GCM modelling of dust: transport and radiative effects

Dust on Mars Workshop

An initiative of the RoadMap Project

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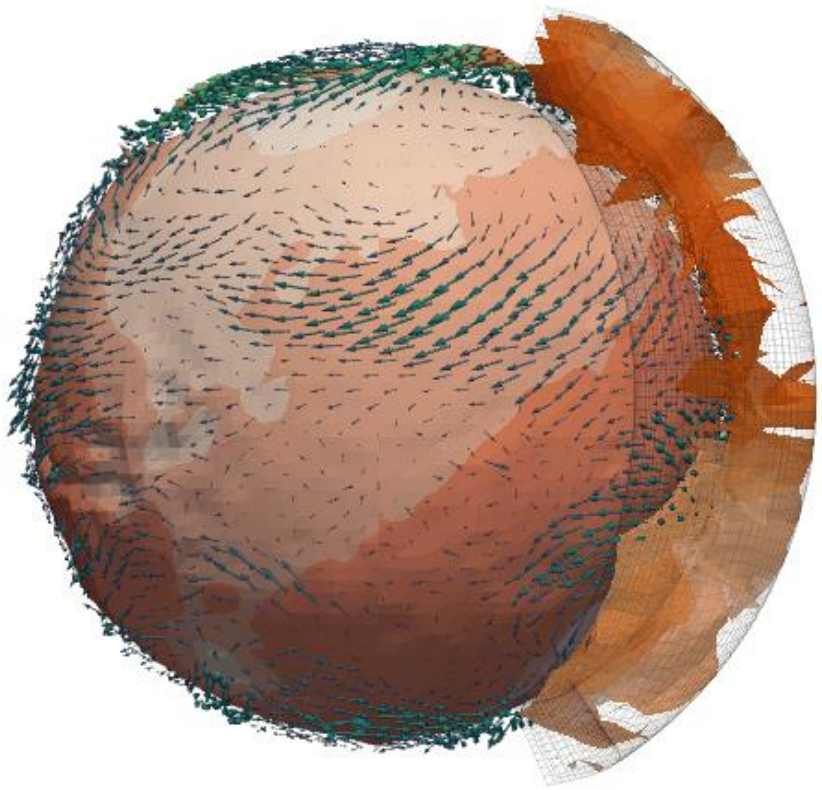
Martian sunset by Spirit Rover at Gusev crater

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004052

19-21 September 2023

Outline

- Part I: An introduction to a Global Climate Model (General Circulation Model) = GCM
- Part II: Characteristics of dust in the Martian atmosphere
- Part III: Current state-of-the-art representation of dust in GCMs
- Part IV: Open questions
- Part V: Useful resources



McCulloch et al., 2022
https://github.com/dannymcculloch/3d_Mars_gif

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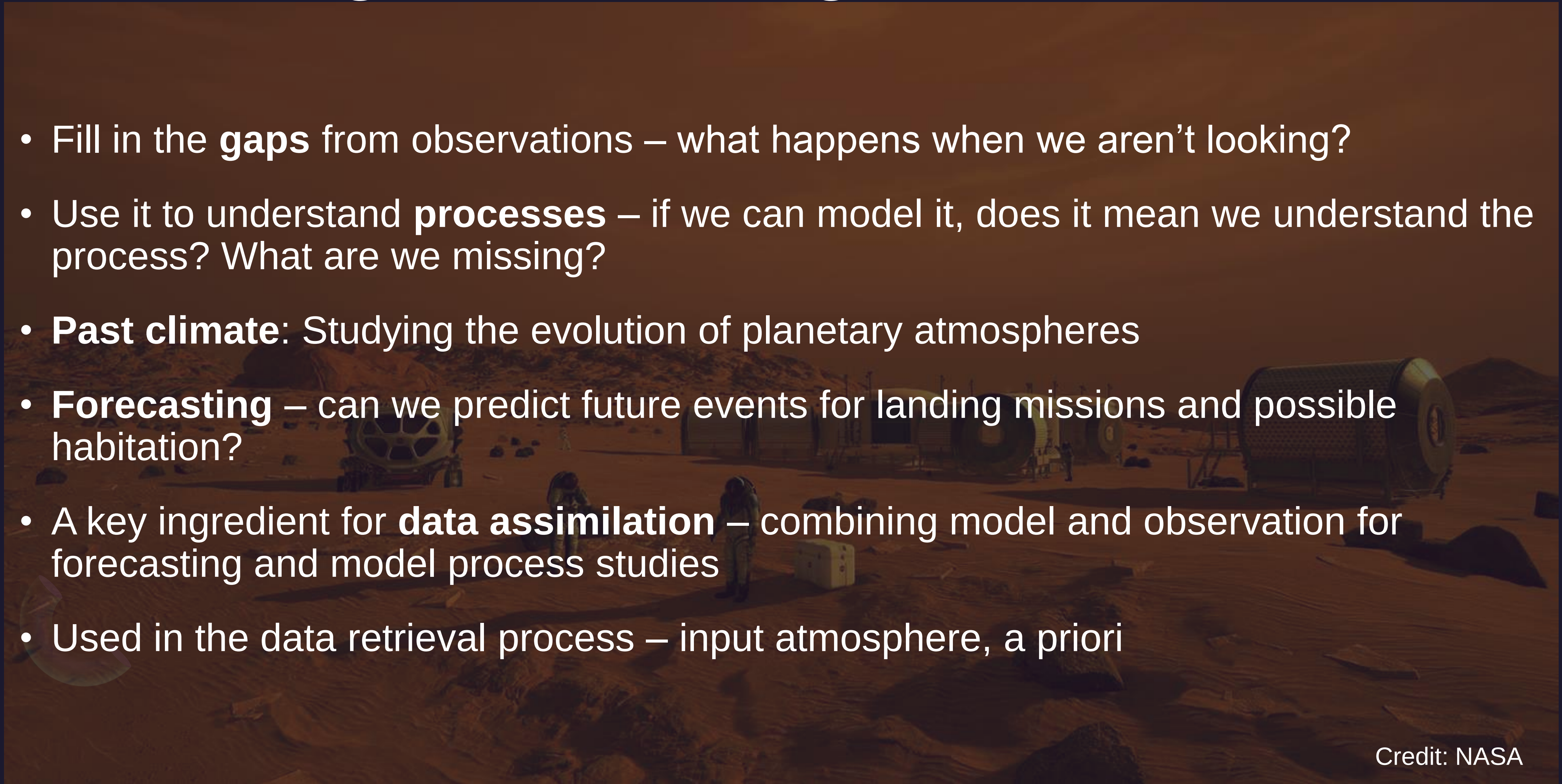
Part I:
Modelling

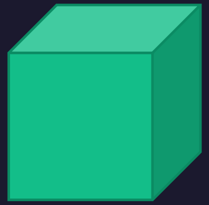
Modelling: What is it good for?

- Fill in the **gaps** from observations – what happens when we aren't looking?
- Use it to understand **processes** – if we can model it, does it mean we understand the process? What are we missing?
- **Past climate**: Studying the evolution of planetary atmospheres
- **Forecasting** – can we predict future events for landing missions and possible habitation?
- A key ingredient for **data assimilation** – combining model and observation for forecasting and model process studies
- Used in the data retrieval process – input atmosphere, a priori

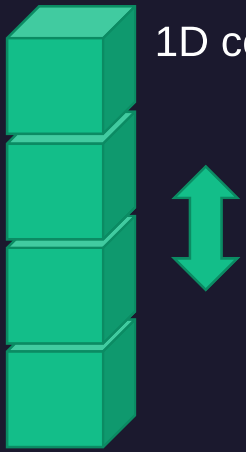


Credit: NASA

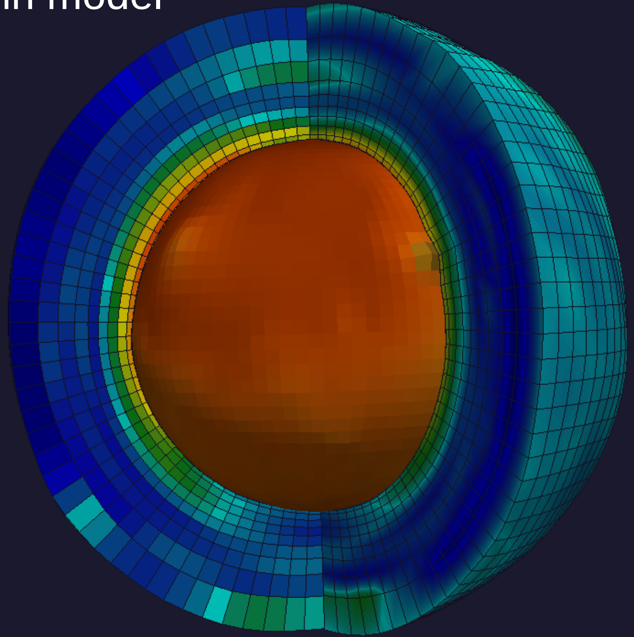
Types of Atmospheric Models



Box model -
one point
varying in time

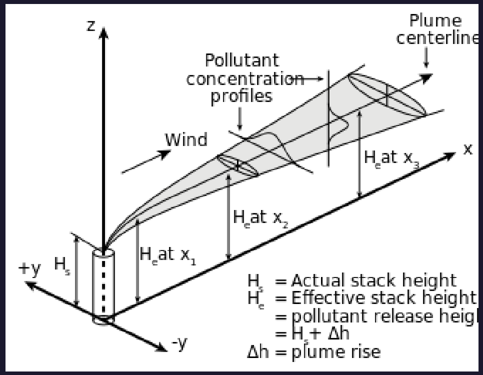


1D column model

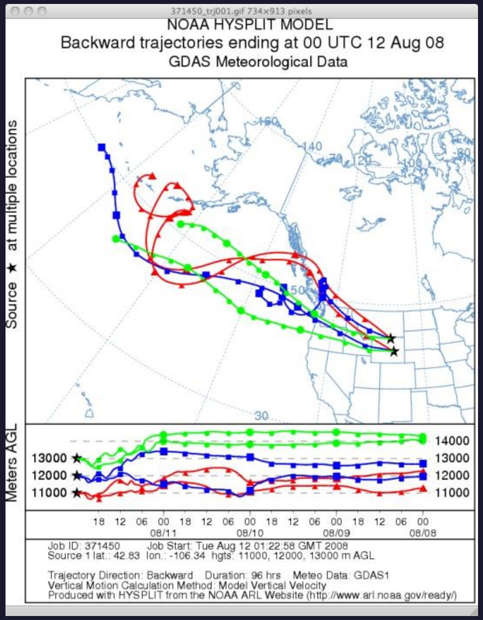


3D Numerical Weather Prediction (NWP),
Global Climate Model (GCM),
Chemistry Transport Model (CTM) (100's of km)

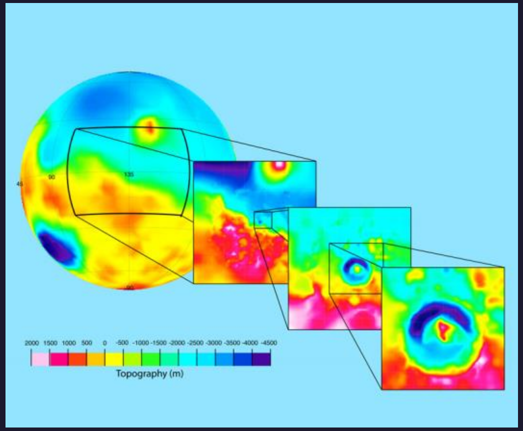
Plume or dispersion model

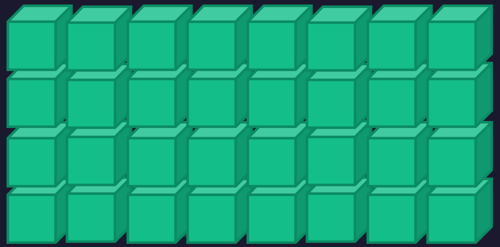


Trajectory model

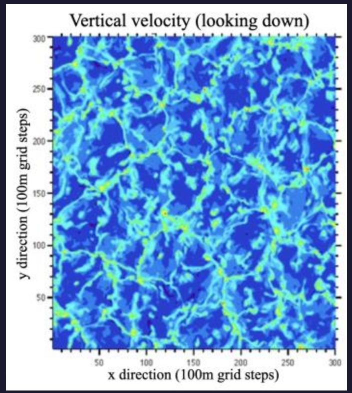


Regional scale, mesoscale, limited area model (10's of km)





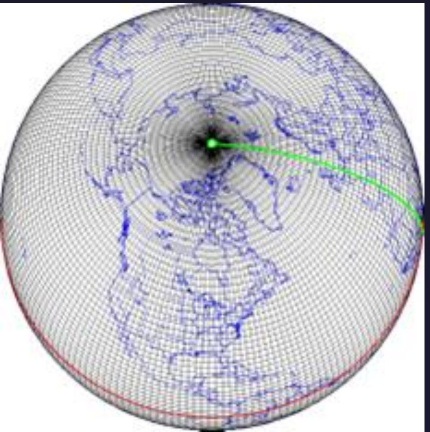
2D (latitude-pressure) statistical-dynamical model

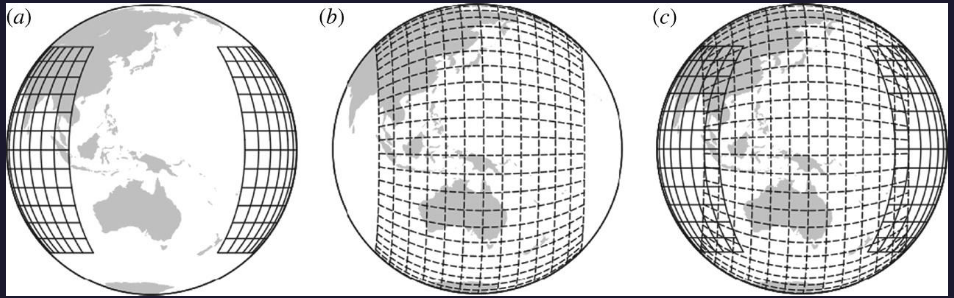


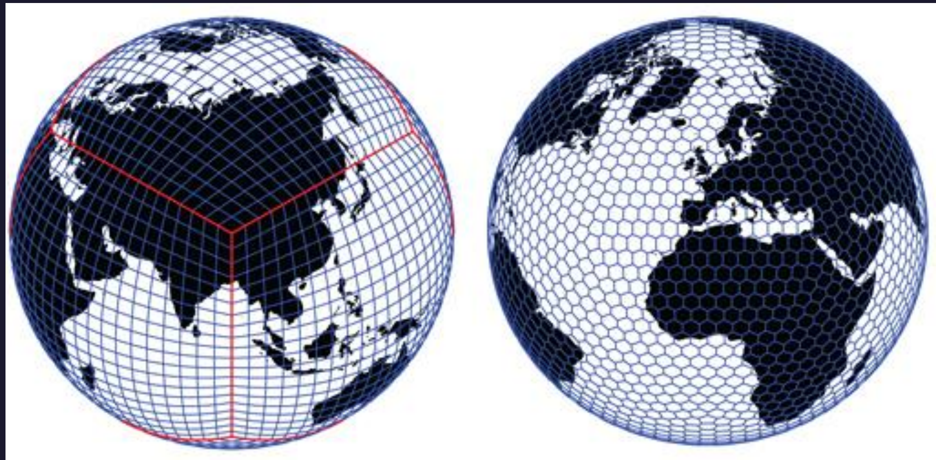
Large eddy simulations, on the order of metres

The Basic Ingredients
Part 1: The dynamical core

- To calculate large scale atmospheric motions, solves the fluid dynamics equations
- Computes wind, temperature tendency due to advection, pressure, transport of trace species
- Different methods to discretize the domain and formulate the equations (e.g. finite difference/element/volume, semi-Lagrangian, spectral)

