Cloud trains associated with mountain lee waves on Mars, I I Mars Years observations

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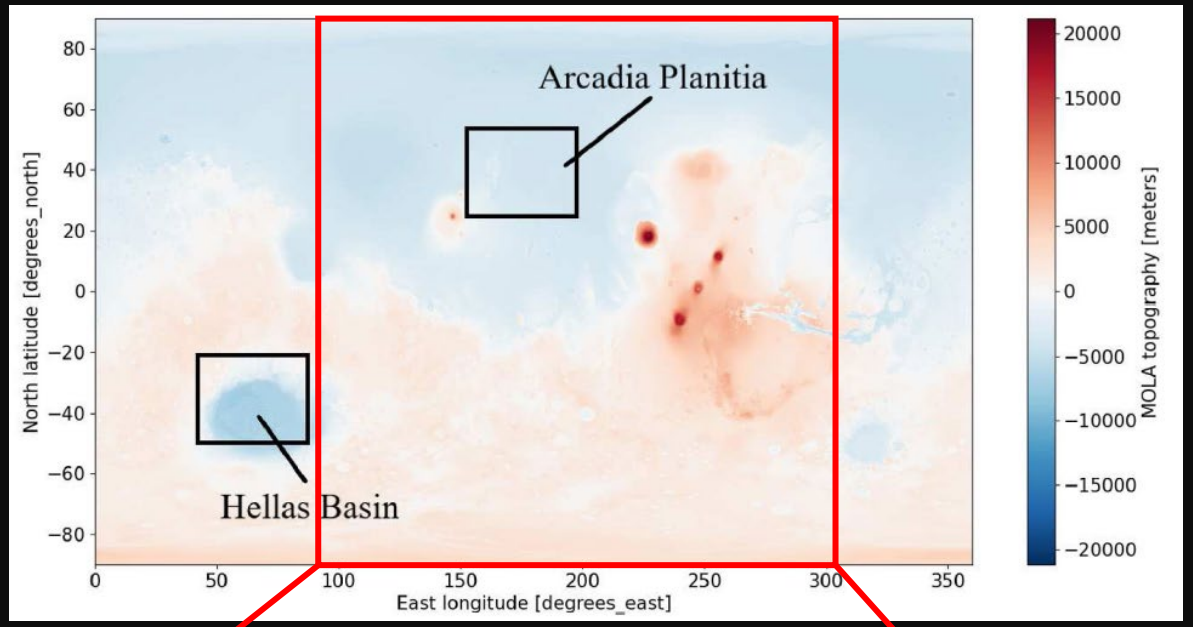
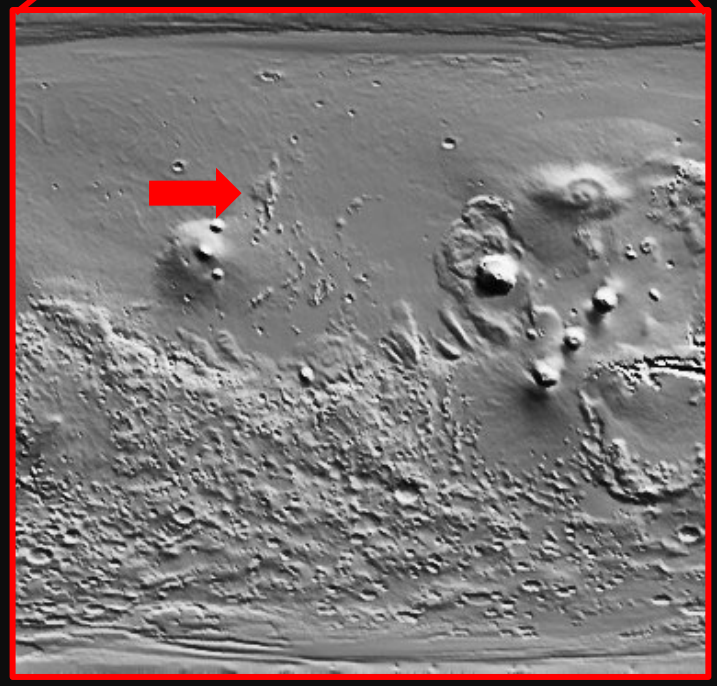
Cloud trains in the Arcadia Planitia

- Frequently observed in MGS/MOC and MRO/MARCI images of Mars
- Frequently found when surveying dust storms
- They are quite similar with wavy clouds associated with mountain lee waves.
- But, seasonality and regionality of such clouds have not been studied.

