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Clouds in the Middle Atmosphere of Mars

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1. The atmospheres of Earth and Mars in comparison

Mars is our neighboring planet in the solar system. Mars is a desert planet that is much colder and drier than the Earth. It is well known that frequent dust storms occur on Mars and some of them grow to a global scale, enshrouding the planet in dust for months at a time. It is less well known that clouds are also omnipresent on Mars. While lower atmospheric clouds on Mars are typically thinner than their equivalents on Earth they still have significant effects on the temperature structure and circulation of the martian atmosphere. Clouds in the middle atmosphere of Mars have quite a few similarities – and notable differences – to mesospheric clouds of the Earth’s polar regions. In the following I want to give a brief overview of our current knowledge of martian middle atmospheric clouds and discuss what we might be able to learn about them by studying polar mesospheric clouds on Earth. Comparing planetary and atmospheric features between our planet and other planets in the solar system – or even outside of our solar system – can help reveal fundamental processes that determine how planets work. These kinds of studies are summarized under the term ‘comparative planetology’.

	Earth	**Mars**
Orbit		
Aphelion	152,098,000 km	249,209,000 km
Perihelion	147,098,000 km	206,669,000 km
Eccentricity	0.017	0.093
Orbital period	365.256 days	686.971 days / 668.599 sols
Planet		
Radius	6371 km	3389 km
Surface gravity	9.81 m/s²	3.71 m/s²
Rotation period	23h 56m 4s	24h 37m 22s
Axial tilt	23.44°	25.19°
Atmosphere		
Surface pressure	1013 mbar	6.1 mbar
CO_2	400 ppm	95.3%
N_2	78.1%	2.7%
Ar	0.9%	1.6%
O_2	20.9%	0.14%
H_2O	0.01% - 4.24%	15 - 1500 ppm

Table 1: Key planetary and atmospheric parameters of Earth and Mars in comparison.

Table 1 compares key parameters of Mars with our planet. Mars is a much smaller planet than the Earth with its planetary radius being only about half the Earth’s radius. This leads to a surface gravity that is only about a third of the gravity on Earth. However, the rotation periods of both planets are very similar, such that a Mars day (typically called a ‘sol’) is only about 40 minutes longer than an Earth day. Also the tilt of its rotation axis against the plane in which the planet orbits around the sun is quite comparable.

This leads to seasons on Mars in the same way it does on Earth. Seasons on Mars are typically defined by the direction of the line between the Sun and Mars with respect to the sky noted as L_s (spoken ‘L sub s’). L_s=0° is defined as the beginning of northern spring, L_s=90° is the beginning of northern summer, L_s=180° is the beginning of northern fall, and L_s=270° is the beginning of northern winter.

Mars is on average about 1.5 times farther away from the Sun than the Earth and hence receives significantly less sunlight. Its orbital period is about twice as long as Earth’s so that a Mars year lasts close to two Earth years. An important difference in the orbital parameters between Earth and Mars is the orbital eccentricity. Earth’s orbit is comparatively round, with the distance between the Earth and the Sun varying only a few million km over an Earth year. In contrast, Mars at its closest point (Perihelion) is about 50 million km closer to the Sun that at its farthest point (Aphelion). The seasonality of these events is such that Mars goes through Perihelion close to the beginning of southern summer and through Aphelion close to the beginning of northern summer. This leads to surface and atmospheric temperatures being considerably warmer during southern summer compared to northern summer temperatures. The increased heating also enables more lifting of dust such that the most prominent dust storms on Mars occur in the southern summer season.

Today’s atmosphere of Mars is much thinner than the atmosphere of the Earth. Geologic evidence like outflow channels and canyons suggests that the martian atmosphere was considerably more massive and probably also warmer and wetter than today. However, a considerable part of this original atmosphere has been lost to space over geologic time scales. Today the average surface pressure on Mars is only about 6 mbar. This is less than one percent of the Earth’s surface pressure, and roughly corresponds to the atmospheric pressure found at 35 km altitude on Earth.

Large differences between Earth’s and Mars’ atmospheres exist in their compositions. While Earth’s atmosphere consists to 78% of molecular nitrogen, in Mars’ atmosphere nitrogen mixing ratios are only 2-3%. The main constituent of the martian atmosphere is CO_2, over 95% of the atmosphere is made up of this gas. On Earth, the CO_2 volume mixing ratio is about 400 ppm (parts per million) and has been slowly rising over the years, largely due to fossil fuel consumption of humankind. 21% of Earth’s atmosphere consists of oxygen, which is largely produced by biologic activity as a byproduct of photosynthesis. To date there are no known biologic processes on Mars, and oxygen in the martian atmosphere is only a trace gas, largely produced by the photolysis of CO_2 in the upper atmosphere.

An important constituent when it comes to cloud formation in the atmospheres of both planets is water vapor. Water vapor in Earth’s atmosphere is abundant, at least in the lower atmospheric layer, the troposphere. Water vapor mixing ratios in Earth’s atmosphere vary strongly depending on latitude, temperature, and weather. In tropical regions, mixing ratios up to 4% can be found. Due to the temperature range found in Earth’s troposphere, clouds formed in the lower troposphere typically consist of liquid droplets, while clouds in the upper troposphere consist of ice particles. In the middle troposphere mixtures of liquid and solid cloud particles can exist. The martian atmosphere is on average a lot drier than Earth’s atmosphere. Water vapor mixing ratios are typically in the ppm range, although values up to 1.5% (1500 ppm) have been measured. Liquid water is not stable in today’s martian climate so water-based clouds in the atmosphere of Mars are made of water ice.