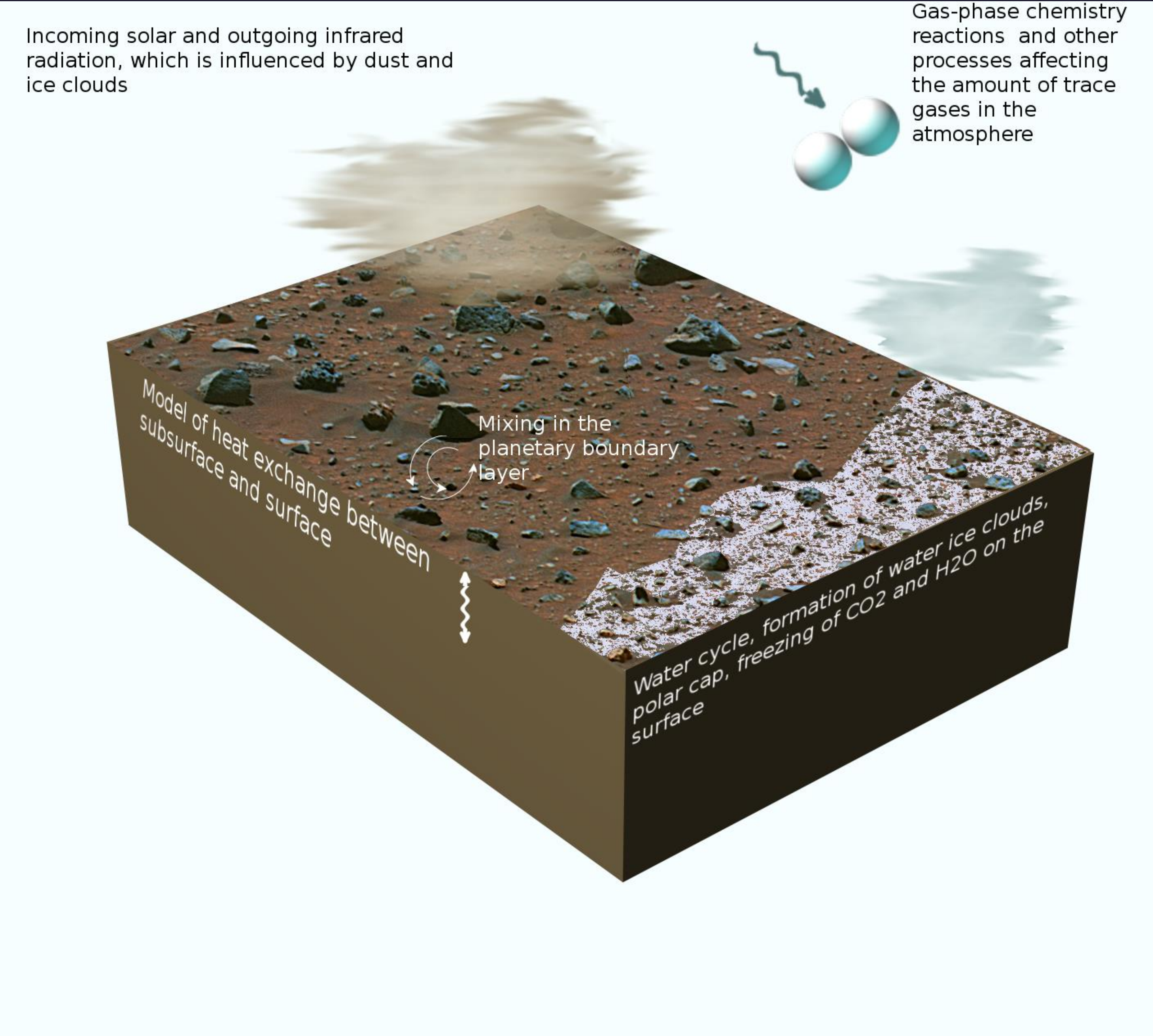






The Basic Ingredients
Part 2: The physical parameterisations

- **Local details that will force the large scale**
  - Radiative heating and cooling of the atmosphere
  - Dust lifting from the surface, mixing in the atmosphere
  - Planetary boundary layer, turbulence, low level drag and blocking, gravity wave drag
  - Surface and subsurface thermal balance, surface atmosphere exchange
  - CO_2 and H_2O condensation/sublimation
  - Cloud formation



Mars GCMs around the world

USA:

- NASA Ames Research Center
- NASA GFDL
- NCAR/NOAA PlanetWRF (MarsWRF)
- NASA GSFC/GISS ROCKE-3D GCM
- Ashima/MIT Mars GCM
- U. Michigan MTGCM

EU/UK:

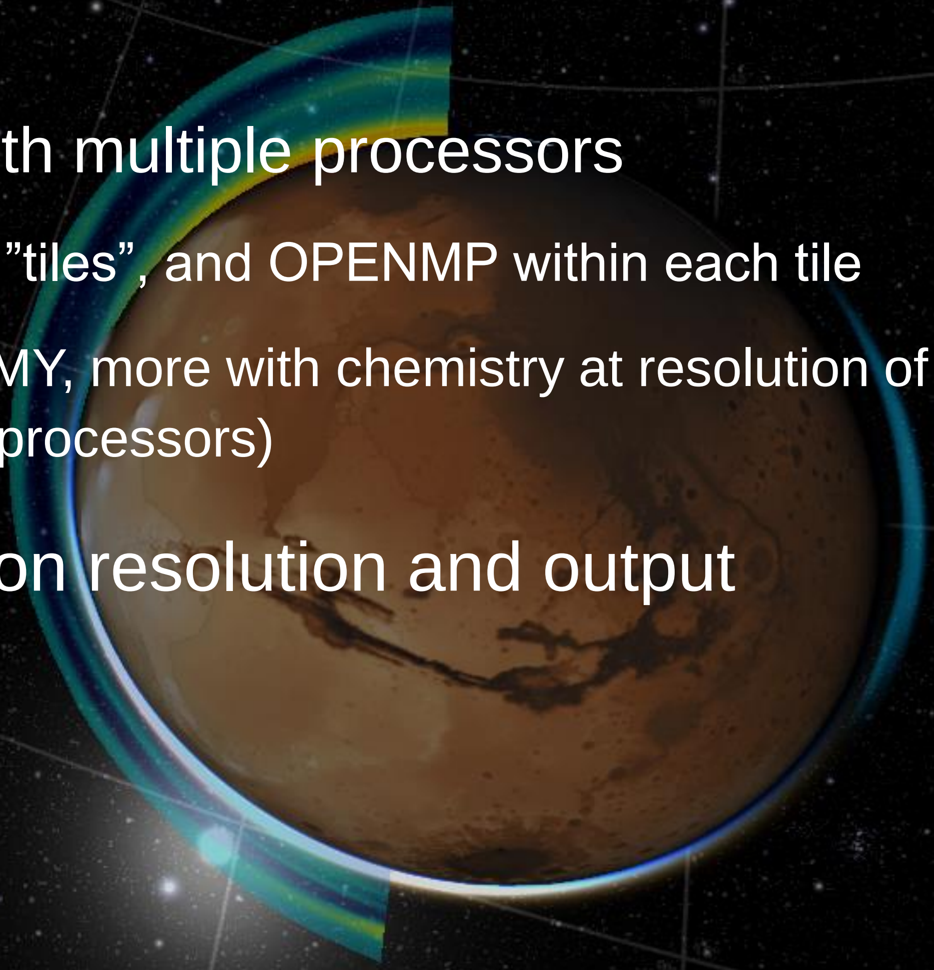
- LMD Planetary Climate Model (PCM)
- BIRA-IASB GEM-Mars
- Max Planck Institute (MAOAM-GCM)
- Oxford-LMD, Open University-LMD
- UK Met office Unified Model

Japan:

- DRAMATIC MGCM

Technical fun facts about GCMs

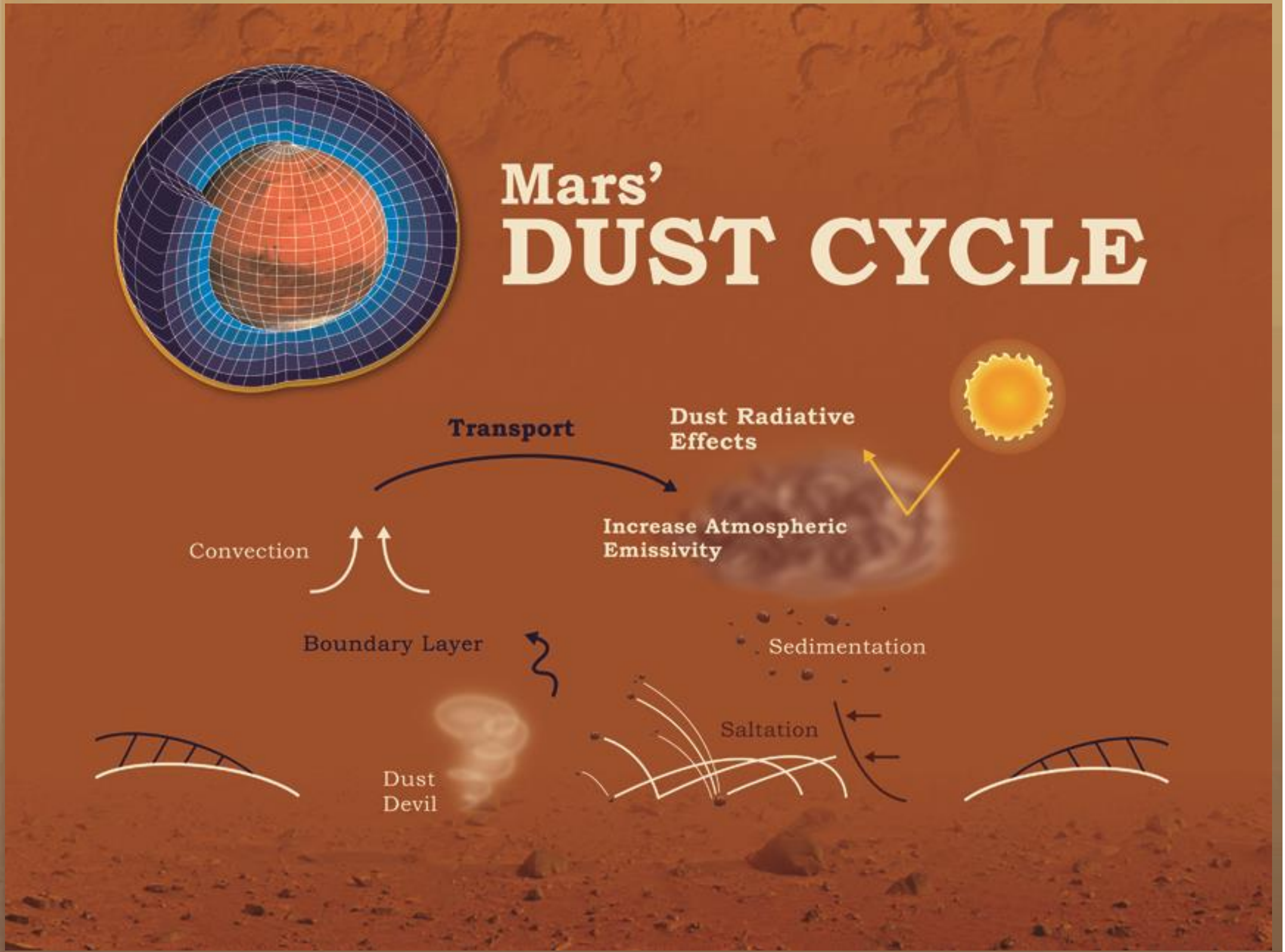
- Most GCMs are written in FORTRAN 😨
- Hopefully – they are fully parallelized to run with multiple processors
  - E.g. GEM-Mars uses MPI to divide the domain into ”tiles”, and OPENMP within each tile
  - GEM-Mars takes on the order of 24 hours to run 1 MY, more with chemistry at resolution of 4ºx4º and 103 vertical levels up to ~150 km (on 24 processors)
- Generates GBs to TBs of data depending on resolution and output frequency



Part II: Dust and its effects

Characteristics of dust in Martian atmosphere

- Main driver of the climate influencing temperature and therefore circulation
- Seasonal cycle with a dusty season at perihelion
- Interannual variability in the dusty season leading to occasional planet-encircling dust storms



https://www.nasa.gov/content/dust-cycle

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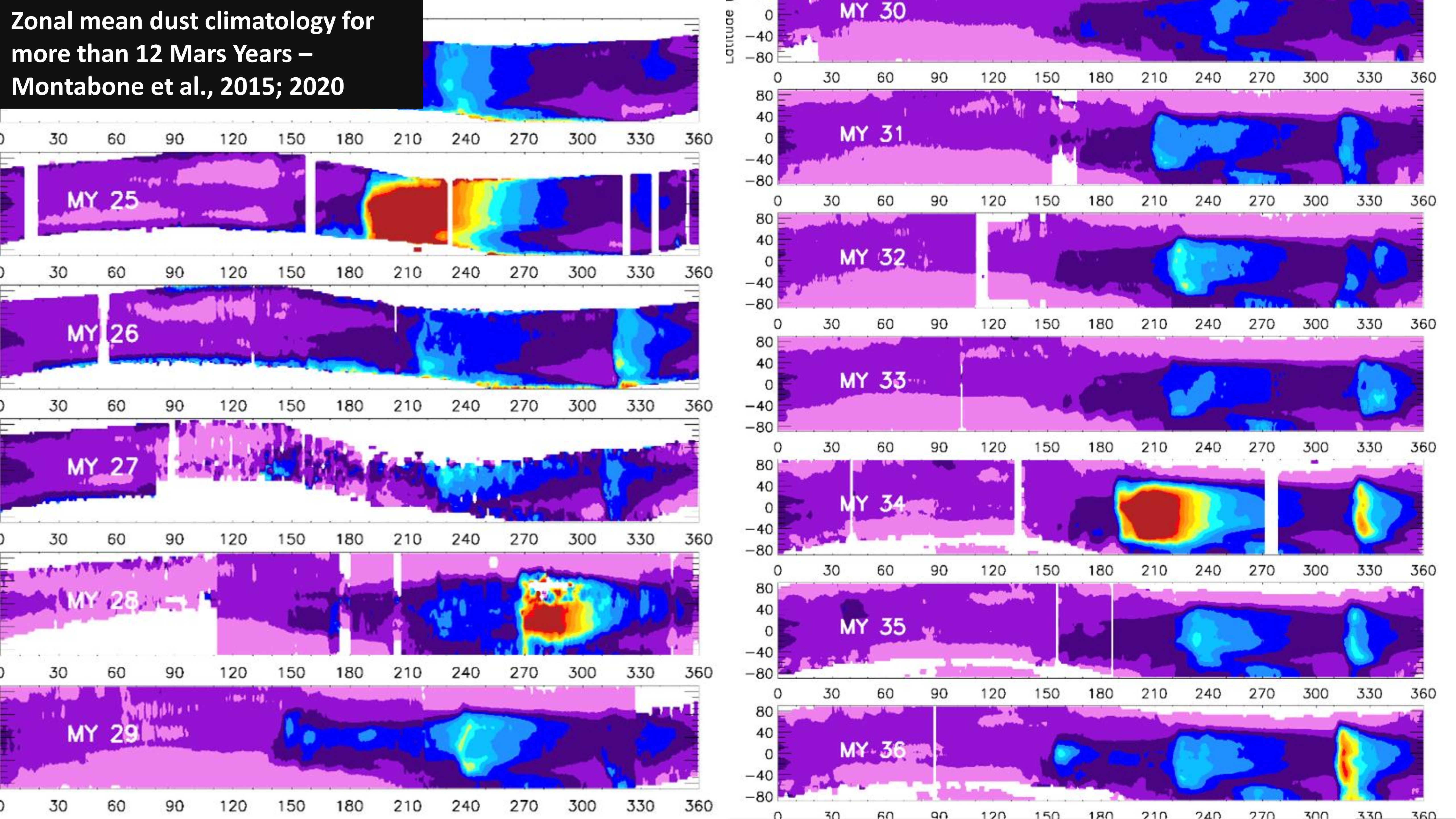
Zonal mean dust climatology for more than 12 Mars Years – Montabone et al., 2015; 2020



Dust in the atmosphere – how does it get there?

- 2 main processes:
  - Lifting due to surface wind stress (saltation and direct suspension)
  - Lifting by convective vortices or “dust devils”

- Other possible processes:
  - Charging or electrical effects
  - Thermal creep
  - CO_2 fountaining, meteoritic impacts

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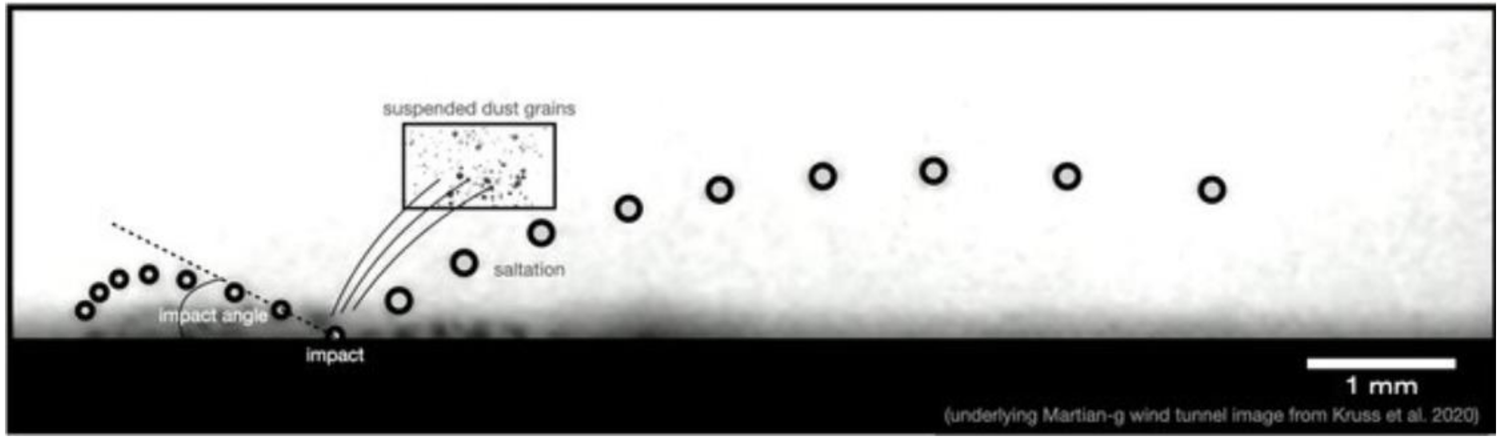
Dust in the atmosphere – the 2 main sources

- **Dust devils:** warm surface, cooler air – updraft – vertical circulation. Dominant source in 1st half of year.
- **Surface wind stress lifting:** when near-surface wind is higher than the threshold for sand-sized particles, **saltation** occurs, and smaller particles are suspended. Strongest impact in 2nd half of year.