Purpose

- Investigating the seasonality of the cloud trains in the western Arcadia Planitia (the eastern side of the Phlegra Montes) and their wavelengths using MGS/MOC data
- Estimating formation altitudes of the clouds from the Martian reanalysis dataset
- After that, we extend the target period to MRO/MARCI, and extend the target area to the global Mars.

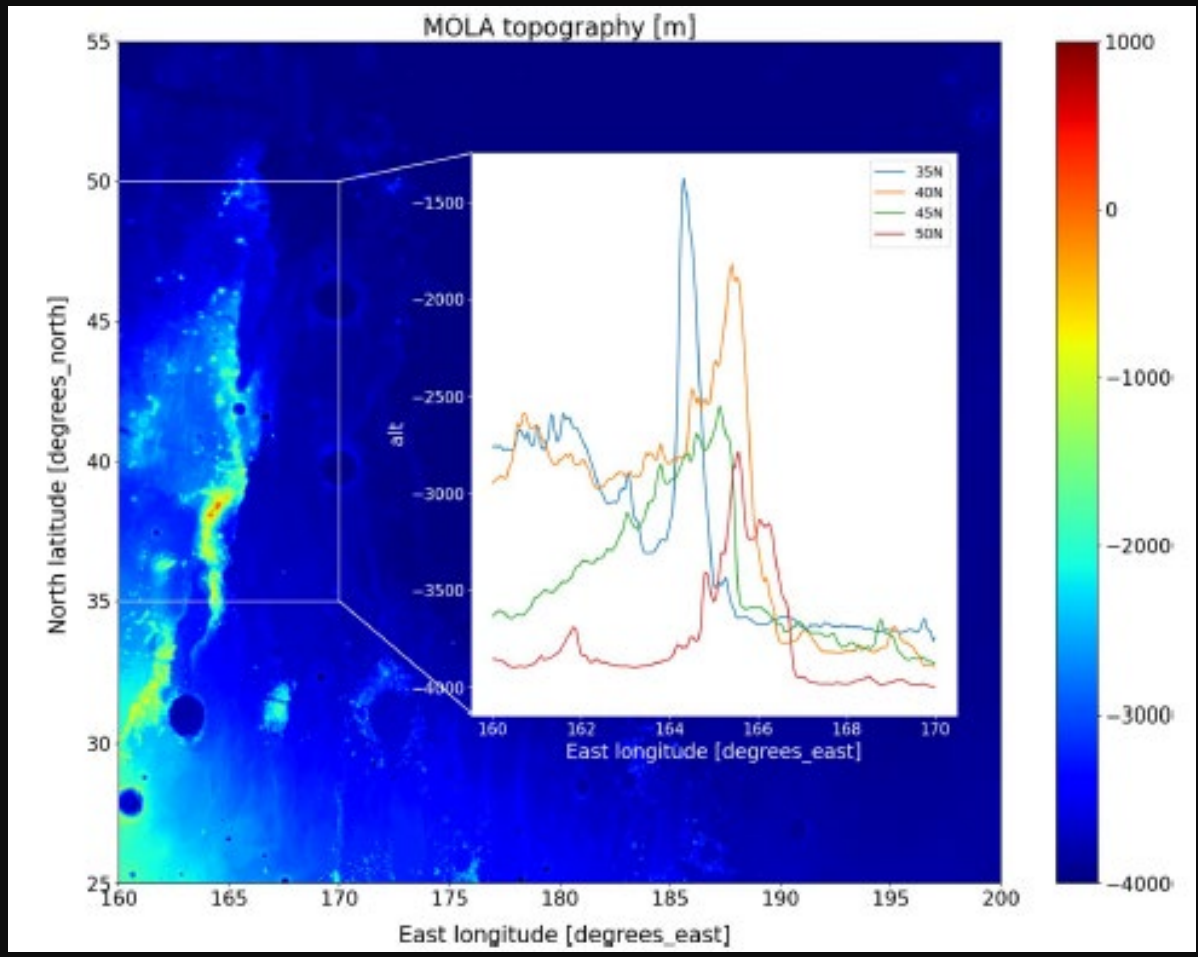




MCD v5.0

Data

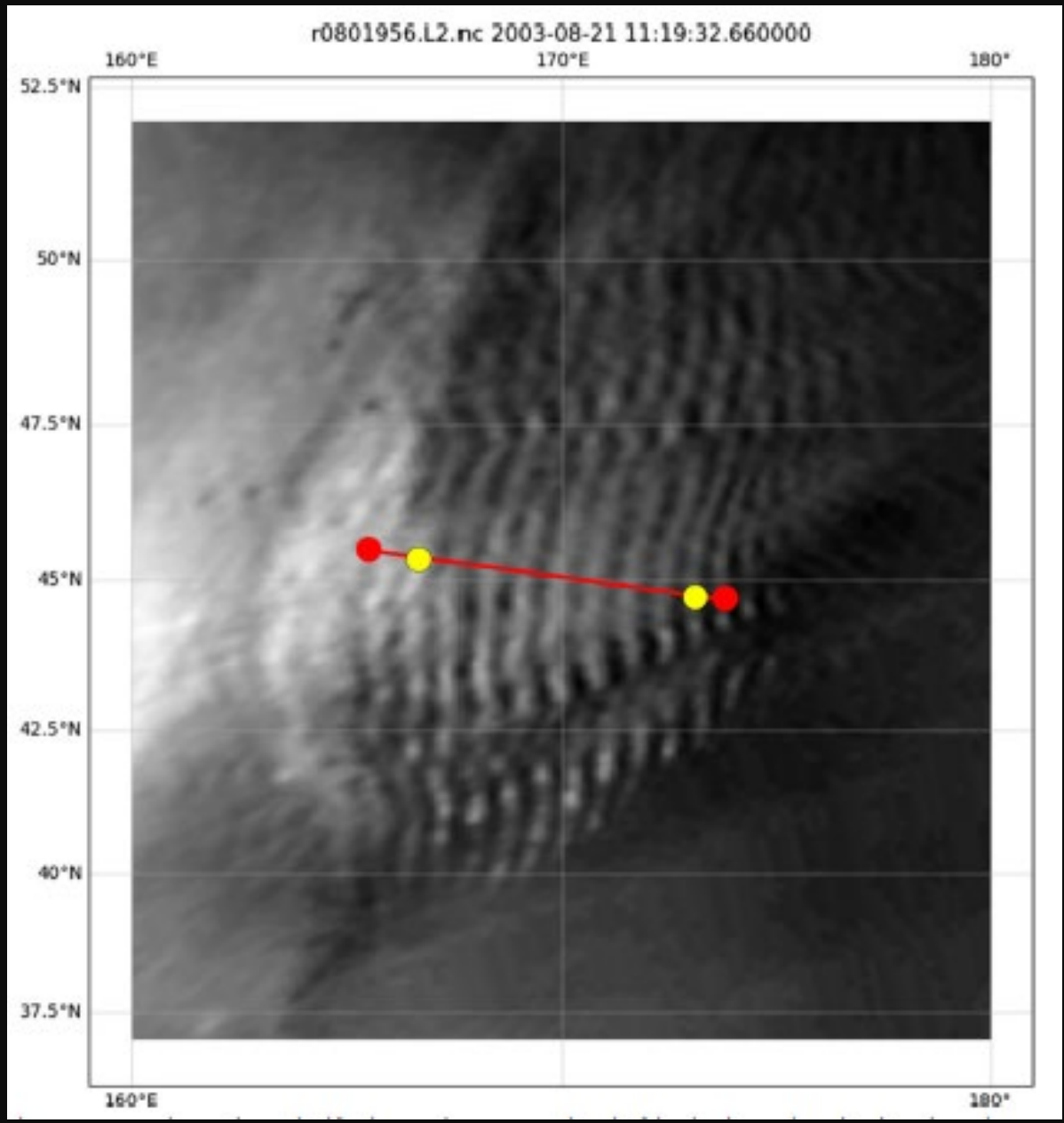
- MGS/MOC, Blue band
  - Arcadia Planitia (180E40N) and the Phlegra Montes
  - 40° x30° trimmed from global swath images
  - 2,476 subsets of 800x600 pixels
- EMARS (Greubush et al. 2019)
  - Assimilation using MGS/TES temperature
  - Horizontal distributions of dust column mass are relaxed toward the observations.
  - 1 hour forecast from the analysis mean dataset that were calculated in the sigma-p hybrid coordinate.