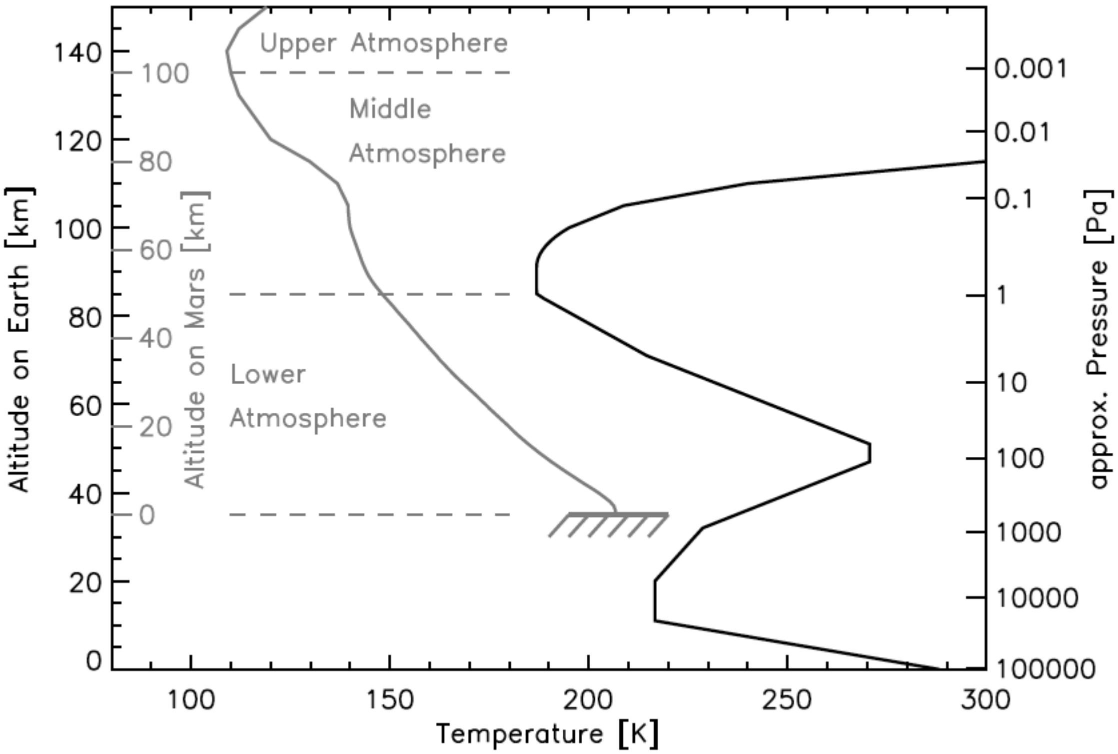

Figure 1: Standard temperature profiles vs. altitude for Earth (black, based on the US standard atmosphere) and Mars (gray, based on the MCS temperature climatology in the non-dusty season in Haberle et al., 2017). The surface pressure on Mars roughly corresponds to the atmospheric pressure on Earth found at 35 km altitude, hence the altitude scale for Mars was offset by 35 km with respect to the altitude scale for Earth. The pressure scale is only approximate due to the differences in atmospheric temperatures.

Figure 1 shows an average temperature profile of Mars in comparison to a standard atmospheric temperature profile of the Earth. Temperatures are plotted vs. an altitude scale. The altitude scale for Mars' atmosphere has been offset by 35 km in comparison to the altitude for Earth's atmosphere as the surface pressure on Mars corresponds roughly to the Earth's atmospheric pressure found at 35 km altitude. The pressure scale on the right hand side of Figure 1 is approximate but valid for both atmospheres. Figure 1 indicates that atmospheric temperatures on Mars are lower than on the Earth at every altitude level. Atmospheric temperatures on Earth close to the surface are about 280-290 K on average. On Mars the average temperature in the lower atmosphere is about 240-250 K. While surface temperatures can exceed the freezing point of water at 273 K in localized areas in the middle of the day, martian atmospheric temperatures rarely reach this value. Another feature easily observed in Figure 1 is that layers in Mars' atmosphere cannot be as easily defined as in Earth's atmosphere. On Earth, atmospheric layers are defined due to changes in the sign of the lapse rate. A dominant feature is the Earth's stratosphere, which has increasing temperatures with height due to atmospheric heating through solar absorption by the ozone layer. Due to the much lower concentration of oxygen, Mars lacks an ozone layer, hence the martian atmosphere lacks the strong temperature changes with altitude found in Earth's atmosphere. Outside of the winter polar regions, Mars' atmospheric temperature typically decreases with height up to an altitude of 40-50 km. Above this altitude, temperatures tend to become more isothermal. At altitudes above ~100 km, temperatures may increase again due to solar absorption, which leads to a strong day/night temperature contrast. Hence the lowest 50 km of the martian atmosphere have been defined as lower atmosphere, the region between 50 and 100 km has been defined as middle atmosphere, and the region above 100 km is considered the upper atmosphere.

2. Martian middle atmospheric water ice clouds

Clouds in the martian atmosphere can be made of water ice or carbon dioxide ice. The latter do not have an equivalent on Earth as temperatures are never low enough for carbon dioxide to freeze. In addition, carbon dioxide is the main constituent of the martian atmosphere so freezing it out (either due to cloud formation or direct deposition to the surface at the winter poles) has a profound impact on the atmospheric pressure cycle and leads to significant pressure variations over the seasons.

Water ice clouds are omnipresent on Mars. Temperatures are typically suitable for the formation of ice clouds and cloud formation mainly depends on the availability of water vapor. On Earth the tropopause provides an effective cold trap for water vapor, leading to very dry conditions in the stratosphere and mesosphere. On Mars the smaller lapse rate in the atmosphere does not provide an effective cold trap for water vapor, and water ice clouds can form in the lower atmosphere as well as in the middle atmosphere. The most prominent cloud feature in the lower atmosphere is the aphelion cloud belt, which was already observed from Earth-based measurements. It is a band of clouds that appears in the equatorial region in the northern spring and summer season. Its typical extend is from about 10°S to 30°N in latitude and the clouds reach up to altitudes of roughly 40 km. The aphelion cloud belt is fed by water vapor coming off the north polar cap in spring and summer. The cooler global temperatures during the aphelion season cause clouds to form in the equatorial region. As the perihelion season approaches, the aphelion cloud belt starts to dissipate due to the rising global temperatures. This corresponds to northern fall. Temperatures drop in the northern high latitudes, causing condensation of water vapor in the lower atmosphere of the polar region that leads to the formation of the northern polar hood cloud. With an extent from the north pole down to 50°N latitude it covers not only the polar region but reaches well into the mid-latitudes. It starts forming in late northern summer around L_s=160° and dissipates again in early northern spring around L_s=20°. The southern polar region also develops a polar hood cloud in southern fall and winter. However, the southern polar water ice clouds are not nearly as dense or as extended as their counterpart in the north. They are present between about L_s=20° and L_s=180°, with a notable gap in occurrence between L_s=70° and L_s=110°. Like the northern polar hood, also the southern polar hood is constrained to the lower atmosphere. However, in contrast to the north, the southern polar hood cloud is shaped like an annulus, mostly covering the latitudes between 60°S and 80°S.