NASA/JPL-Caltech/SSI

Becker et al., 2022



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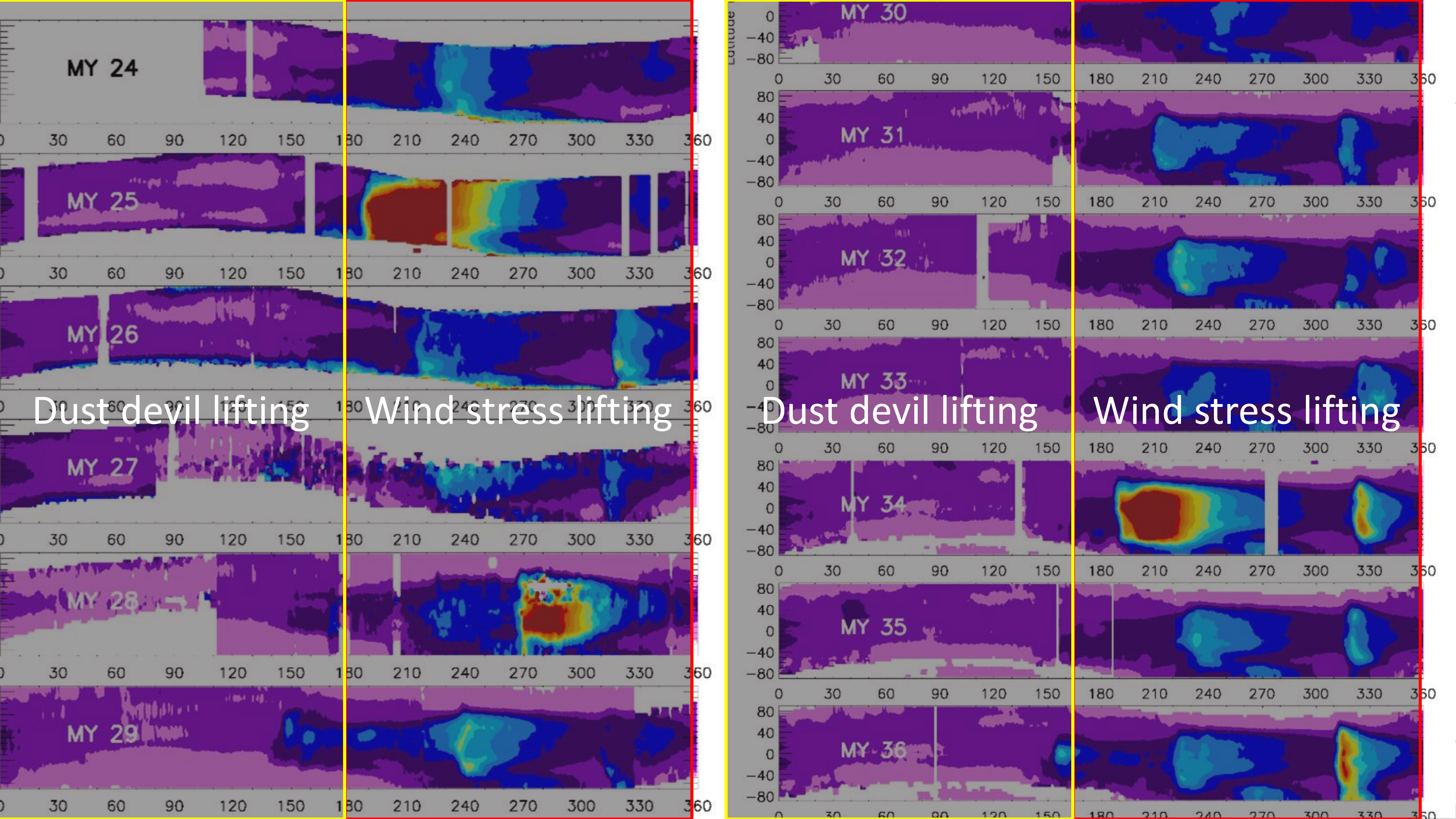
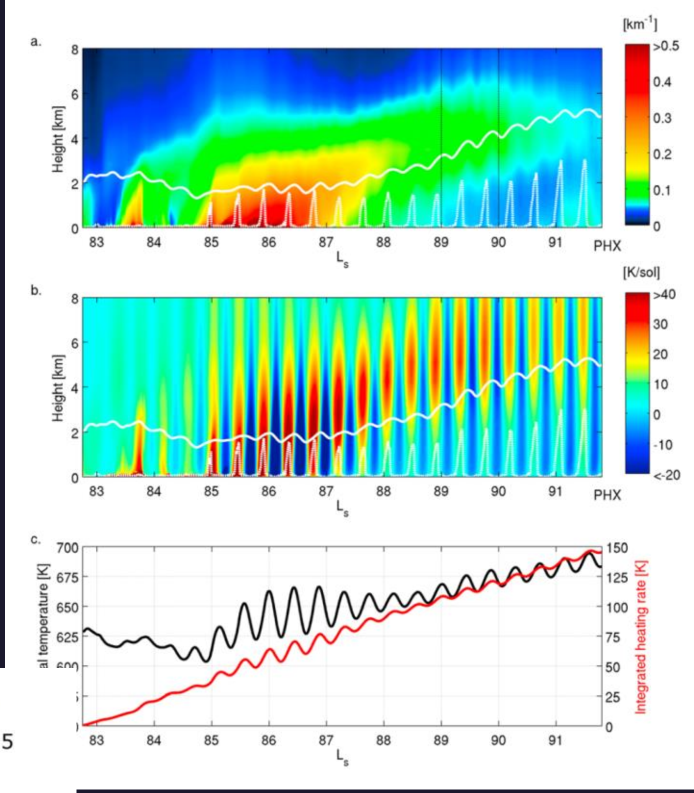
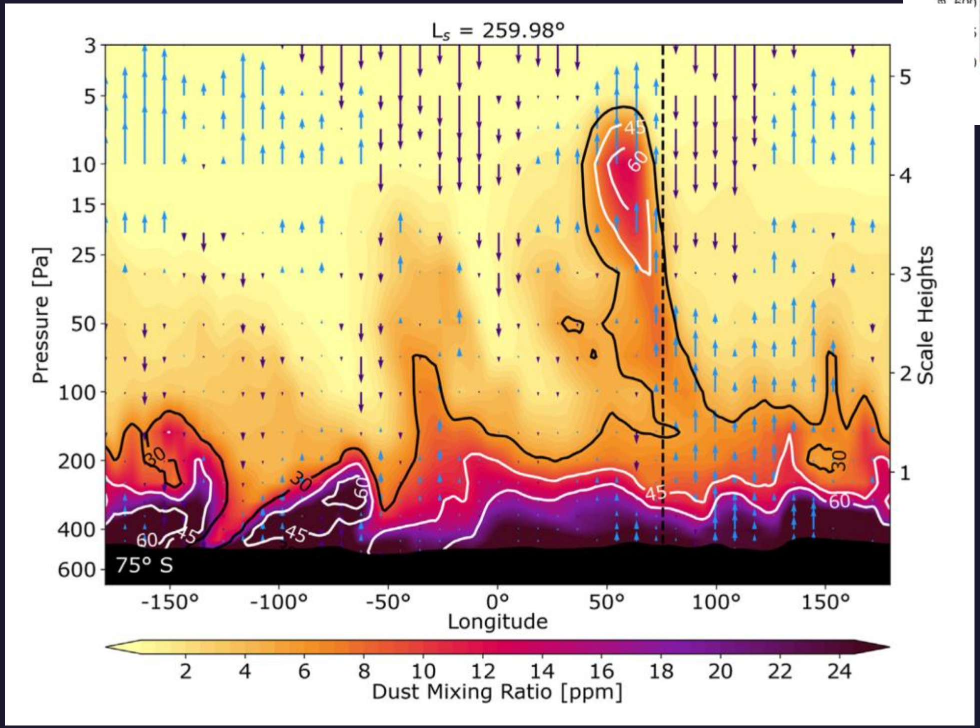

MY 24
MY 25
MY 26
MY 27
MY 28
MY 29
MY 30
MY 31
MY 32
MY 33
MY 34
MY 35
MY 36
Dust devil lifting
Wind stress lifting
Dust devil lifting
Wind stress lifting
0 30 60 90 120 150 180 210 240 270 300 330 360
80 40 0 −40 −80

Transport and movement of dust

- Advection (large scale winds)
- Turbulent eddy diffusion (smaller scale mixing in the vertical)
- Radiative-dynamic feedbacks (convection, plumes, solar escalator effect)
- Gravitational sedimentation

Daerden et al., 2015





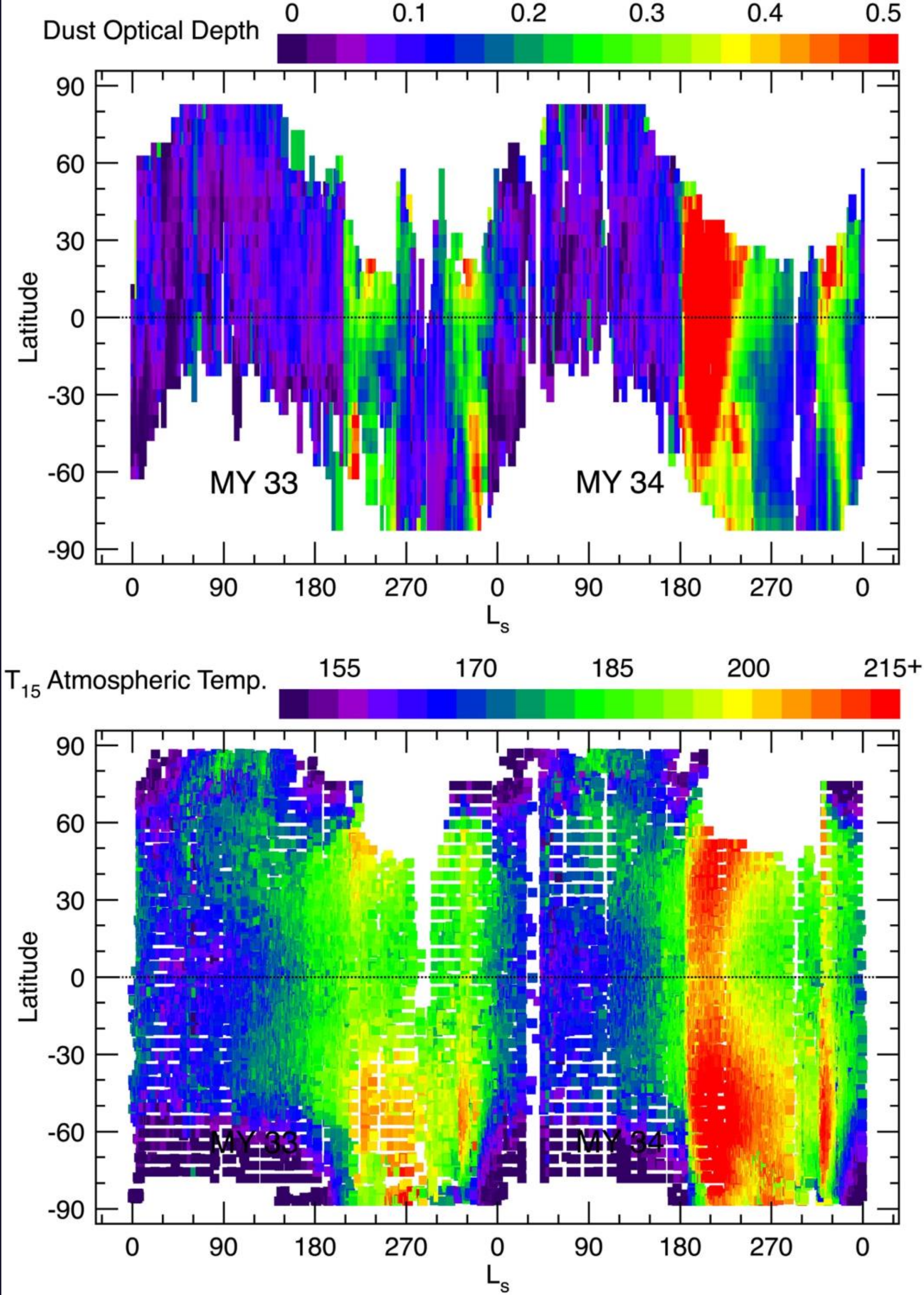
Batterson et al., 2023

How dust affects the atmosphere (as seen by observations)

Temperature

Smith, 2019 Figure 6

2 years of THEMIS observations of dust optical depth and atmospheric temperature (at ~0.5 hPa)



How dust affects the atmosphere (as seen by observations)

