Japan-France planetary atmospheric modeling workshop,
2015/05/11, Kobe Univ.

Development of the Japanese-German Mars GCMs: Toward the coupling between lower and upper atmosphere

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And more collaborators…

Our brief history

- Kuroda started to develop a MGCM based on CCSR/NIES (Center for Climate System Research, Univ. of Tokyo / National Institute for Environmental Studies) AGCM as a student of CCSR (get master in 2001, and Ph.D. in 2006).
- Also Kuroda started to work at the Max Planck Institute for Solar System Research since 2004, and engaged in the development of a MGCM there (MAOAM). Medvedev also started to work there in the same year.
- We have produced publications about atmospheric dynamics mainly; baroclinic waves [Kuroda et al., 2007], semi-annual oscillations [Kuroda et al., 2008], winter polar warming [Medvedev and Hartogh, 2007; Kuroda et al., 2009], etc…
- We published a review paper about the effects of dust on the martian meteorology [Medvedev et al., 2011, Aeolian Research].
- Our recent main topics are gravity waves, CO_2 snowfall, etc… (shown later)
- Now the collaborations between Tohoku Univ. and MPS with the "Promotion of the strategic research program for overseas assignment of young scientists and international collaborations" of JSPS is ongoing (October 2013 – March 2016), and Kuroda stays in MPS for about a year in total during this period (actually I just came back from Germany last Saturday!).

Review paper from Aeolian Research

Aeolian Research 3 (2011) 145–156

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Review Article

Influence of dust on the dynamics of the martian atmosphere above the first scale height

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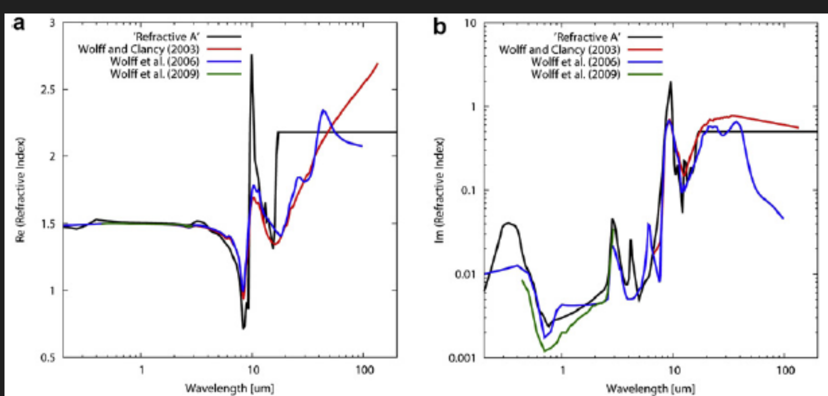
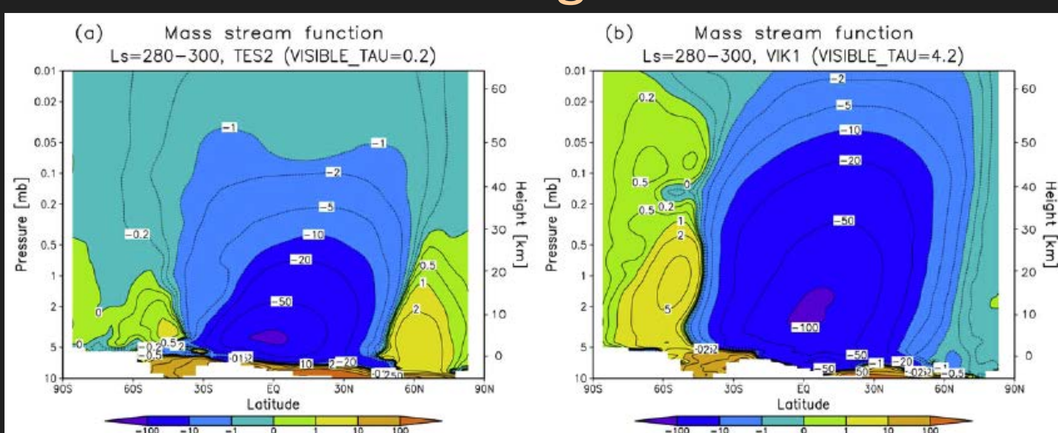
Refractive index of dust