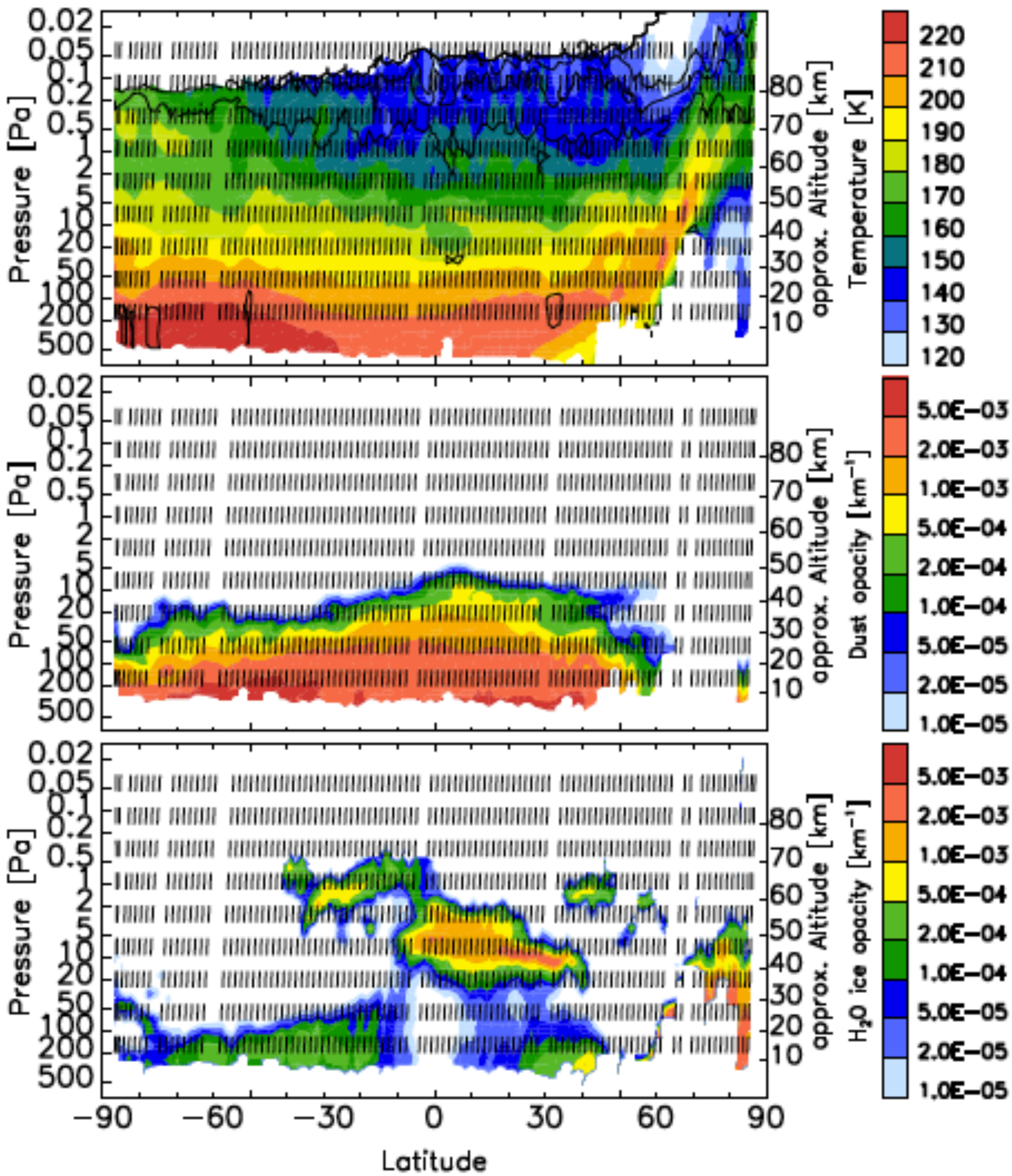

Figure 2: Transect of atmospheric temperature (top), dust opacity (center, at 463 cm^{-1}) and water ice opacity (bottom, at 843 cm^{-1}) as measured by MCS in September 2009 (L_s=247°). The nearly vertical dashed lines indicate the locations of individual measurements. Water ice clouds reach altitudes of 60-70 km at this season.

Figure 2 shows a pole-to-pole transect of temperature, dust and water ice opacity at L_s=247° during northern fall as measured by the Mars Climate Sounder (MCS). MCS is a thermal emission radiometer on board the Mars Reconnaissance Orbiter (MRO). It has eight channels in the mid- and far-infrared and one channel covering a broad band in the visible and near-infrared wavelength region. It predominantly measures in limb geometry, which means that it looks at the horizon of the planet. The limb geometry provides a long optical path, which increases the sensitivity of the measurement, and it allows the observation of the vertical structure of dust and clouds. From the radiance measurements, profiles of atmospheric temperature, dust and water ice are retrieved from the surface to ~80 km altitude with a vertical resolution of ~5 km. The most prominent feature of Figure 2 is a cloud in the equatorial region. This is not during the season of the aphelion cloud belt. However, a temperature minimum at 30-50 km altitude between about 10°S and 40°N causes water vapor to condense and form a cloud. In addition, temperature minima at higher altitudes to the south (40°S-10°S) and to the north (40°N-60°N) lead to cloud formation. Water ice clouds in these regions are found at altitudes of 60-70 km in the middle atmosphere. This shows that at least in this season, water vapor can penetrate high enough into the atmosphere to allow the formation of water ice clouds in the middle atmosphere. The measurements of these clouds were made with an MCS infrared channel at 12 µm, suggesting that these clouds consist of moderate-size ice particles, likely of order 1 µm radius, a size typical for clouds in the lower atmosphere. This is significantly larger than the particle sizes of polar mesospheric clouds on Earth. However, other measurements in the ultraviolet or near-infrared wavelength ranges, like solar occultation observations from Mars Express or observations by the CRISM instrument on MRO have also suggested clouds with particle sizes down to ~0.1 µm radius, which would be more in line with polar mesospheric cloud particle sizes on Earth. Other features that can be identified in Figure 2 include the northern polar hood cloud, which was discussed previously. It extends from the pole to about 60°N in the lower atmosphere. The extent of the polar hood cloud at this season is determined by the polar vortex, a region of confined air formed by the descent of airmasses over the northern polar region.