Ogohara and Ro (2023)

How to measure mean wavelength

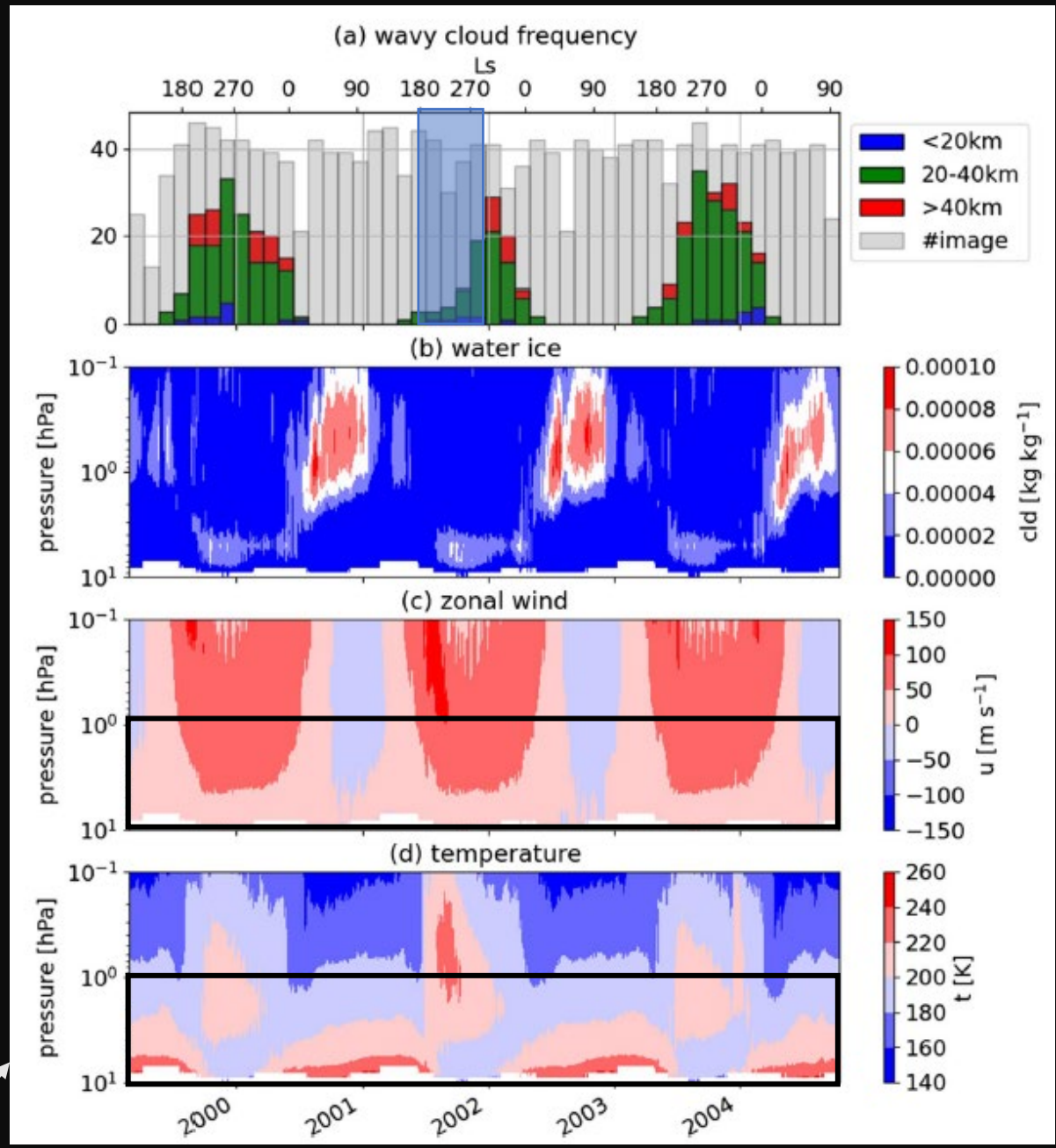
- Hand-made GUI that determines the edge points visually and divide distance between them with wavenumber between them
- Mean wavelength is measured in the direction perpendicular to the phase line of cloud train.
- What's measured here is the total wavenumber exactly. But it is close to the zonal wavenumber because phase lines of the wave are approximately along the latitudinal direction in most cases.