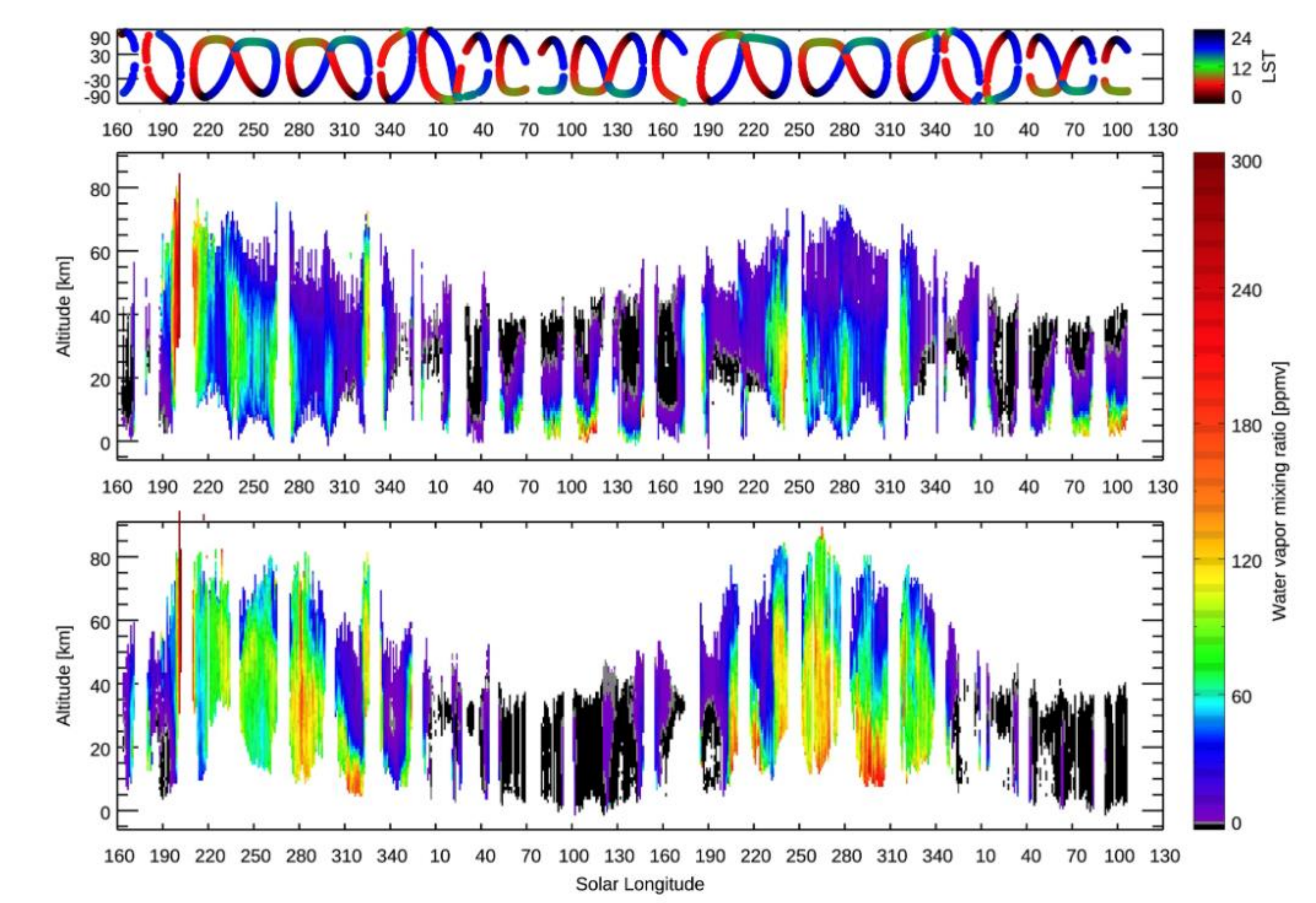
Water Vapour

Aoki et al., 2022 Figure 3

Water vapour profiles from L_s = 160 in MY34 to L_s = 130 in MY 36

Northern Hemisphere

Southern Hemisphere

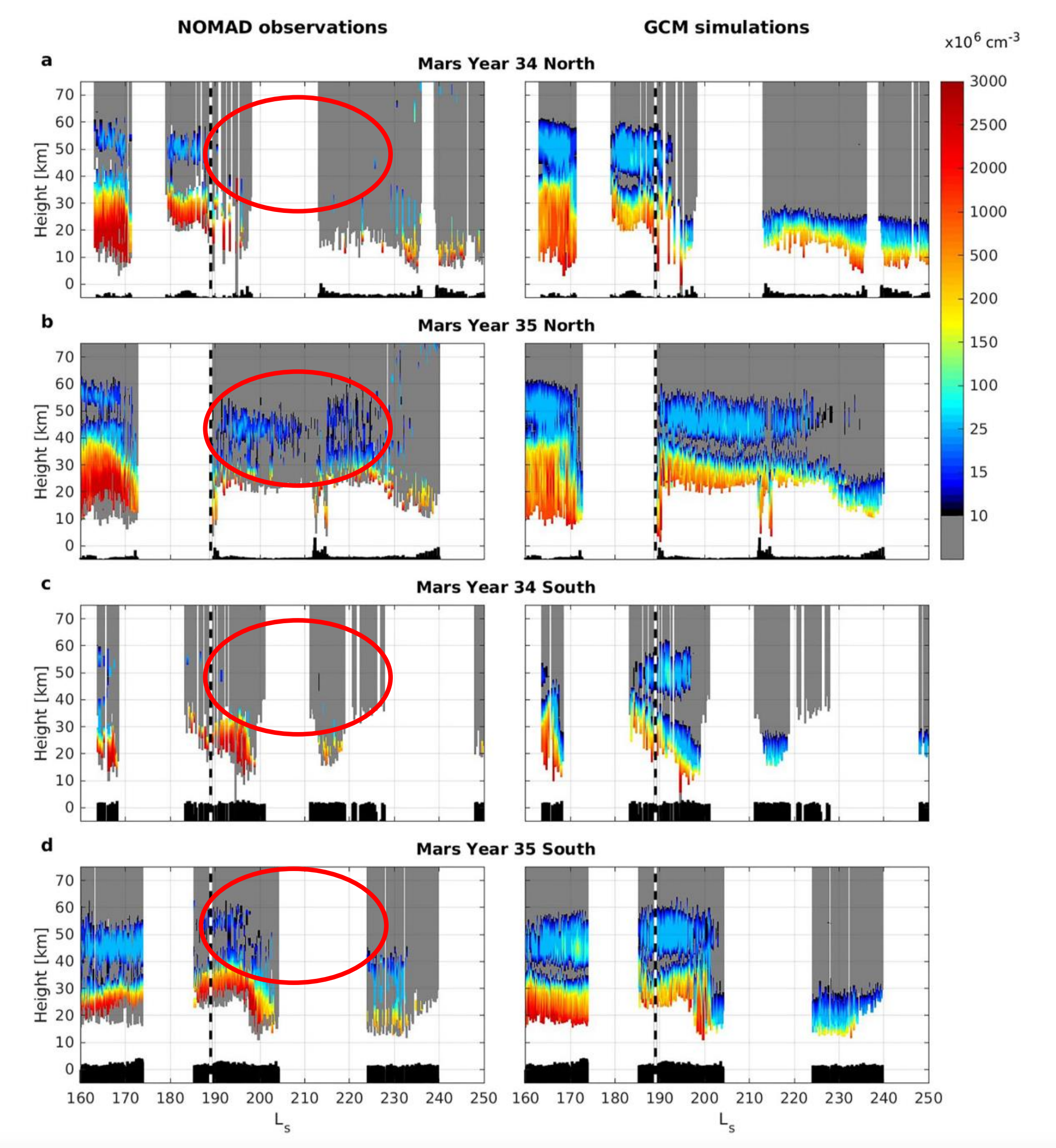


How dust affects the atmosphere (as seen by observations)

Impact of 2018 (MY34) global dust storm on O_3

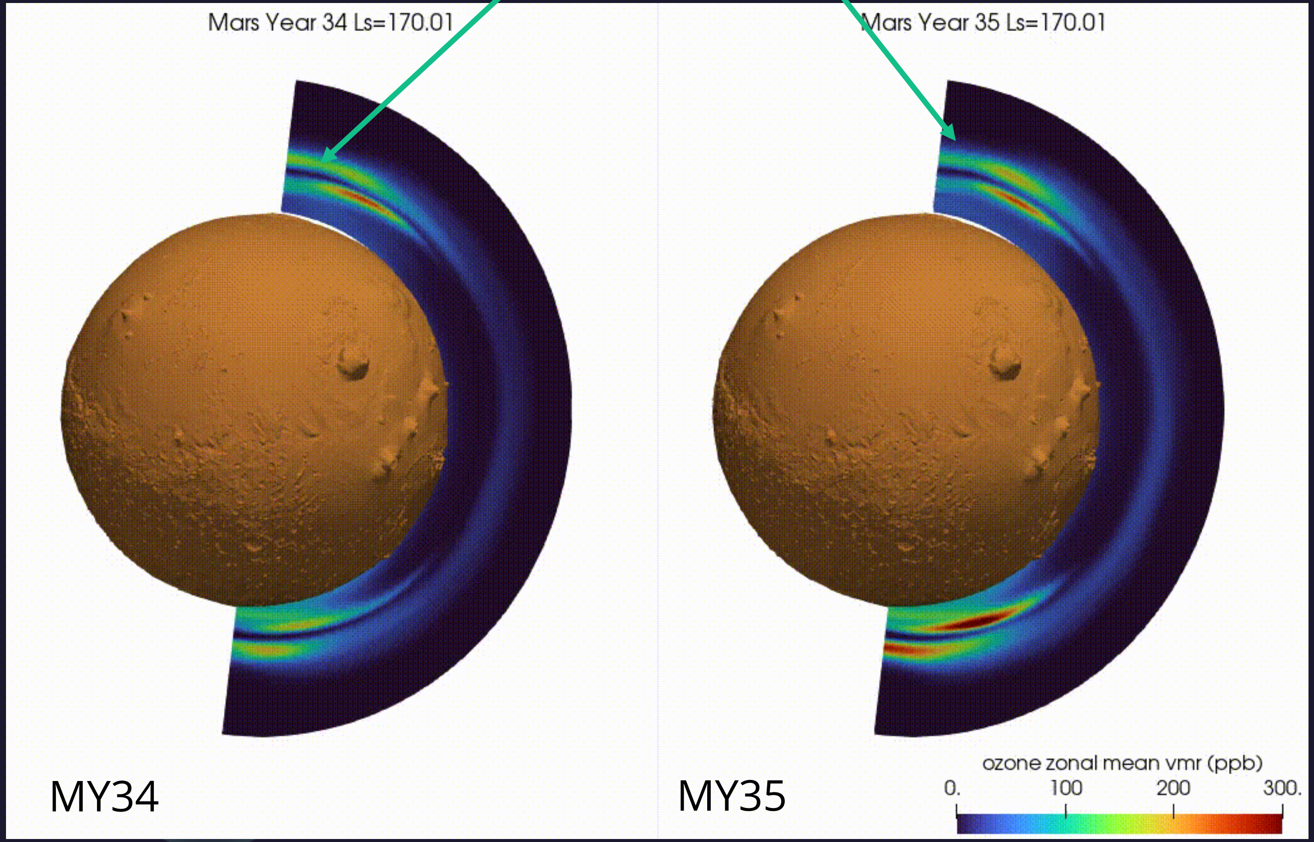
- ExoMars TGO/NOMAD observed a significant drop in O_3 in MY34 at the start of the dust storm compared to one year later with no dust storm

- The model confirms middle atmospheric O_3 decrease in the dust storm and predicts increased photochemical production of hydrogen



Impact of 2018 (MY34) global dust storm on O_3

O_3 depletion in dust storm



H_2O

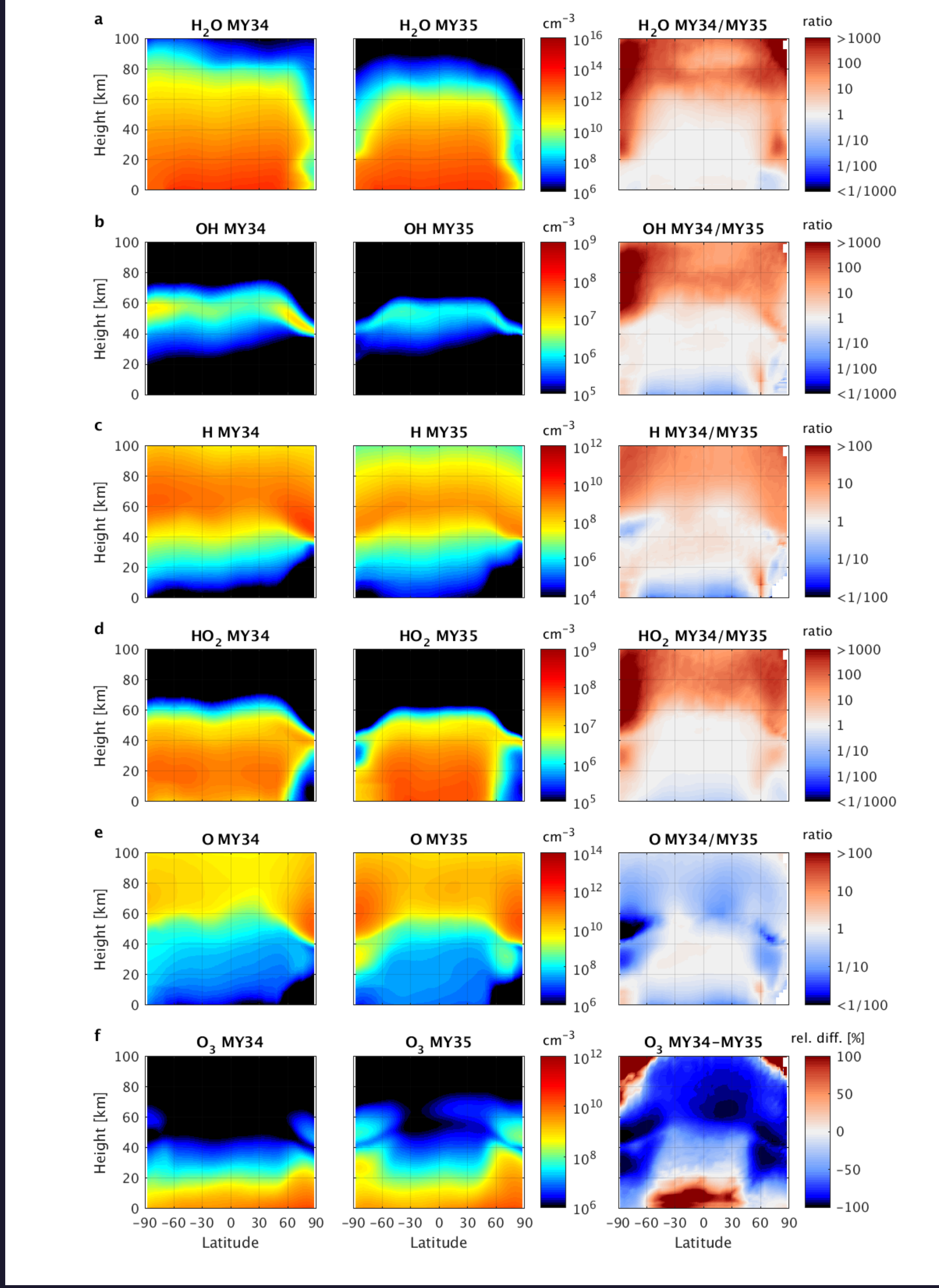
OH

H

HO_2

O

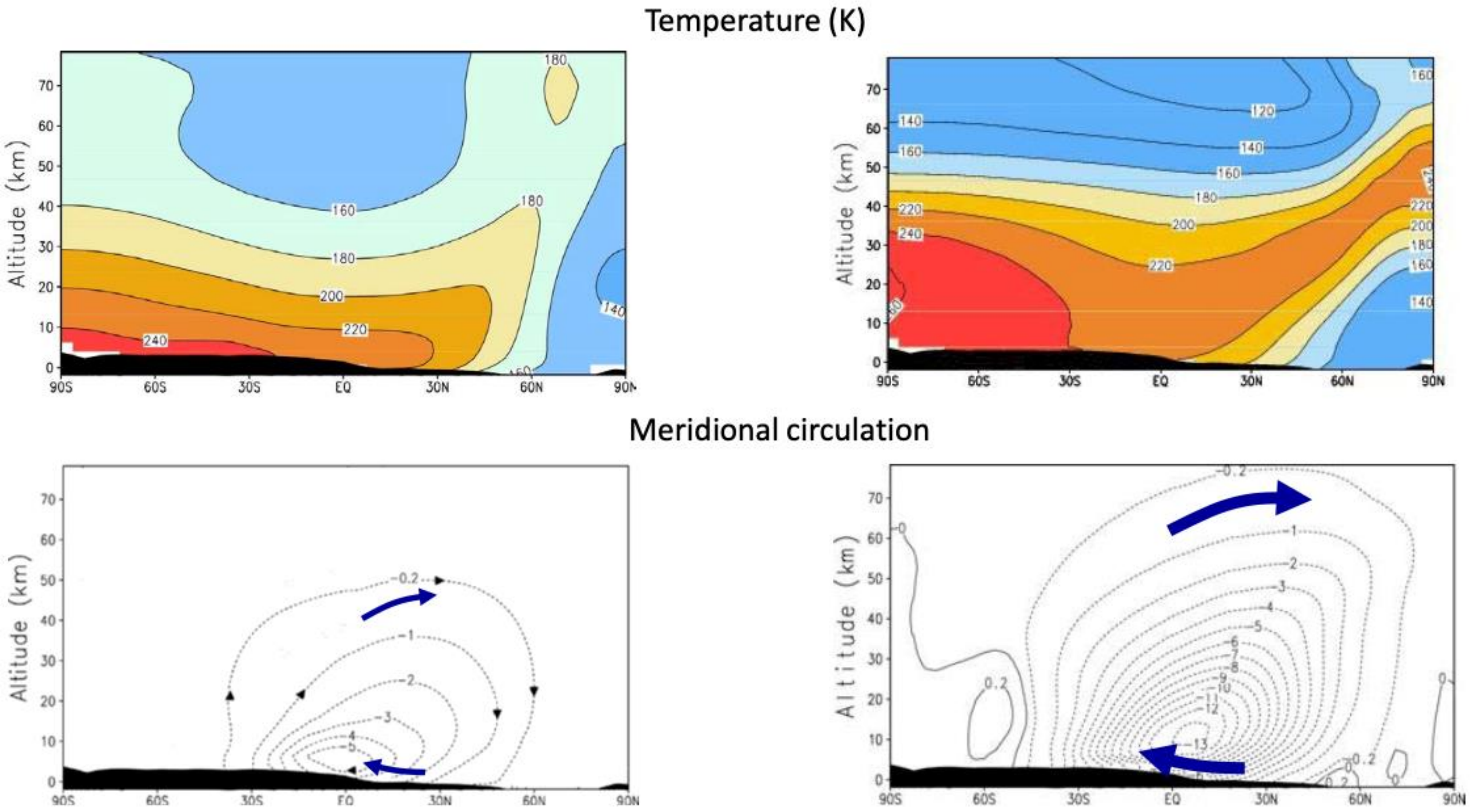
O_3



MY34 MY35 MY34/MY35

Animation can be found at http://gem-mars.aeronomie.be

Impact of dust on temperature and winds (in a GCM)



Clear atmosphere

Dusty atmosphere

Strong feedback – more dust, warmer temperatures, stronger circulation.

Stronger surface winds causes more lifting, more dust in the atmosphere.

Credit: F. Forget Mars V Workshop

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Part III: Dust in the GCM

Modelling dust in the GCM

We need:

- Dust lifting scheme (usually saltation and dust devils)
- Transport of dust (dynamical core) + smaller scale turbulent mixing, dry convective processes, sedimentation
- Radiative properties of dust for the calculation of heating/cooling

---- with just these, one can get a repeatable dust season ----

- Most GCMs scale the column dust opacity to a climatology (Montabone et al. provides daily maps) to study a particular year.

