Global 3D modelling of Martian CO_2 clouds

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Summary

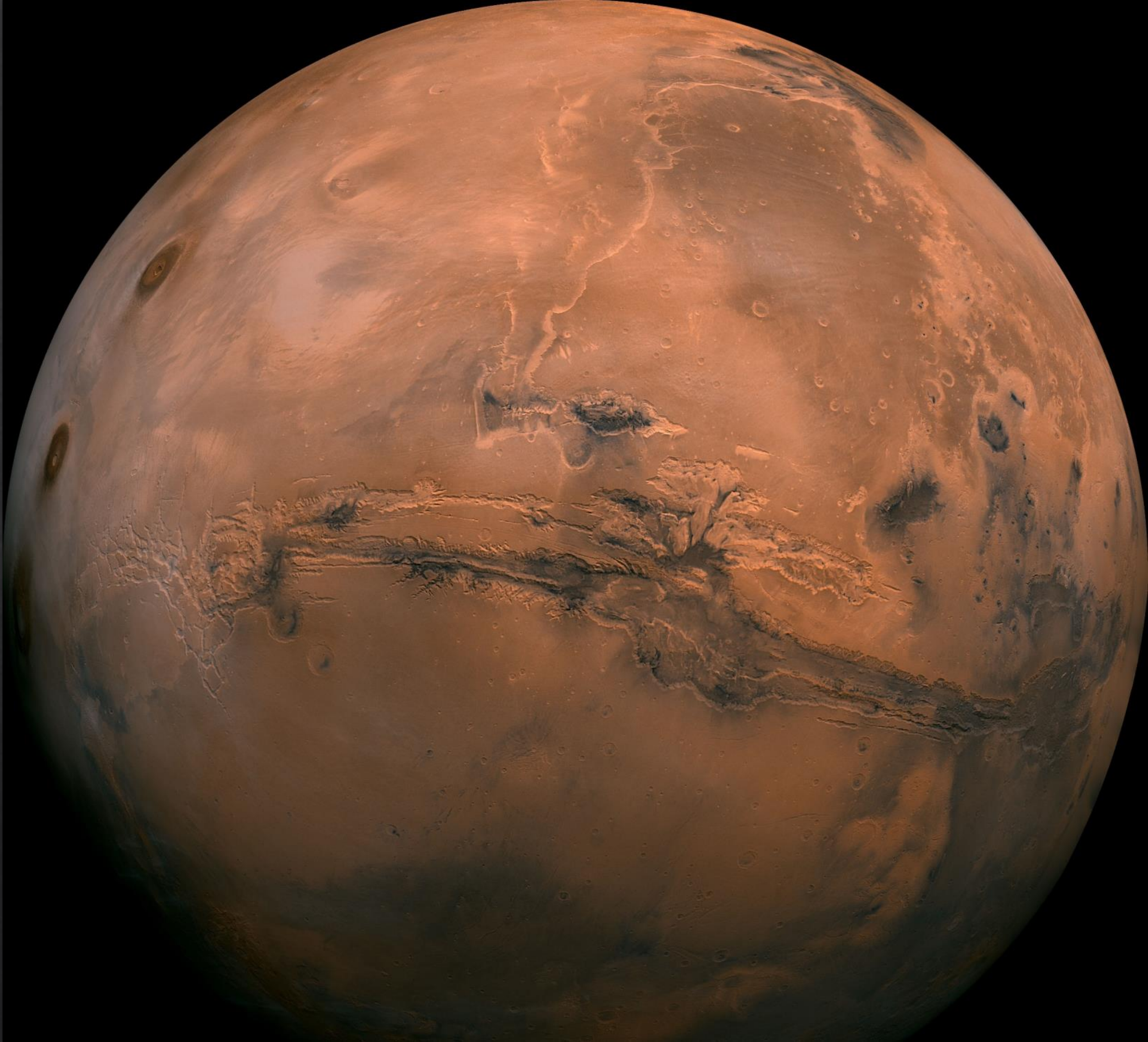
Introduction

The Martian atmosphere

- Composition:
  - CO_2 (95%)
  - N2 (2.8%)
  - Ar (2%)
  - O, CO, H_2O, and trace gases

- $\langle T_{surf} \rangle = 215$ K
- $\langle P_{surf} \rangle = 610$ Pa

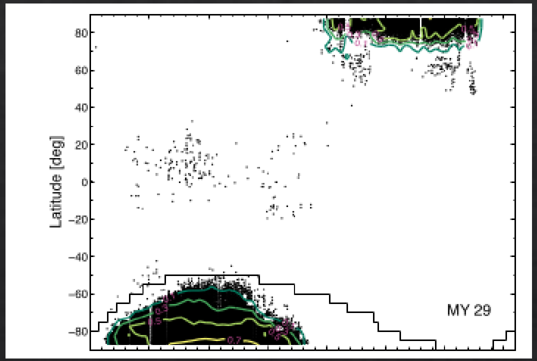
- Tropopause at ~ 1 Pa (45 km)
- Mesopause at ~ 0.01 – 0.001 Pa (100 – 120 km)
- Thermopause around 200 km



CO_2 clouds observed on Mars

Carbon dioxide clouds have been revealed by numerous instruments around Mars from the beginning of the XXI century. Two kinds of clouds involving different formation processes:

- Polar clouds
  - Located in the polar troposphere during winter



Credit: Hu et al., 2012

- Equatorial and mid-latitudes clouds
  - Before northern autumn equinox: located in the equatorial region and southern mid-latitudes
  - After northern autumn equinox: in northern mid-latitudes

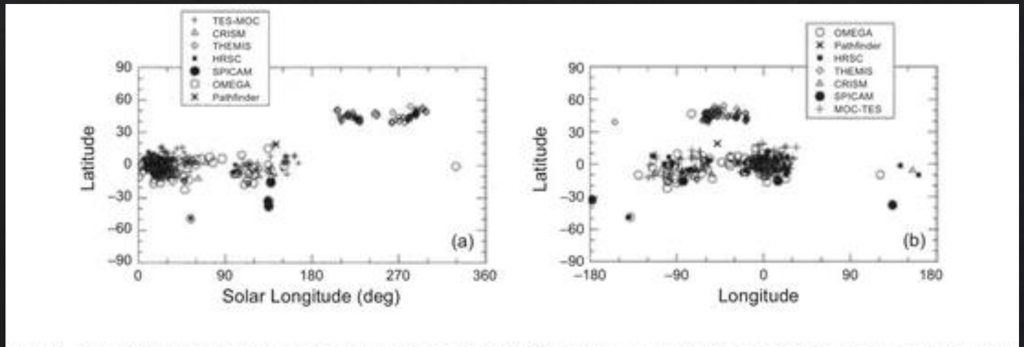


Fig. 6. **(a)** Latitude-solar longitude map of datasets on mesospheric clouds, as noted in the legend. **(b)** Latitude-longitude map of datasets on mesospheric clouds, as noted in the legend. The Pathfinder rover observation of bluish clouds is also marked.

Credit: Määttänen et al., 2013

Purpose & Questions

Formation processes of theses clouds are still not fully understood

However, modeling studies have revealed processes necessary for their formation:

- Atmospheric waves to perturb the atmosphere leading to a temperature below the condensation of CO_2 [Kuroda et al., 2013; Gonzalez-Galindo et al., 2011; Spiga et al., 2012]
- Sources of condensation nuclei to trigger the cloud formation [Listowski et al., 2014]

Using our full microphysical model of CO_2 clouds formation coupled to a Global Climate Model (GCM), we intend to investigate:

- Seasonal and spatial distribution of CO_2 clouds
- Major actors of both tropospheric and mesospheric in formation of CO_2 clouds
- The impact of CO_2 clouds on the Martian atmosphere

Methodology

Description of the microphysical cloud model

A state-of-the-art microphysical column (1D) model for CO_2 clouds in a Martian atmosphere was developed at LATMOS [Listowski et al., 2013, 2014].

The model contains:

- Source of condensation nuclei
  - Dust
  - H_2O ice (possible)
  - Exogenous source in the mesosphere (from meteor ablation) [not use here]
- Nucleation, contact parameter of CO_2 ice on:
  - Dust = 0.78 [Nachbar et al. 2016]
  - H_2O ice = 0.95 [Glandorf et al., 2002]
- Condensation/sublimation (modified for a near-pure vapor [Listowski et al., 2013])
- Sedimentation

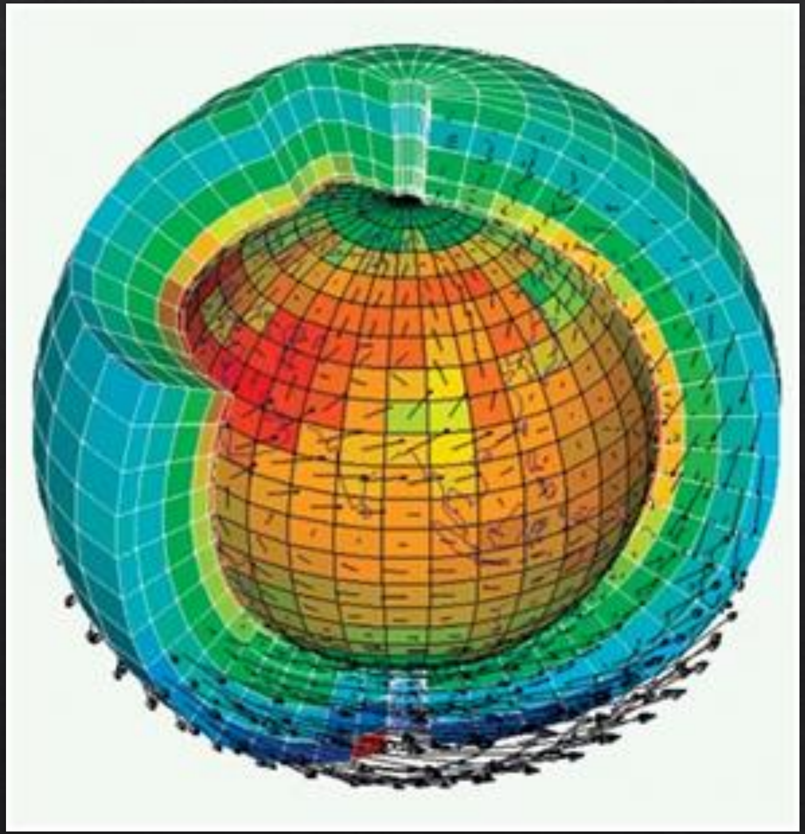
Description of the Martian Global Climate Model

The Martian Global Climate Model has been developed by the LMD in collaboration with many laboratories including LATMOS [Forget et al., 1999].

It is a sigma-hybrid coordinate in a latitude-longitude grid.

The MGCM includes:

- ◈ Dust scenarii coming from observations [Montabone et al., 2015]
- ◈ Dust cycle
- ◈ Water cycle [Navarro et al., 2014]
- ◈ CO_2 cycle



Representation of the spatial grid in a GCM.
Credit: L. Fairhead, LMD

Description of the 4 performed simulations

- Simulation of 1 Martian year
- Horizontal grid resolution: 64 x 48 (5.6258°longitude x 3.758° latitude)
- Vertical grid resolution: 32 levels (top at ~ 120 km, ~ 3×10^{-3} Pa)
- Dust scenario: climatology (regular scenario)

- Dynamical time step: 1.5 minutes
- Physical time step: 15 minutes
- Microphysical time step: 18 seconds
- Outputs time step: 2 hours

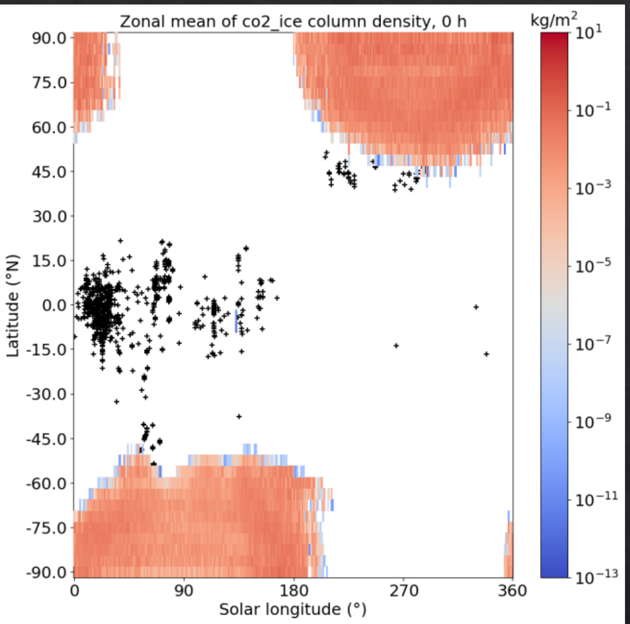
Simulation number	Name	CO_2 clouds Microphysics	Water ice as CN	CO_2 clouds radiatively active
1	Reference	Yes	-	-
2	CO2useH2O	Yes	Yes	-
3	RT	Yes	-	Yes
4	RT+CO2useH2O	Yes	Yes	Yes

Results

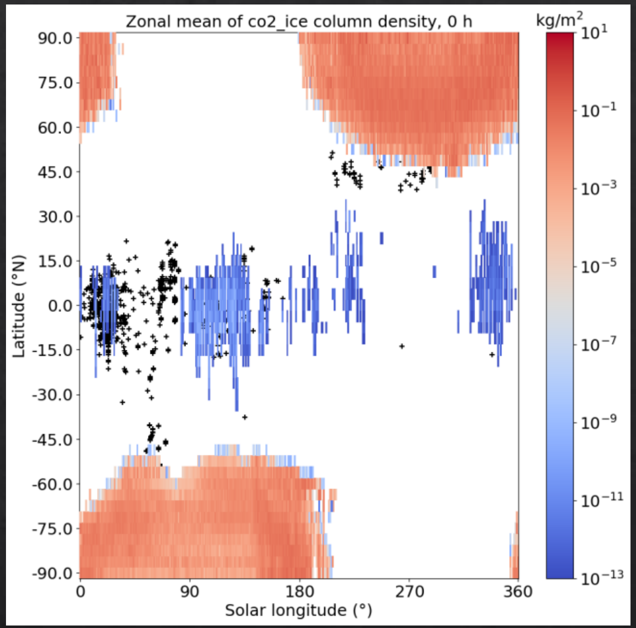
Global results of CO_2 clouds

Seasonal and spatial distribution of CO_2 clouds

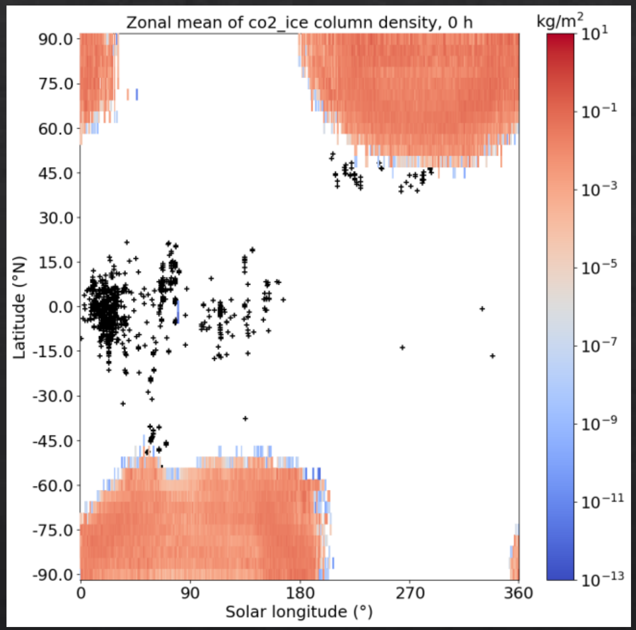
Reference



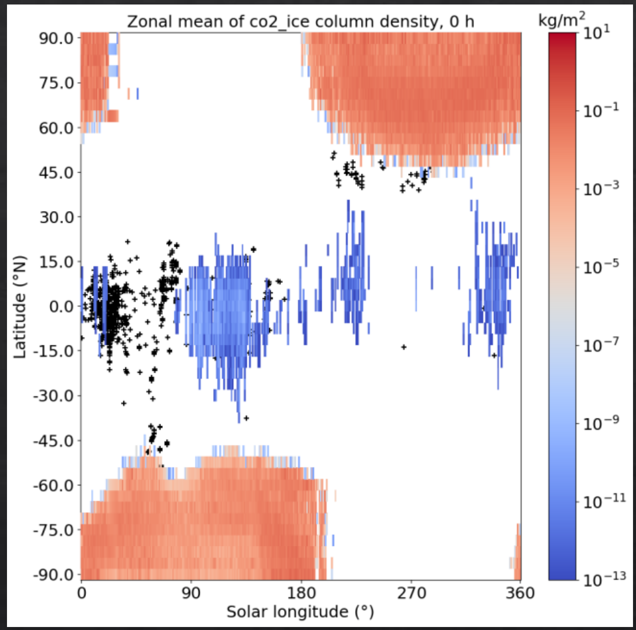
CO2useH2O



RT



RT+CO2useH2O



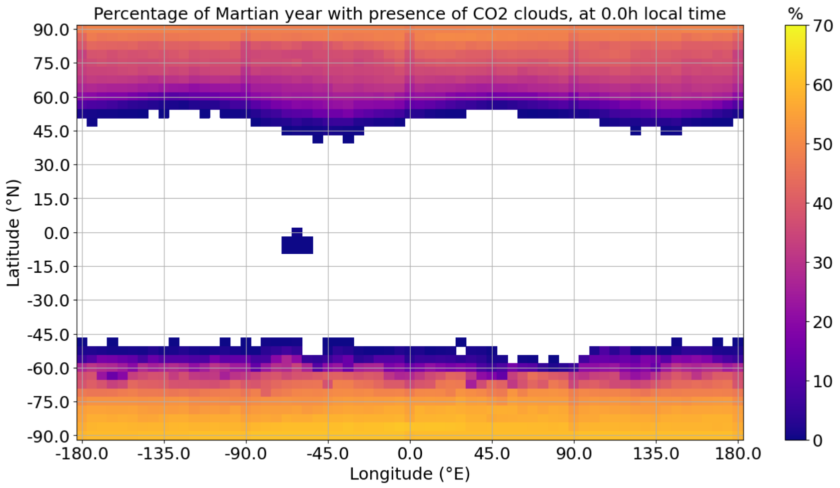
- Use H_2O ice as CN help to form CO_2 clouds in the equatorial region
  - Theses clouds are located in the mesosphere (see after)
  - Good match with the mesospheric clouds observed

- RT simulation don’t show significant variations (back-up)

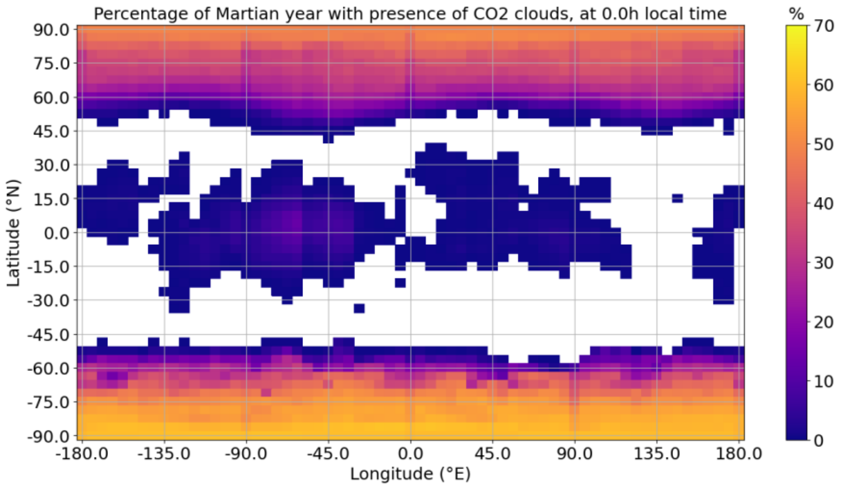
Cross: mesospheric clouds observed

Frequency of CO_2 cloud formation over a Martian year

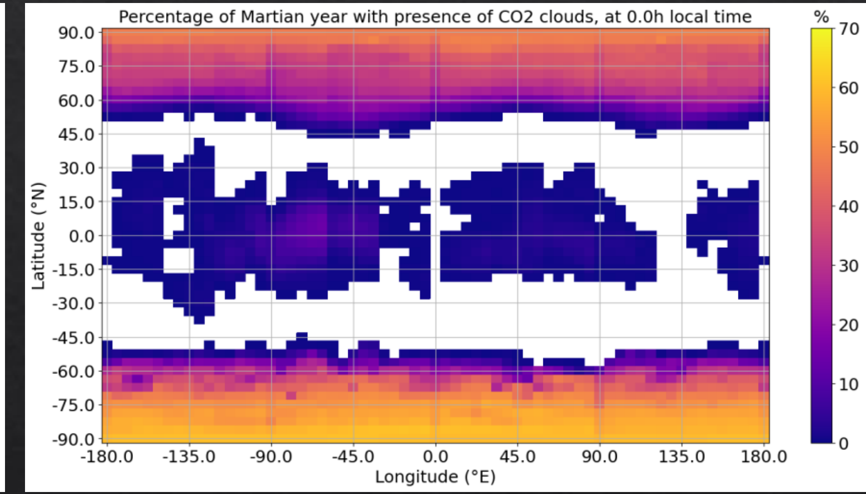
Reference



CO2useH2O



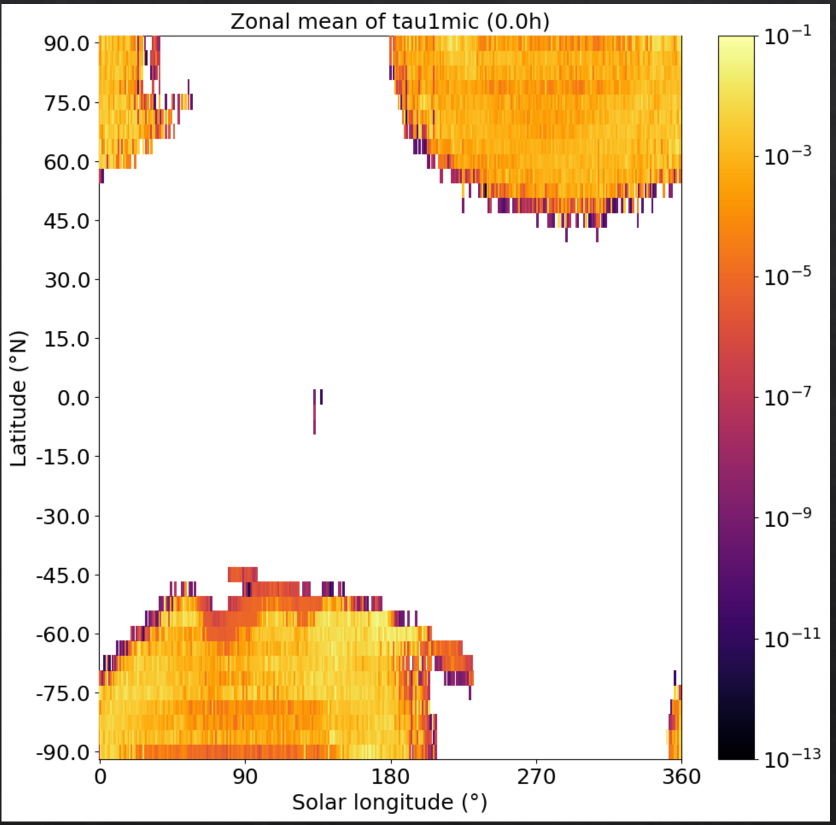
RT+CO2useH2O



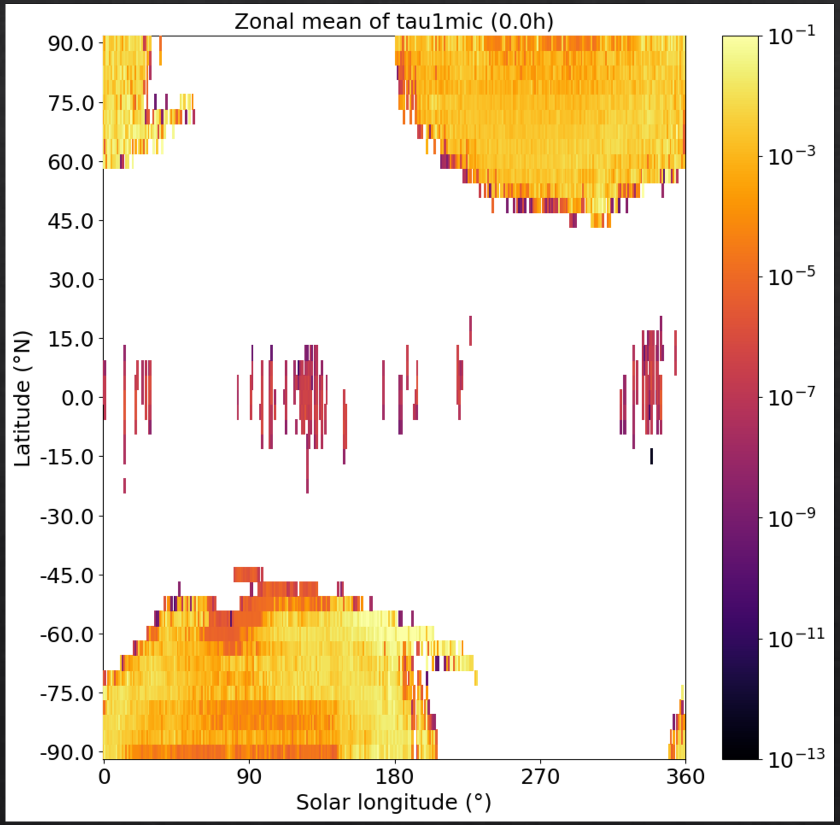
- CO_2 clouds reach 45° around each pole during winter
- As for equatorial region, they are located between ± 40°N