3. Martian middle atmospheric carbon dioxide ice clouds

In the previous section it was shown that water ice clouds on Mars can reach mesospheric altitudes. This happens predominantly in the perihelion season (L_s=180°-360°) when the atmosphere is dustier and lower atmospheric temperatures are higher, allowing the transport of water vapor to higher altitudes of the atmosphere.

However, parts of the martian atmosphere can become cold enough to allow carbon dioxide to condense, leading to the formation of CO_2 ice clouds. A feature that makes this process particularly intriguing is that CO_2 is the main constituent of the martian atmosphere. In the lower atmosphere of the polar regions, temperatures in winter regularly drop to values at which CO_2 condenses. The condensation of CO_2 is the main driver of the seasonally varying surface pressure on Mars. In Figure 2, temperatures drop below the frost point of CO_2 (~145 K at martian pressures in the lower atmosphere) in the center of the vortex close to the pole. Hence the conditions in these regions are favorable for the formation of lower atmospheric CO_2 ice clouds. Due to the high abundance of CO_2 in the martian atmosphere, these clouds are expected to grow to large particle sizes rather quickly, causing CO_2 snowfall in the winter polar region.

Observations of high clouds or detached aerosol layers in the aphelion season raised the question whether the martian mesosphere could also become cold enough to allow atmospheric CO_2 to condense and form mesospheric clouds. In 1997 the atmospheric temperature profile reconstructed from the entry trajectory of the Mars Pathfinder lander revealed temperatures below the CO_2 frost point in the middle atmosphere, suggesting that CO_2 cloud formation may be possible. Shortly thereafter, these measurements were used together with early observations by the Mariner 6 and 7 as well as the Viking missions, ground-based submillimeter observations, and pre-dawn cloud observations by Pathfinder from the martian surface to provide evidence for the existence of middle atmospheric carbon dioxide clouds on Mars.

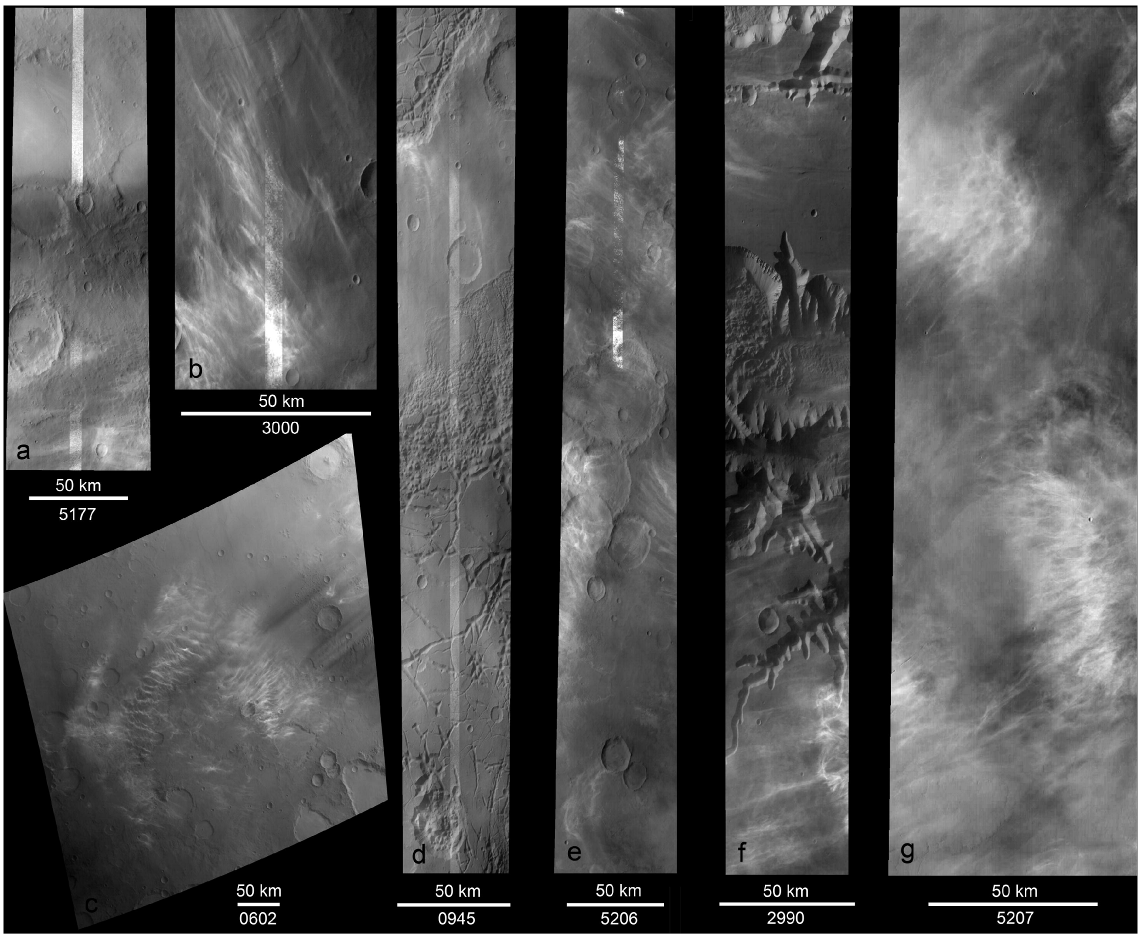

Figure 3: Image examples of martian ice clouds taken by the HSRC camera onboard Mars Express. Vertical stripes in the center of images (a), (b), (d), and (e) indicate simultaneous measurements with the OMEGA imaging spectrometer onboard the same spacecraft. From Määttänen et al. (2010), used with permission.