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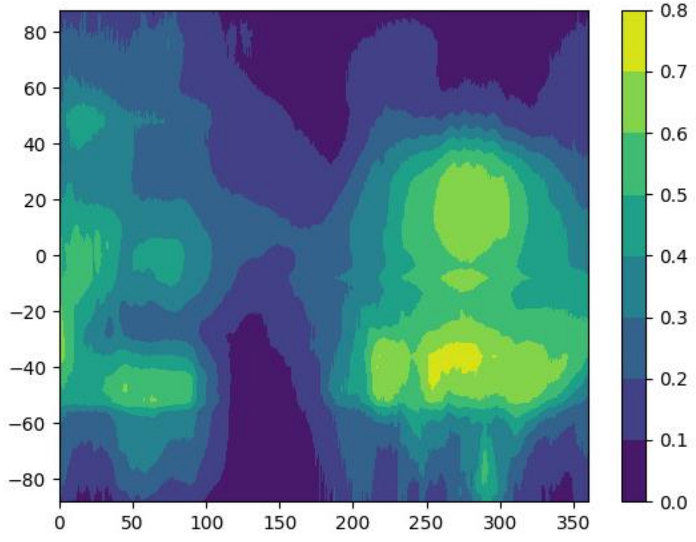
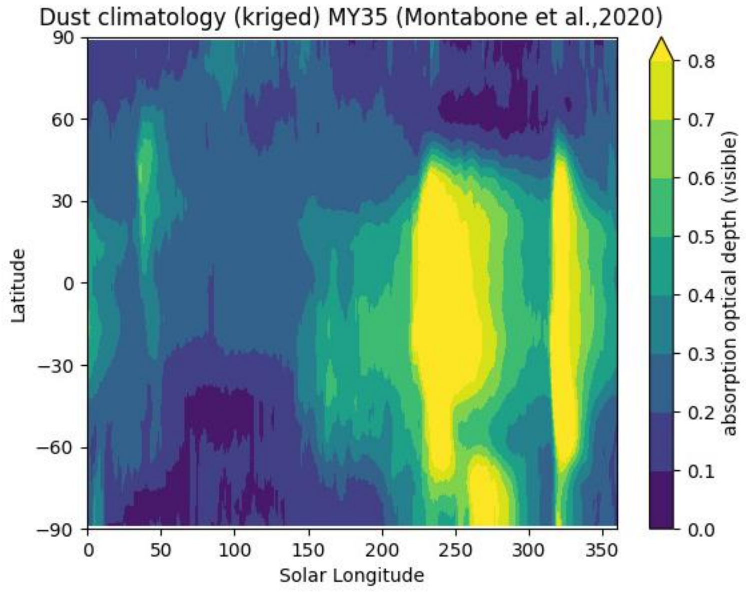
Zonal mean dust opacity “free” dust vs climatology



GEM-Mars “free” dust – same year after year



Climatology for MY35

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Dust lifting due to saltation (at least in GEM-Mars…)

Dust mass flux (kg/m²/s) based on Kahre et al., 2006:

$$F_w = G_p(2.3 \cdot 10^{-3})\alpha\tau^2\left(\frac{\tau - \tau^*}{\tau^*}\right)$$

Modelled surface wind stress using roughness length, temperature, winds

"proportionality factor" 😂 tuned to observations

Gustiness probability function (Newman et al., 2002)

$$G_p = (k/u^*)((u_g/u^*)^{k-1})e^{-(u_g/u^*)^k}$$

$u^* = \sqrt{\tau/\rho}$, k=2.5, u_g=0.1

Threshold wind stress

$$\tau^* = \eta dv_g/dz$$

Dynamic viscosity of CO_2 (depends on T)

Gas flow height profile from Musiolik et al., 2018 (Parabolic flight data)

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Dust lifting due to dust devils (again, in GEM-Mars)

Dust mass flux (kg/m²/s): $F_D = \alpha_D F_s(1-b)$

Tuneable efficiency parameter = 1e-9 kg/J

Vertical sensible heat flux (W/m²)

$$b = \frac{(p_s{}^{\chi+1} - p_t{}^{\chi+1})}{(p_s - p_t)(\chi+1)p_s{}^{\chi}}$$

p_s = surface pressure
p_t = pressure at top of PBL
X = spec. gas const/spec heat capacity

Dust fluxes are applied to the dust mixing ratios for 3 size bins (0.1, 1.5 and 10 µm)

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Sedimentation

Size dependent Stokes settling velocity (V) with Cunningham slip-flow correction (Jacobson, 2005):

$$V = \frac{2{r_p}^2(\rho_p - \rho_a)g}{9\eta}(1 + Kn[1.246 + 0.42e^{-.87/Kn}])$$

Where r_p is particle size, ρ_p is particle density, ρ_a is air density, g is gravity, η is dynamic viscosity, and Kn is the Knudsen number.

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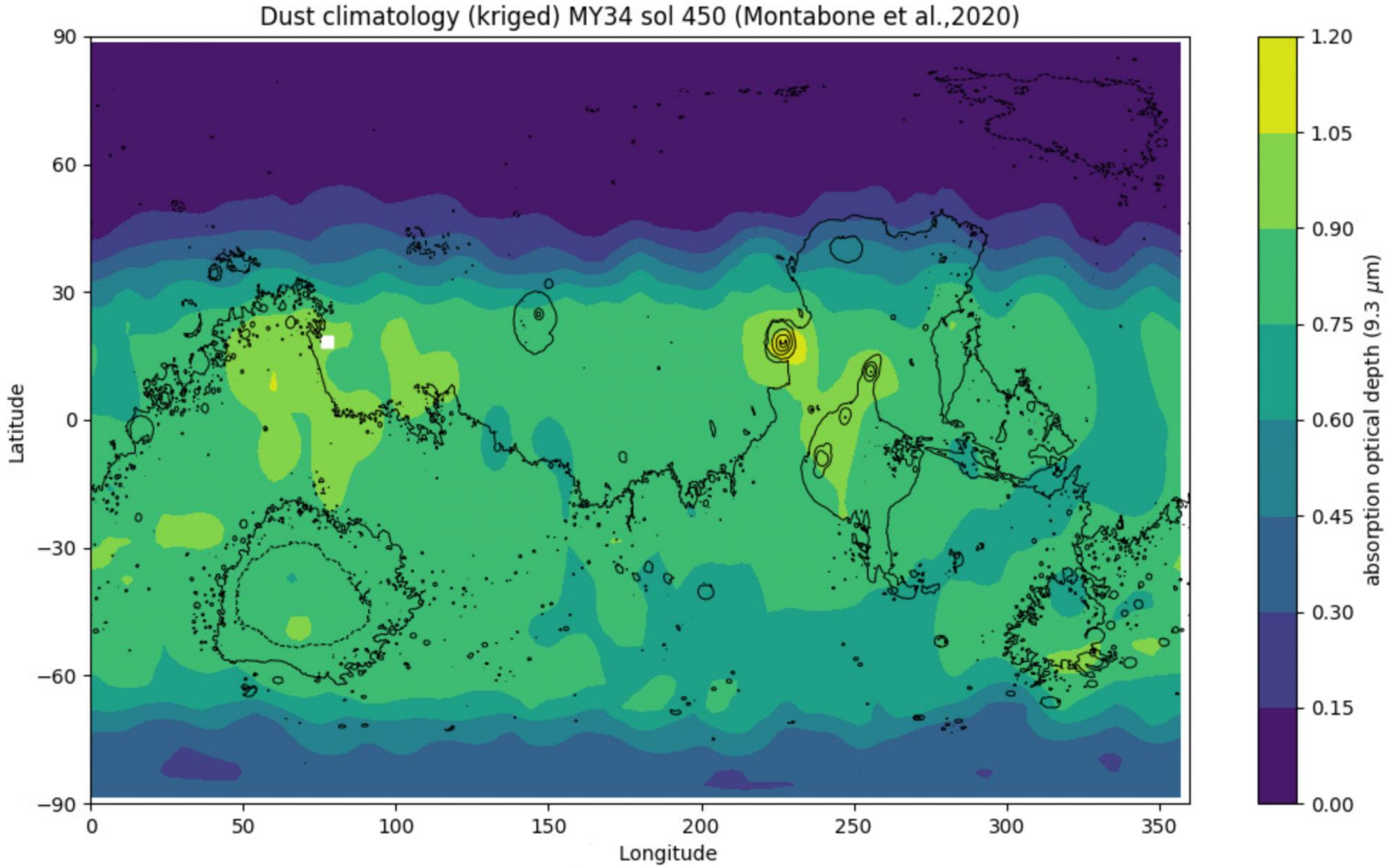
Scaling to climatology

- Dust climatology gives daily maps of column optical depth
  - Lift, transport – compare and scale
  - Or compare and lift to match
- But – climatology only gives information about the total column amount (not vertical profile)



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Vertical distribution of dust

Old school way: prescribe using Conrath parameter (see Montmessin et al. 2004), v = 0.007

$$q = q_o \exp\left\{ \nu \left[1 - \left(\frac{p_{ref}}{p_s} \right)^{70/z_{\max}} \right] \right\},$$

Depends on L_s and latitude

New way: let the model freely transport and mix the dust in the vertical…

… and keep adding new processes to try to match the observed profiles with limited success… (see part IV and Antoine's talk)

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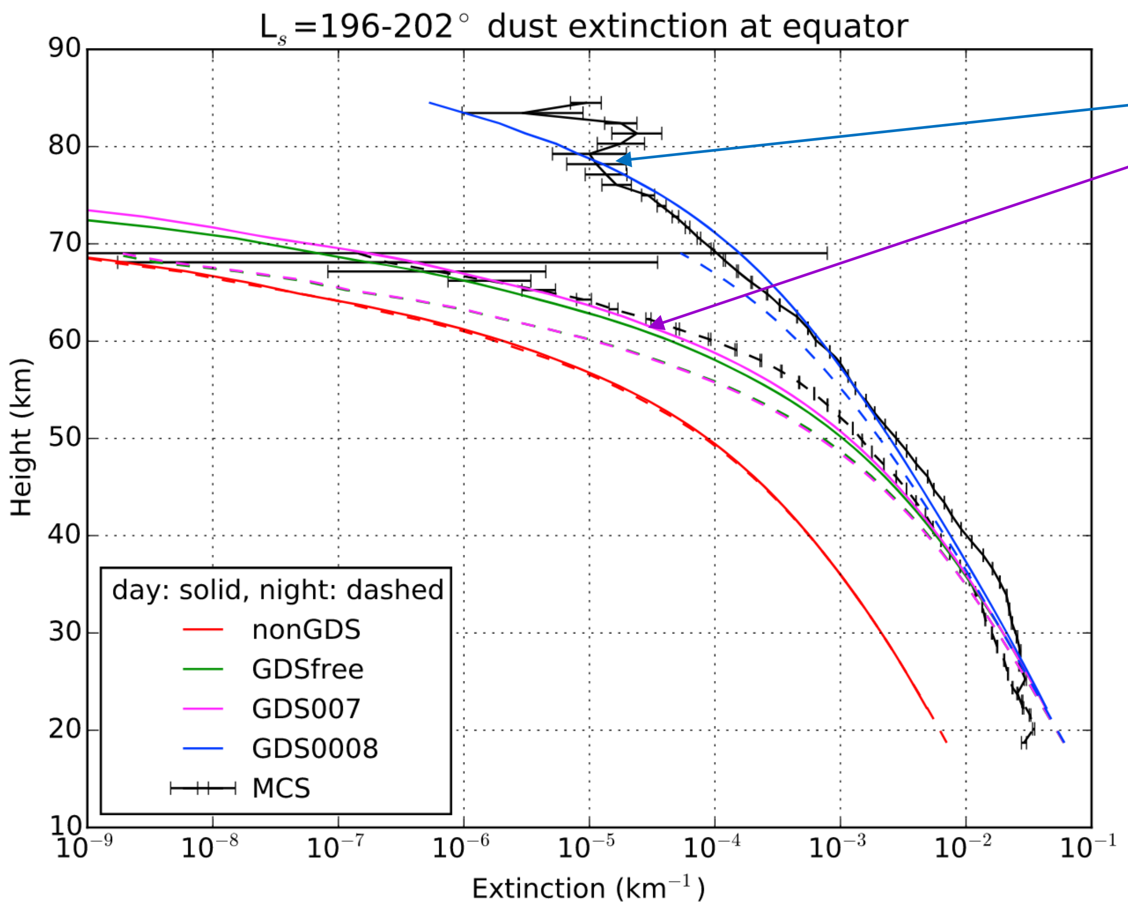
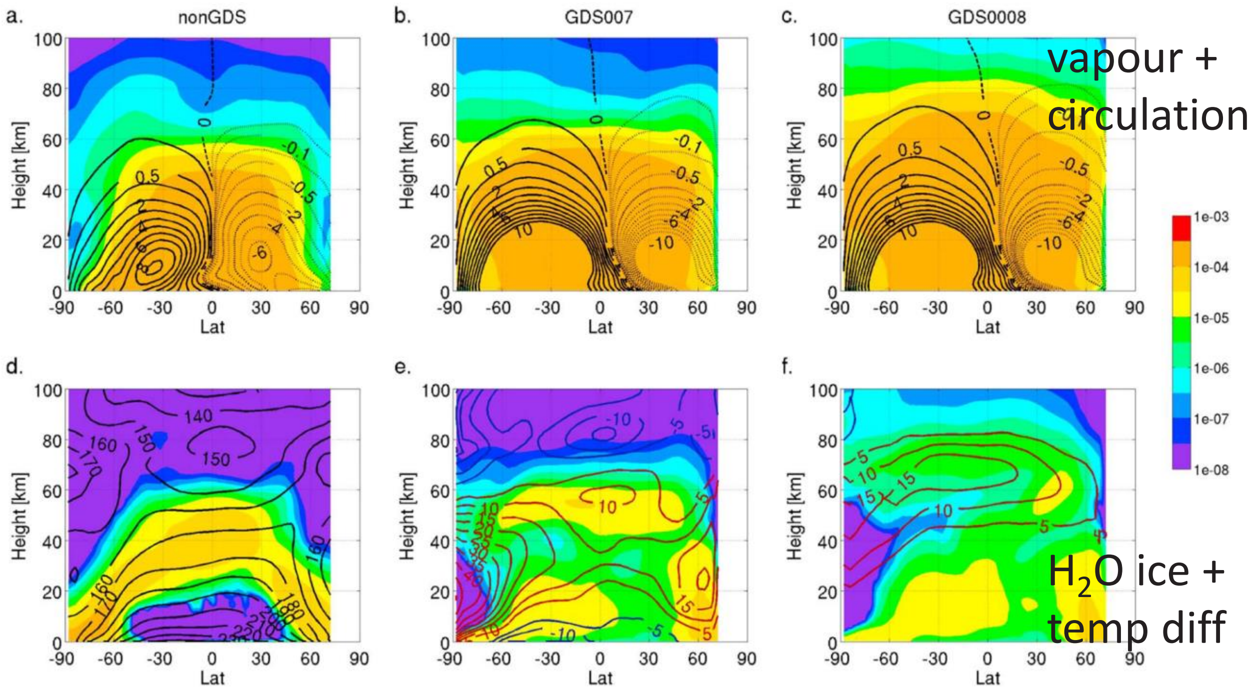
Why the vertical distribution is important

Modelling the MY34 dust storm

Strength of circulation not that different, but radiative effect is large





vapour + circulation

H_2O ice + temp diff

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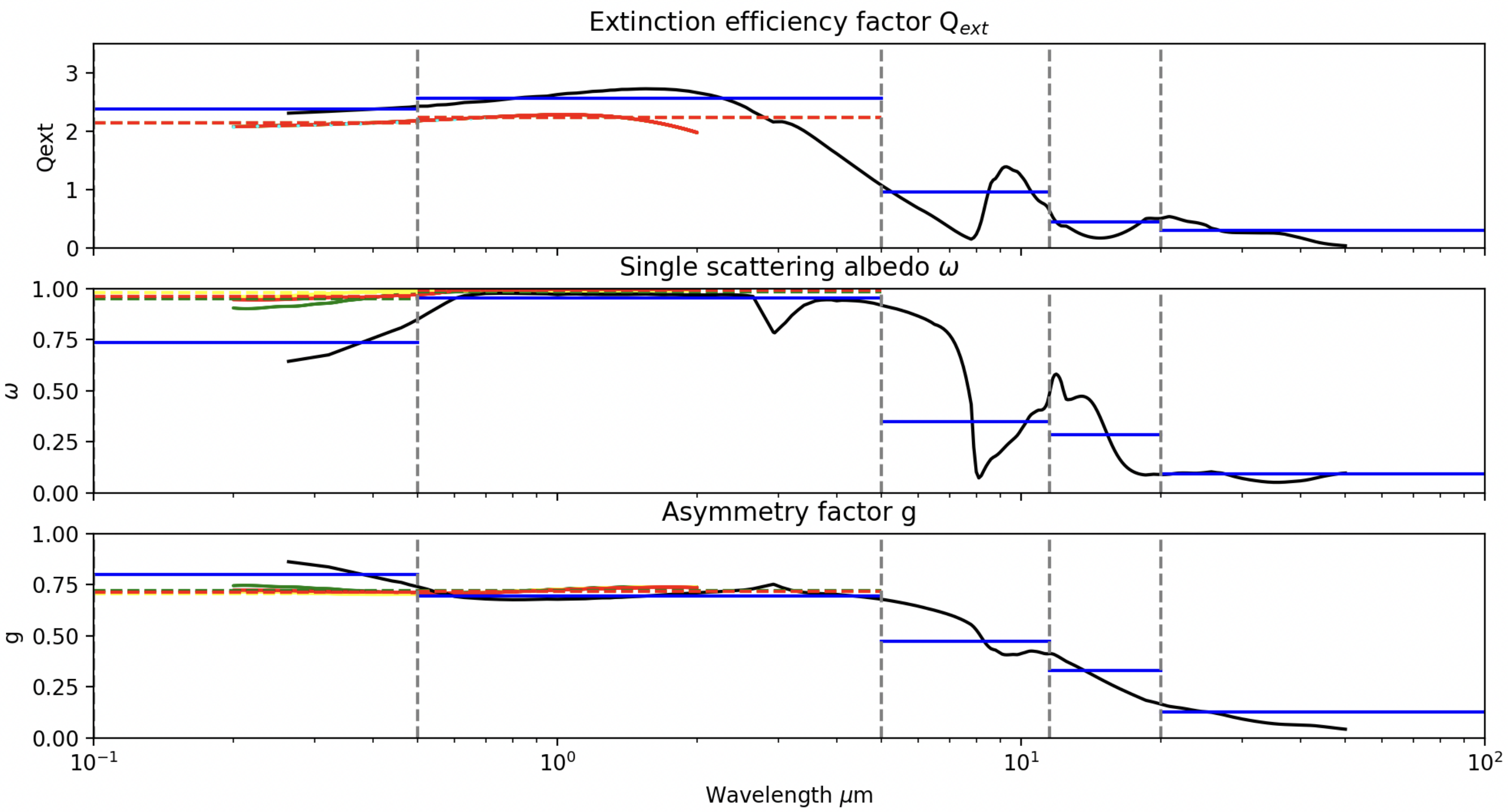
Radiative impacts

We use a two-stream method to compute the radiative effects of dust using 5 wavelength bins (2 in uv/vis, 3 in infrared).