Ogohara and Ro (2023)

Result

- Cloud trains were found in 531 out of 2476 MGS/MOC blue images.
- Peak season: the northern winter
  - The lowest atmosphere is wet enough for cloud (resolvable with the GCM) to form.
  - The atmosphere is highly stable in the northern mid latitudes.
  - Westerly jet
- Water vapor data is missing in the database during this period (Greybush, personal communication)
- Wavelength from 20 to 40 km is comparable with the typical scale of the mountain's eastern slope.



Time-pressure variation in water ice, zonal wind and temperature at 14:00LT

Ogohara and Ro (2023)

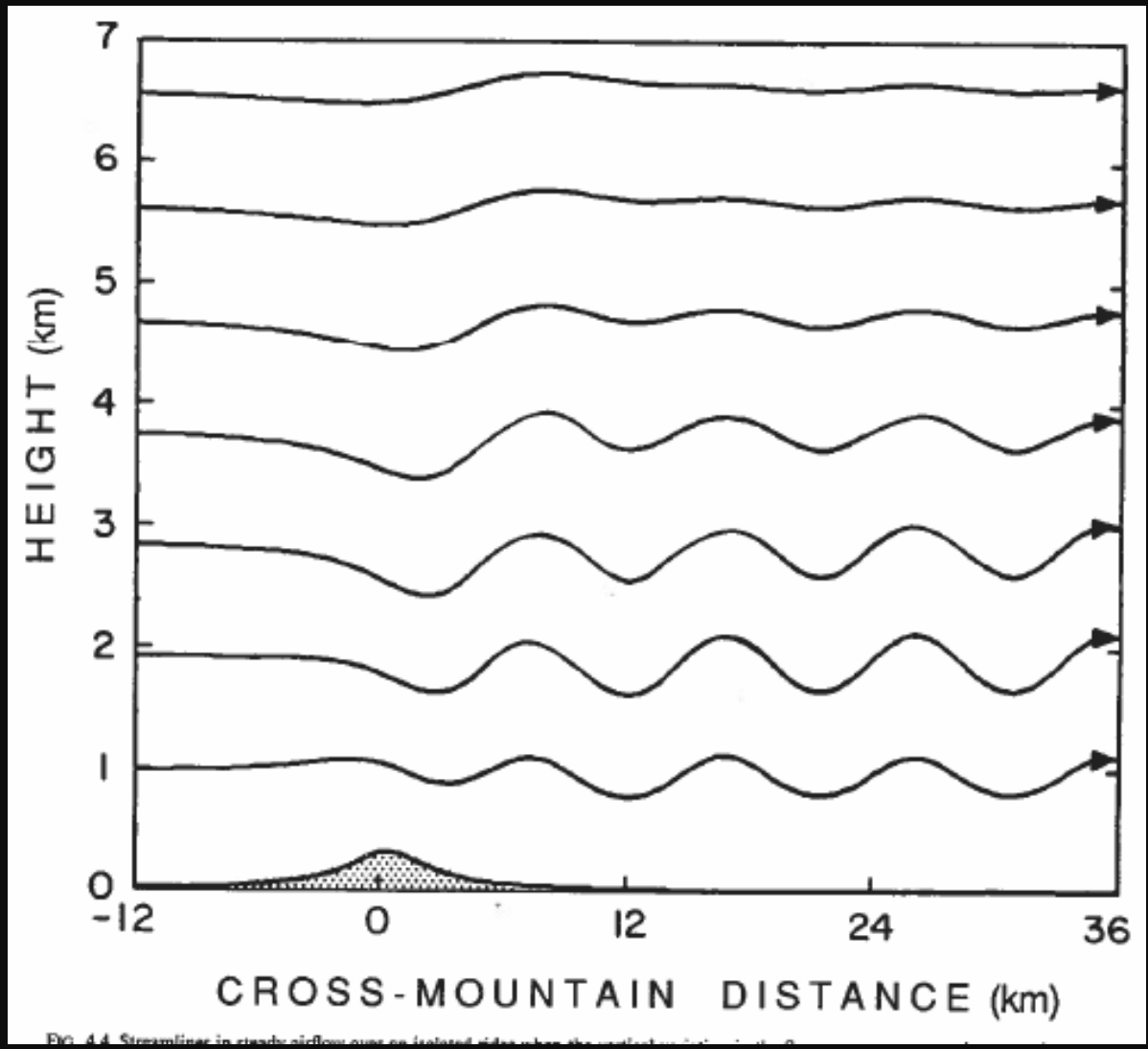
Scorer number