Opacity of CO_2 clouds at 1 micron

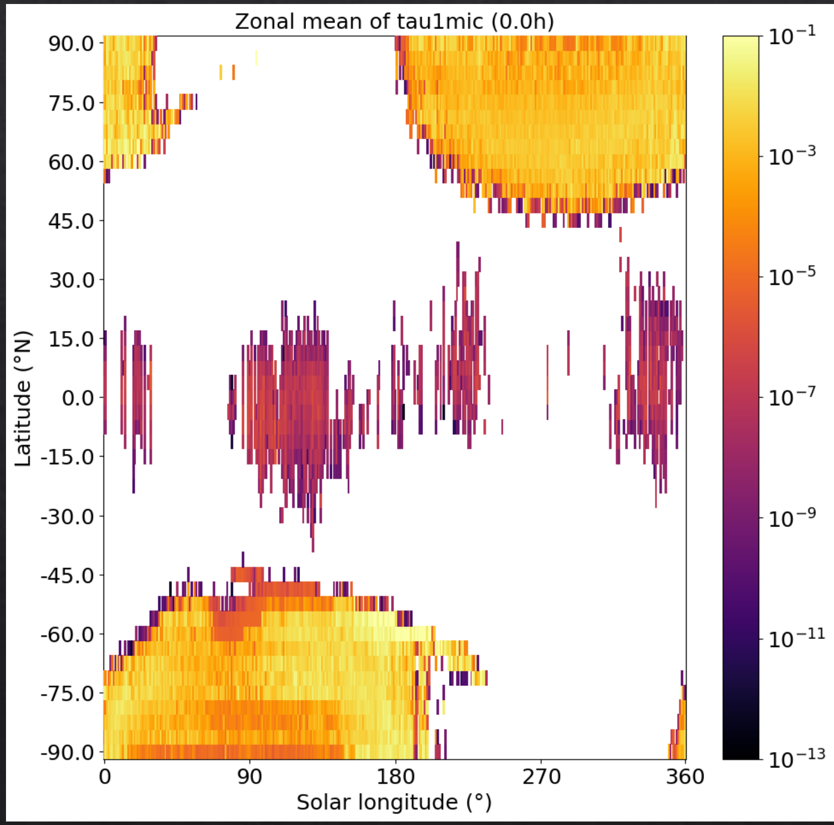
Reference



CO2useH2O



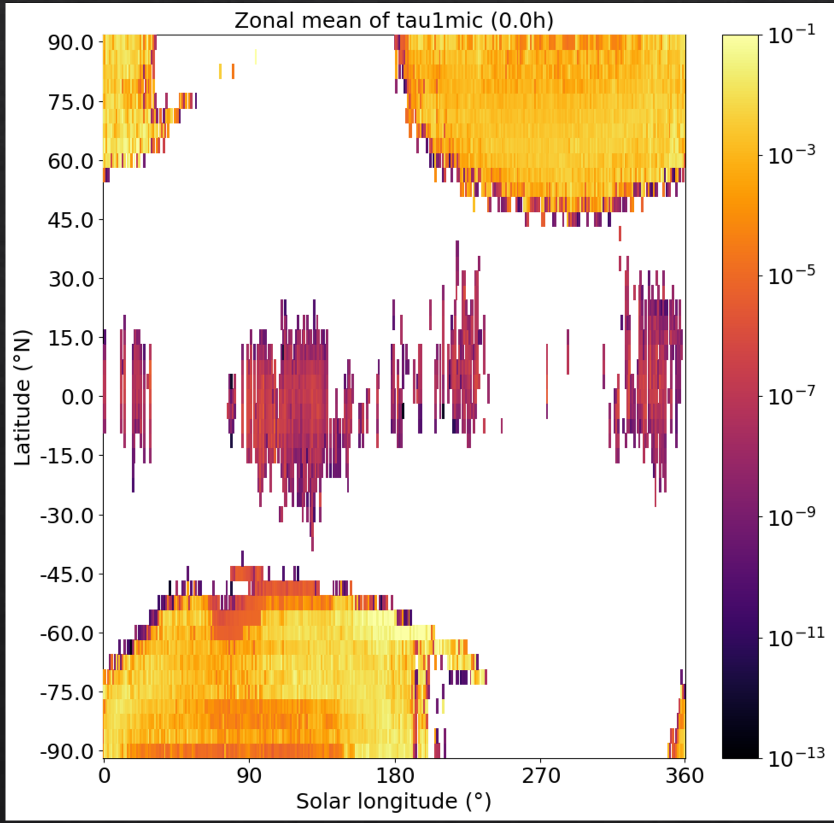
RT+CO2useH2O



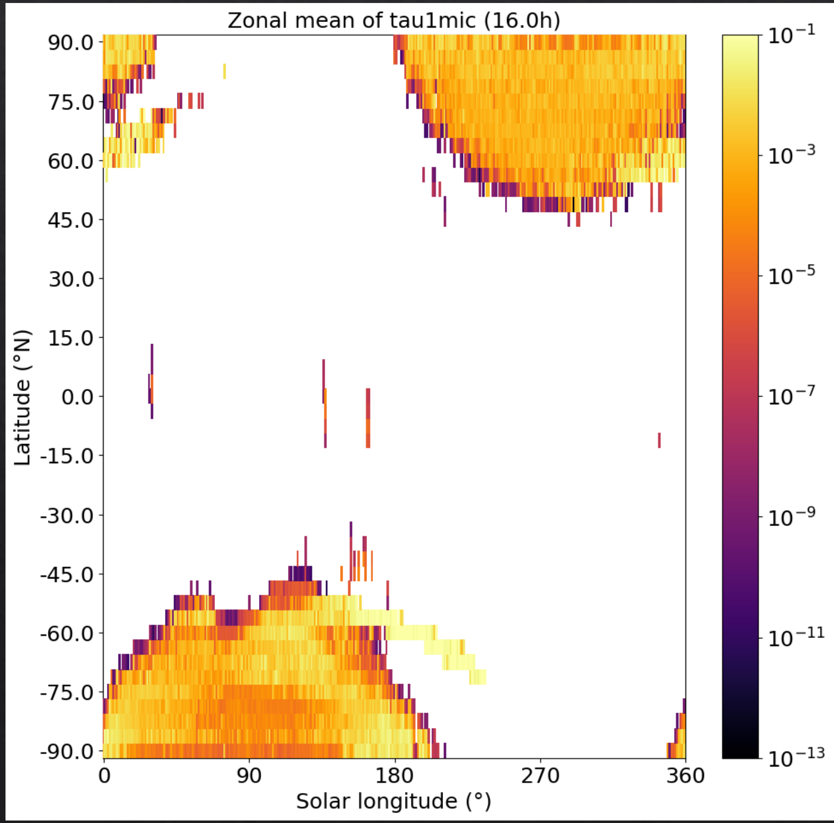
Activate radiatively CO_2 clouds increase the opacity at 1 micron in the case with RT+CO2useH2O

Opacity of CO_2 clouds at 1 micron RT+CO2useH2O

0h



16h



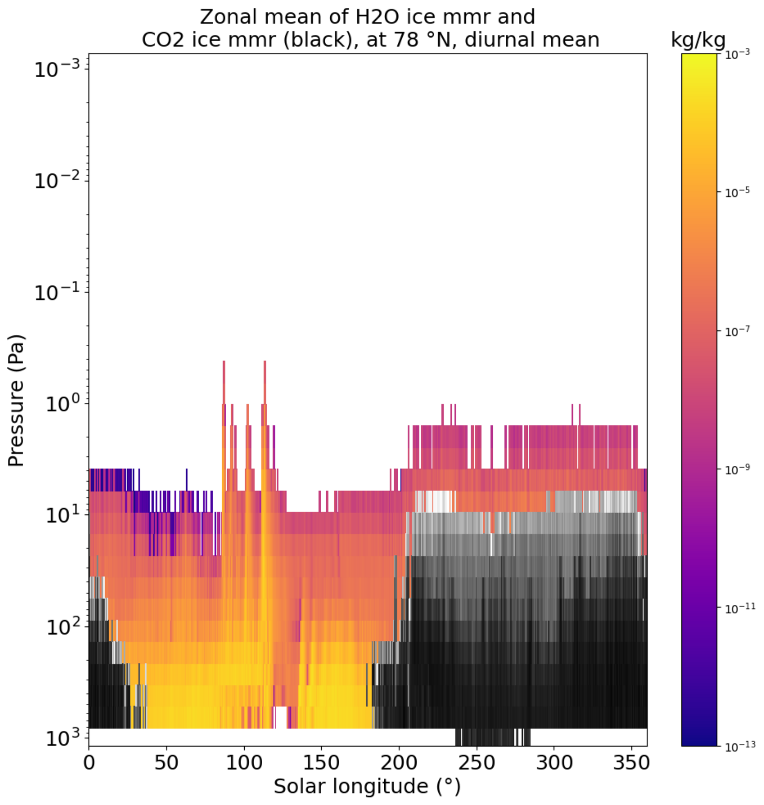
Few equatorial clouds at 16 h and their opacity is far below OMEGA observations ($\tau_{1\mu m} < 0.01 - 0.6$ at 16h for equatorial mesospheric clouds [Määttänen et al., 2010])

Results

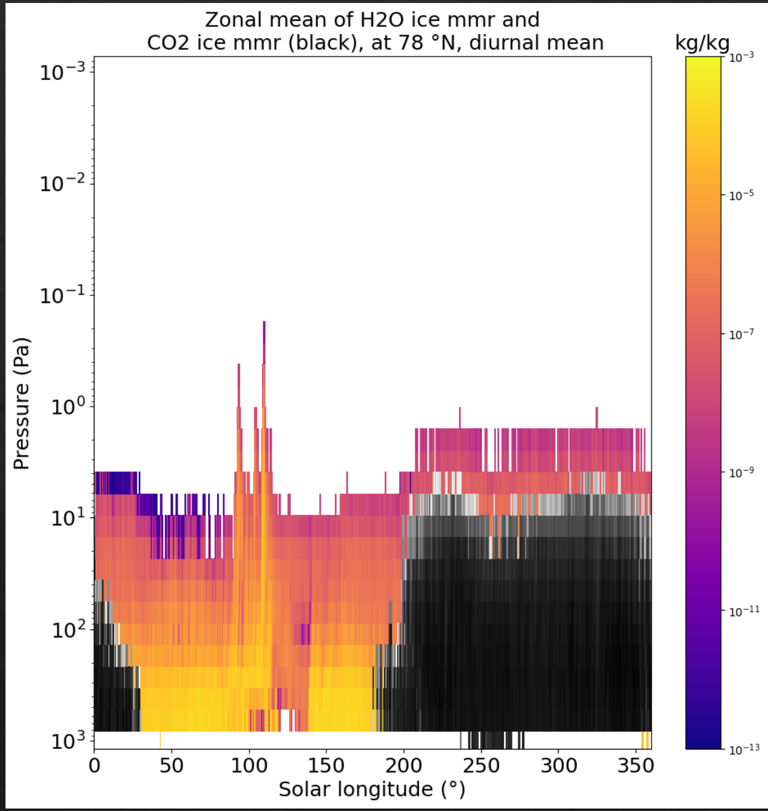
Focus on polar CO_2 clouds

Slice of H_2O (color) and CO_2 (black) ice mmr profiles at 78°N

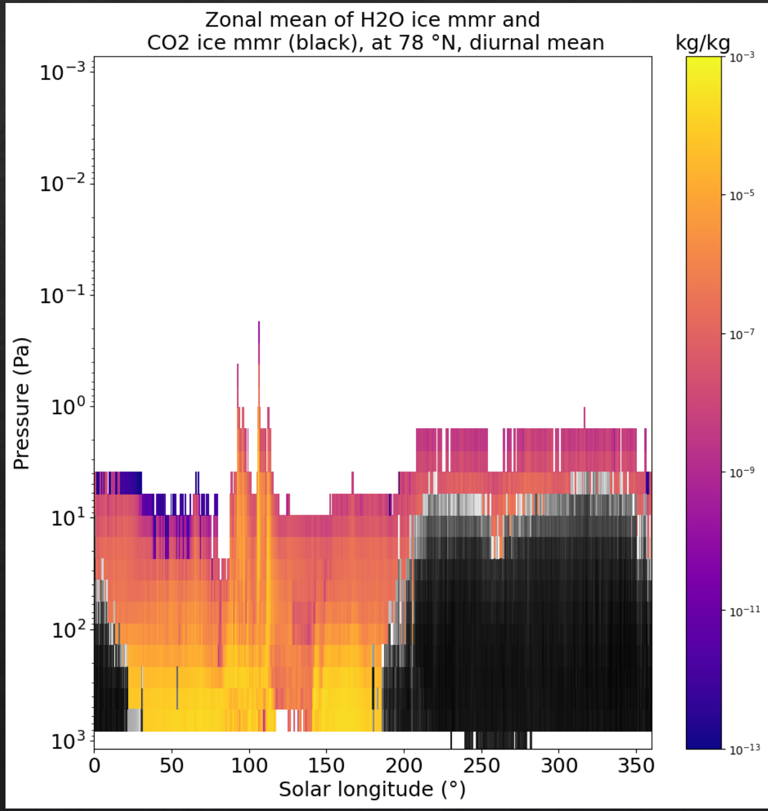
Reference



Co2useh2o



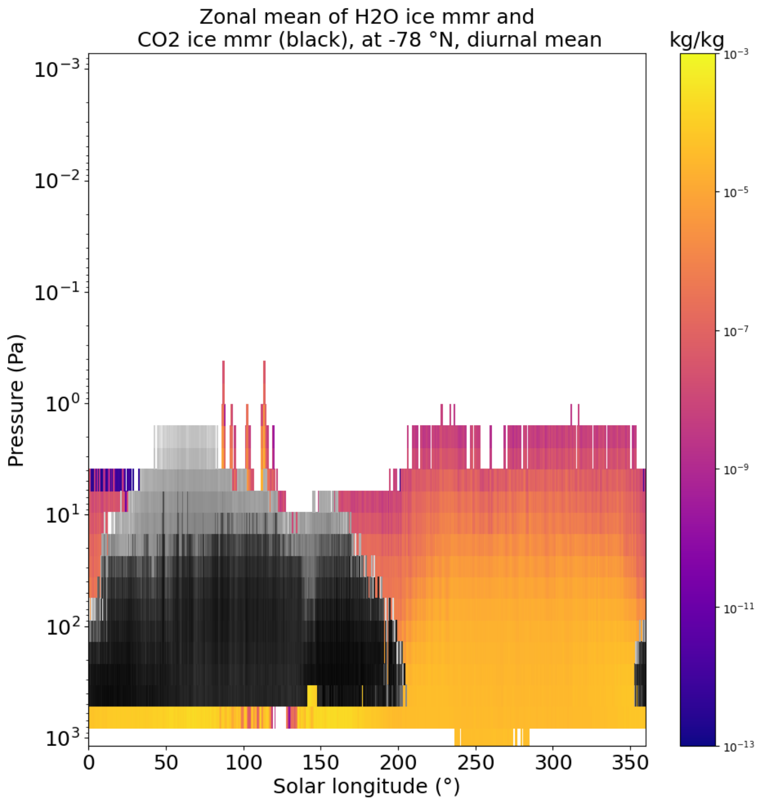
RT+Co2useh2o



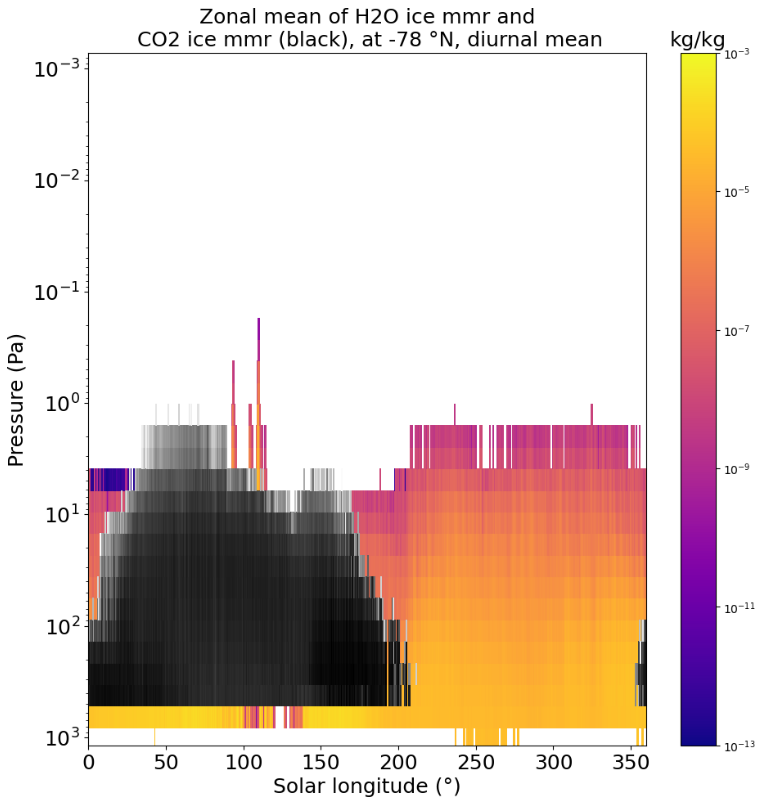
- CO_2 ice clouds are lower than H_2O ice clouds
- H_2O ice allows to form more CO_2 ice clouds at all atmospheric levels
- Activate radiatively CO_2 clouds shows no significant variations

Slice of H_2O (color) and CO_2 (black) ice mmr profiles at 78˚S

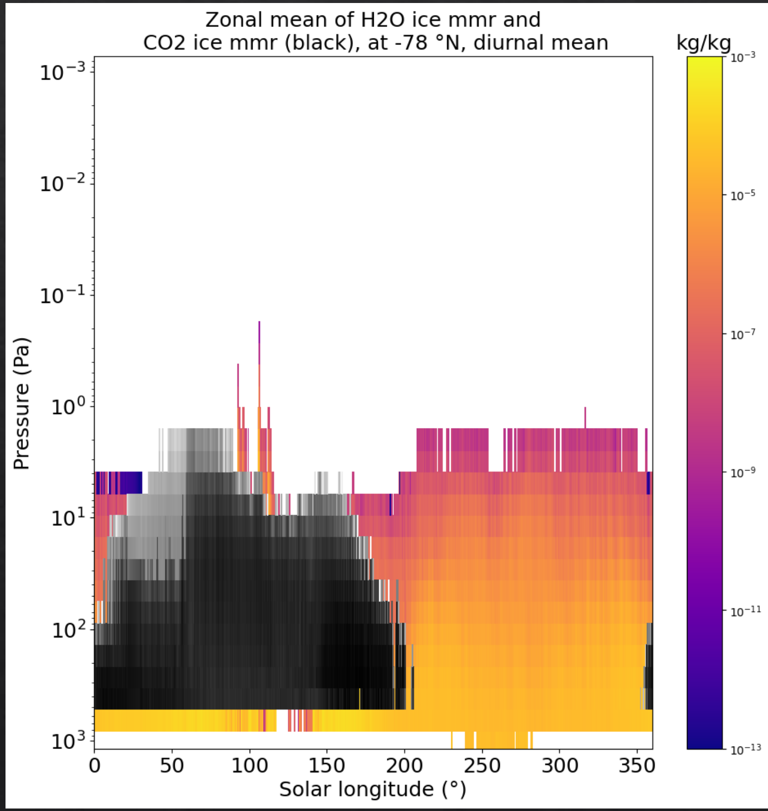
Reference



Co2useh2o



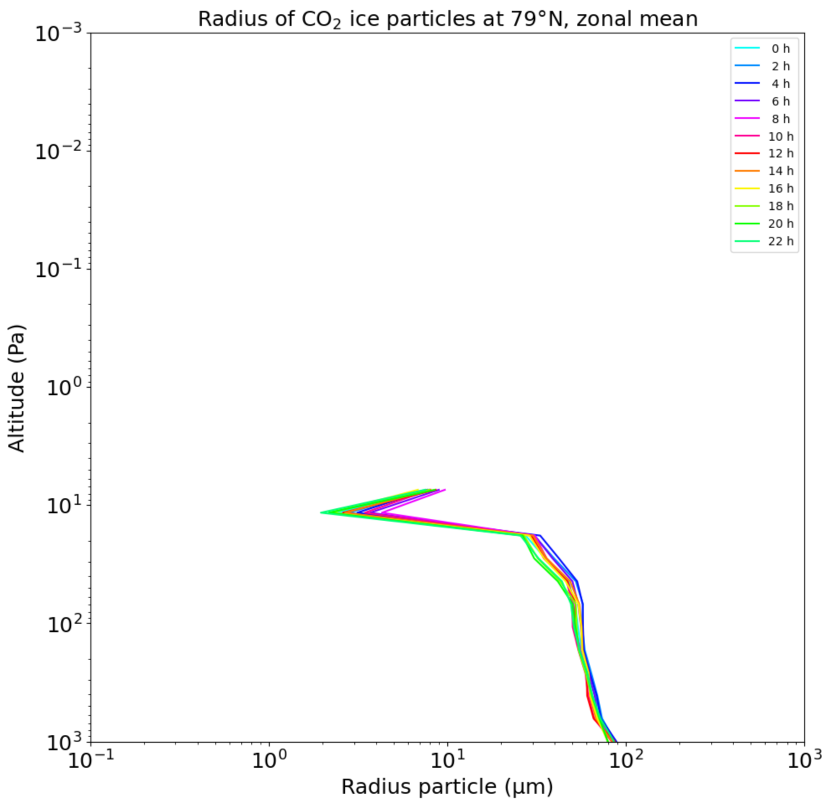
RT+Co2useh2o



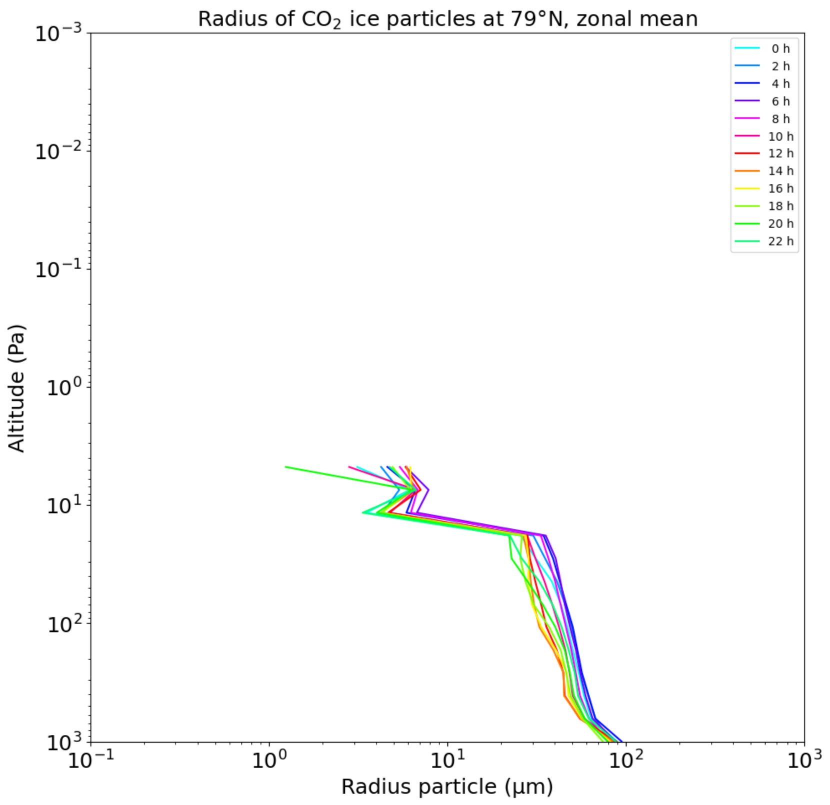
- CO_2 ice this time are upper than H_2O ice, closed to the tropopause at 1 Pa
- Activate radiatively CO_2 clouds forms less CO_2 clouds above 3 Pa around Ls=50°