We require:

- Extinction efficiency factor
- Single scattering albedo
- Asymmetry factor

What we get out: heating rates!

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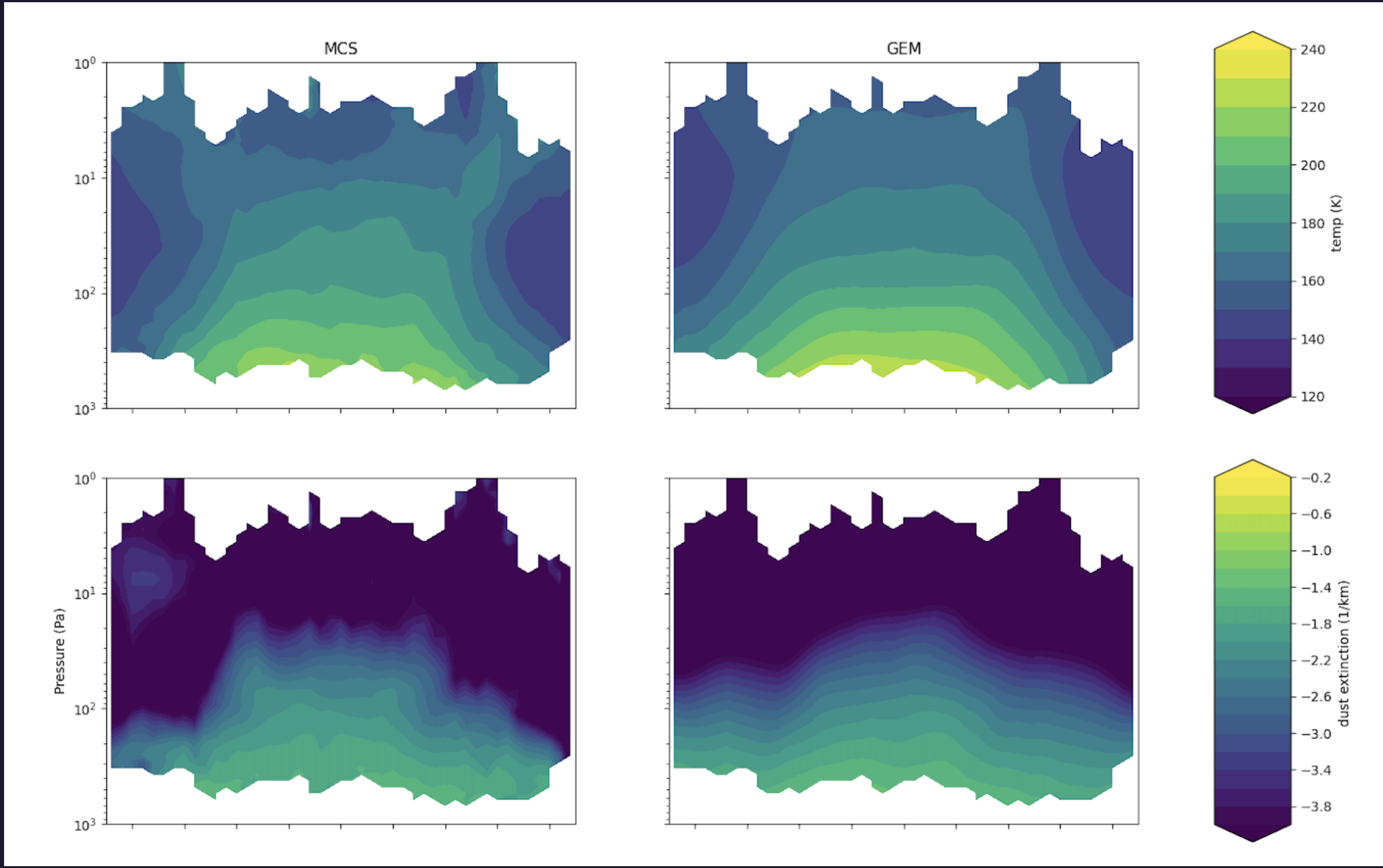
Putting it all together

L_s = 0, MY 35
Temperature (top)
Dust extinction (bottom)

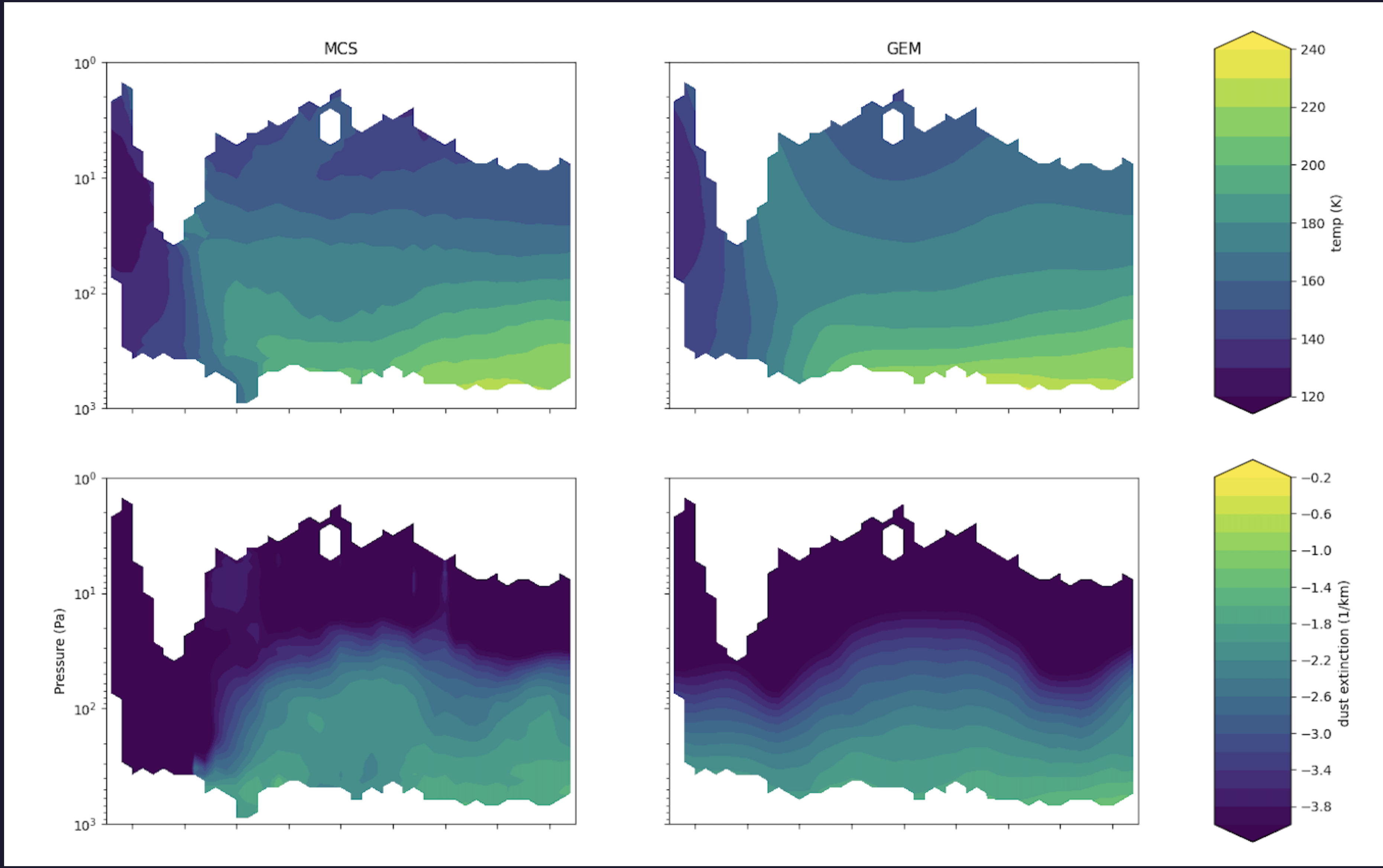
MCS (left), GEM-Mars (right)



Putting it all together

L_s = 90, MY 35
Temperature (top)
Dust extinction (bottom)

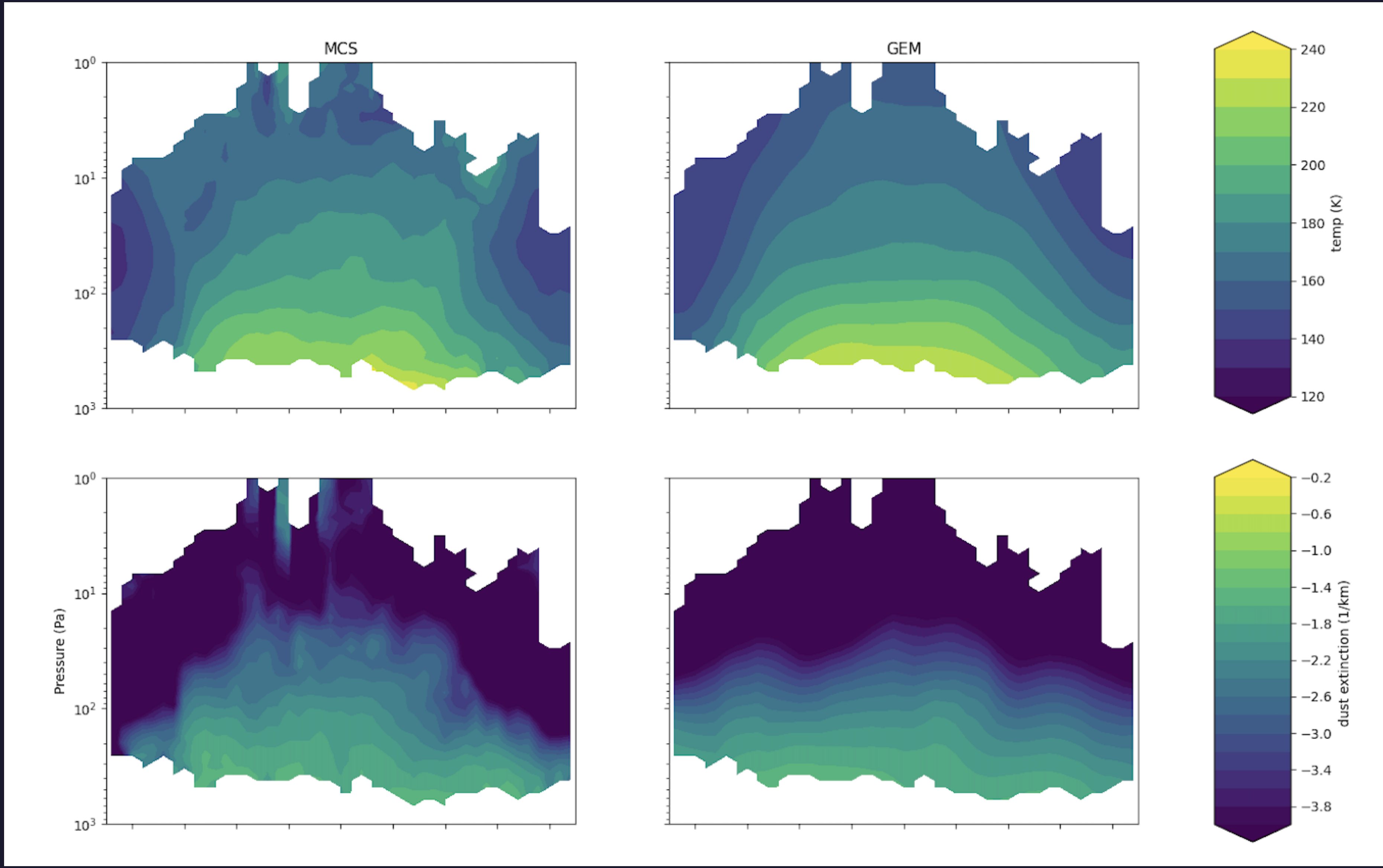
MCS (left), GEM-Mars (right)



Putting it all together

L_s =180, MY 35
Temperature (top)
Dust extinction (bottom)

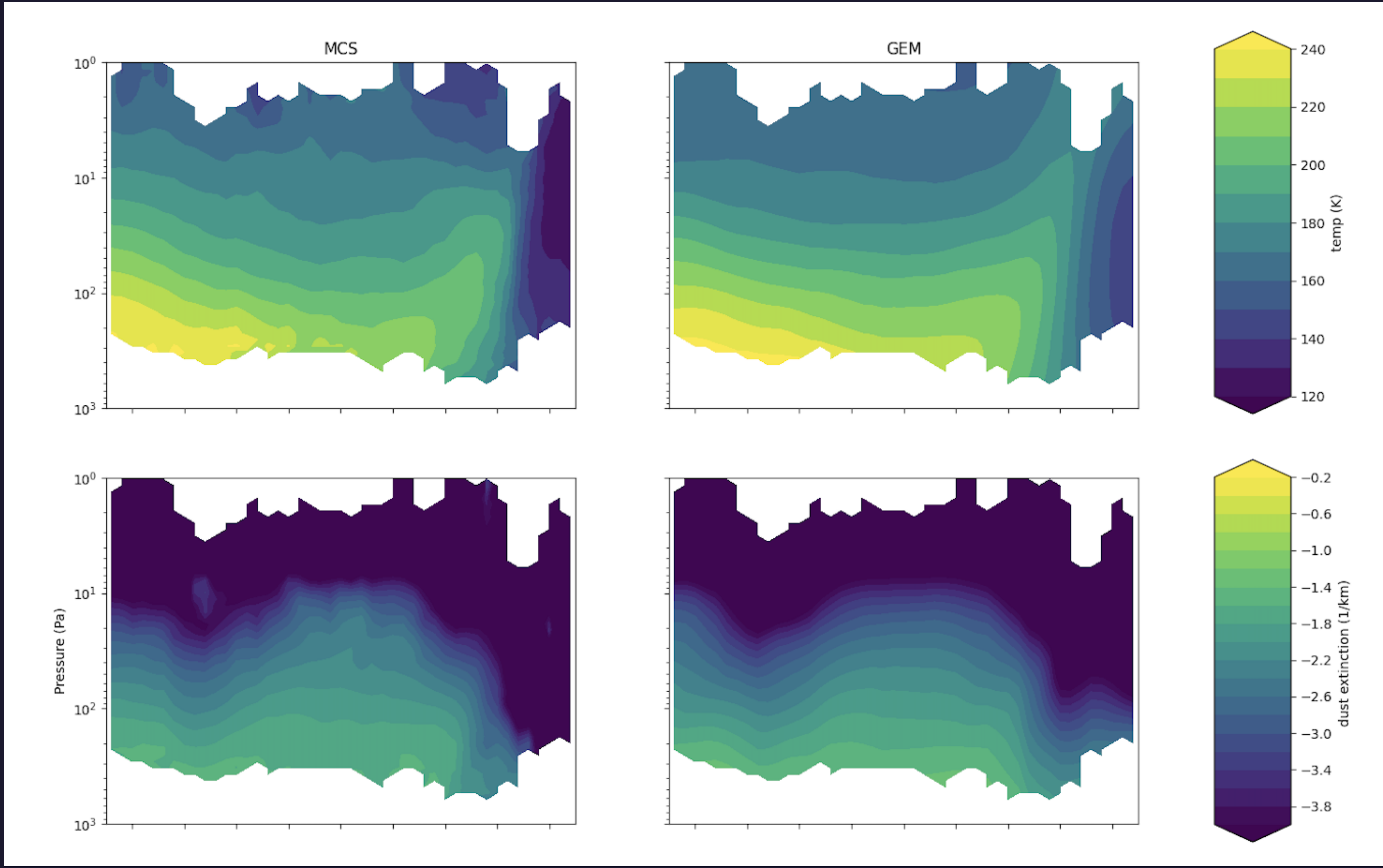
MCS (left), GEM-Mars (right)



Putting it all together

L_s = 270, MY 35
Temperature (top)
Dust extinction (bottom)

MCS (left), GEM-Mars (right)



Part IV: Open questions and efforts to address them

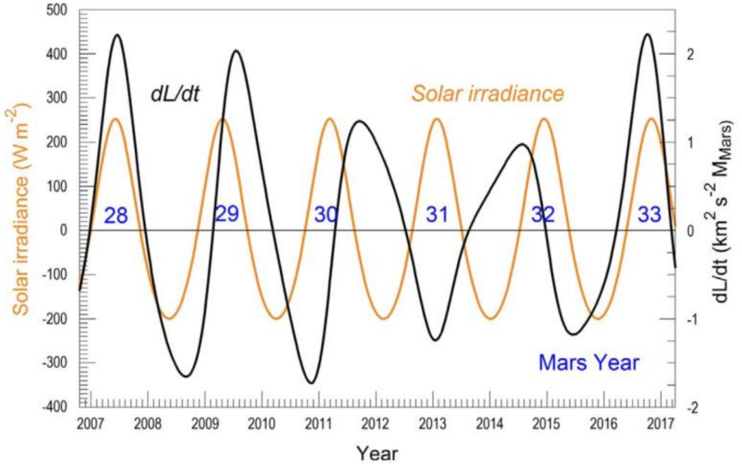
- What causes the interannual variability?
- What is the size distribution in the atmosphere?
- What are the radiative properties of those particles?
- What are the mechanisms to transport dust from the surface?
- What are the mechanisms to transport dust in the vertical?