- For stationary waves, Durran (1986)

$$\frac{\partial^2 \hat{w}}{\partial z^2} + (l^2 - k^2)\hat{w} = 0,$$

$$l^2 = \frac{N^2}{U^2} - \frac{1}{U}\frac{d^2 U}{dz^2}$$

- where $\hat{w}$ and k are the vertically dependent amplitude of the vertical wind perturbation and the wavenumber in the direction parallel to a mean wind, respectively. N is Brunt-Vaisala frequency, U is the mean wind, l^2 is the Scorer number for a stationary mountain wave.
- A long cloud train occurs when a short wave is trapped in the lower atmosphere on the lee side of the mountain.



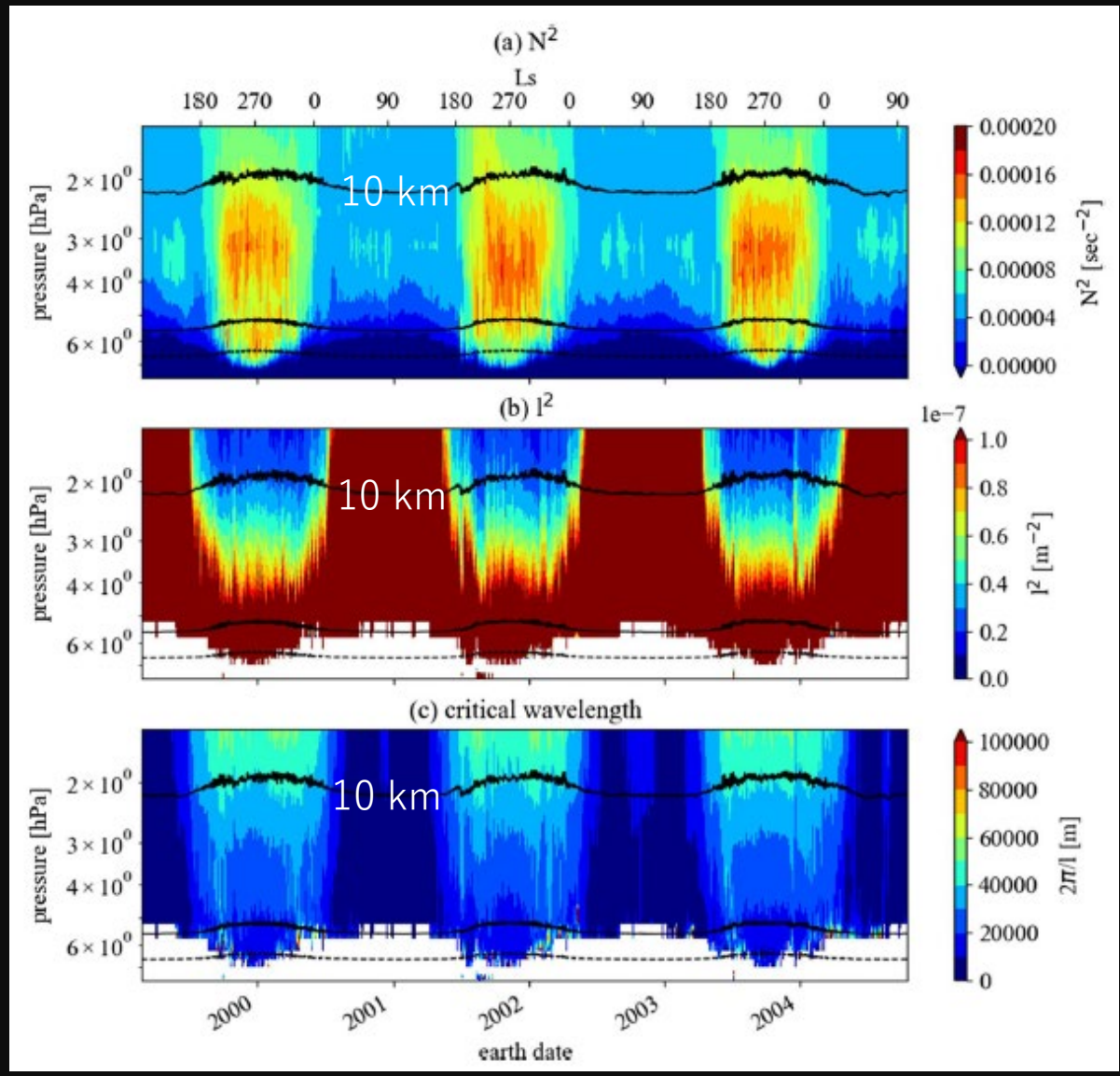
Upper boundary for short wave propagation