Polar CO_2 particle radius variation at 79°N during winter, at different local times

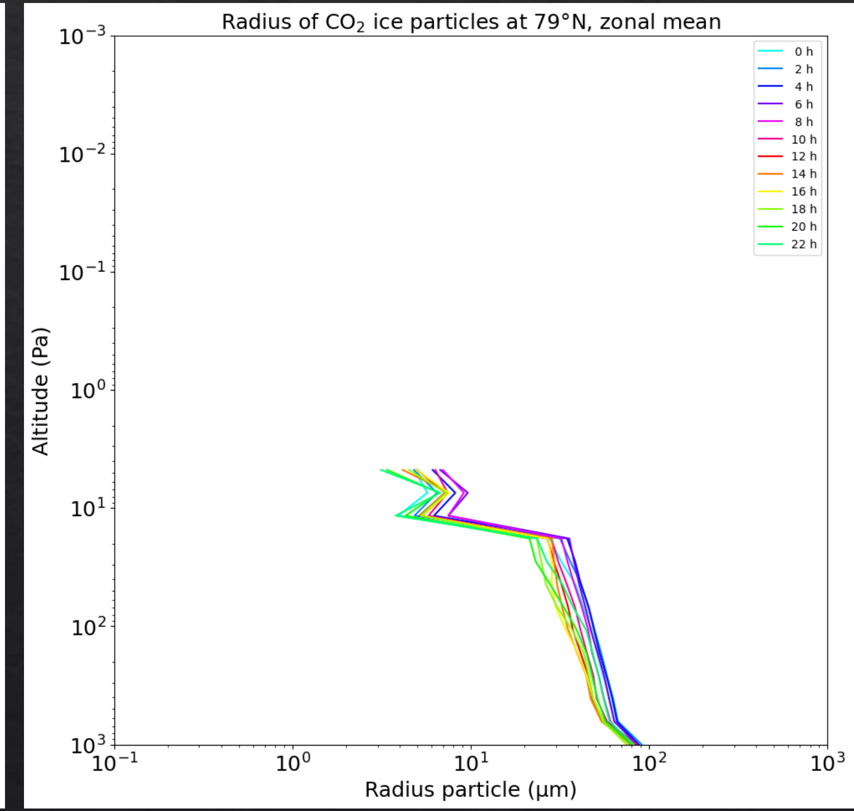
Reference



Co2useh2o



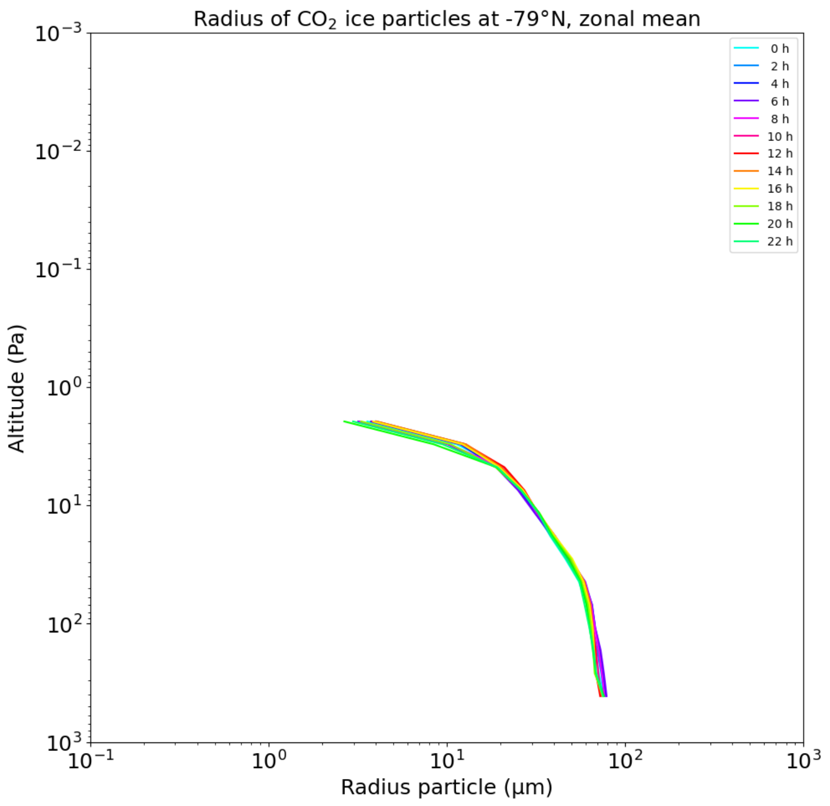
RT+Co2useh2o



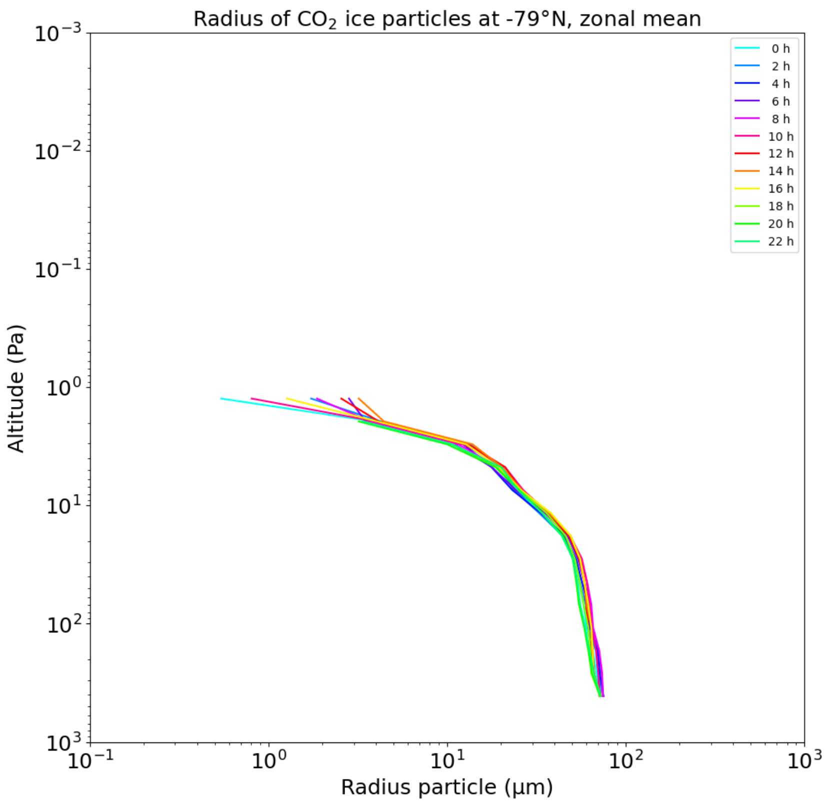
- Weak variations in local time of CO_2 ice radius particles with the case using H_2O ice particles as CN
- CO_2 ice particles reach size of ~100 µm radius closed to the surface and drop down to few microns around 10 Pa

Polar CO_2 particle radius variation at 79°S during winter, at different local times

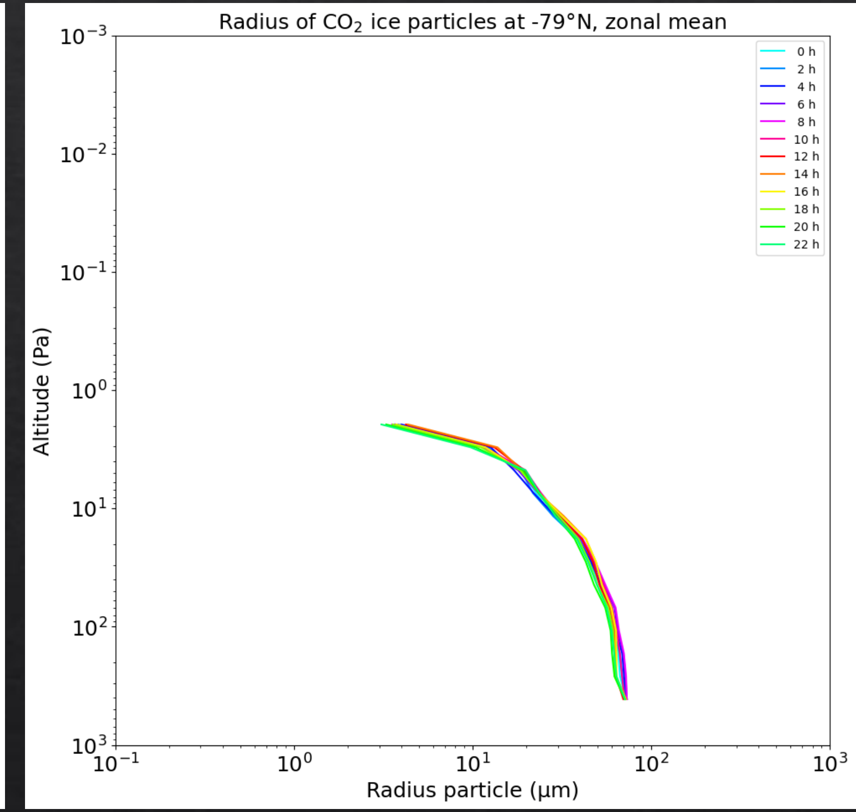
Reference



Co2useh2o



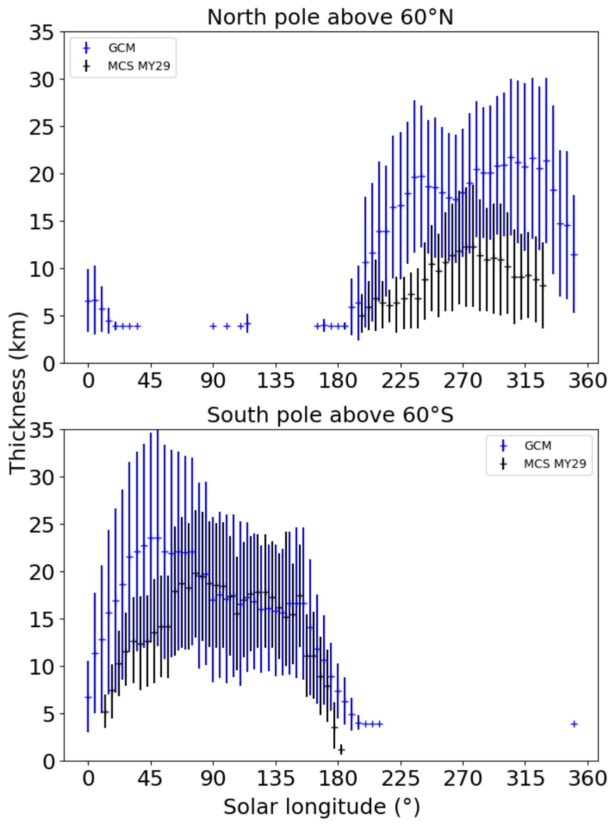
RT+Co2useh2o



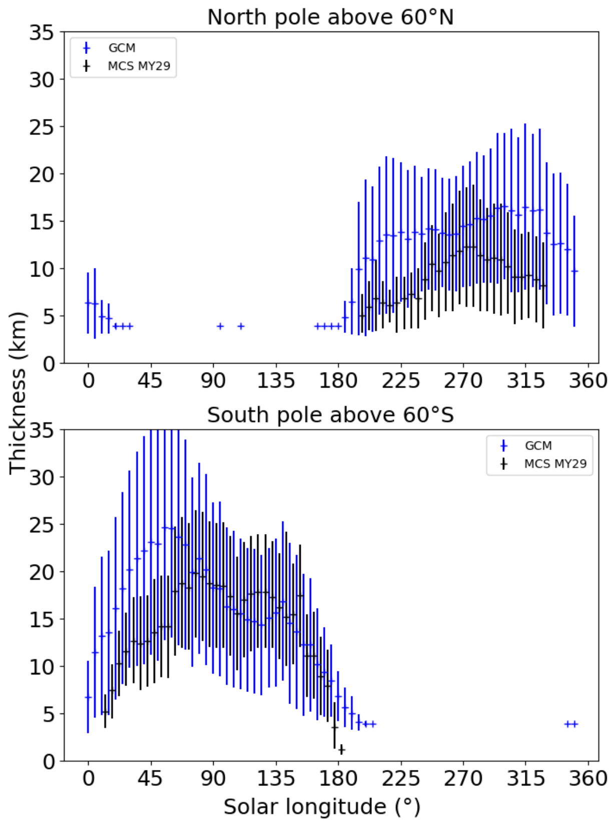
- No variations in local time of CO_2 ice radius particles
- CO_2 ice particles reach size of ~100 µm radius closed to the surface and drop down to few microns around 1 Pa

Thickness of the supersaturated layer at poles: comparison to MCS [Hu et al., 2012]

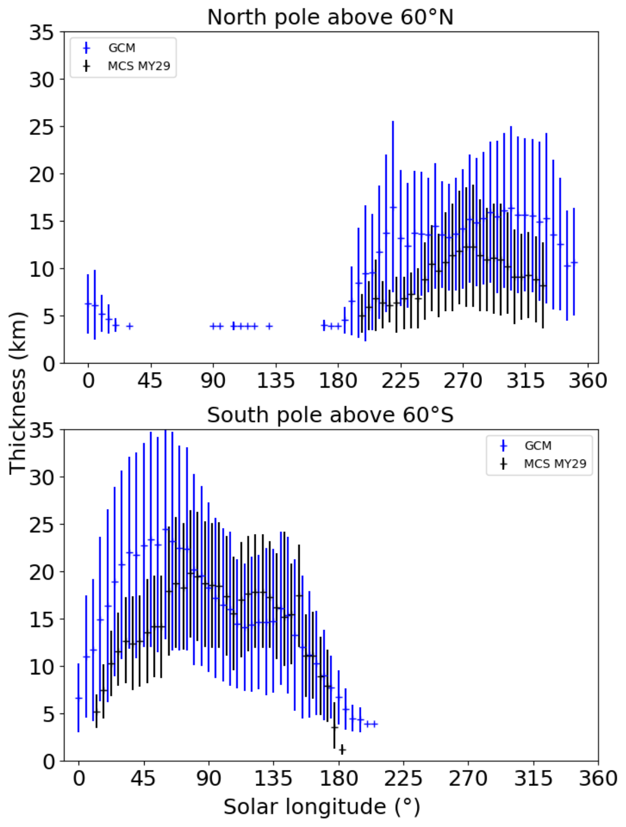
Reference



CO2useH2O



RT+CO2useH2O



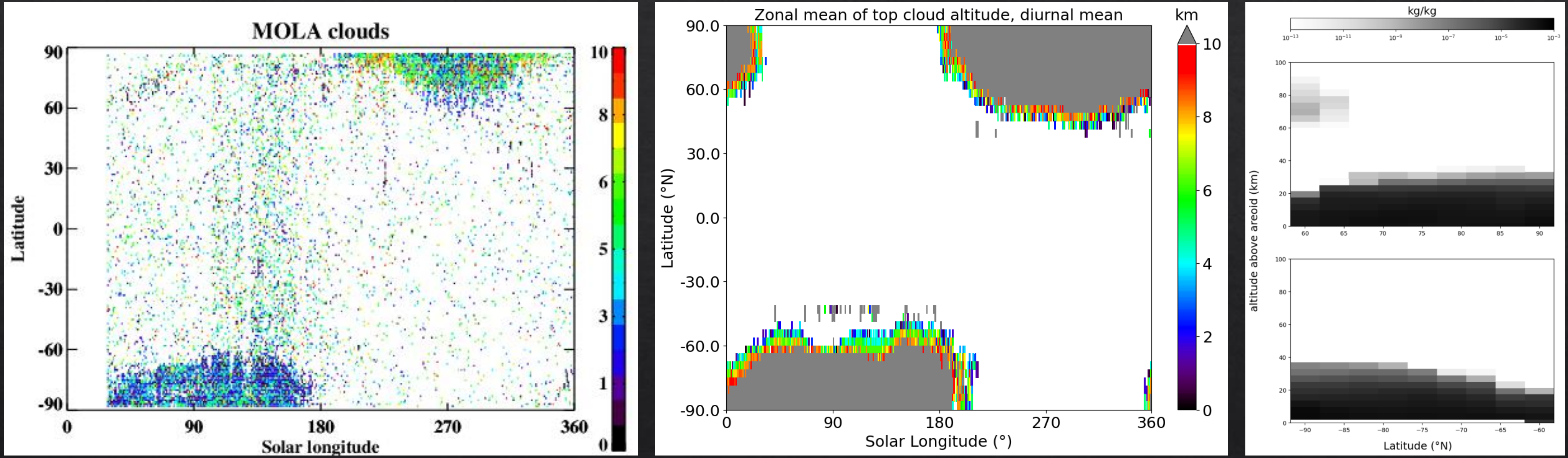
Quite good agreement with MCS observations in the south pole.

At the north, the saturated layer thickness is still high. Our CO_2 ice clouds reach high altitudes

Activate radiatively CO_2 clouds allow thicker supersaturated layer in the north polar region at the beginning of autumn

Average of saturation profiles: at all local times, all longitudes and latitudes > 60°

Comparison to MOLA observations: top altitude of CO_2 clouds (CO2useH2O)



- Top altitude of CO2 clouds simulated higher (~ 64 km) than MOLA observations for all simulations.
- Compute from Eq. 22 in Tobie et al., [2003]: $z_{top} = when\left(\rho_{atm} N_{CO2} > 2.10^{-8}\, R_{CO2}^{-2}\right)$

Emissivity comparison to 32µm MCS observations to the integrated emissivity simulated (CO2useH2O)

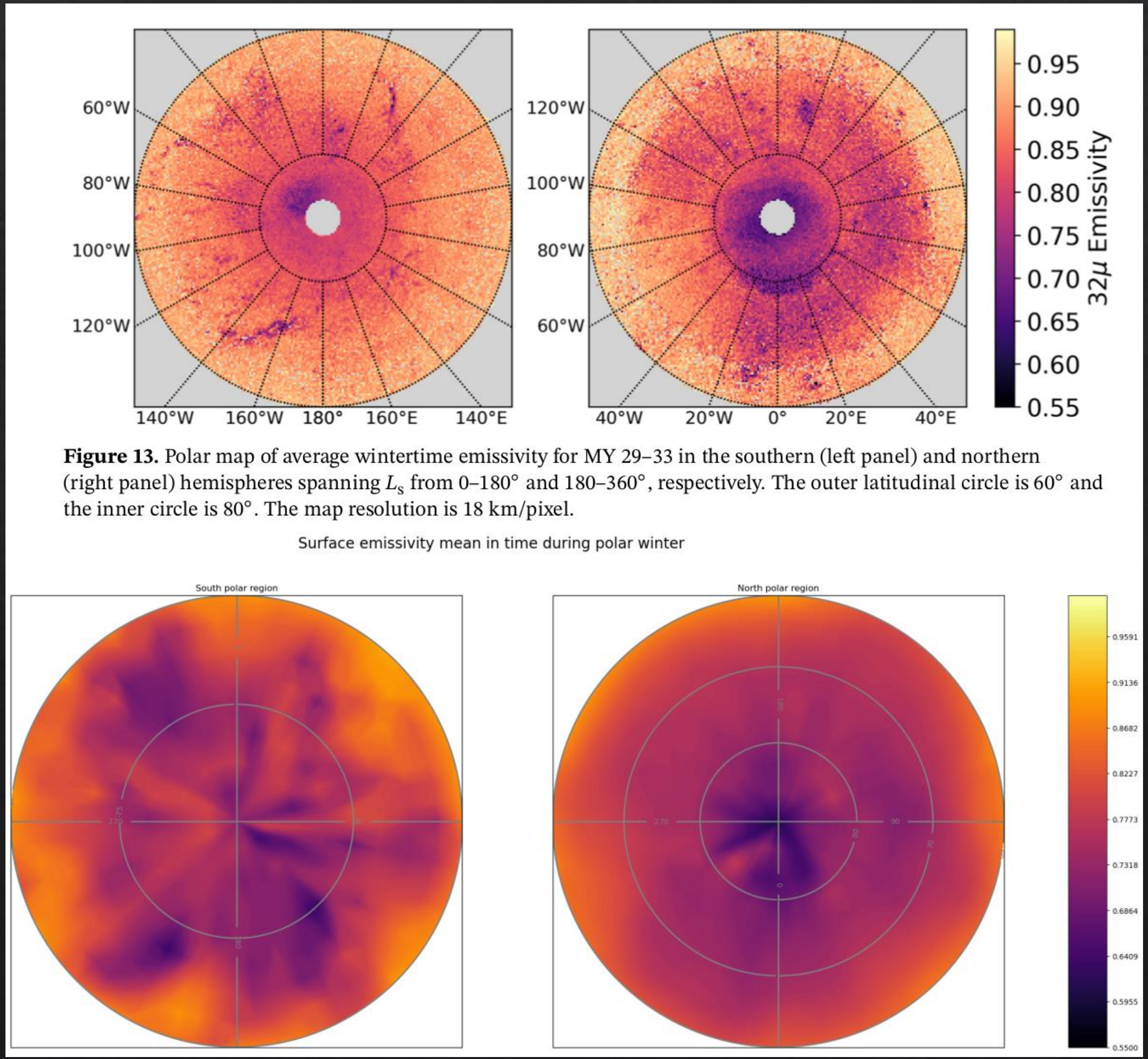


Figure 13. Polar map of average wintertime emissivity for MY 29–33 in the southern (left panel) and northern (right panel) hemispheres spanning L_s from 0–180° and 180–360°, respectively. The outer latitudinal circle is 60° and the inner circle is 80°. The map resolution is 18 km/pixel.