Interannual variability

Can we forecast the next big dust storm?

Not yet but some promising research is being done (e.g. Mulholland et al., 2012) using varying lifting thresholds based on the surface dust density at each grid point.

Other theories include orbit spin coupling (Shirley et al., 2017; 2020)



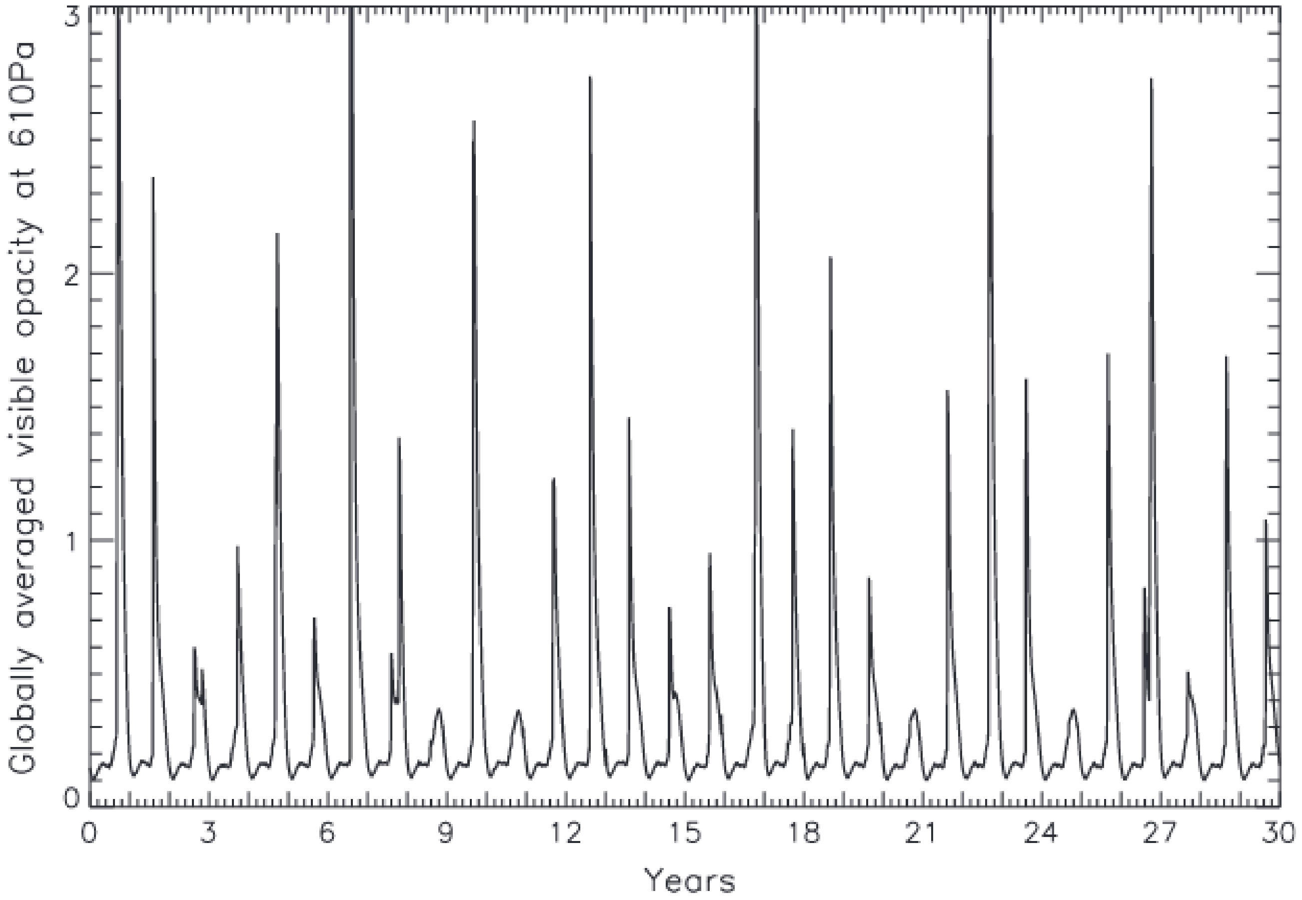


Fig. 4. Globally averaged visible optical depth over a period of 30 model years.

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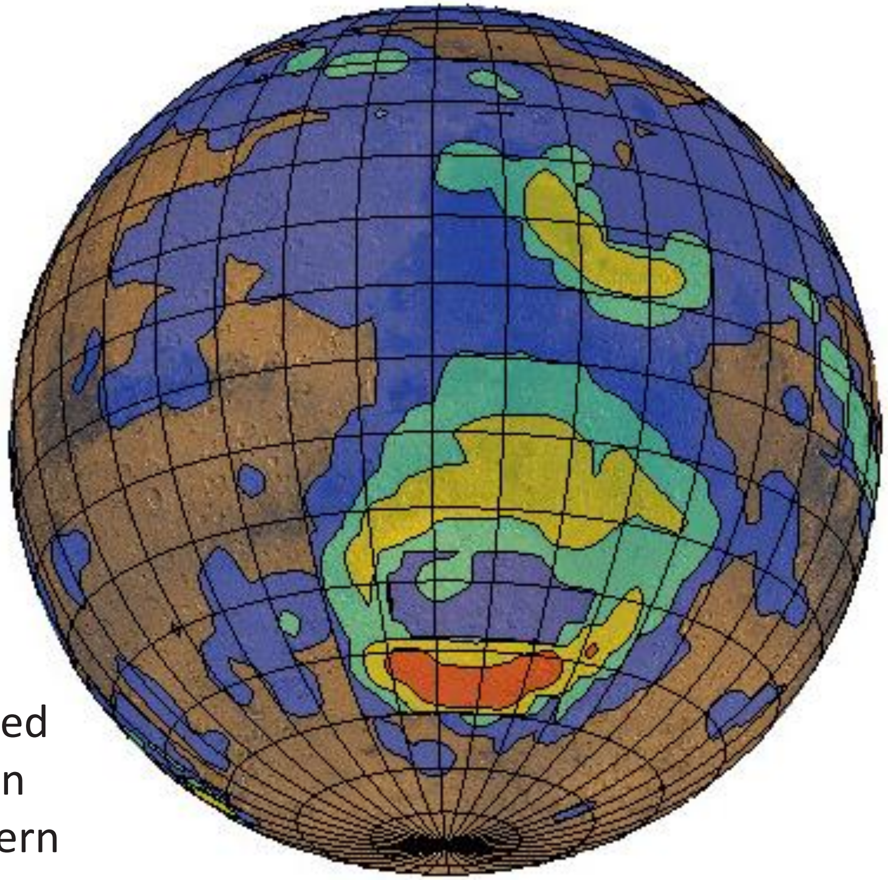
Ongoing work with GEM-Mars: Finite dust reservoir

- Work in progress – tracking the deposition of dust, adjusting the threshold based on available dust



Snapshot of 10 µm dust deposited on surface at L_s = 87º showing an accumulation around the southern rim of Hellas basin.

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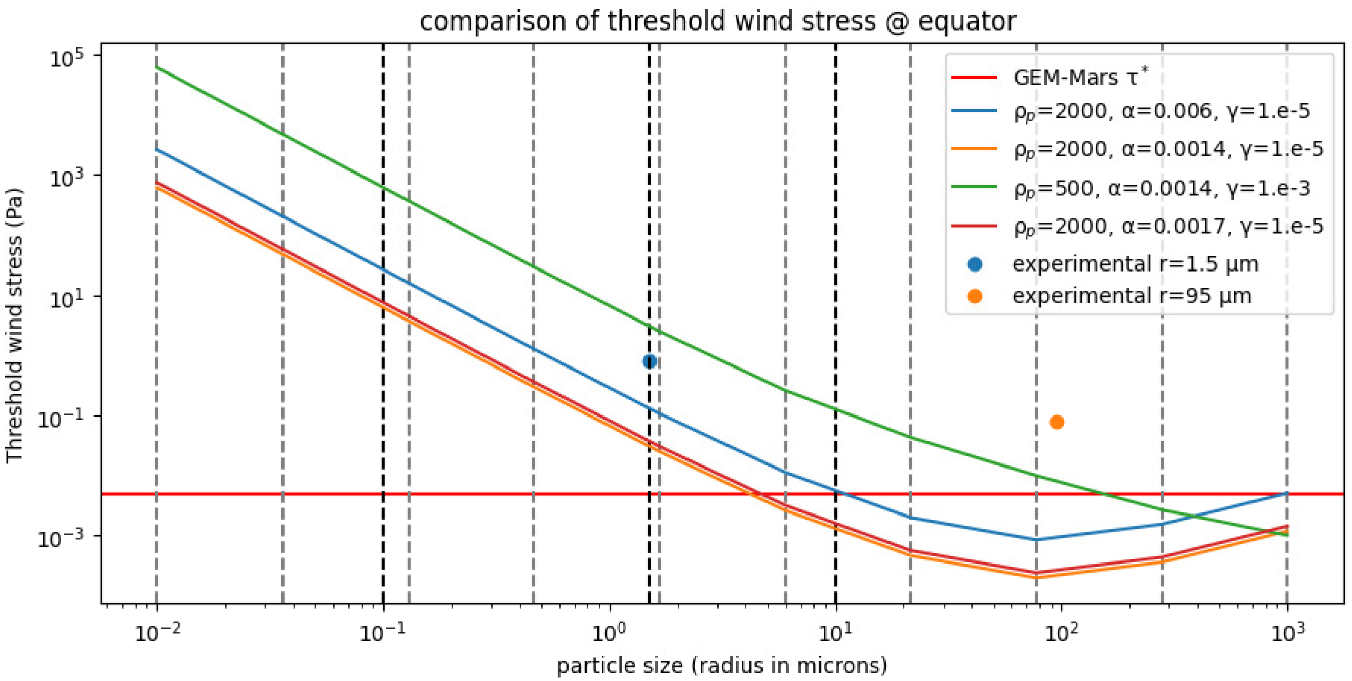
Dust lifting – one equation to rule them all

shear stress = + gravity + cohesion - thermal creep - delta P – charge

or

$$\tau_{thr} = \alpha Q_C \left(\frac{1}{9}\rho_p g d + \frac{\gamma}{d} - \frac{L_t}{L_a + L_t}\frac{\rho_g R}{6\mu}\Delta T \frac{Q_T}{Q_P} - \frac{\Delta P}{6} - \frac{1}{6\pi\epsilon_0}\frac{{q_P}^2}{d^2} \right)$$

We explored values of threshold wind stress for wind, gravity, and cohesion depending on particle size, but generally the thresholds are higher than what we normally have (less dust lifted).

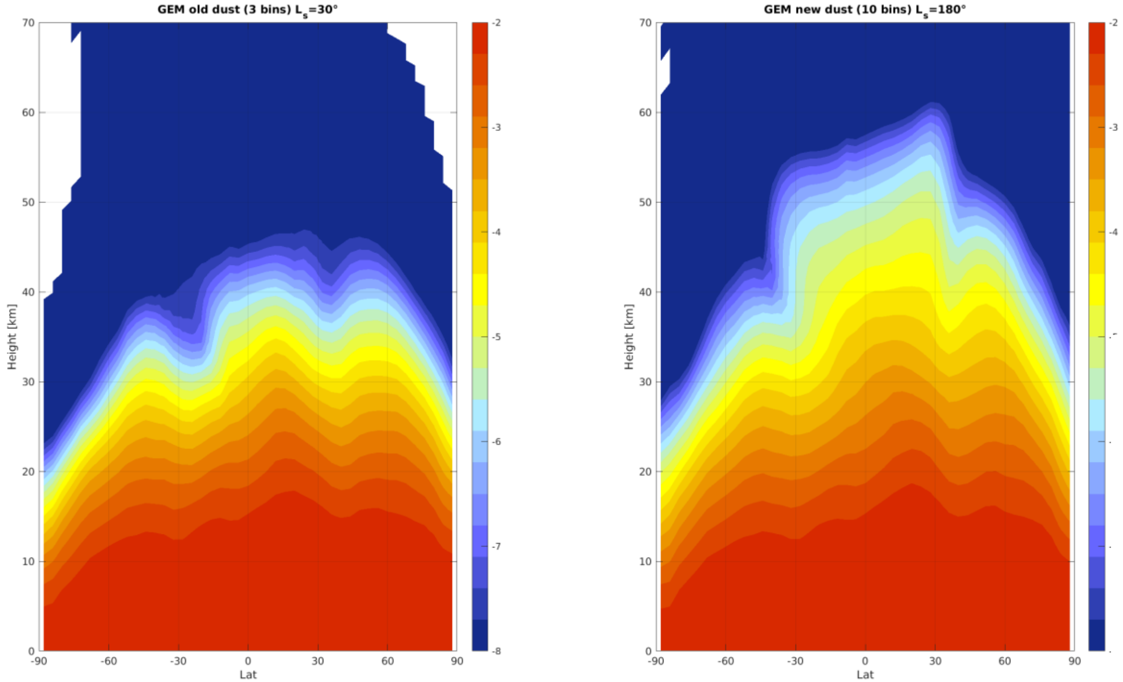


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004052

Ongoing work: Particle size distribution

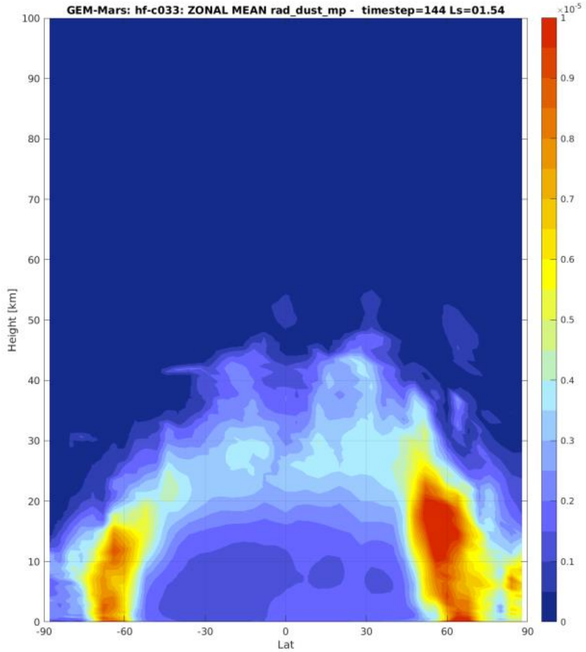
We are increasing the number of size bins in GEM-Mars to see the impact on the vertical and horizontal distribution of dust in the atmosphere.

We see higher extinction in the upper altitudes, which is interesting, and may lead to some new insights.



Zonal mean extinction profile with 3 bins (left) and 10 bins (right).

Snapshot of zonal mean profiles of dust particle radius. Lots of detail!