Dust storm changes circulation



http://c.gp.tohoku.ac.jp/~promotion/index-en.html

日本語

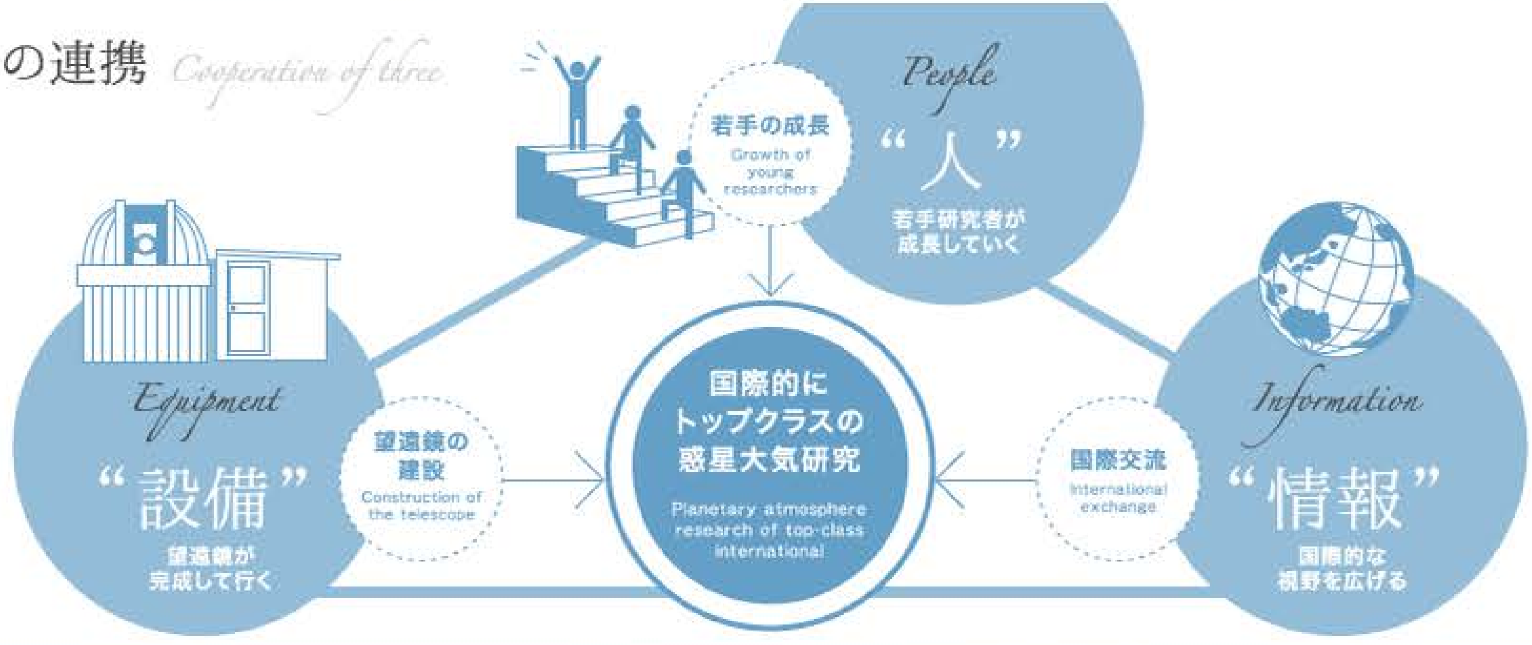
プロジェクトの紹介 Introduction to the project | 研究者たち Researchers | フォトギャラリー Photo galleries | リンク Link