- Direct value comparison is dangerous
- Low emissivity patterns are encouraging
- We will develop a tool to get the 32 µm emissivity for a better comparison with MCS observations

Credit: Garry-Bicas et al. [2020]

Emissivity comparison to 32µm MCS observation to the integrated emissivity simulated (CO2useH2O)

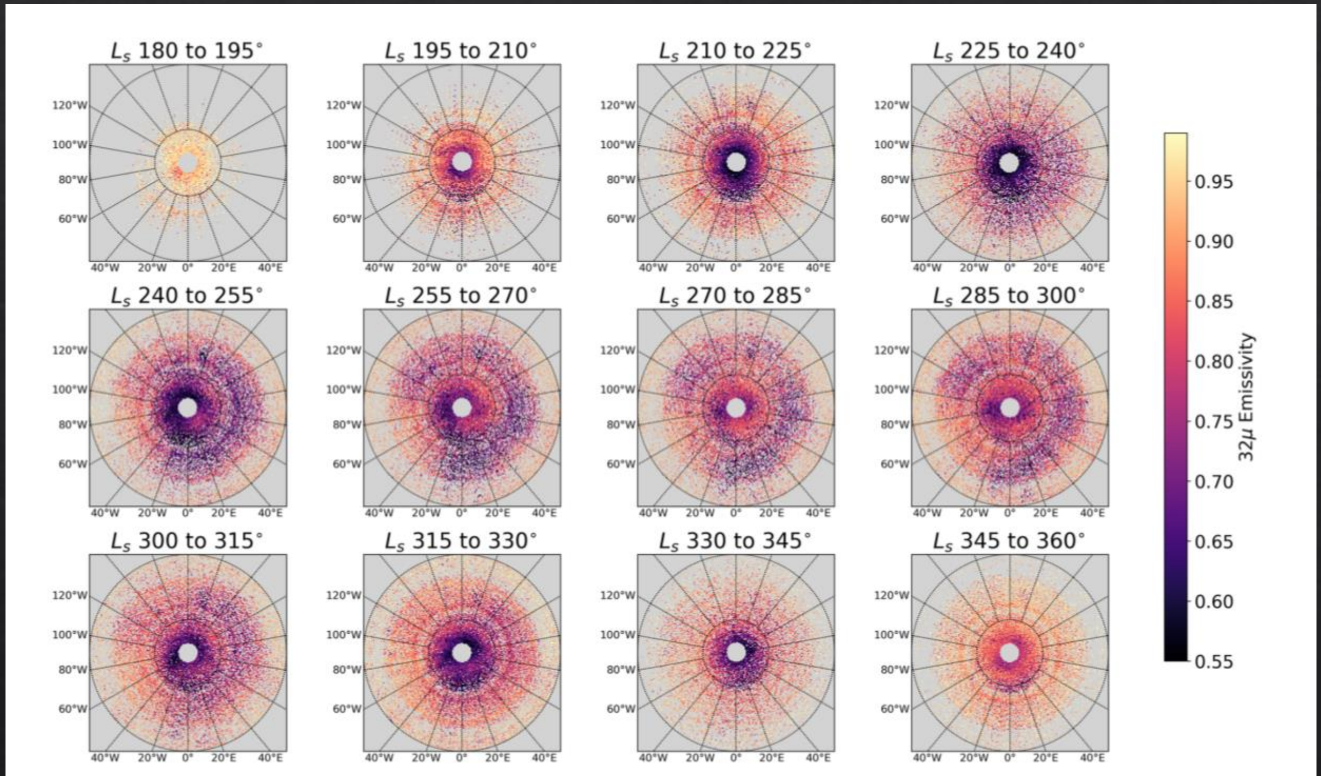
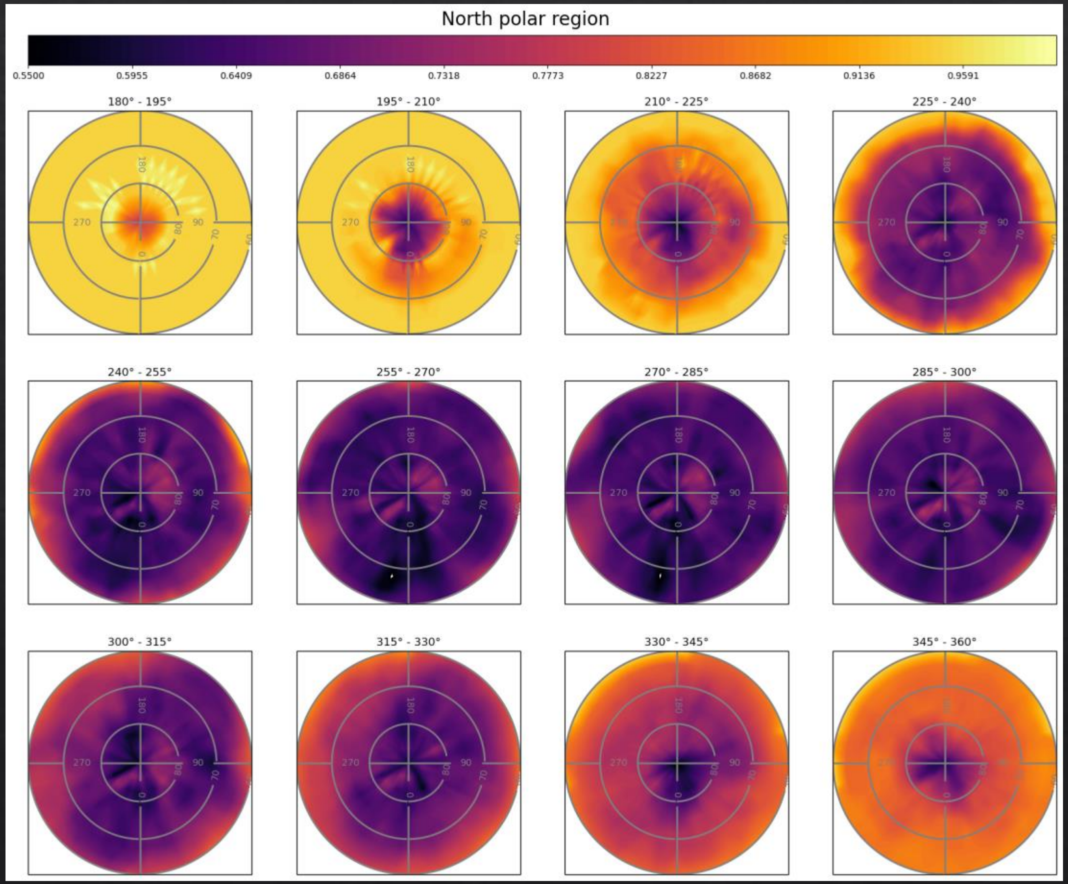


Figure 11. Polar maps of emissivity in the northern hemisphere for locations with solid CO_2 on the surface. Each plot is a time-bin of 15° of L_s and spans from 180–360° L_s. The concentric rings are an artifact due to instrumental calibrations for MCS. The data spans up to 60° in latitude (larger latitude circle), smaller circle is the 80° latitude. Gray gaps imply lack of data, not to be confused with any emissivity value. Maps include data extending to 60°N latitude, from MY 29–33, with a resolution of 18 km/pixel.



NORTH: Values do not be compared, but tendencies emissivity are closed between observation and simulation

Credit: Garry-Bicas et al. [2020]

Emissivity comparison to 32µm MCS observation to the integrated emissivity simulated (CO2useH2O)

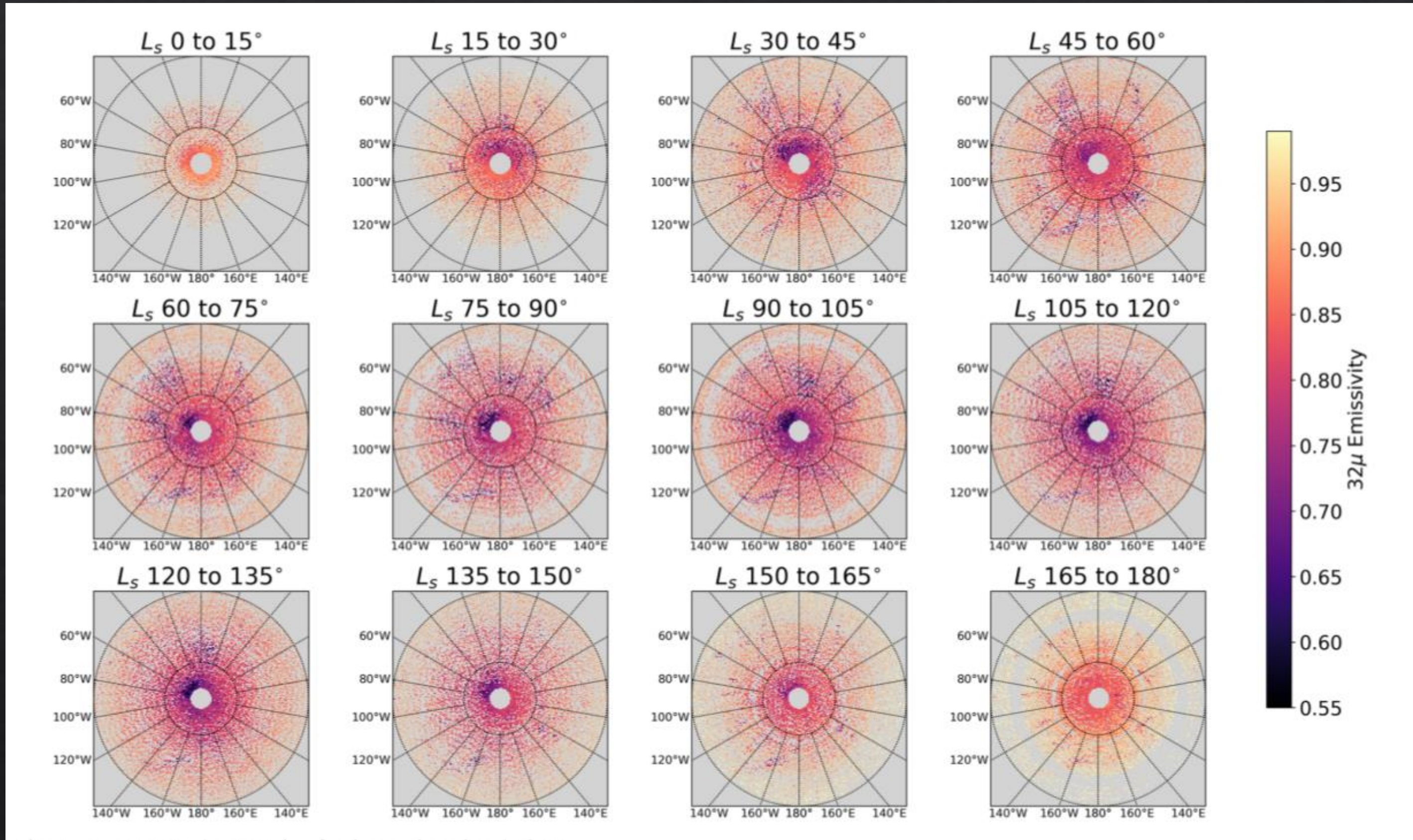
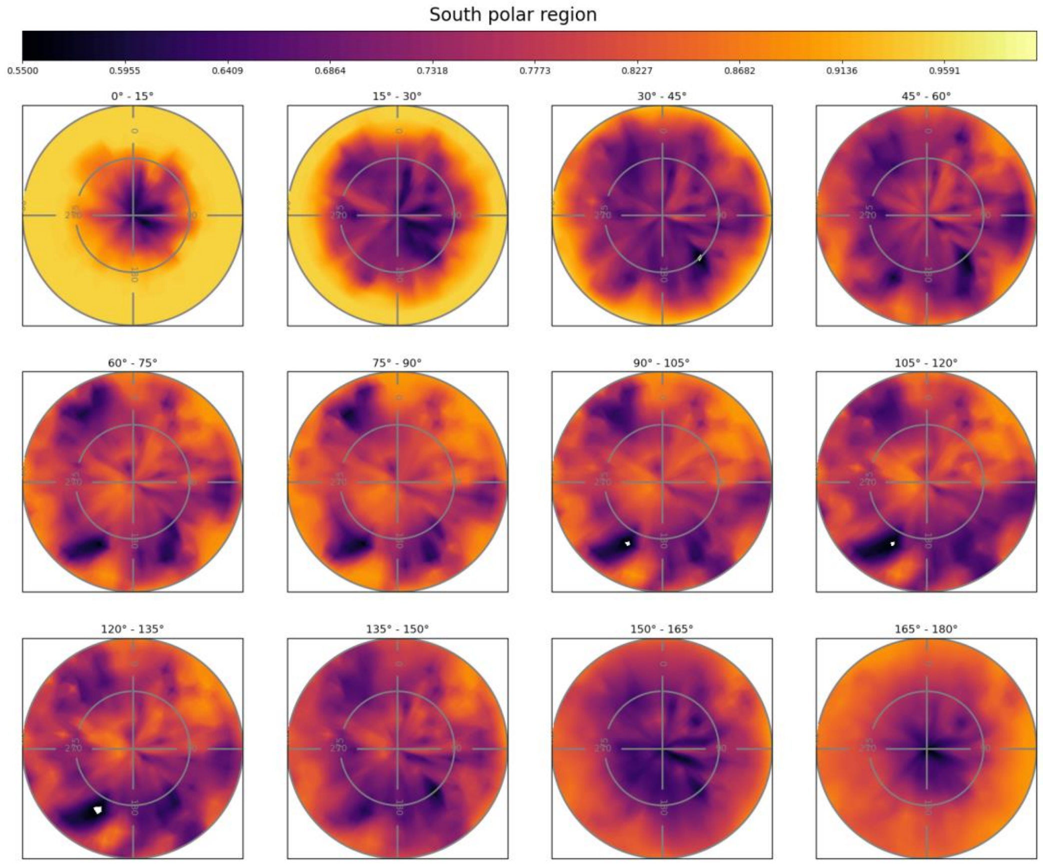


Figure 12. Same as Figure 11, but for the southern hemisphere.



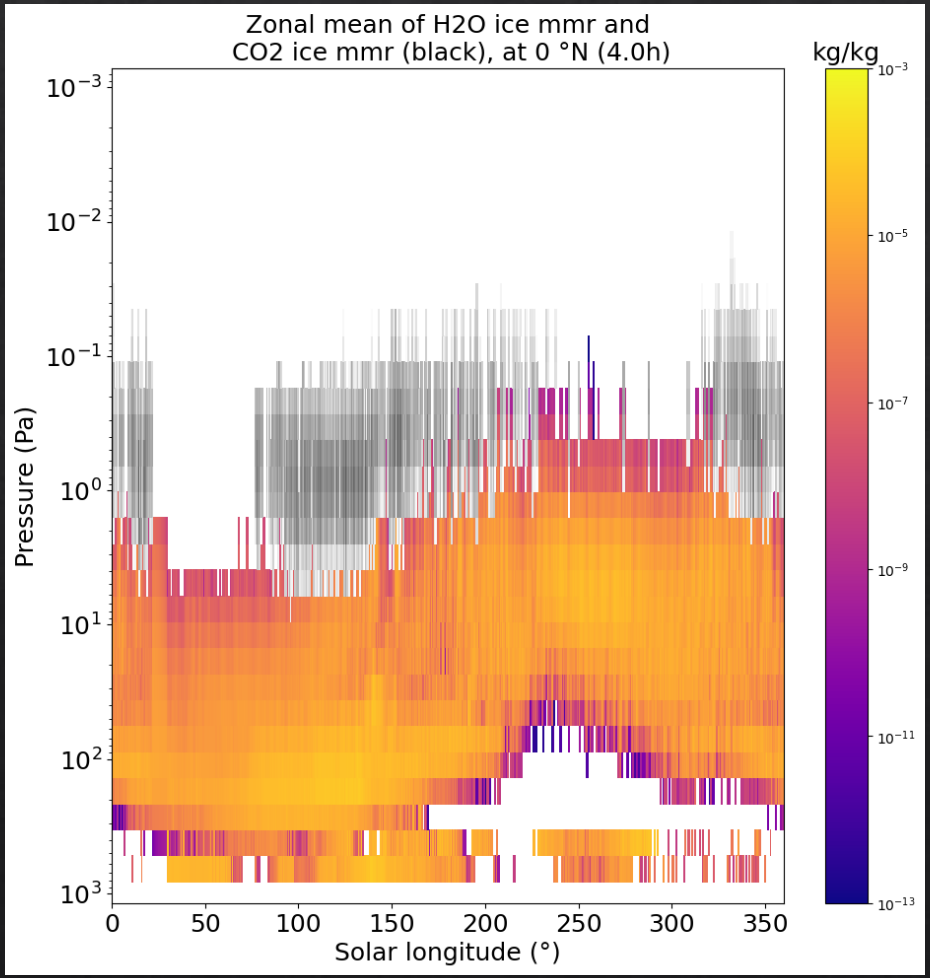
SOUTH: Values do not be compared, but tendencies emissivity are closed between observation and simulation

Credit: Garry-Bicas et al. [2020]

Results

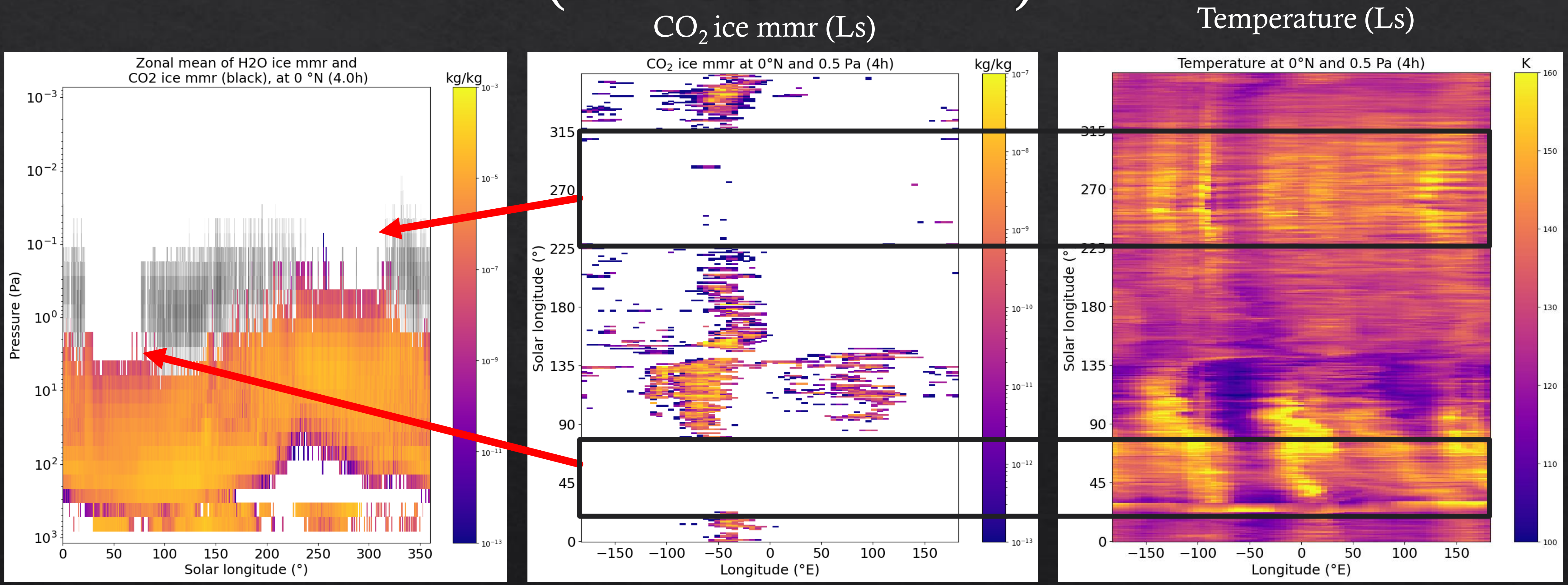
Focus on mesospheric CO_2 clouds

Slice of H_2O (color) and CO_2 (black) ice mmr profiles at 0°N (RT+CO2useH2O)



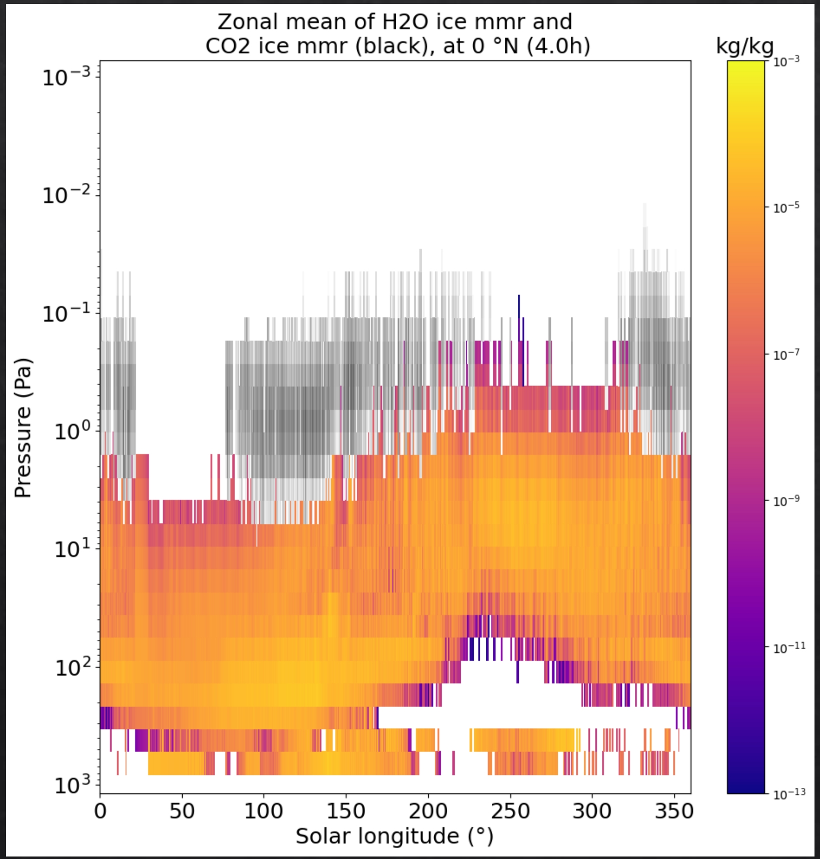
- CO_2 clouds are located above the H_2O clouds for all seasons
- During two periods, models do not form CO_2 clouds:
  - Ls = ~[20, 80]°
  - Ls = ~[220, 330]°

Lack of mesospheric CO_2 clouds (RT+CO2useH2O)

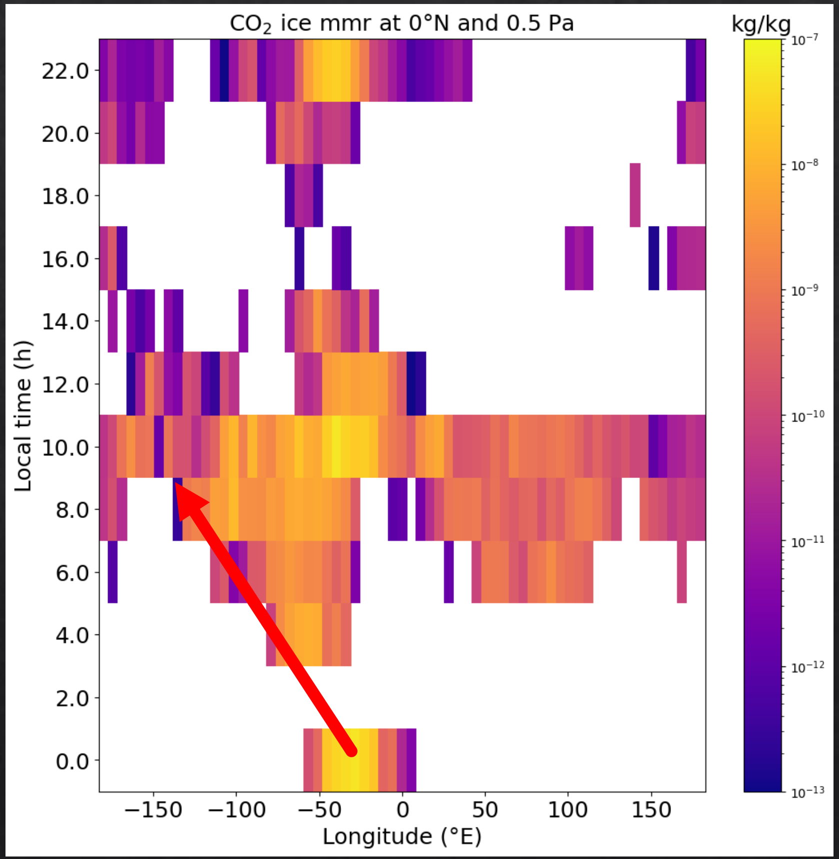


- CO_2 clouds are formed mainly around -50°E, and around +/- 100°E around Ls=100°
- During the 2 Ls periods described before, the atmosphere is hotter on averaged compared to the rest of year