- A stationary wave with horizontal wavelengths shorter than (wavenumber larger than) $2\pi/l$ (l) cannot propagate upward.
- E. g., stationary waves having a horizontal wavelength that is shorter than 40 km are confined below 2 hPa.

$$\frac{\partial^2 \hat{w}}{\partial z^2} + (l^2 - k^2)\hat{w} = 0,$$

$$l^2 = \frac{N^2}{U^2} - \frac{1}{U}\frac{d^2U}{dz^2}$$

Ogohara and Ro (2023)



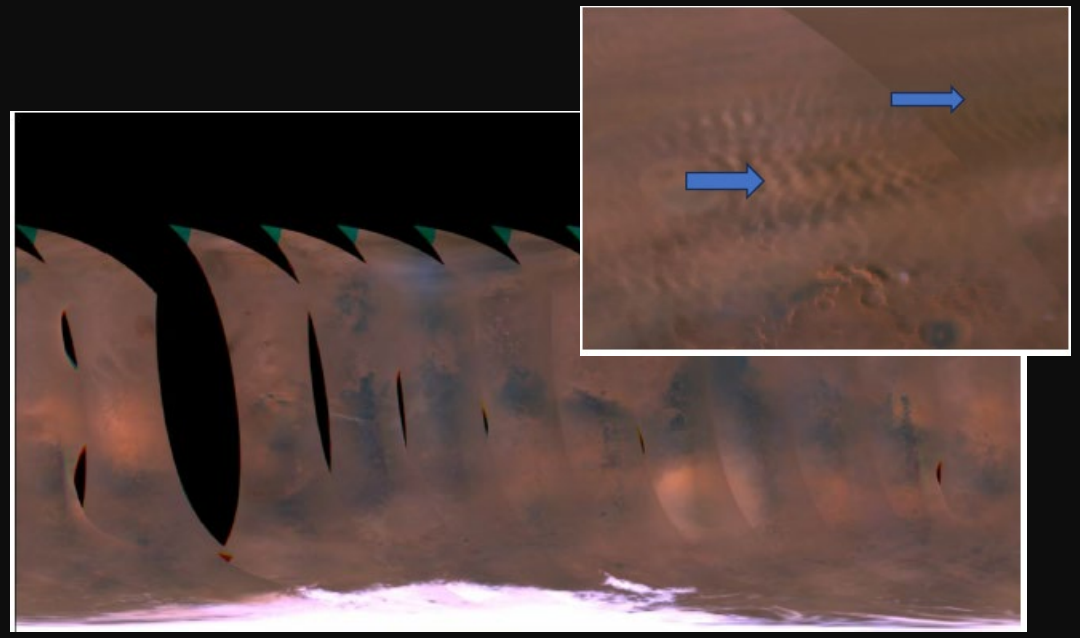
That's all results of MGS/MOC.