Since the 2000s, observations by instruments on several Mars orbiters including Mars Global Surveyor (MGS), Mars Express (MEx), Mars Odyssey (ODY), and the Mars Reconnaissance Orbiter (MRO) have been providing a multitude of evidence of martian middle atmospheric CO_2 clouds. Limb observations by the camera and thermal emission spectrometer instruments on MGS allowed the detection of mesospheric clouds and provided estimates of their altitudes. Stellar occultation observations from MEx, by which the absorption of starlight is observed as the star sets or rises through the atmosphere, also provided cloud extinctions and their vertical distribution. In addition, atmospheric density measurements by same instrument could be used to derive temperature structure and to show that cold pockets with atmospheric temperatures below the CO_2 frost point existed in the vicinity of the detected clouds. Nadir-viewing imagers and imaging spectrometers also provided evidence for mesospheric clouds. Figure 3 shows a set of mesospheric could images by the HSRC camera onboard Mars Express. These images can be used to identify clouds and evaluate cloud structures. The images show striking similarities to images of Polar Mesospheric Clouds (PMCs) on Earth taken with camera instrumentation flown on Antarctic circumpolar balloon flights or with the CIPS instrument onboard the AIM satellite from Earth orbit. While the lateral extent of mesospheric clouds can be easily determined from images, it is much harder to derive the cloud altitude. Knowing the solar illumination angle it is possible to derive cloud altitude from the shadow that is cast by the cloud onto the surface. However, this works only for clouds that are sufficiently optically thick to cast a discernable shadow on the surface. Another possibility for altitude determination is the use of the parallax in two or more subsequent images taken at varying off-nadir angles. In an image taken strait down in nadir geometry a cloud will obscure a different part of the surface than in an image taken at an angle in off-nadir geometry. With the knowledge of the spacecraft positions at the times the two images were taken and the observation angles, the altitude of a cloud can be calculated. This method was used extensively to characterize clouds imaged with the visible subsystem of the THEMIS instrument on Mars Odyssey.

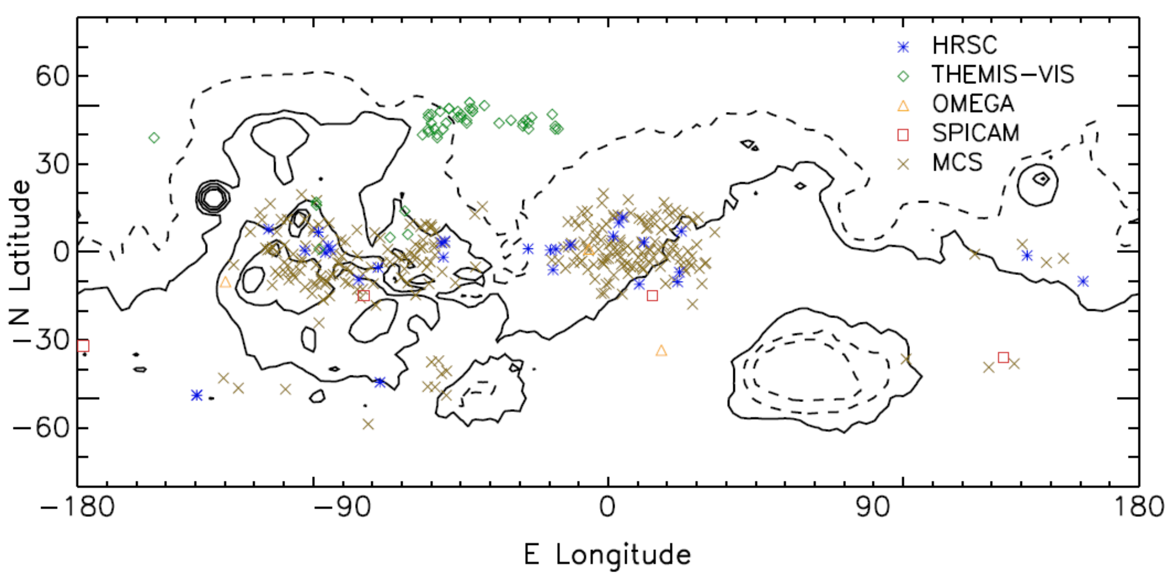

Figure 4: Latitude/Longitude distribution of mesospheric clouds on Mars as measured by various instruments from Mars orbit. MCS measurements have been restricted to be between L_s=0°-90° (northern spring) and above 60 km altitude. Contours show Mars topography (solid: positive, dashed: negative) in intervals of 3 km.

None of these methods are equally suited to determine that a cloud actually is composed of CO_2 ice rather than water ice so for many of the identified mesospheric cloud examples the actual composition is not necessarily known. Limb observations of cloud extinction can be combined with limb observations of temperature, either based on the density structure as derived from solar or stellar occultation measurements or directly measured by means of thermal emission radiometry. If the temperatures in the vicinity of a cloud are close to the CO_2 frost point the cloud is likely composed of CO_2 ice. Direct evidence for cloud composition requires the spectroscopic identification of CO_2 ice in the clouds. This has been achieved by identifying the CO_2 ice scattering peak at 4.24 µm in near-infrared observations by the OMEGA instrument, an imaging spectrometer onboard Mars Express. The CRISM imaging spectrometer has also been used to identify cloud composition and estimate particle sizes. Its observations suggest typical particle sizes of order 0.5 µm radius for mesospheric CO_2 clouds.

Figure 4 shows the latitude/longitude distribution of mesospheric clouds identified in measurements from various instruments. A significant fraction of the observed mesospheric clouds occur in a band of about 20° latitude around the equator. They cluster around longitudes of 90°W and 10°E, a few clouds were also observed around 120°-150°E. Most of these clouds are made of CO_2 ice. The clustering is related to regional temperature minima in the martian mesosphere. In addition, the clustering occurs in regions close to large changes in topography, suggesting that gravity waves driven by wind over high topography may play a role in the formation of the clouds. Equatorial mesospheric clouds typically form in the aphelion season around L_s=0°-150°. Figure 4 also shows the occurrence of mesospheric clouds in mid-latitudes. Most of these mid-latitude clouds tend to appear in fall of their hemisphere (around L_s=50° in the southern hemisphere and around L_s=250° in the northern hemisphere). It is thought that most of these mid-latitude clouds also consist of CO_2 ice although the occurrence of water ice clouds cannot be excluded (compare Figure 2).