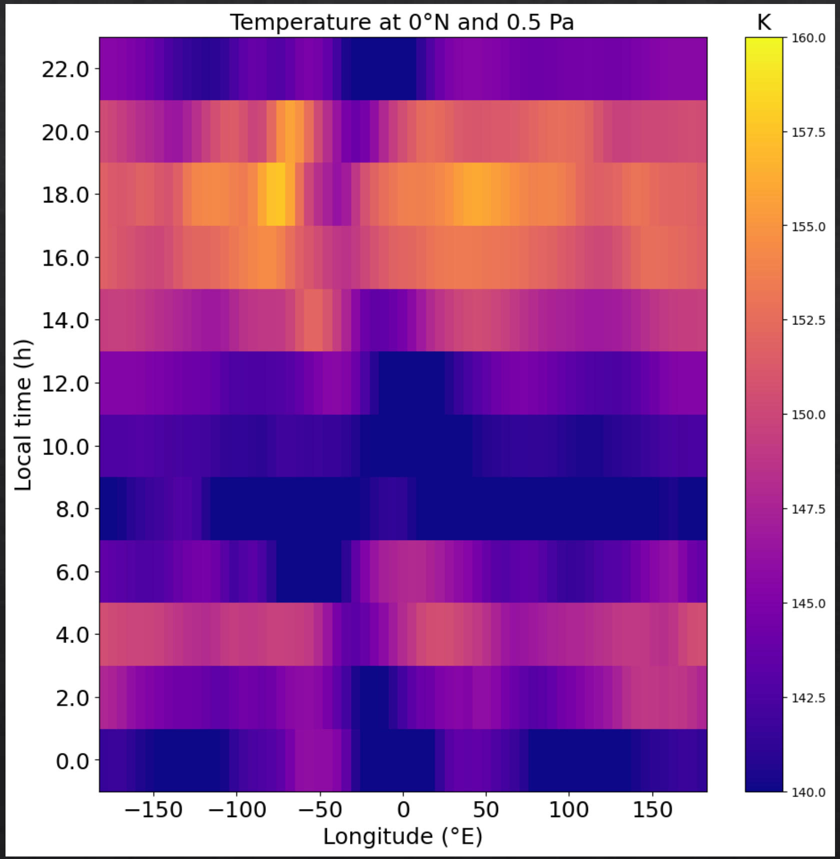
Thermal tides (RT+CO2useH2O)



CO_2 ice mmr (local time)



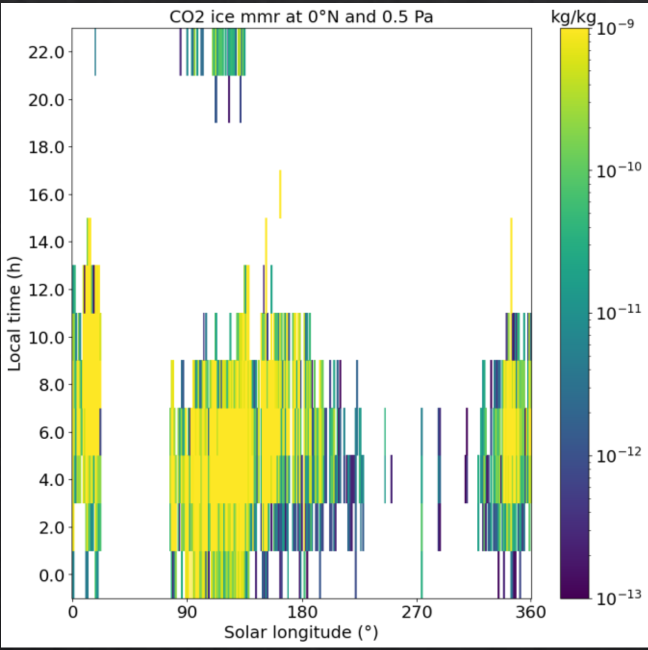
Temperature (local time)



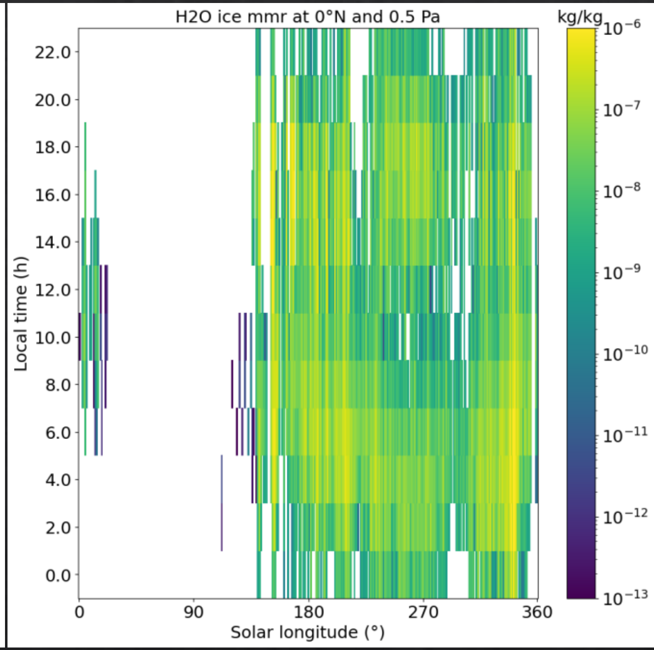
- CO_2 clouds appear around -50°E at the beginning of the night and go westerly vanishing during afternoon
- CO_2 clouds appear close to the sunset (6-8 h) at all longitudes

Day-night clouds at 0°N, at 0.5 Pa along seasons (RT+CO2useH2O)

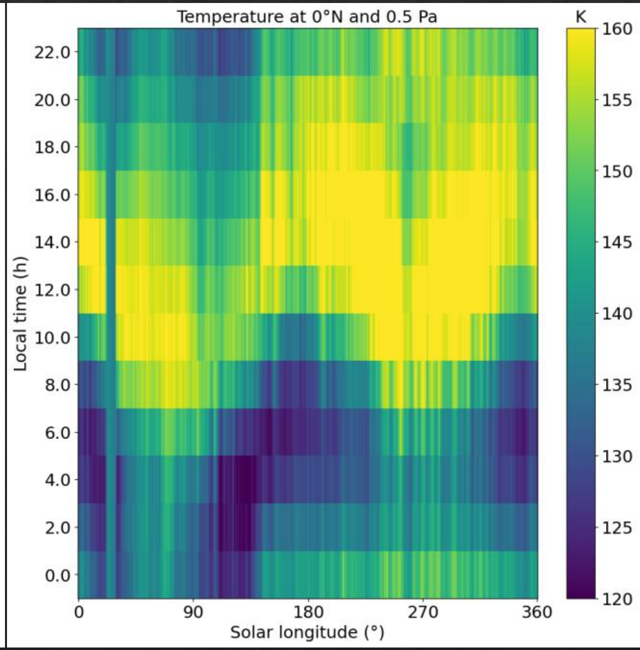
CO_2 ice mmr



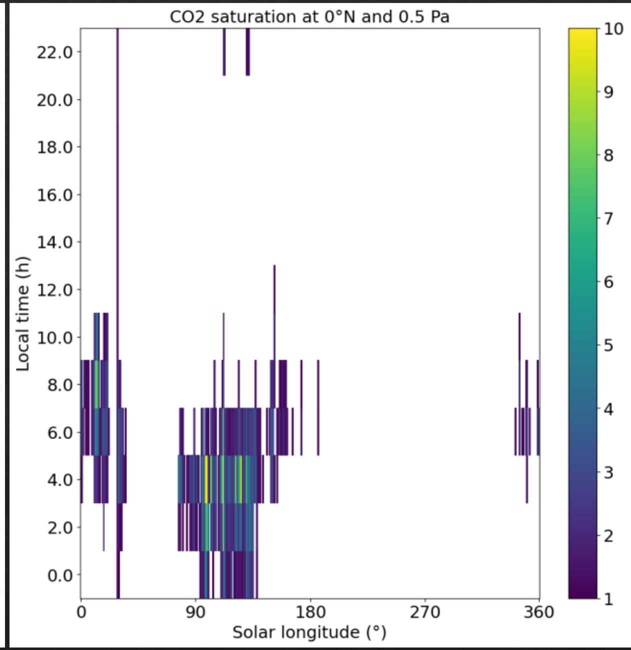
H_2O ice mmr



Temperature



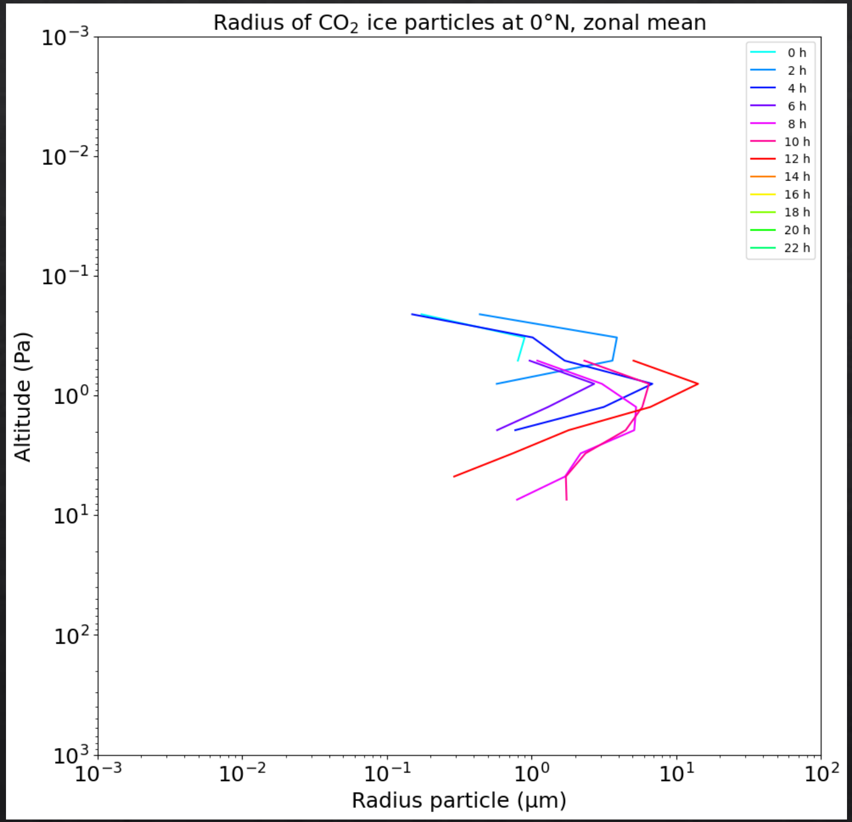
Saturation CO_2



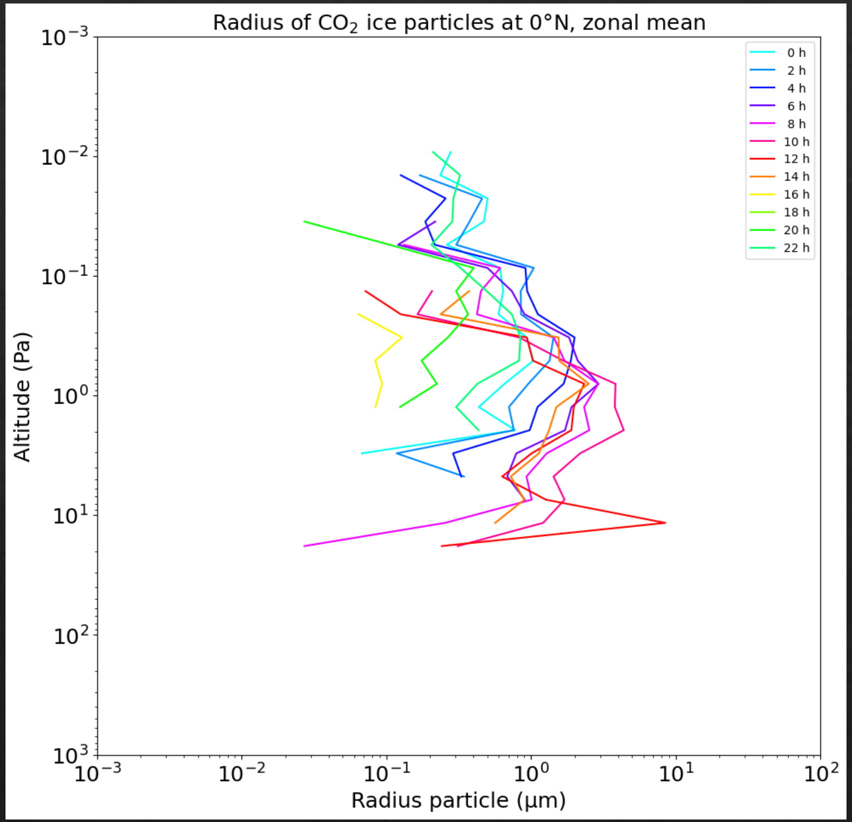
Mesospheric CO_2 clouds are formed at the beginning of the night and vanished during the day

Mesospheric CO_2 particle radius variations at 0˚N

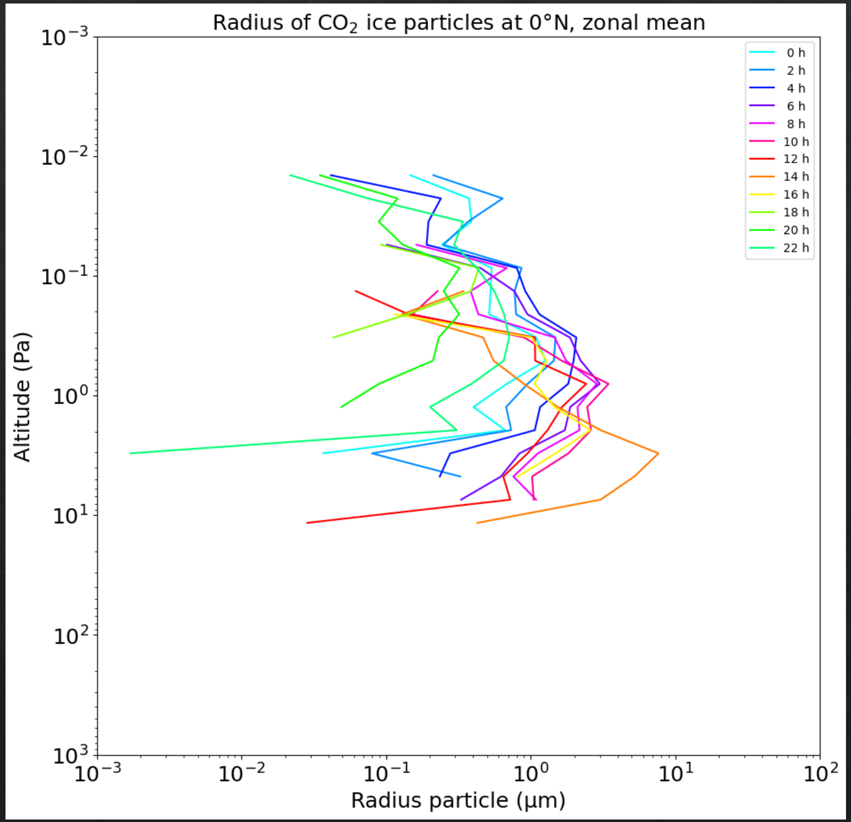
Reference



CO2useH2O



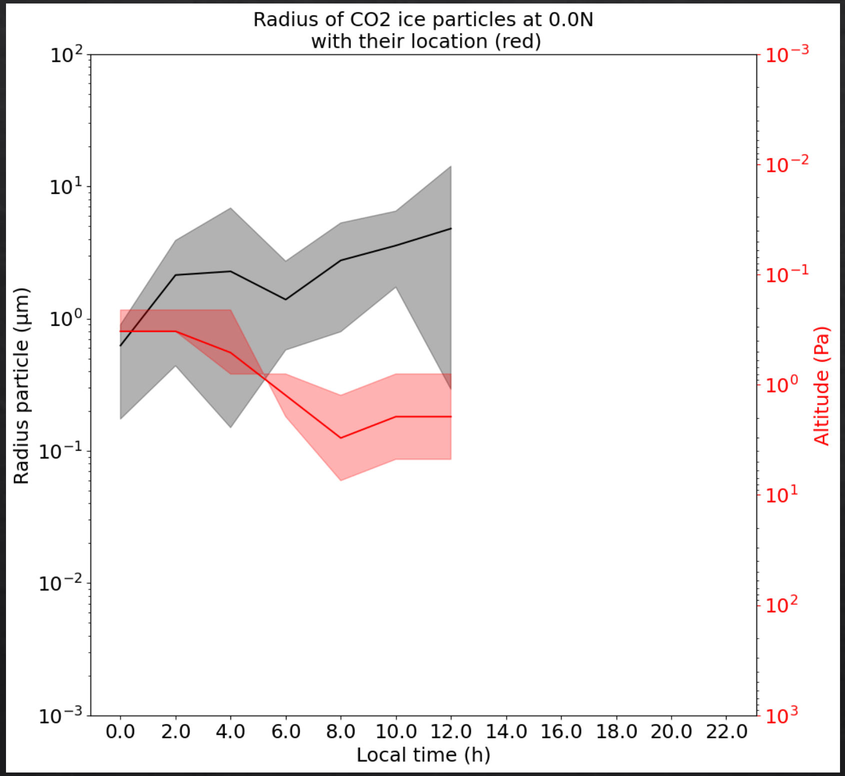
RT+CO2useH2O



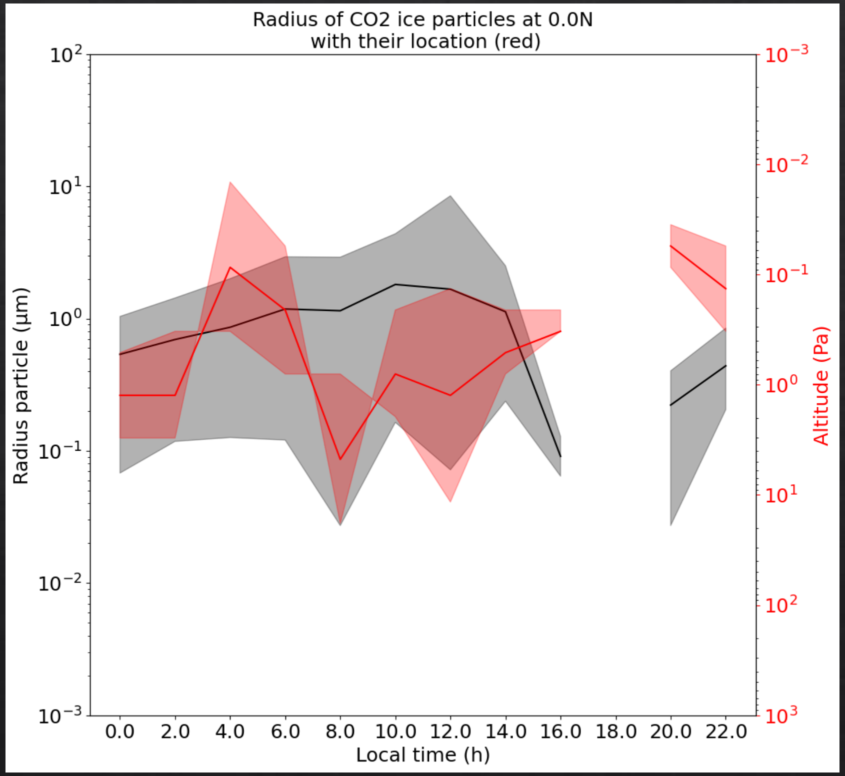
CO2 particle radius start growing at 18h and reach a maximum at 12h the next day

Radius information depending on local time

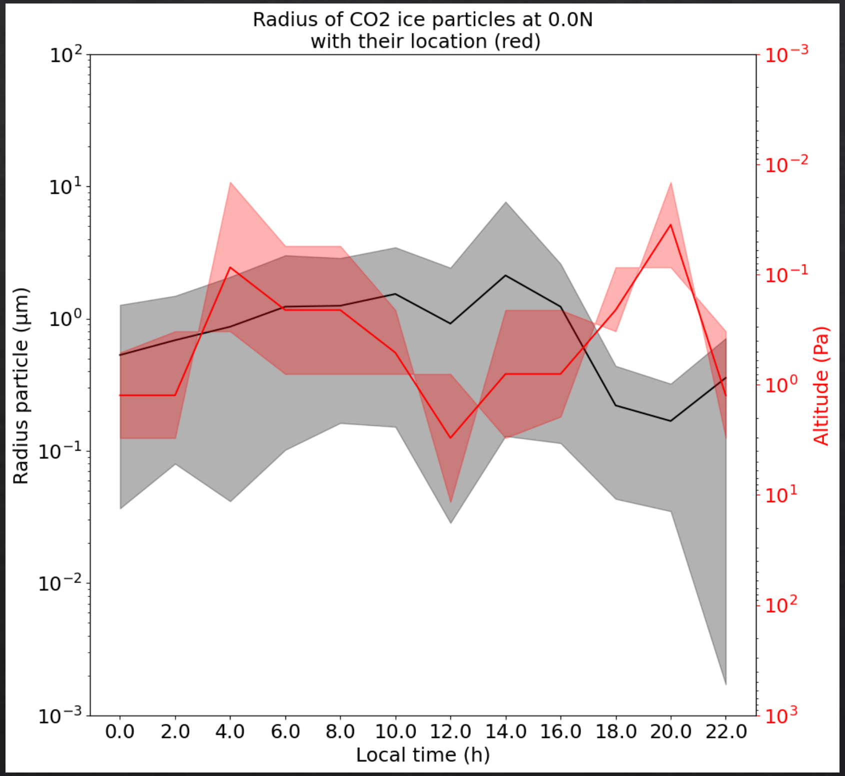
Reference



CO2useH2O



RT+CO2useH2O



CO_2 ice particles radius have few microns size

Conclusions

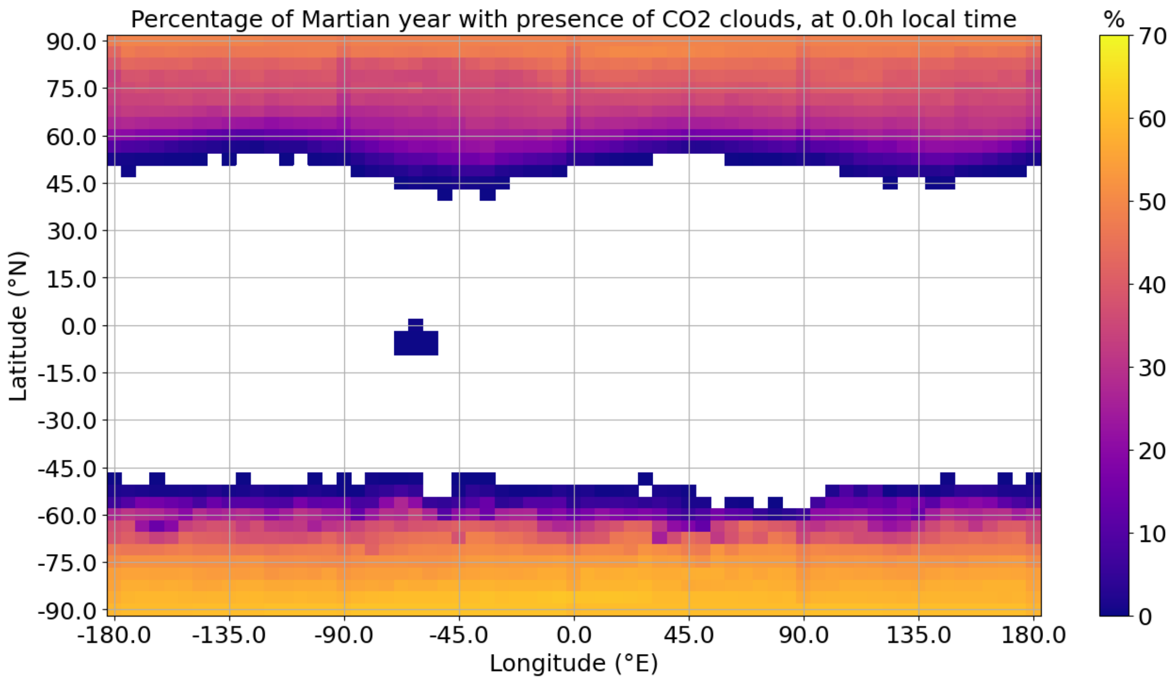
- Mesospheric clouds
  - Planetary wave plays a key role in the mesospheric CO_2 cloud formation [Gonzàlez-Galindo et al., 2011]
  - Water ice clouds are a good source of condensation nuclei for CO_2 ice clouds in the mesosphere but are not sufficient for formation of daytime
  - 16h clouds close to missing while that have been observed by many instruments [Määttänen et al., 2013]
  - Optical thickness of these clouds are still weak $\tau_{1\mu m} < 10^{-4}$ at best compared to 0.01 – 0.6 observed by OMEGA [Määttänen et al., 2010]
  - Radius particles are few microns size, thicker than ~100 nm observed by SPICAM [Montmessin et al., 2013]
- Polar clouds
  - Good latitudinal coverage of CO_2 clouds compared to observations
  - CO_2 clouds are much higher in altitude compared to observations
  - Radius particles are ~100 μm size