MRO/MARCI (Arcadia)

- 29 Sep. 2006 – 30 Nov. 2020
- 543 (+249 ambiguous cases) out of 3877 images
- The seasonal variation in cloud frequency is similar with those derived from the MGS/MOC data.
- 3-6 cases within 10 deg in Ls
- The ratio (#cloud/#image) tends to decrease during the solstitial pause. Such seasonal variations are similar with the seasonal variations in dust storm frequency in the northern mid-latitudes.

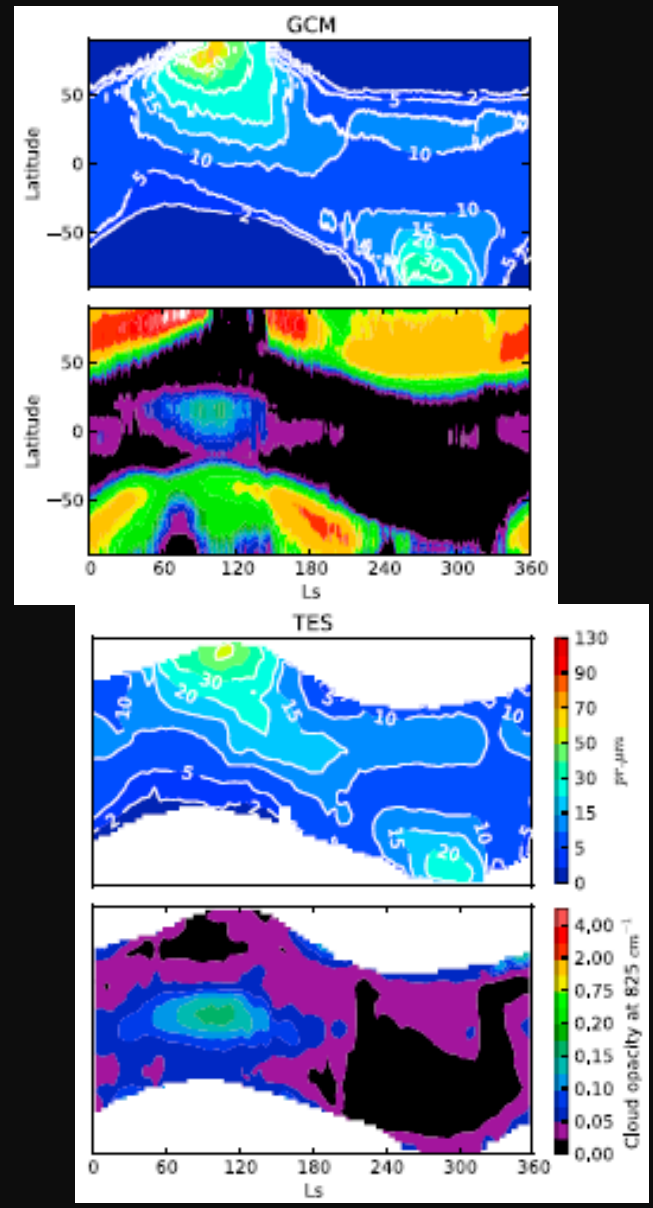
MDGM (MRO/MARCI)

- Mars Daily Global Map (Wang and Richardson 2015)
- 2 Mars years (Ls=130 in MY28 – Ls=110 in MY30)
- 3238 cases out of 1263 MDGMs
- Mid to high latitudes except for the two basins.
- The three Planitias (Arcadia, Acidalia, and Utopia) are famous for many dust storms, but are too smooth to excite lee waves?



MDGM (MRO/MARCI)

- Around Ls=170-180, wave trains jump from the southern hemisphere to the northern hemisphere.
- Around Ls=10-20, wave trains jump from the northern hemisphere to the southern hemisphere.
- A clear border near 40N and 40S



Navarro et al. (2014)

Summary

- The peak season of the cloud trains: the northern winter
  - Strong westerly jet → prevents gravity waves propagating upward
  - Super-stable lower atmosphere → enables ~40 km mountain waves to propagate to 2 hPa (~10km).
- 20-40 km lee waves are trapped below 10km altitude and become resonant.
- Observations by MRO/MARCI are consistent with those by MGS/MOC.
- Cloud trains in the southern mid-latitudes jump to the northern mid-latitudes, and vice versa.
- Latitudes where cloud trains are observed seem to be associated with water vapor amount and zonal wind.