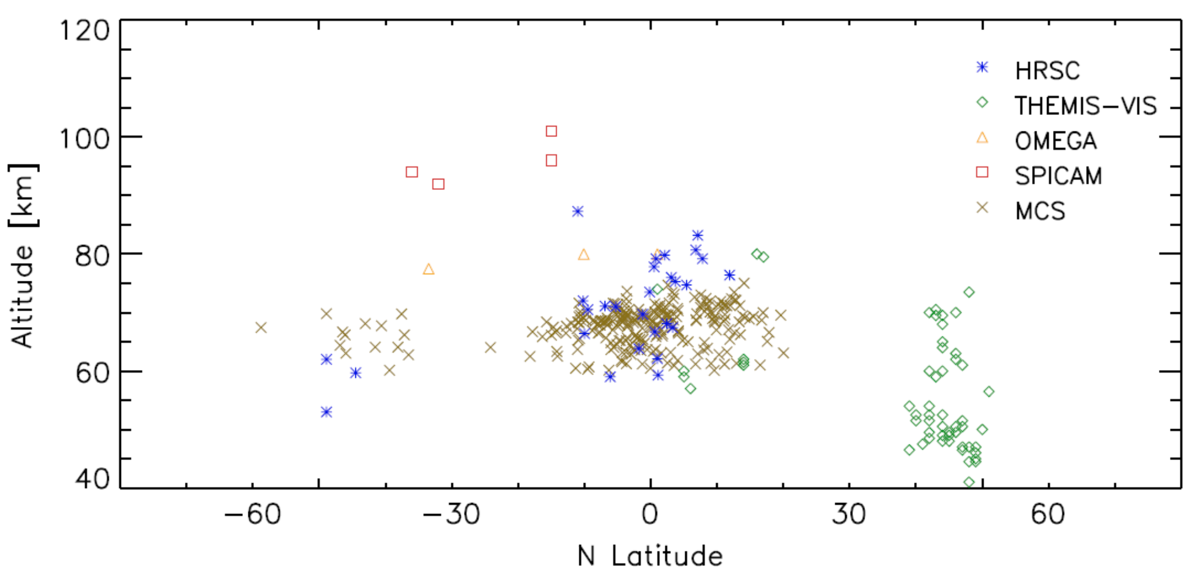

Figure 5: Latitude/Altitude distribution for the same set of mesospheric clouds on Mars as in Figure 4. Again, MCS measurements have been restricted to be between L_s=0°-90° (northern spring) and above 60 km altitude.

Figure 5 shows the vertical distribution of the clouds in Figure 4. The bulk of the equatorial clouds in the aphelion season occur at altitudes between 60 and 90 km. A few clouds have even been observed to occur as high as 100 km. Clouds found at mid-latitudes in both hemispheres tend to occur at lower altitudes and occupy a typical altitude range of 40-70 km.

4. Temperature structures controlling cloud formation on Mars

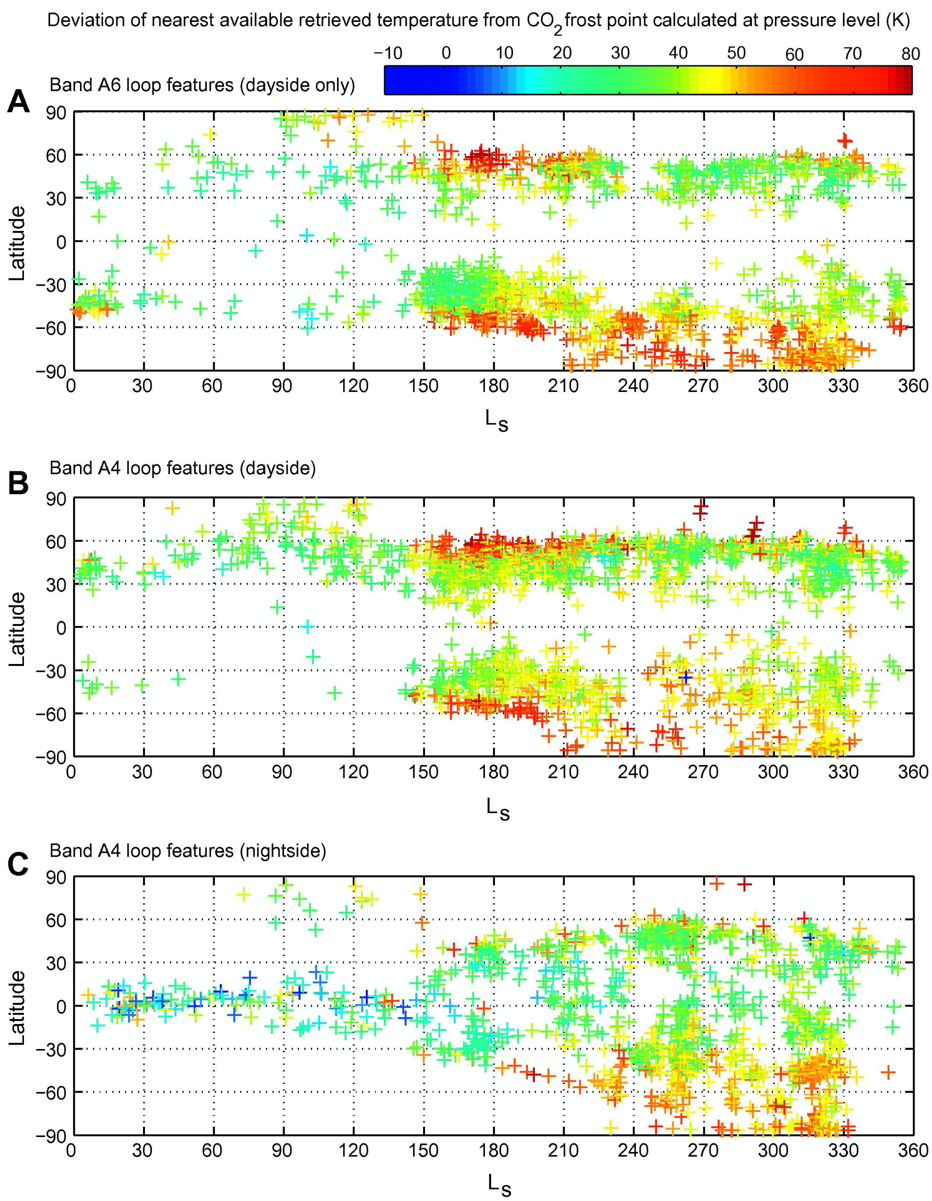

Figure 6: Latitude/L_s distribution of mesospheric clouds from MCS. Band A6 corresponds to the MCS visible/near-IR channel while Band A4 corresponds to the MCS infrared channel centered at 12 µm. The color coding indicates atmospheric temperature deviation from the CO_2 frost point from the temperature measurement closest the cloud measurement. From Sefton-Nash et al. (2013), used with permission.