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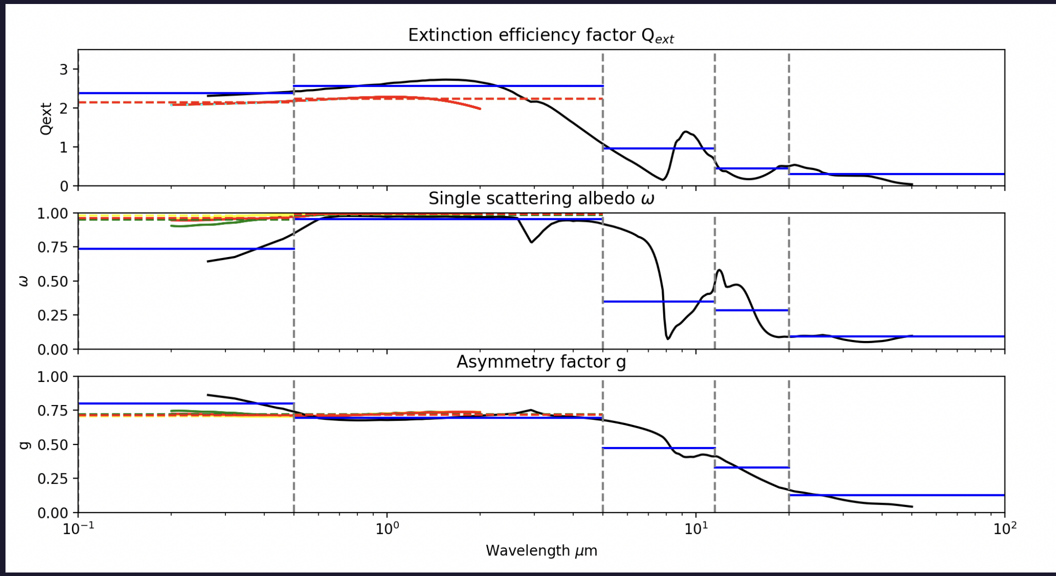
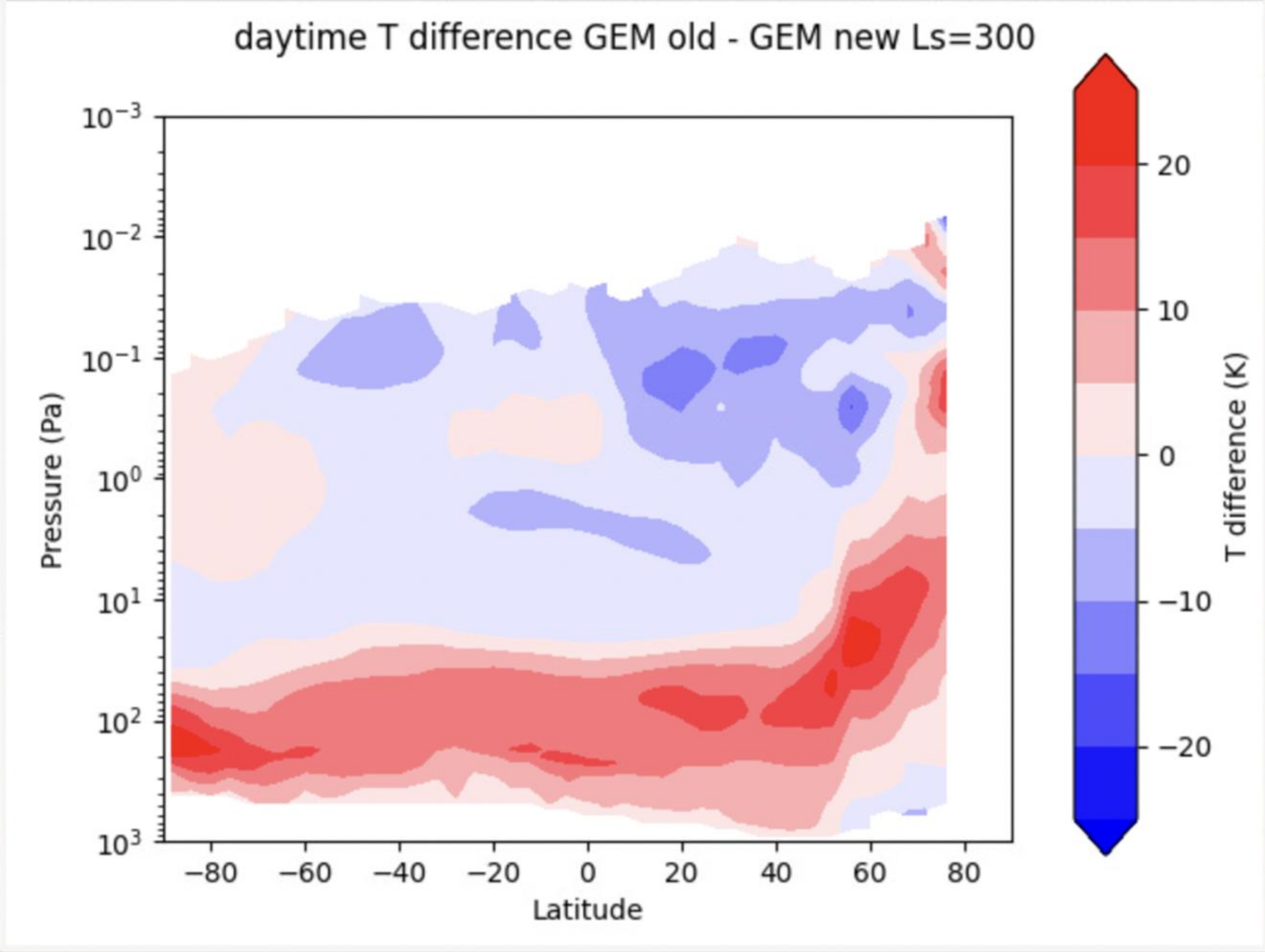
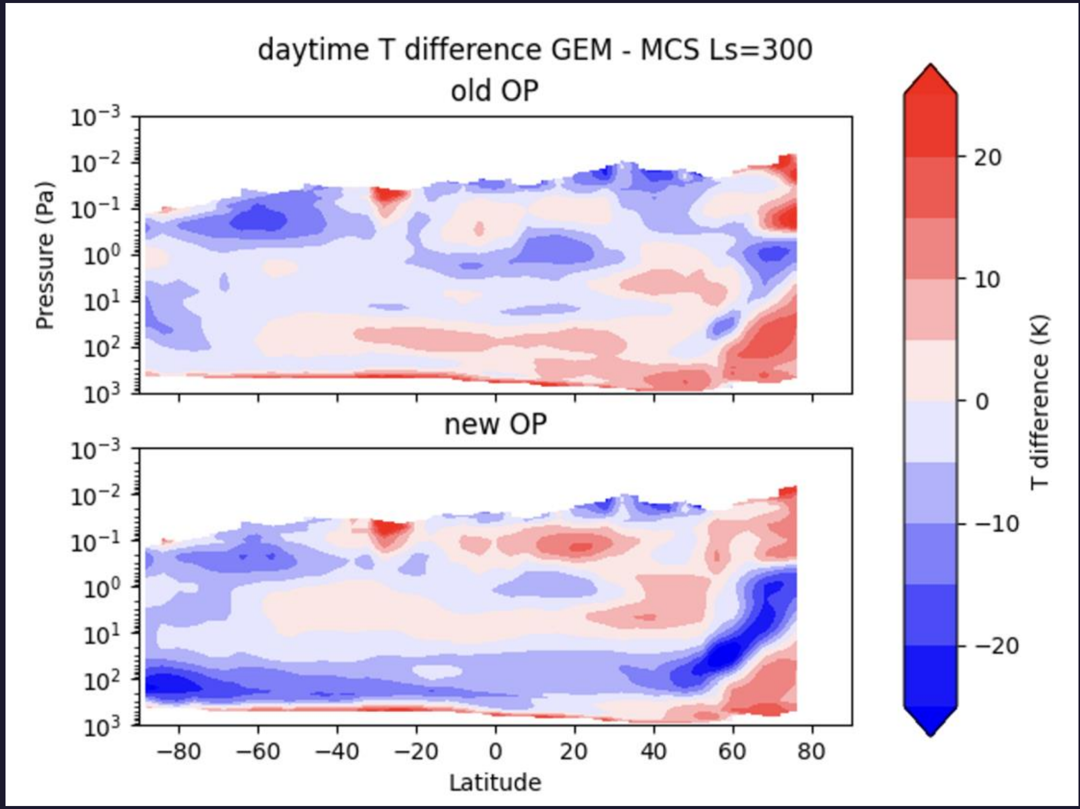
Ongoing work: Radiative effects

Testing optical properties from IAA







Outstanding questions – detached dust layers

Most GCMs have some trouble reproducing the observed vertical distribution of dust.

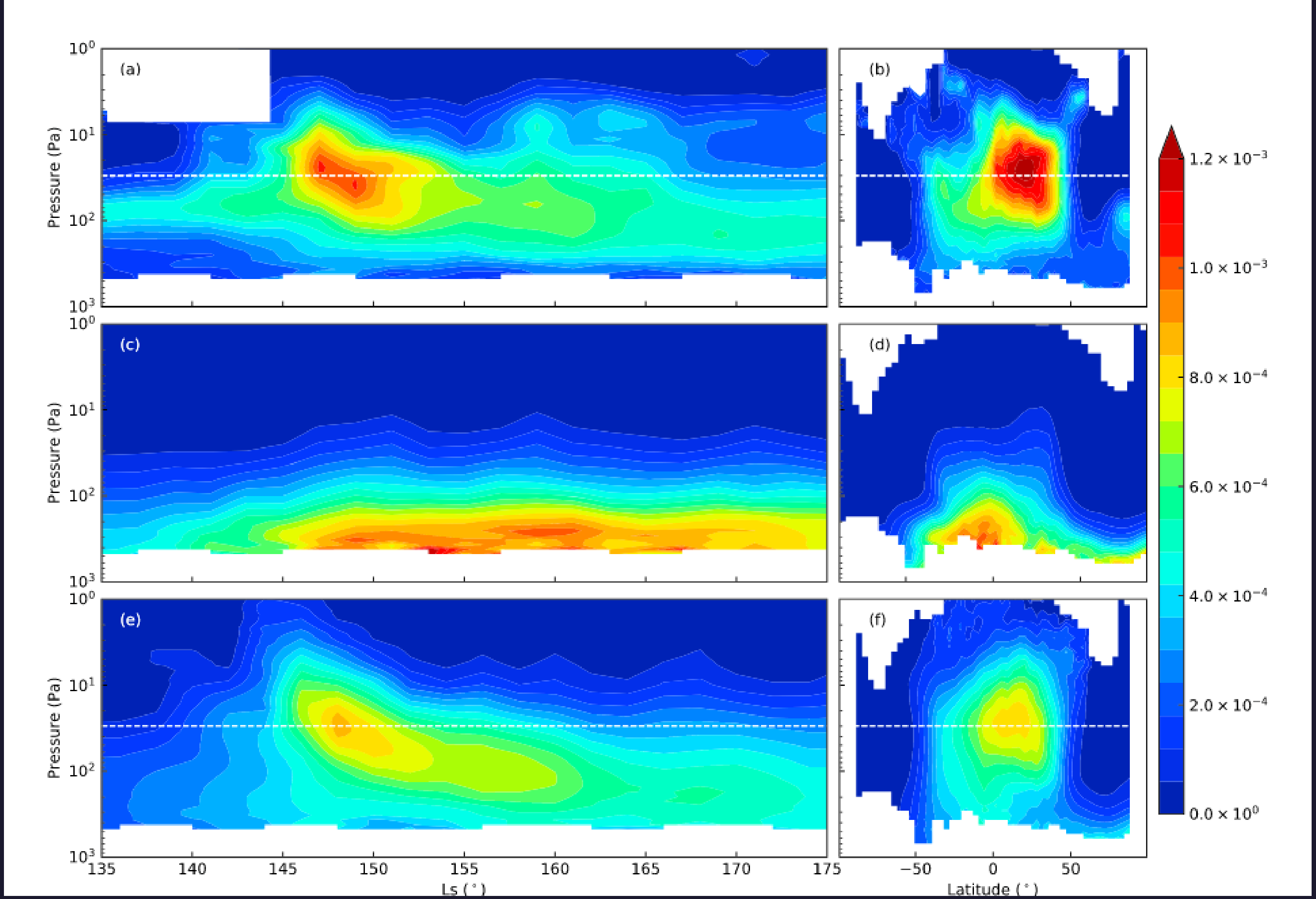
Some solutions:

- Rocket dust storm parameterisation
- Sub-grid scale upslope wind effects

These work in some places at some times, but it is not a complete solution.

See Antoine's talk next!!

From Wang et al., 2018



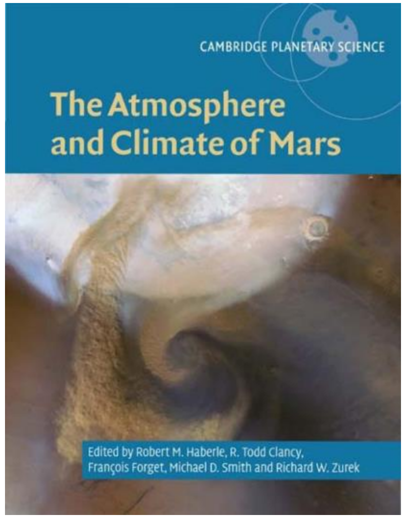
Top: MCS observed nighttime dust density-scaled opacity (DSO)
Middle: standard GCM simulation of DSO
Bottom: GCM with rocket dust storm parameterisation

Part V:
Useful resources

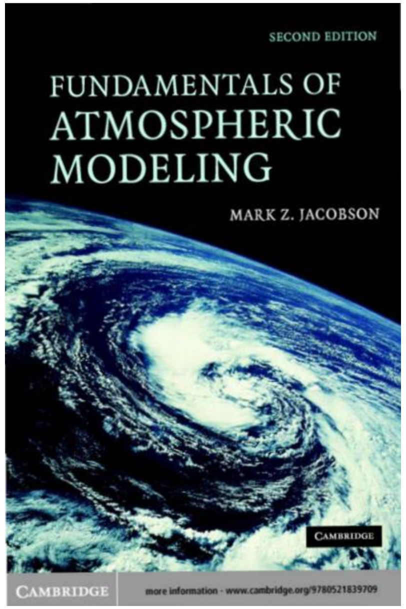
Public access to GCM data

- Mars Climate Database: LMD France, using LMD PCM
- OpenMars: Open University, UK using data assimilation with UK-LMD GCM
- EMARS (Ensemble Mars Atmosphere Reanalysis System): Penn State U. using data assimilation with NASA/GFDL GCM
- Europlanet VESPA (Virtual European Solar and Planetary Access): GEM-Mars GCM (+ TGO/NOMAD observations!)
- Ask your friendly neighbourhood modeller for specific data/scenarios!

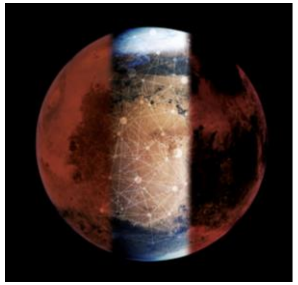
Useful references related to GCM modelling, Mars and dust



The Atmosphere and Climate of Mars, Haberle et al., 2017



Fundamentals of Atmospheric Modeling, Jacobson, 2005



Past MAMO abstracts: https://www-mars.lmd.jussieu.fr/paris2022/

A model intercomparison of sorts:
Newman et al., 2021. Multi-model Meteorological and Aeolian Predictions for Mars 2020 and the Jezero Crater Region. Space Sci Rev 217, 20. https://doi.org/10.1007/s11214-020-00788-2

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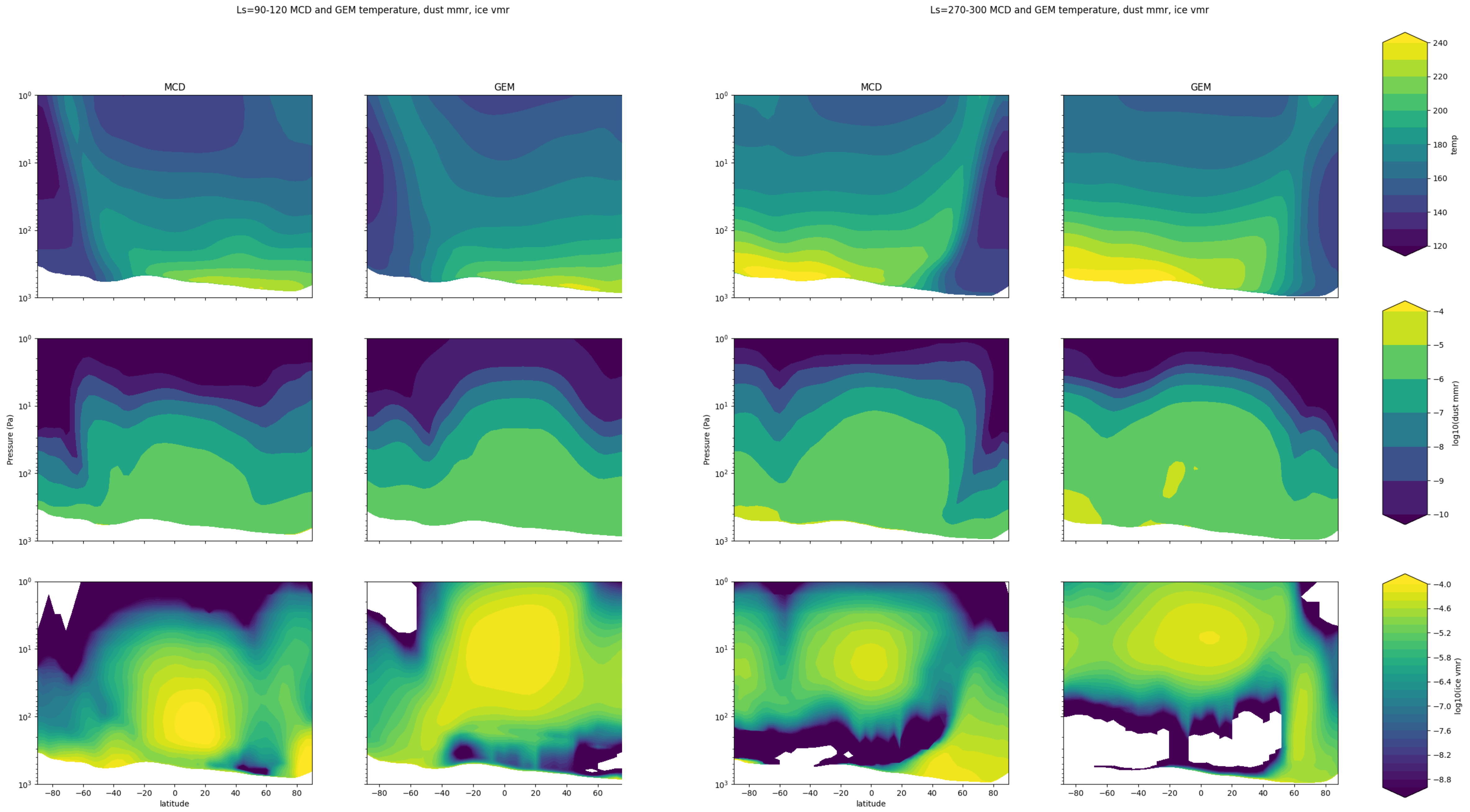

Ls=90-120 MCD and GEM temperature, dust mmr, ice vmr
Ls=270-300 MCD and GEM temperature, dust mmr, ice vmr
MCD
GEM
Pressure (Pa)
latitude
temp
log10(dust mmr)
log10(ice vmr)

THANK YOU!
MORE INFO?

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http://roadmap.aeronomie.be

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