Perspectives

- Add meteoritic flux as condensation nuclei to investigate 16h clouds missing and/or low opacities simulated[Listowski et al., 2014, Plane et al., 2018]
- Use different dust scenario (scenarios for corresponding years to study interannual variations)
- Increase the horizontal and vertical grid resolution to solve small-scale waves

Frequency of CO_2 cloud formation over a Martian year

Reference



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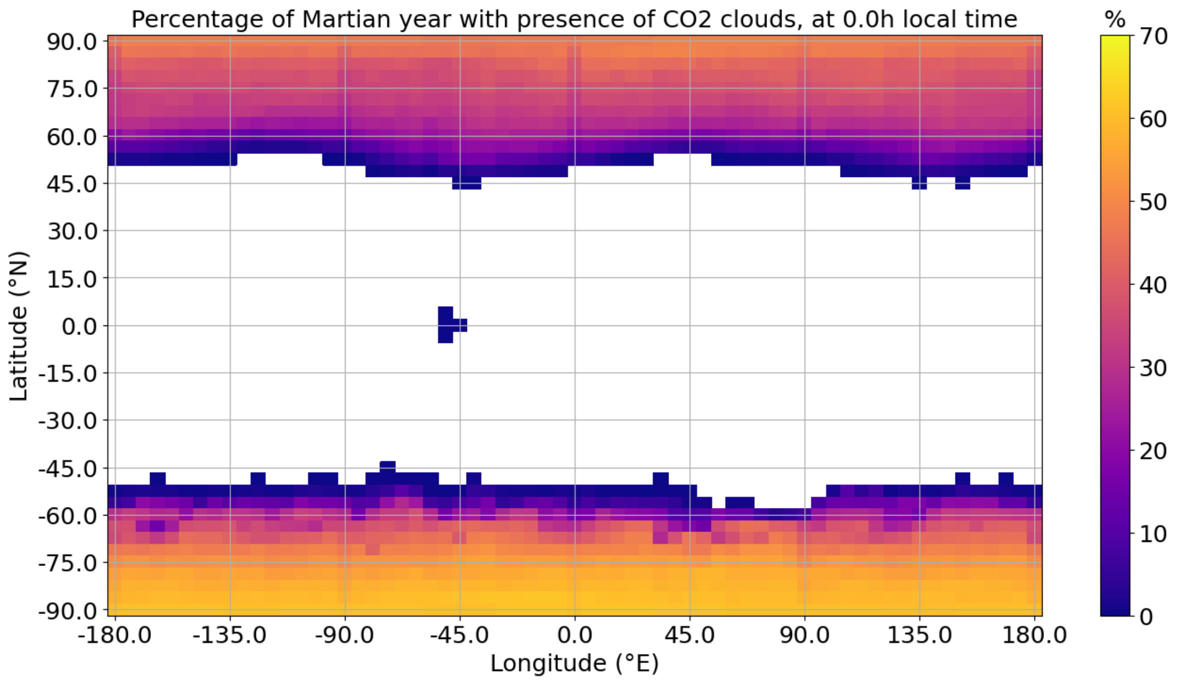
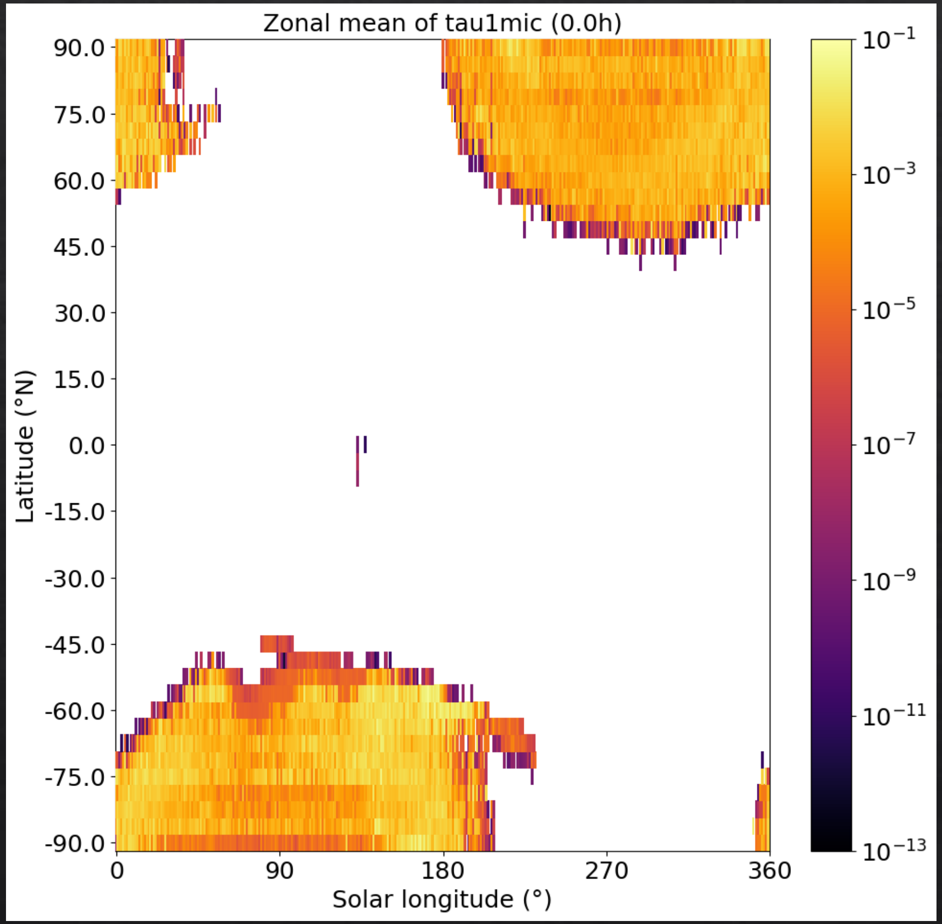


Opacity of CO_2 clouds at 1 micron

Reference



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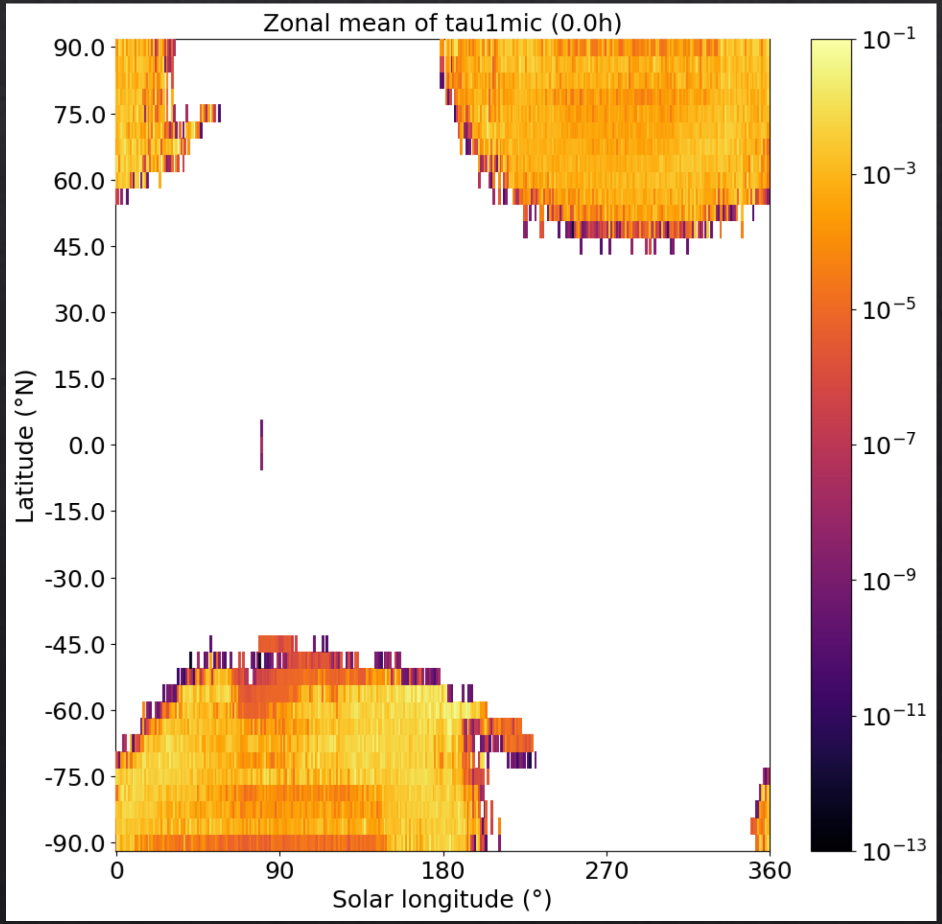
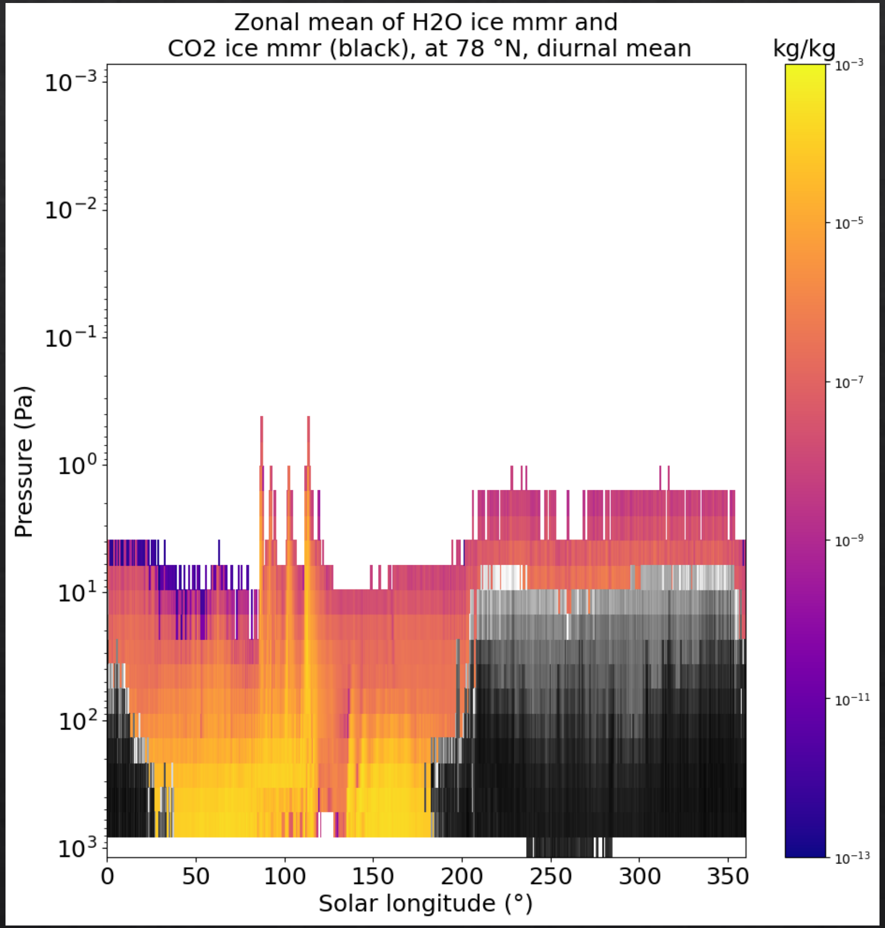


Slice of H_2O (color) and CO_2 (black) ice mmr profiles at 78°N

Reference



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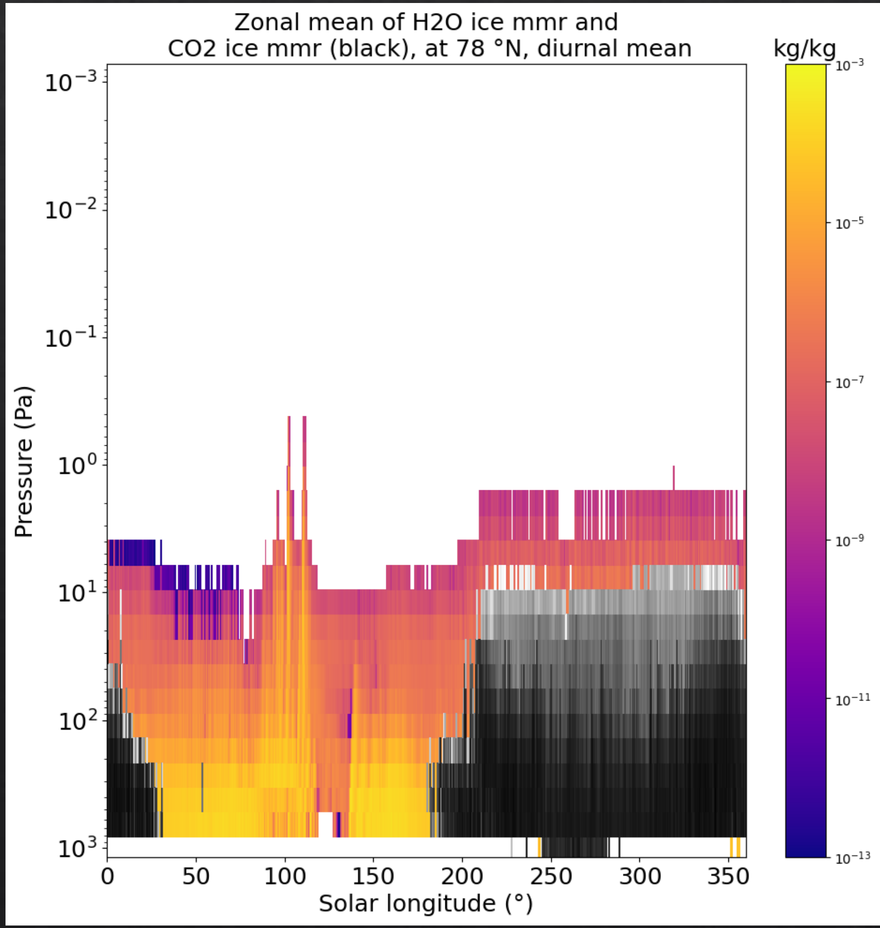
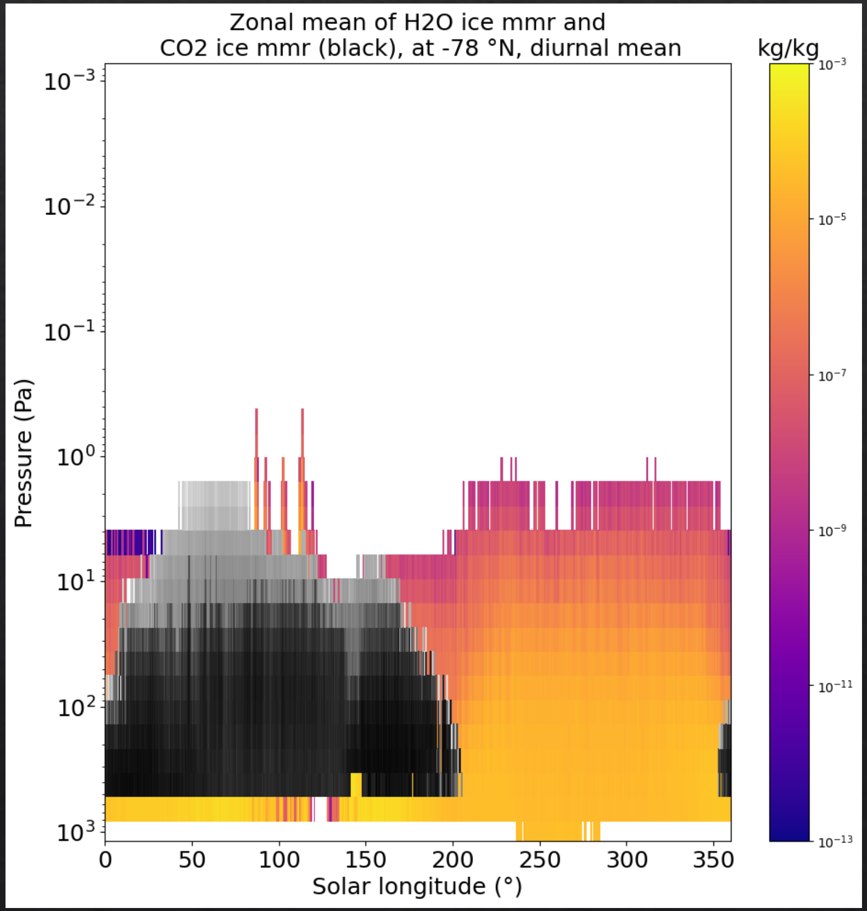


Slice of H_2O (color) and CO_2 (black) ice mmr profiles at 78˚S

Reference



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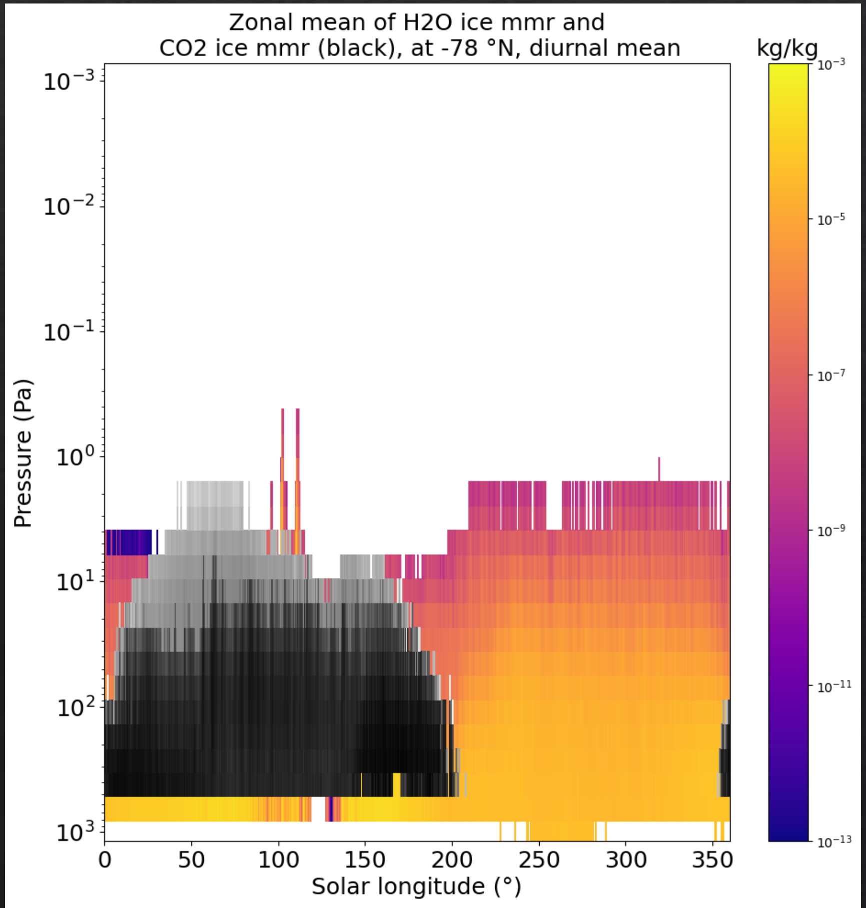
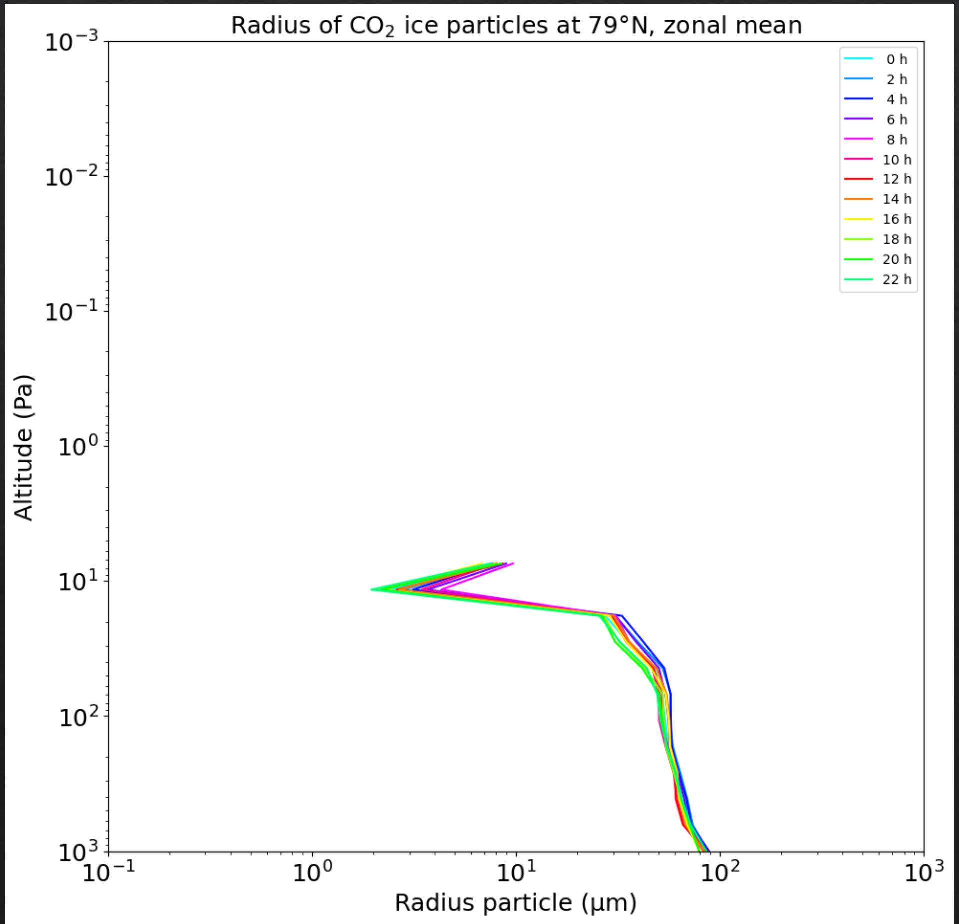


Polar CO_2 particle radius variation at 79°N during winter, at different local times

