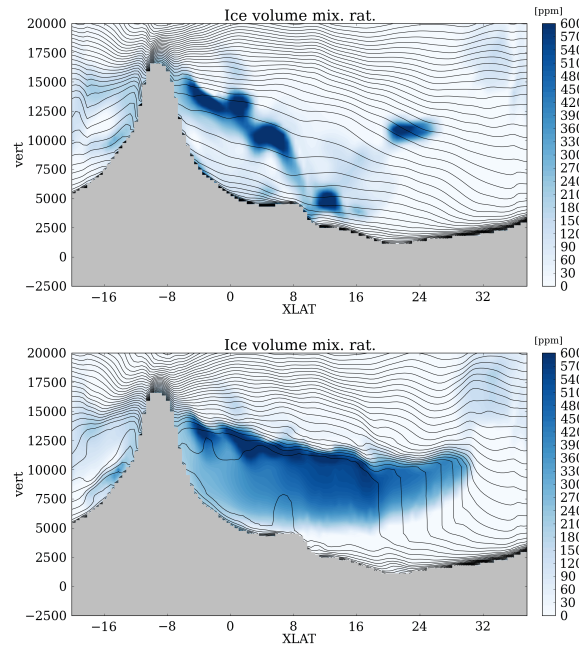

Figure 3: Latitude/altitude cross-section of water ice volumetric mixing ratio (shaded) and potential temperature (contours) at the longitude of Arsia Mons, the season of the aphelion cloud belt, and the local of performed radio-occultations (∼5AM). Top plot is without radiatively active water-ice clouds; bottom plot includes this effect. Our mesoscale simulations show that radiative cooling at cloud top could destabilize the atmosphere and give rise to the mixed layers (quasi-vertical contours of potential temperature, meaning heat mixing within those layers), similar to the signature evidenced by Mars Global Surveyor and Mars Reconnaissance Orbiter[20].

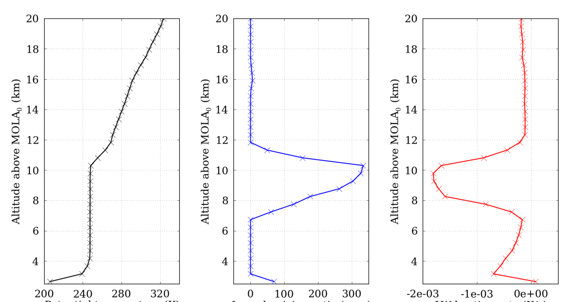

Figure 4: Results of mesoscale simulations with radiatively-active water-ice clouds. Profiles in a grid point where a water ice cloud is present, from left to right: potential temperature, water ice mixing ratio, longwave radiative heating rate.

Large-Eddy Simulations and Perspectives

The convective motions driven by radiative destabilization that give rise to the nighttime mixed layers are not resolved in our mesoscale simulations, in which mixed layers result from parameterized mixing [35]. To further characterize the small-scale circulations underlying the Martian nighttime mixed layers, unprecedented turbulence-resolving Large-Eddy Simulations were carried out [36] with transported radiatively-active water vapor and cloud ice as in the aforementioned mesoscale simulations [8]. The results of those Large-Eddy Simulations will be described at the conference, with a proposed terminology for the new phenomena unveiled by those simulations. We will also discuss the many implications of this work for the Martian water cycle.

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