Promotion of the strategic research program for overseas assignment of young scientists and international collaborations

Intensification of international collaborations for planetary plasma and atmospheric dynamics research based on the Hawaiian planetary telescopes

Planetary and Space Physics Group
Graduate School of Science Tohoku University, Japan

3つの連携 *Cooperation of three*



DRAMATIC MGCM (Japanese)

Developments up to now

Dynamical core

CCSR/NIES(/FRCGC) AGCM 5.4.02 (Kuroda's master thesis, 2001) →5.4g (Kuroda's first paper, 2005 and Ph.D. thesis, 2006)→5.6→5.7b (MIROC 4.0 at present)
3-D primitive equations (spectral solver)

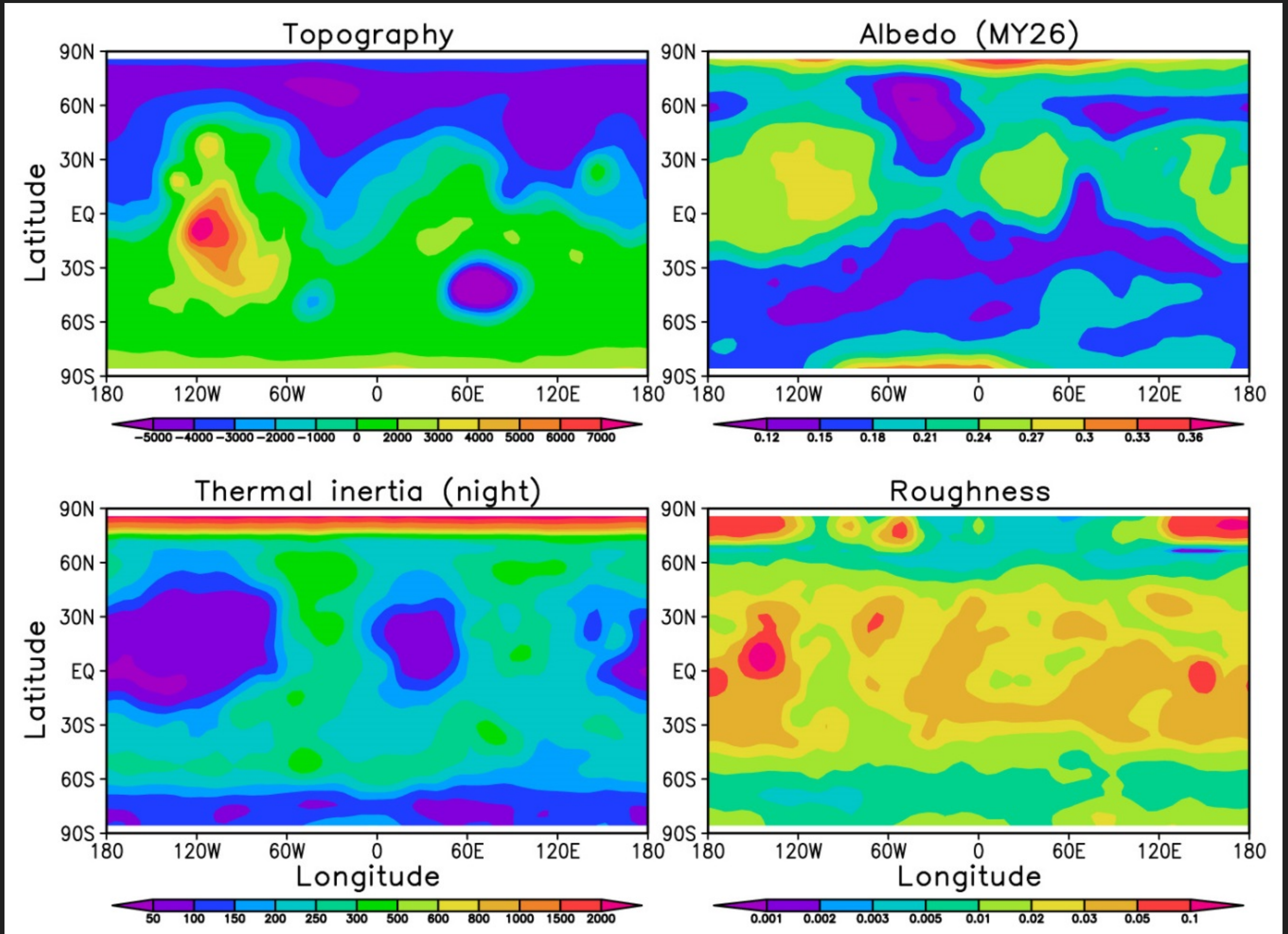
Started to be called as "DRAMATIC MGCM" since ~2010
(DRAMATIC = Dynamics, RAdiation, MAterial Transport and their mutual InteraCtions)