What causes clouds to form in the martian mesosphere? A clue can be found by studying cloud occurrence in relation to the temperature structure of the martian atmosphere. Figure 6 shows the distribution of mesospheric clouds observed in various channels of the MCS instrument over the course of a martian year. The color coding gives the temperature that was measured by MCS in the thermal infrared at the closest location and the same pressure level as the cloud observation. Note that the temperature is given as the deviation to the CO_2 frost point, which is of order 100-120 K at pressures typical for the martian mesosphere. Figure 6 shows that temperatures close to clouds observed during the aphelion or northern spring and summer season tend to be within 10-20 K of the local CO_2 frost point. This suggests that most of the mesospheric clouds during this season are made of CO_2 ice. Starting around northern fall equinox (L_s=150°-180°) an increasing number of clouds is found for which nearby temperatures are much higher, in many cases 40-50 K and in some cases even 70-80 K above the CO_2 frost point. These temperatures indicate that the clouds observed in these locations are water ice clouds. Note that at equatorial latitudes around L_s=180°-210° and at northern mid-latitudes around L_s=270°-330° there are cloud populations with nearby temperatures around 20-30 K above the CO_2 frost point. It is possible that local temperature perturbations could bring these temperatures close to the frost point, allowing CO_2 clouds to form even at this season.

In order to better understand the conditions under which mesospheric clouds form we should have a closer look at the processes controlling the temperature structure. One of the main drivers of temperature variations in the martian atmosphere are atmospheric tides. Tides are periodic changes in atmospheric parameters like temperature, pressure, and wind that have periods of a fraction of a solar day. They are driven by the changes of solar energy input to the Mars surface and atmosphere over the course of a day. This is in contrast to ocean tides on Earth that are driven by the gravitational pull of the moon and the sun. Due to the thin atmosphere on Mars, most of the solar radiation reaches the surface, where it causes strong differences in temperature between day and night. Surface temperature maxima are typically reached at local noon or slightly later, while surface temperature minima are reached in the early morning. The heat flux from the surface causes changes in pressure and temperature in the lowermost atmosphere. The propagation of these changes gives rise to global oscillations in atmospheric pressure and temperature, and subsequently also wind. The most prominent oscillation is the diurnal tide, which has a period of one solar day, meaning that for example temperature will exhibit one minimum as well as one maximum over the course of a day. While thermal tides also exist on Earth, their temperature perturbations typically start to become significant only at altitudes of the upper mesosphere and above. On Mars, thermal tides cause significant temperature variations throughout the atmosphere.

Figure 7 illustrates the diurnal tide in the temperature field as observed by MCS. Due to the sun-synchronous orbit of MRO, MCS collects temperature data predominantly around 3 AM and 3 PM local time. In Figure 7 these temperature measurements were combined to zonal averages separately for day and night and then used to create diurnally averaged temperatures and temperature differences between day and night. The average temperature field shows a temperature structure that is typical for atmospheric conditions close to equinox (L_s=135°–165°), with cold temperatures in the lower middle atmosphere of both polar regions, overlaid by layers of warmer temperatures, and cold temperatures in the equatorial middle atmosphere. The temperature differences show a complex pattern of minima and maxima, which is highlighted in the schematic in the bottom left panel of Figure 6. A temperature maximum is found above the equatorial surface. Above the this region, the temperature deviations show a nodal pattern consistent with the expectation of a vertically propagating tide with a vertical wavelength of order 40 km. Around 30° N and S the phase of the tide reverses, such that in northern and southern mid-latitudes temperature minima are located at altitudes of temperature maxima in the equatorial region and vice versa.

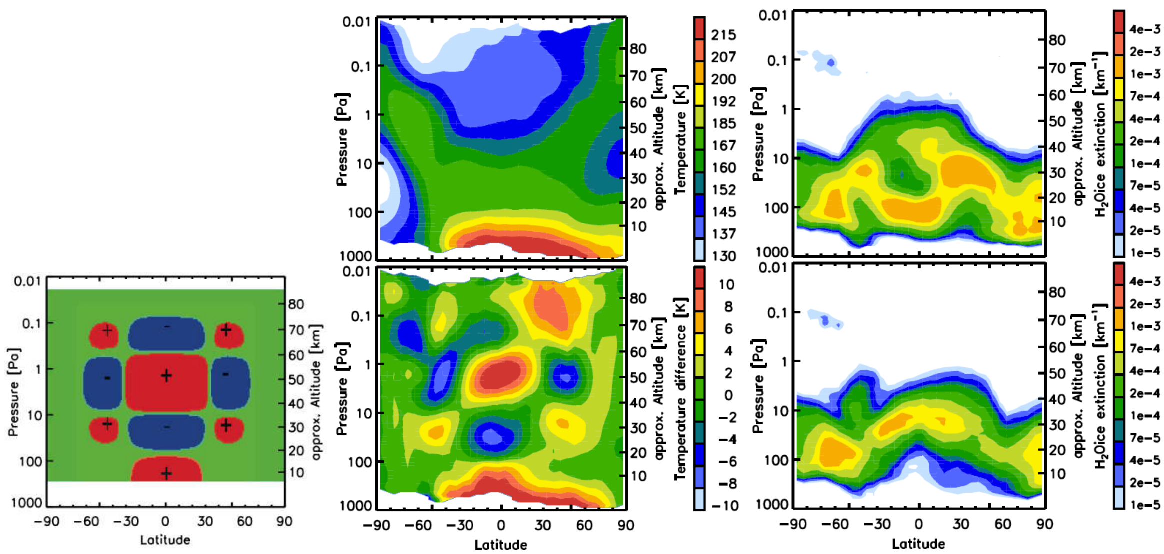

Figure 7: Diurnally-averaged temperature (top center panel) and day/night temperature difference (bottom center panel, defined as (T_{PM}-T_{AM})/2) as a function of latitude and pressure for the period from L_s=135°-165° derived from MCS data. The far left panel shows a schematic of the temperature minima and maxima. The right panels show water ice clouds from MCS data at different local times (top: 3 AM, bottom: 3 PM) and indicate that cloud coverage is strongly correlated with temperature minima.