Reference



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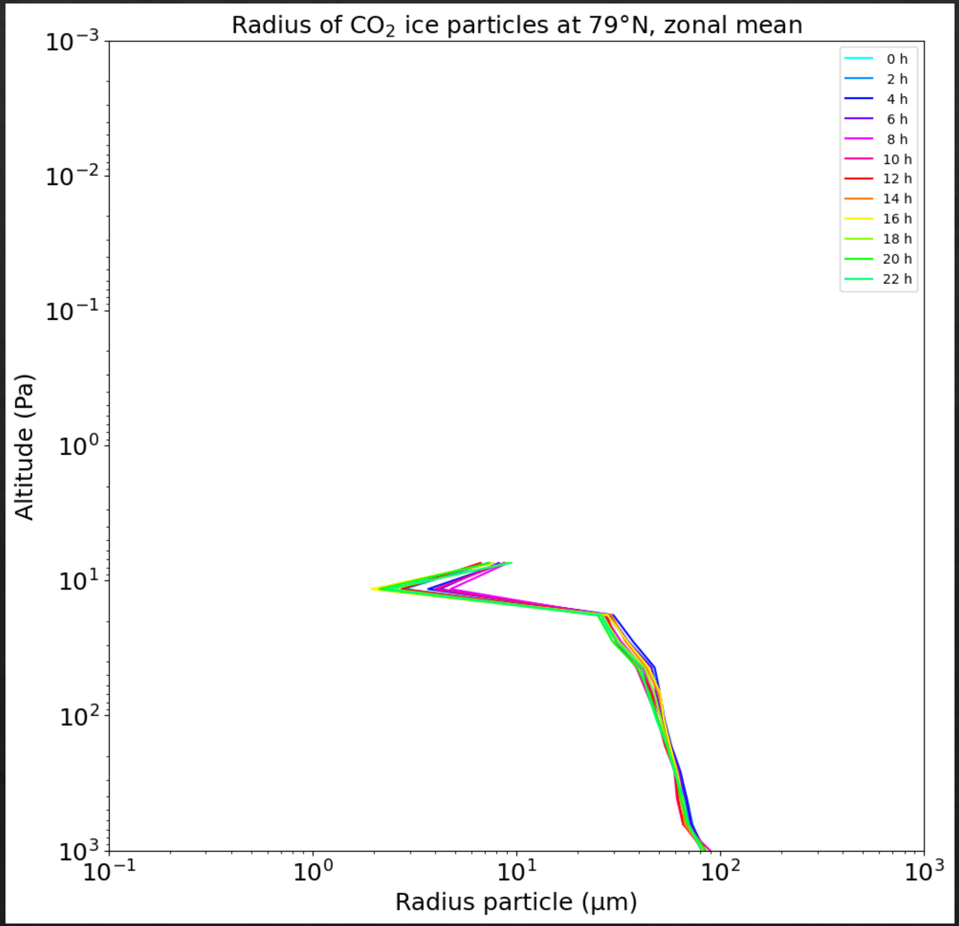
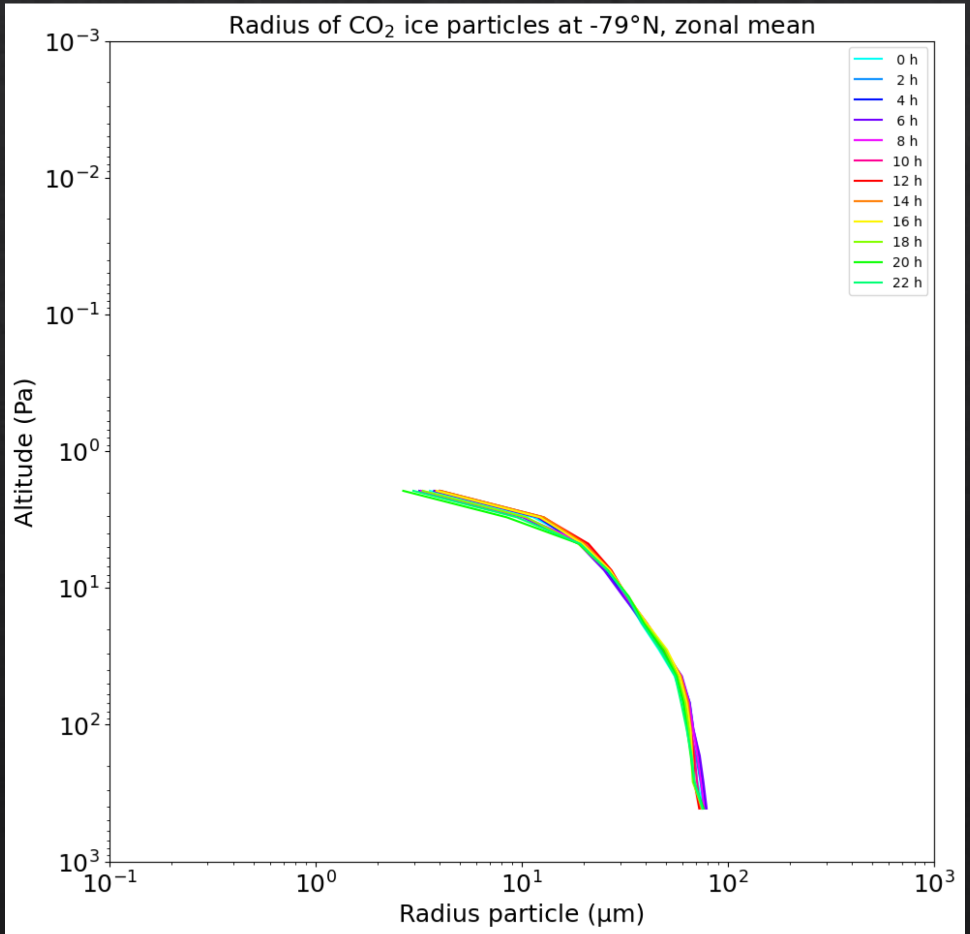
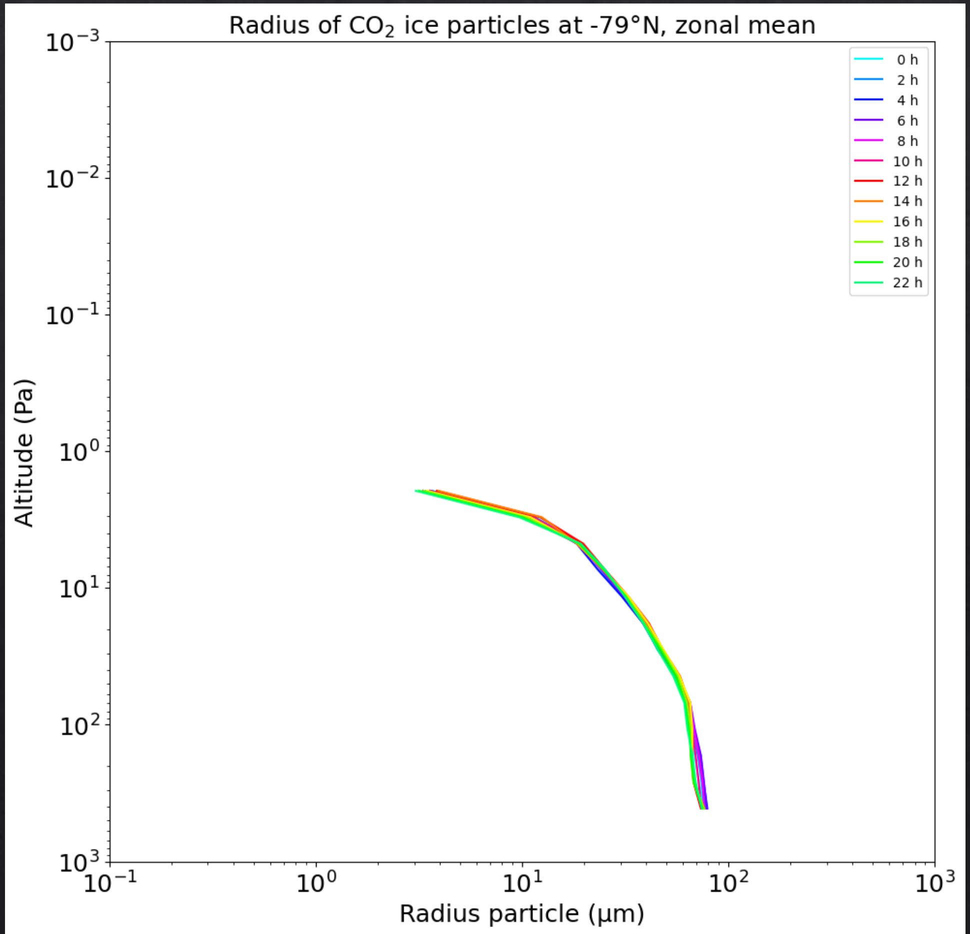


Polar CO_2 particle radius variation at 79°S during winter, at different local times

Reference

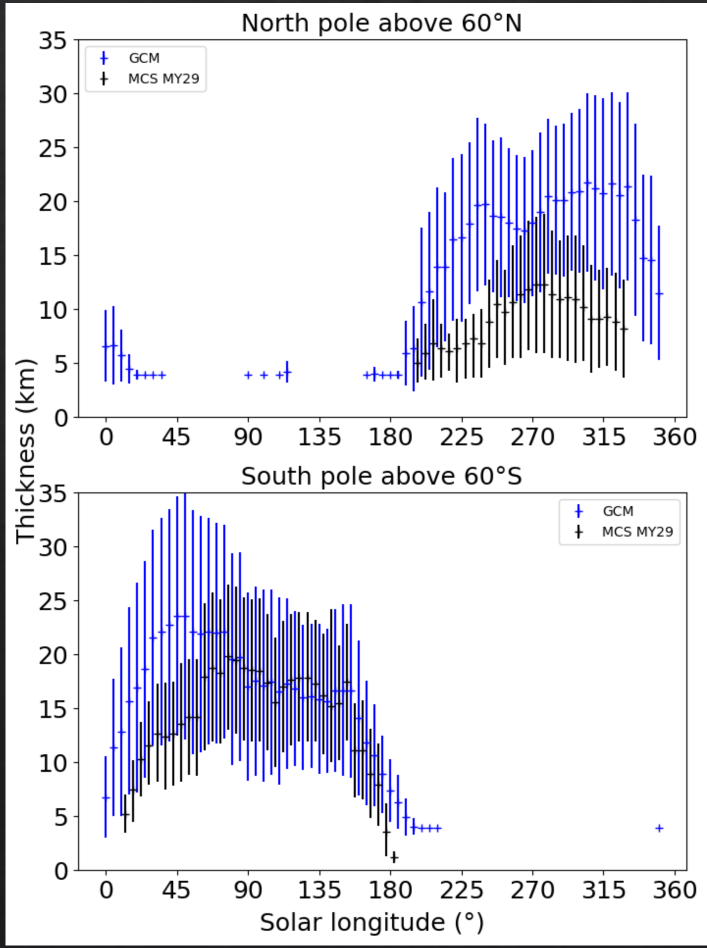


RT

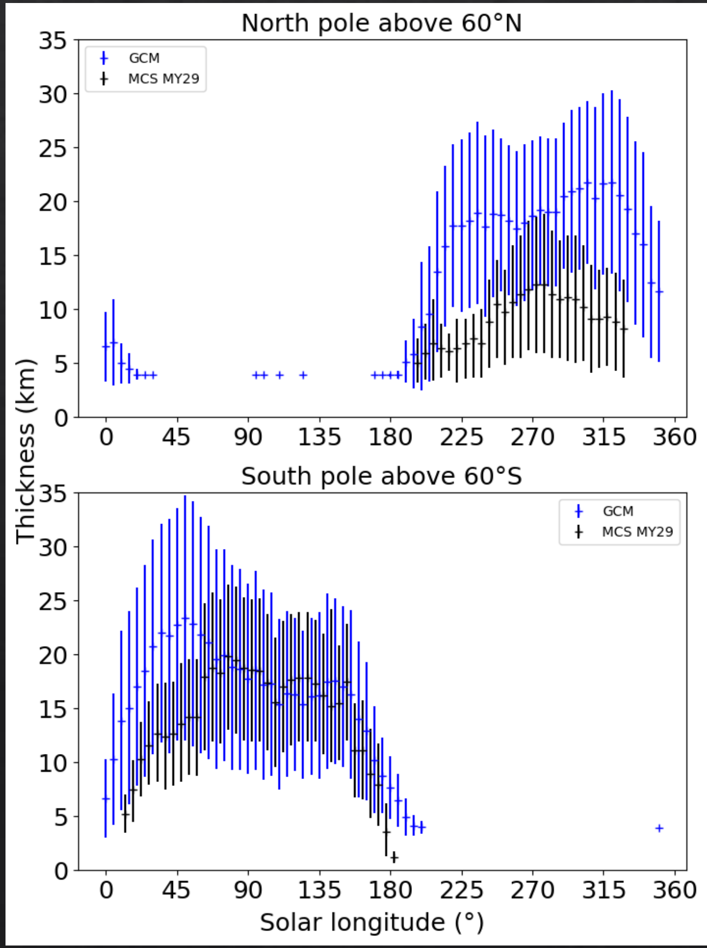


Atmospheric layer thickness of CO_2 saturation: comparison to MCS [Hu et al., 2012]

Reference

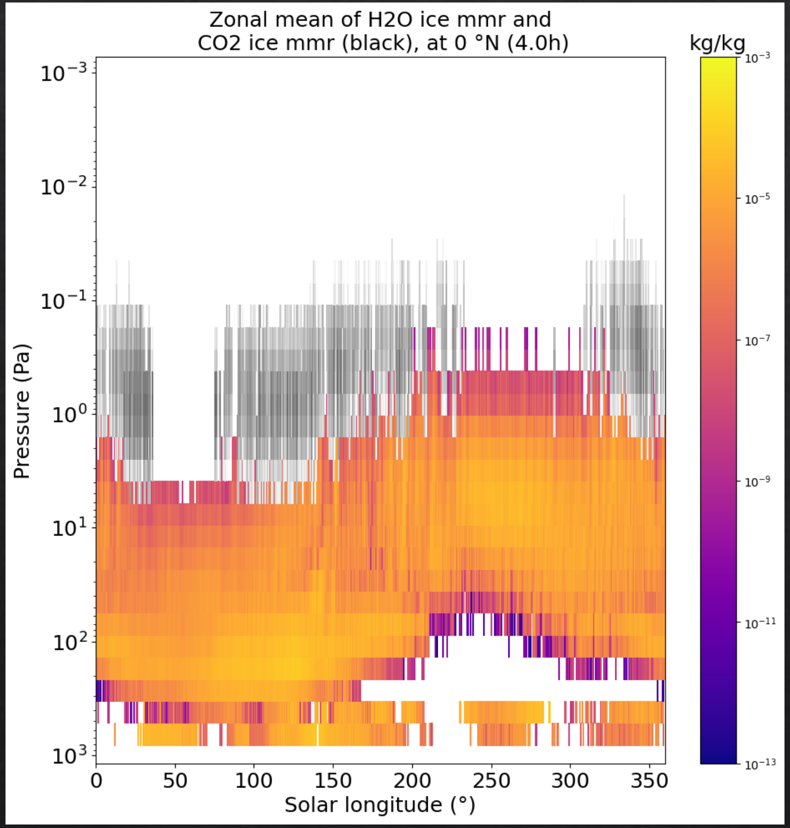


RT

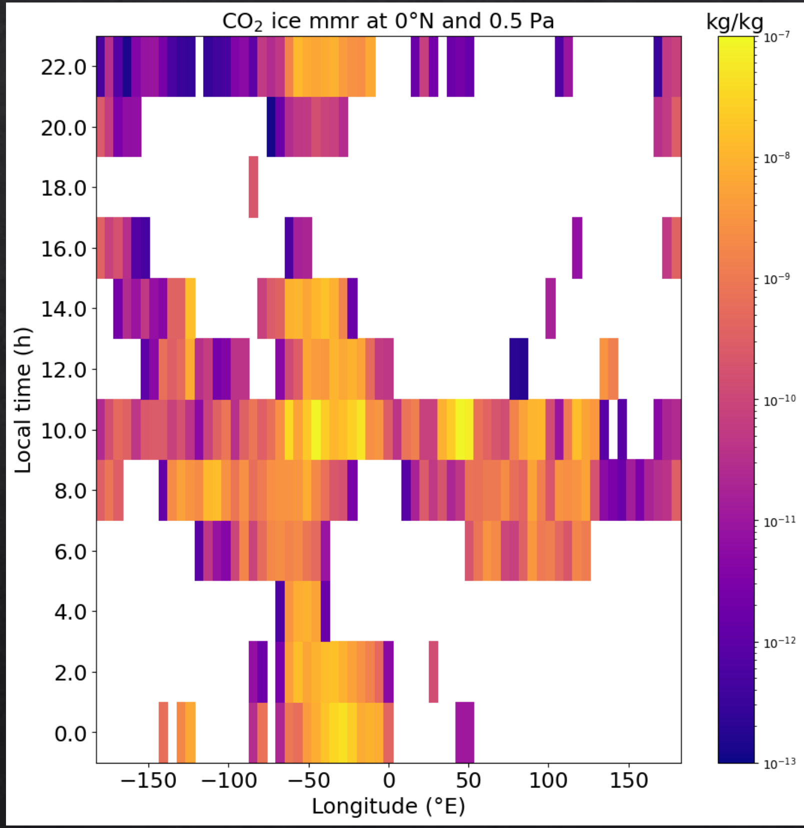


Location of H2O (color) and CO2 (black) ice at 0°N

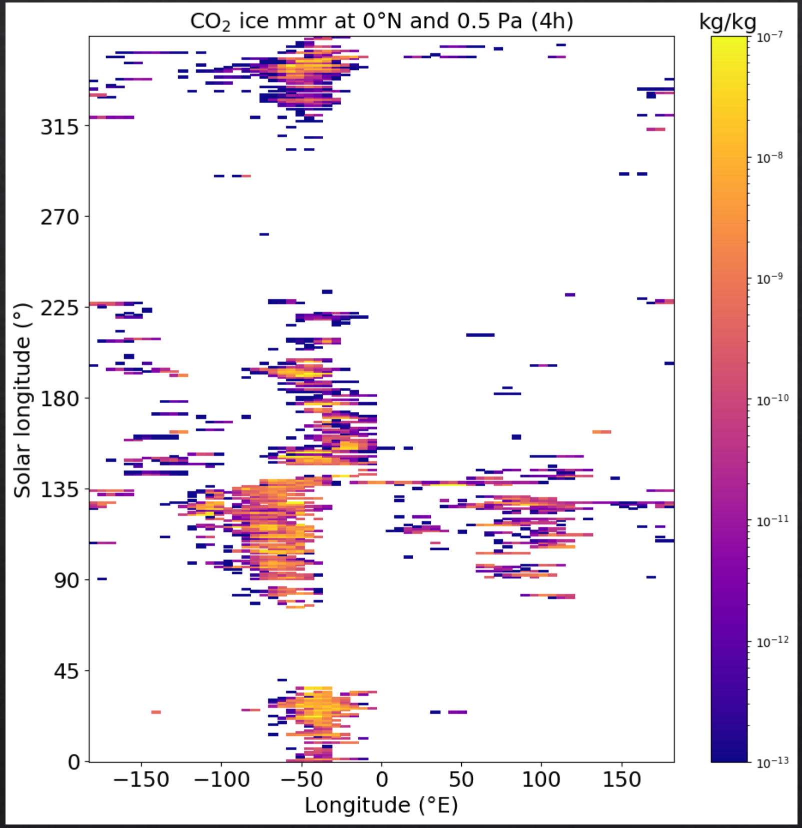
CO2useH2O



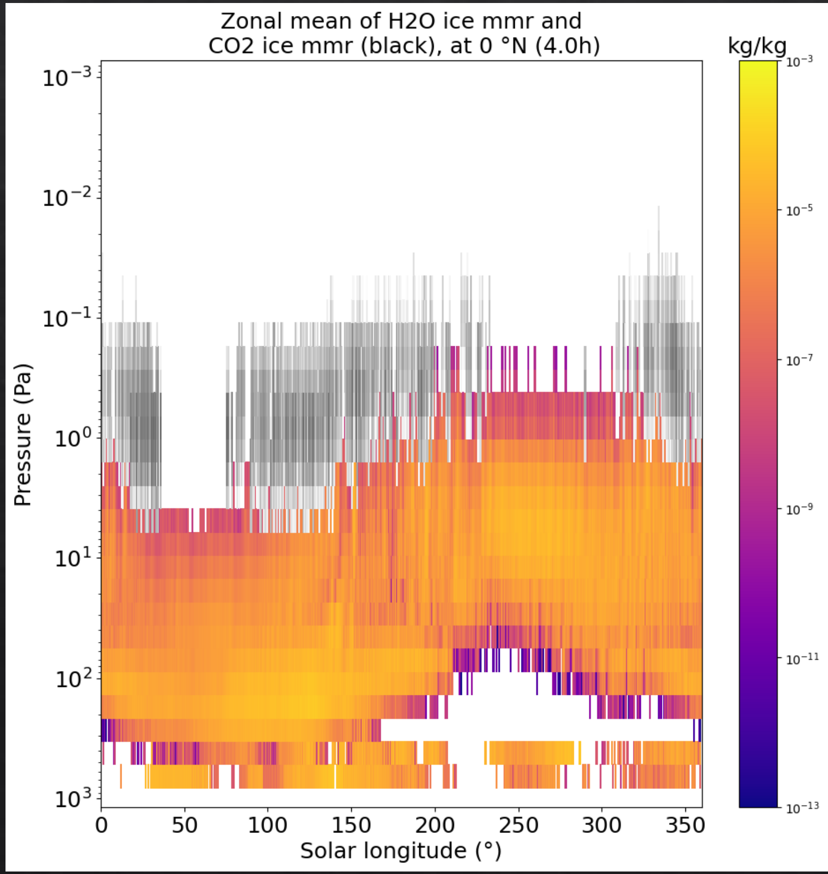
CO_2 ice mmr (local time)



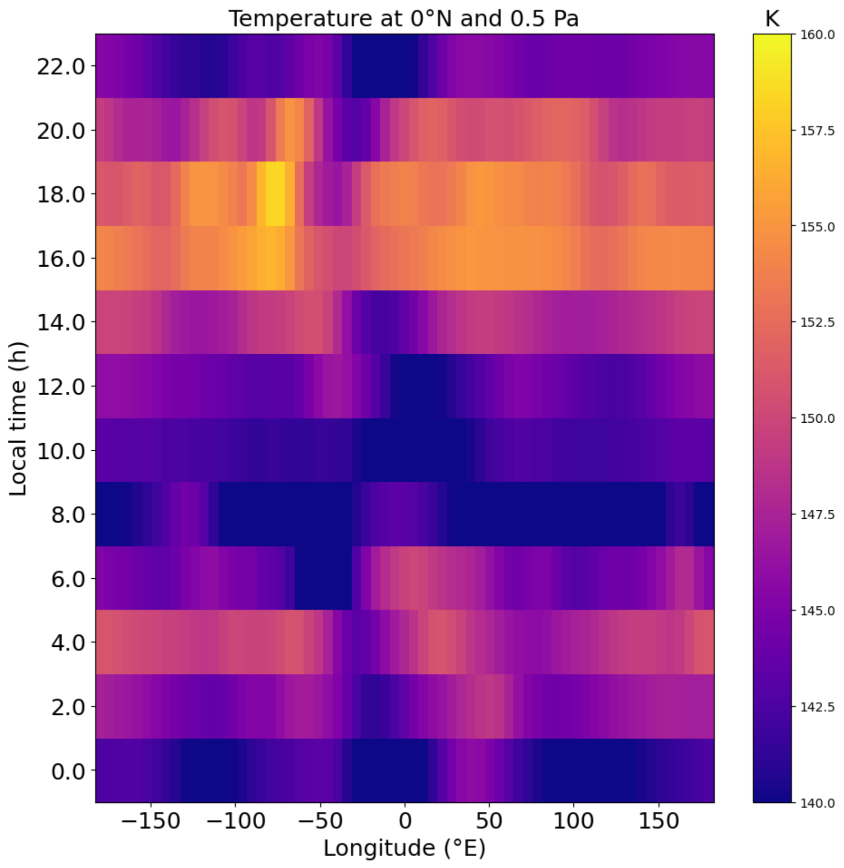
CO_2 ice mmr (Ls)