The right panels of Figure 7 show the occurrence of water ice clouds as observed by MCS, separated for day and night. Few water ice clouds are observed above 50 km altitude in this season. The only notable cloud occurrence in the upper middle atmosphere is observed at 60°-70°S around 70 km altitude, coincident with very low temperatures found in this region. Elsewhere water ice clouds mainly from in locations consistent with temperature minima driven by the diurnal tide. At nighttime, clouds tend to from close to the surface and around 40 km altitude in the equatorial region. At daytime the pattern reverses and clouds tend to form predominantly between 20 and 30 km altitude, where the equatorial daytime temperatures are lower than at night. The formation of water ice clouds is very common at temperatures found in the martian atmosphere and limited largely by the availability of water vapor. During aphelion season, water vapor in the middle atmosphere is limited by the extensive cloud formation below 40-50 km such that water ice clouds at mesospheric altitudes are rare. During perihelion season (southern spring and summer) the warmer and dustier lower atmosphere allows water vapor to be transported to higher altitudes, enabling the frequent formation of water ice clouds. Small dust particles, advected together with water vapor to mesospheric altitudes, could serve as nuclei for cloud condensation. The presence of clouds at altitudes of 50-70 km in perihelion season (Figure 2) indicates localized water vapor mixing ratios of tens of ppm, which would be about an order of magnitude higher than in Earth’s stratosphere and mesosphere.

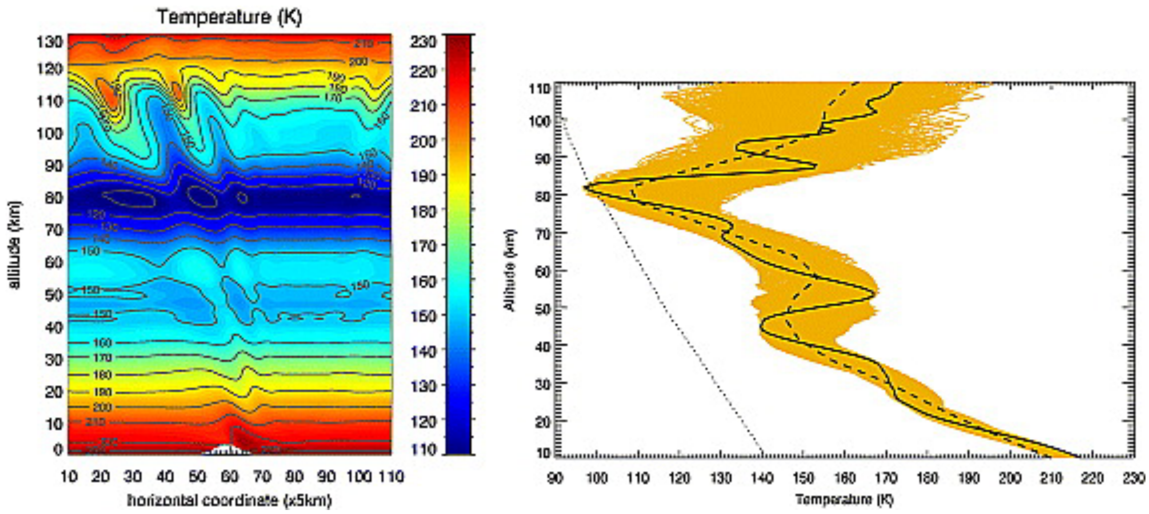

Figure 8, left: Mars atmospheric temperature structure derived from a regional-scale numerical computer model for conditions of wind passing over a mountain range and causing gravity waves. Right: Cross-section through the temperature structure of the left panel showing the undisturbed background temperature (dashed) and the perturbation range due to gravity waves (yellow-shaded area). The solid line indicates a temperature profile within this range that reaches the CO_2 frost point. From Spiga et al. (2012), used with permission.

The formation of CO_2 ice clouds is obviously not limited by vapor supply as CO_2 is the main constituent in the martian atmosphere. However, measurements show that temperatures in the martian middle atmosphere rarely reach the CO_2 frost point. In addition, computer models that are used to simulate the Mars atmospheric circulation on a global scale do not tend to simulate temperatures at the frost point outside of the winter polar regions. Figure 8 gives a clue about the processes that are likely required for the formation of mesospheric CO_2 ice clouds. It shows temperature simulations by a regional-scale computer model. The banded temperature structure in the left panel of Figure 8 shows the temperature variation with altitude as it would be simulated with a global model. This temperature structure is controlled by radiative processes, the global atmospheric circulation, and atmospheric tides. The perturbations in the banded structure are caused by gravity waves due to the wind in the lower atmosphere passing over a mountain range (depicted as a white spot at the bottom of the left panel of Figure 8). As the wind passes over the mountain, it induces gravity waves that propagate into the upper atmosphere. As they propagate to higher altitude their amplitudes grow due to the decrease in atmospheric density. The right panel of Figure 8 shows a cross-section through the temperature structure. The dashed line indicates the background temperature due to the general circulation and the tides. The yellow-shaded area gives the temperature perturbations caused by gravity waves. If the phase of a gravity wave coincides with the tidal structure such that the gravity wave deepens a temperature minimum caused by the tide (black line) the perturbation can be large enough to reach the CO_2 frost point (dotted line). This process is thought to be essential for the formation of CO_2 ice clouds in the martian mesosphere. The temperatures are still not low enough to allow homogeneous nucleation, such that the formation of CO_2 ice requires some form of condensation nuclei. It is suggested that particles from meteoric infall could provide these condensation nuclei, similar to what is suggested for the formation of PMCs in Earth's mesosphere.

Continued operations of limb sounding instruments like MCS on MRO and the deployment of new limb sounding instruments would complete and further refine the climatology of mesospheric clouds in the martian atmosphere. Characterization of the atmospheric environment will help separating water ice and CO_2 ice clouds and further constrain the conditions required for cloud formation. Imaging of martian mesospheric clouds by orbiters and landed assets and the analysis of small-scale cloud structures could help to characterize gravity waves in the martian atmosphere and their influence on mesospheric clouds. Analysis of these images could be done analogously to image analyses of spaceborne or suborbital images of PMCs on Earth. This would provide additional details to further our understanding of the formation and development of mesospheric clouds on Mars.

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