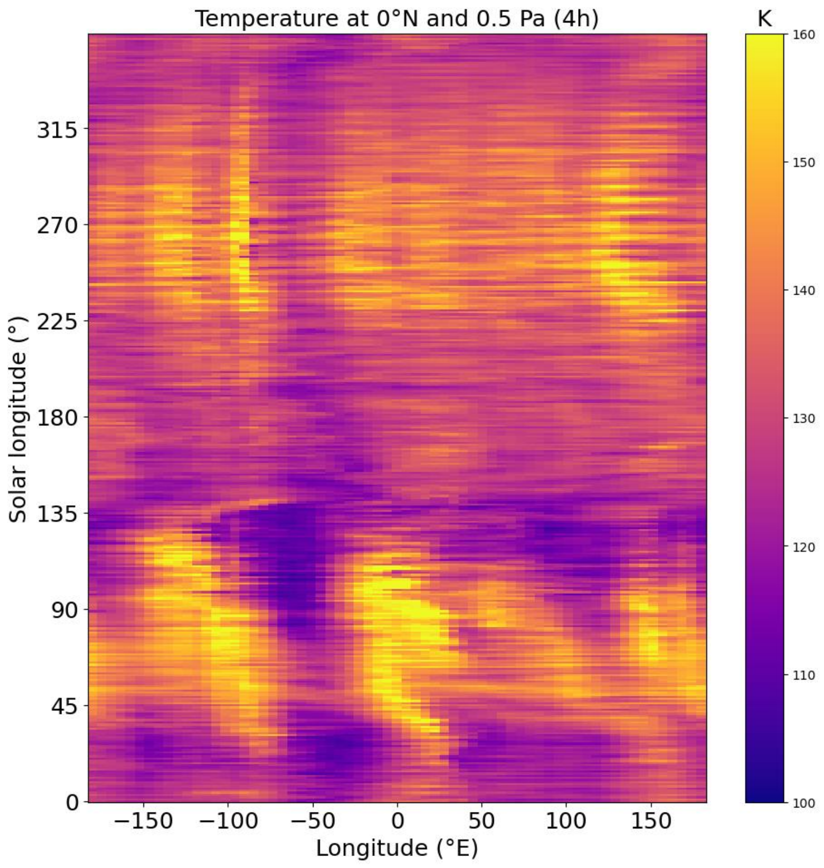
CO2useH2O



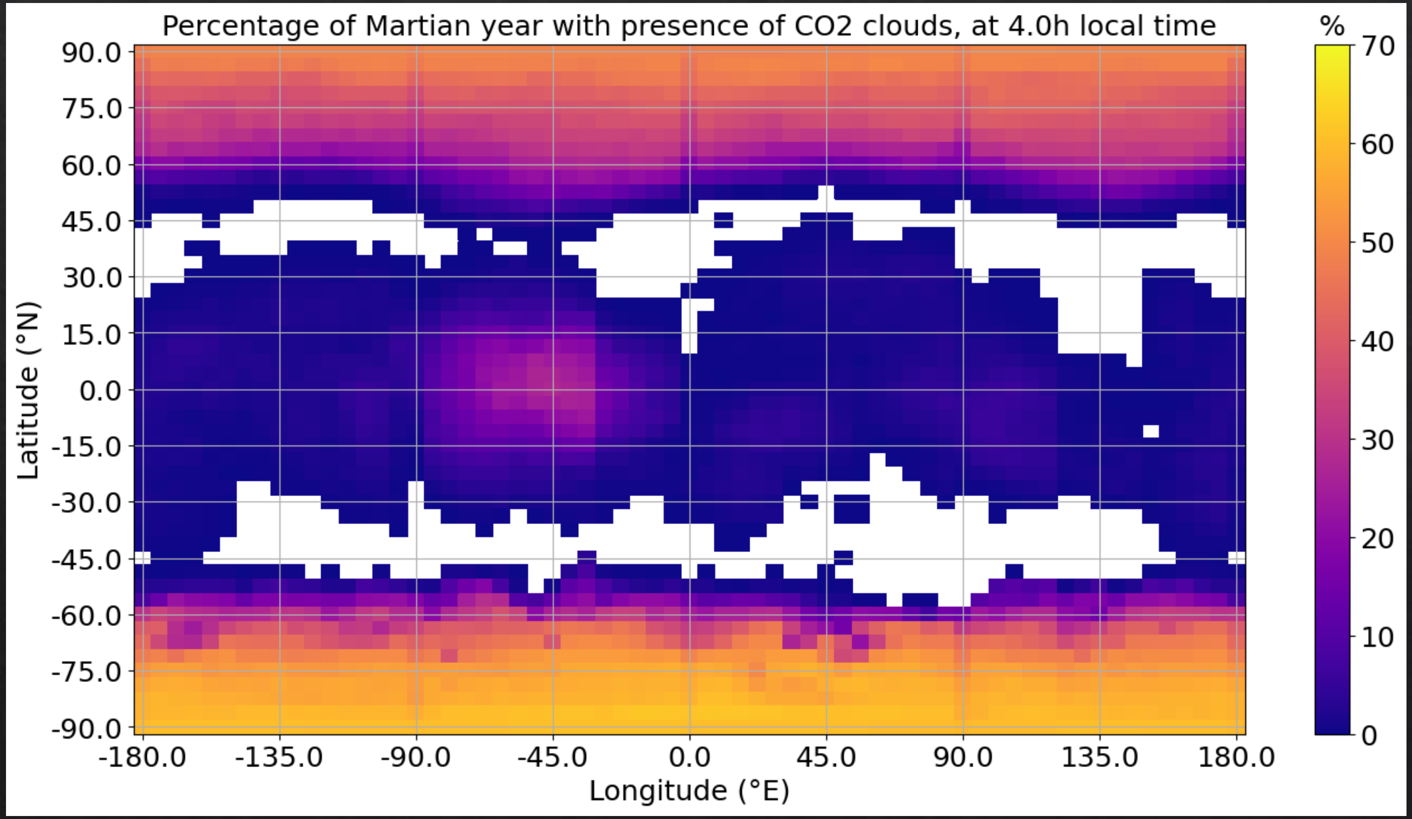
Temperature (local time)

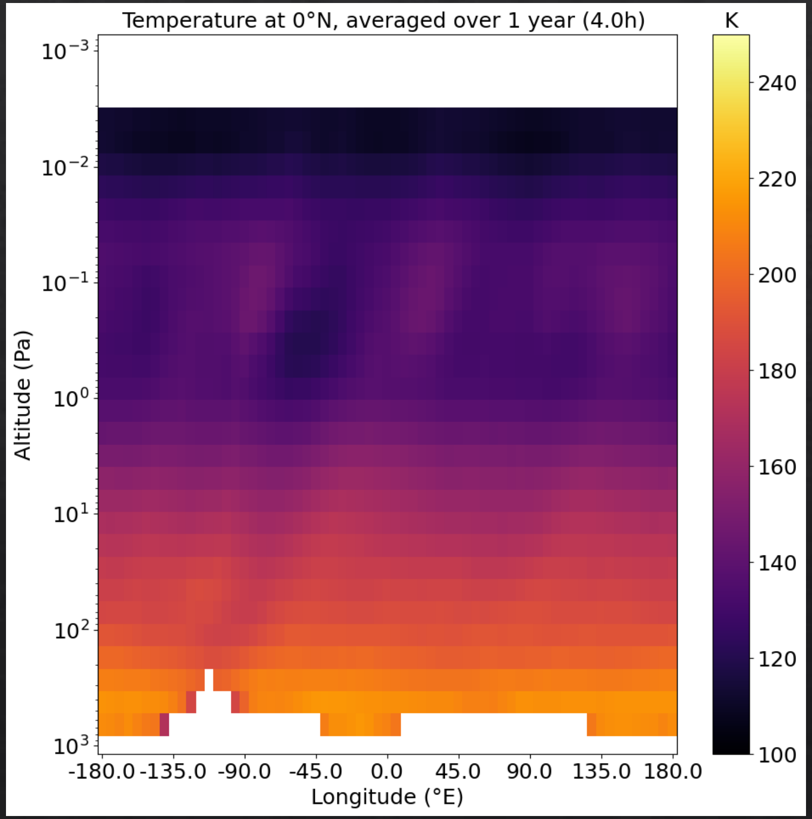


Temperature (Ls)

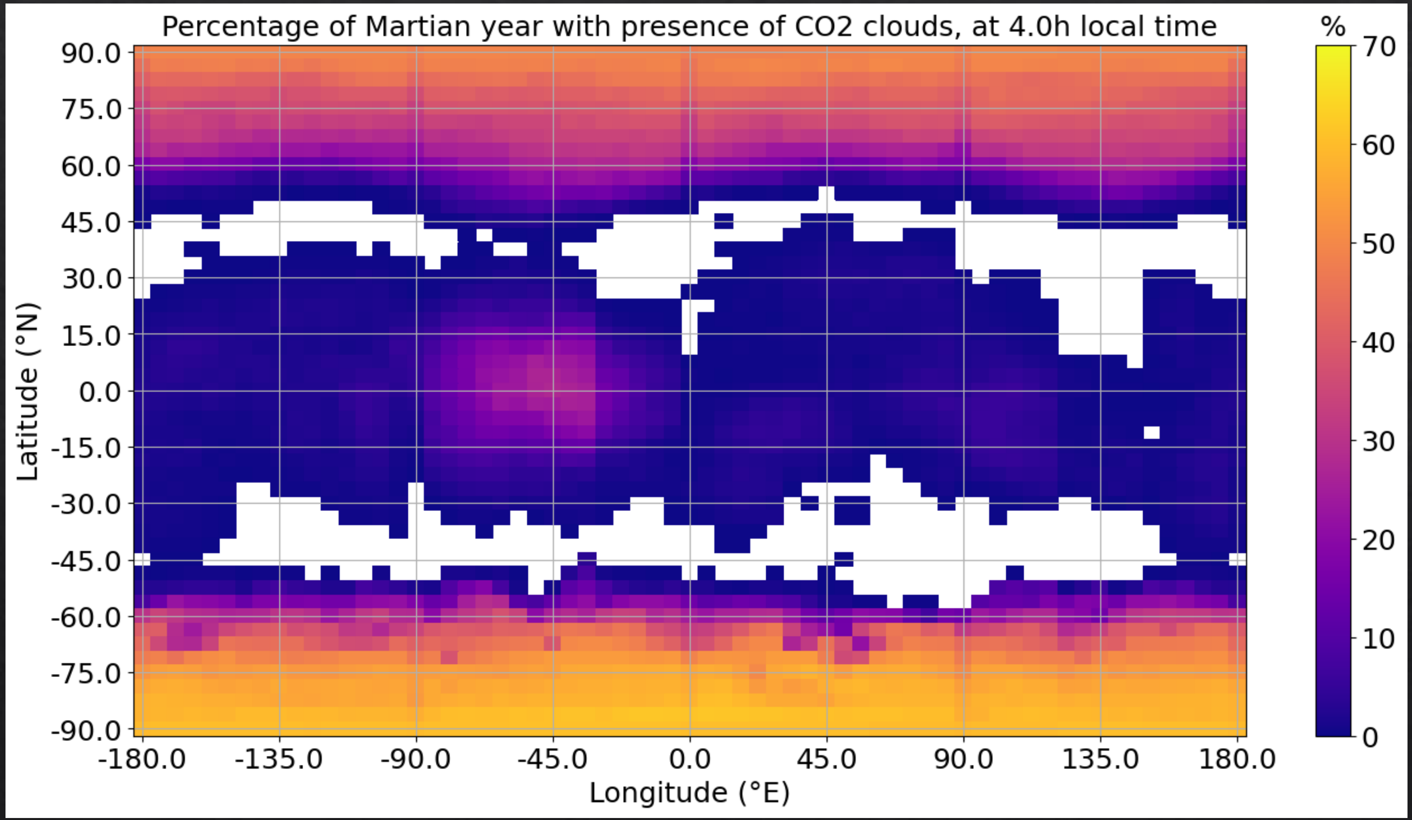


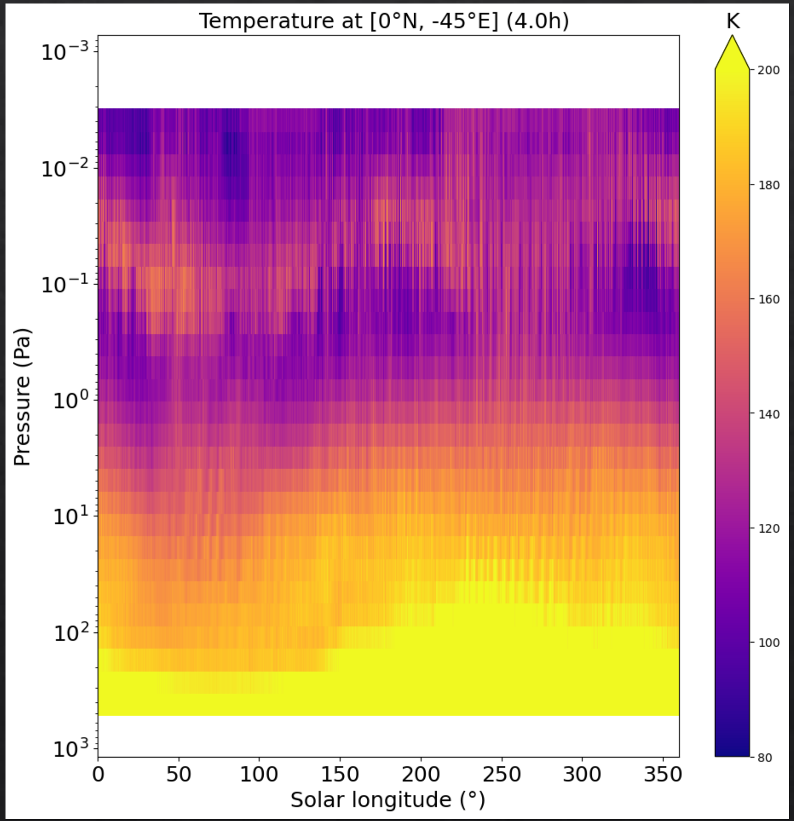
Temperature (CO2useH2O)





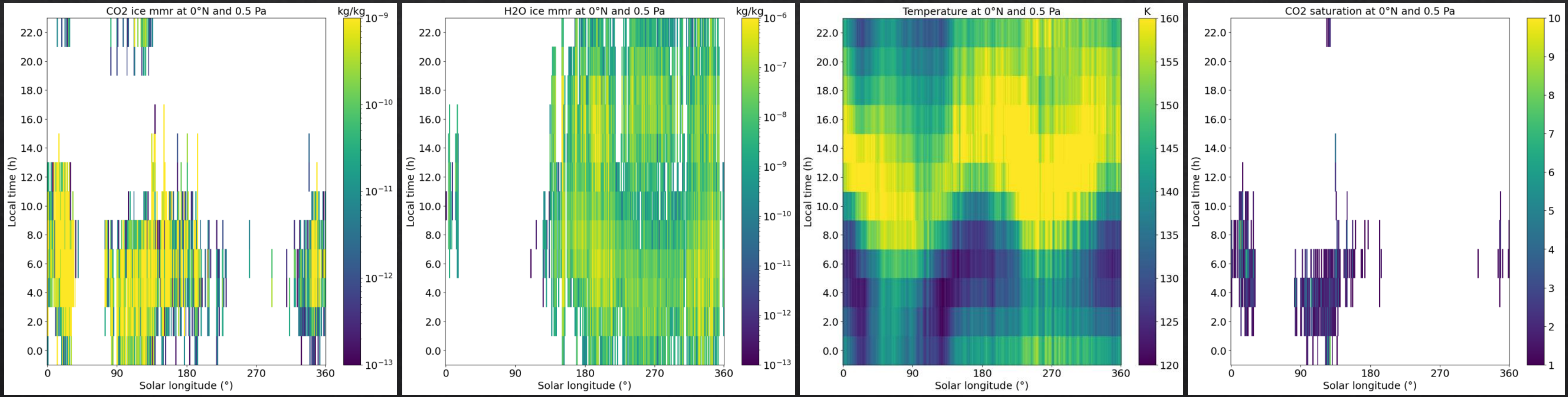
Temperature at 0°N and -45°E (CO2useH2O)





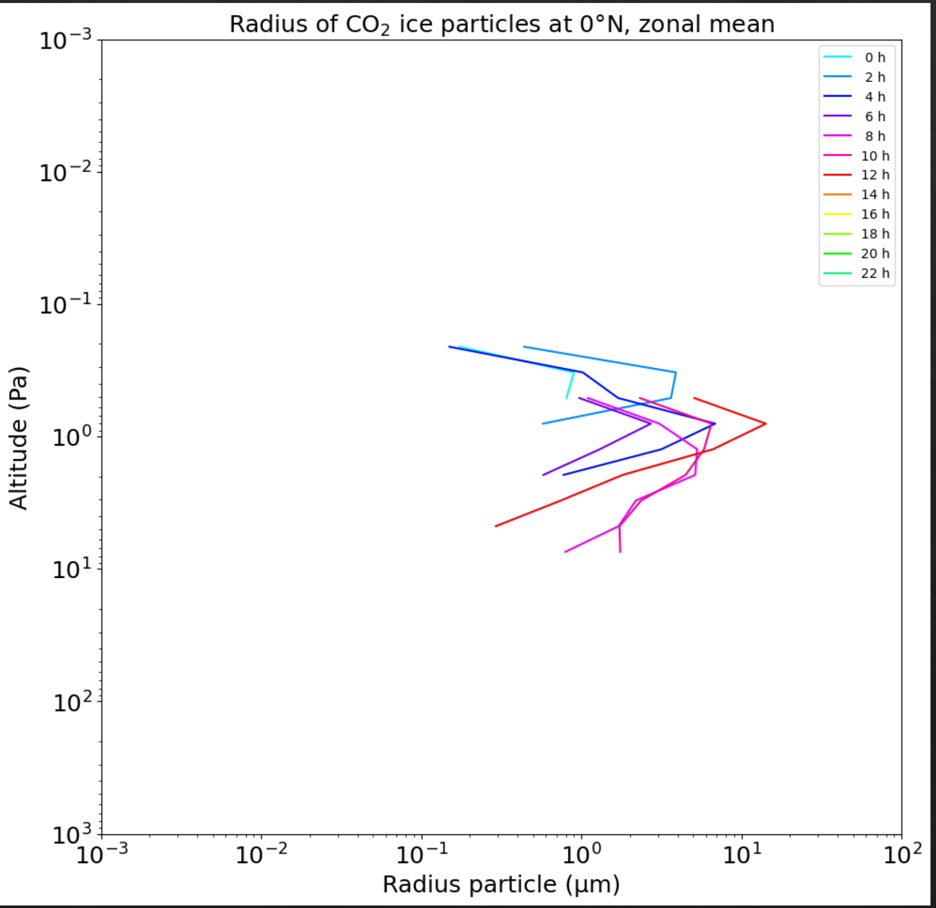
Day-night clouds at 0°N at 0.5 Pa (CO2useH2O)

CO2 ice mmr | H_2O ice mmr | Temperature | Saturation

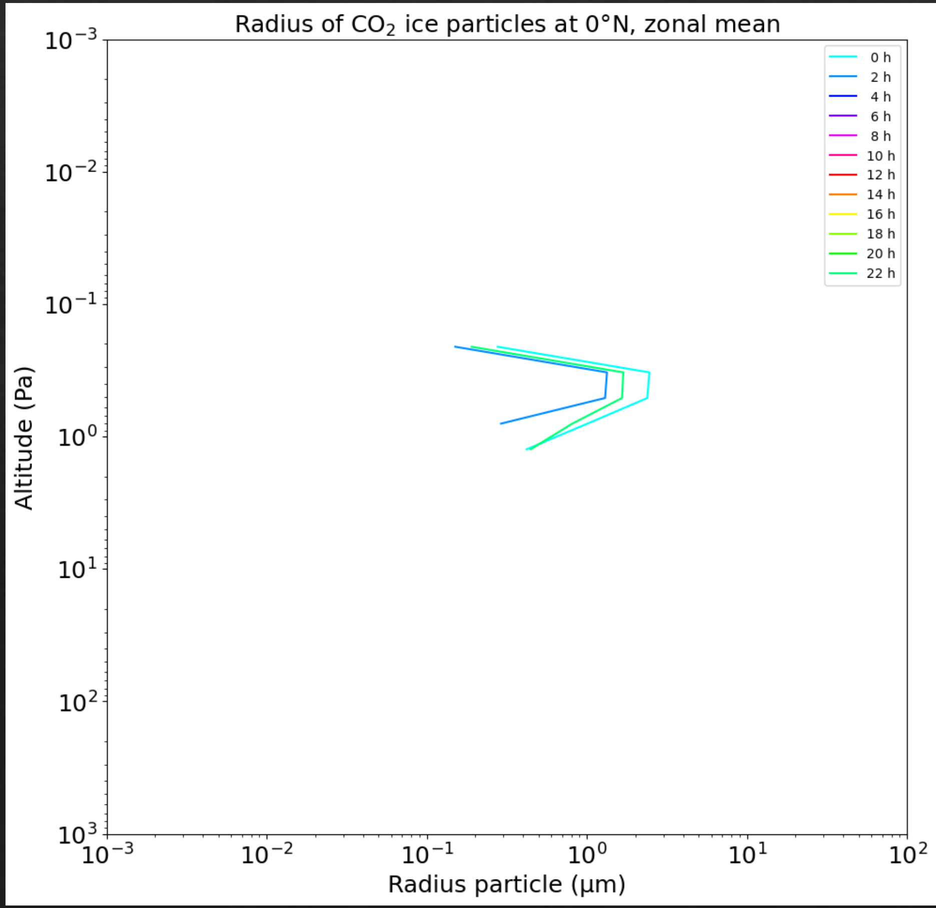


Mesospheric CO_2 particle radius variations at 0˚N

Reference

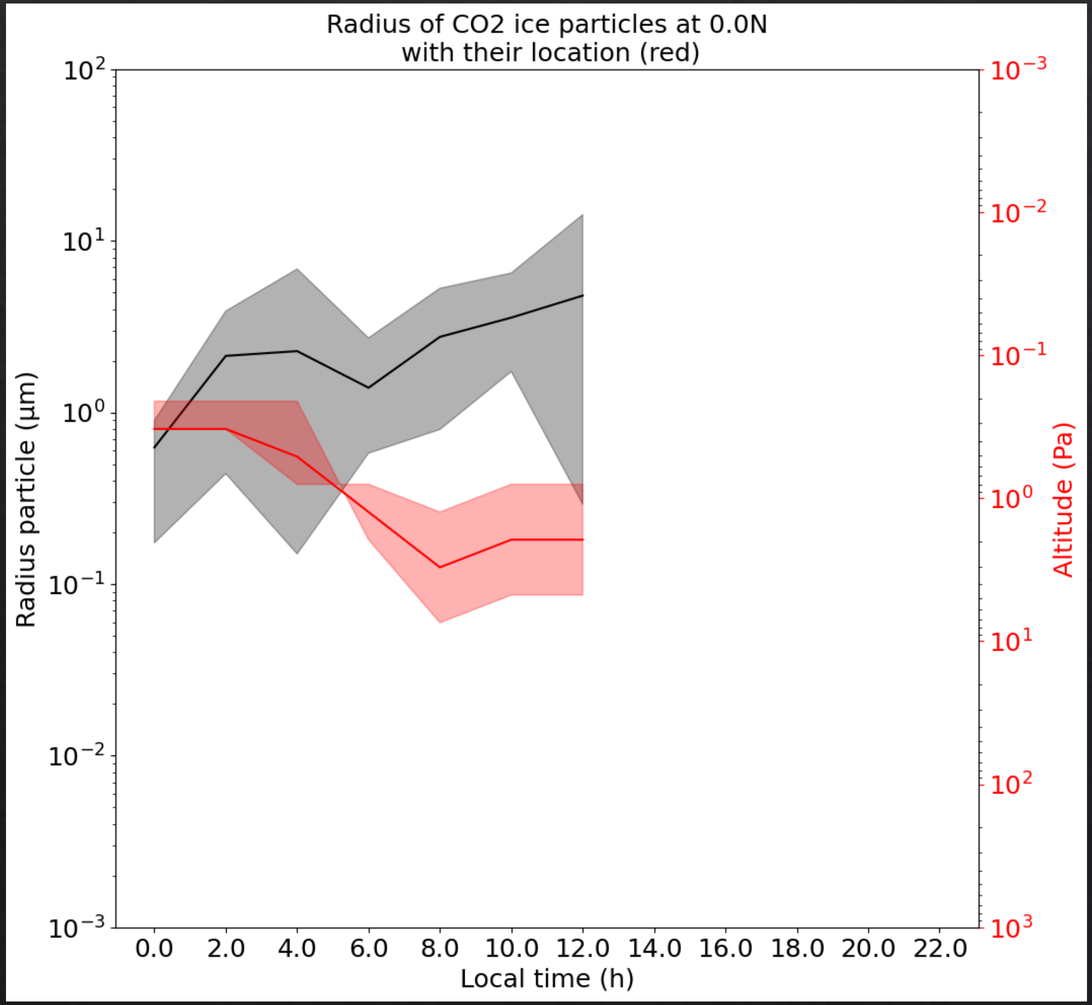


TR



Radius information depending on local time

Reference



RT