Resolution

- Horizontal: T21(~5.6º× 5.6º, grid interval in equator of ~333km)
- Vertical: σ level, currently 49-69 layers
  (model top of ~80-100 km)

Surface parameters (current)

- Topography: MGS-MOLA observations [Smith et al., 1999]
- Albedo and thermal inertia: MGS-TES observations [Putzig and Mellon, 2007]
- Roughness: From MGS-MOLA data [Heavens et al., 2008]



CO_2 phase change (1)

From Forget et al. [1998]

The condensed CO_2 ice falls by the gravitational sedimentation. Then the thermodynamic effects (①-③ below) and resulting exchange between atmosphere and ice are made.

If T^*(predicted temperature) $<$ T_c(condensation temperature)

$$T^* = T_c$$

$$\delta m_N = \frac{c_p M_N}{L}\left(T_{c_N} - T_N^*\right)$$

$$\delta m_l = \underbrace{\frac{c_p M_l}{L}\left(T_{c_l} - T_l^*\right)}_{①} - \frac{1}{L}\left[\underbrace{g\left(z_{l+1} - z_l\right)}_{②} + \underbrace{c_{ice}\left(T_{c_{l+1}} - T_{c_l}\right)}_{③}\right]\sum_{k=l+1}^{N} \delta m_k \quad (\text{in } l \le N\text{-}1)$$

If all the falling ice sublimes in layer l $\left(\text{i.e.} -\delta m_l > \sum_{k=l+1}^{N} \delta m_k\right)$,

$$T_l = T_l^* + \frac{1}{c_p M_l}\left[-L + g\left(z_{l+1} - z_l\right) + c_{ice}\left(T_{c_{l+1}} - T_{c_l}\right)\right]\sum_{k=l+1}^{N} \delta m_k$$

At surface ($l = 0$), $c_p M_l$ is replaced by $c_s A$,

and $\sum_{k=0}^{N} \delta m_k$ is added to the ground ice amount m_0.

If the ground ice completely sublimes $\left(\text{i.e.} -\delta m_0 > m_0 + \sum_{k=1}^{N} \delta m_k\right)$,

$$T_0 = T_0^* - \frac{L}{c_s A} m_0 - \frac{1}{c_s A}\left[L - g\left(z_{l+1} - z_l\right) - c_{ice}\left(T_{c_1} - T_{c_0}\right)\right]\sum_{k=1}^{N} \delta m_k$$

Accounting for the loss of atmospheric mass due to condensation,

$$\delta p_0 = -\frac{g}{A}\sum_{k=0}^{N} \delta m_k$$

Modify the surface pressure to conserve the total mass of CO_2 (caps + atmosphere)

① Release of the latent heat

② Potential energy released by ice falling

③ Energy used to heat the ice to the condensation temperature of lower level

Previously the condensed CO_2 fell to the surface immediately, but with the way the result of CO_2 ice cap thickness largely depended on the timestep of calculation: bad for different resolution or model top height.

CO_2 phase change (2)

Implementation of gravitational sedimentation (since 2010)

Modified Stokes' law [Kasten, 1968]

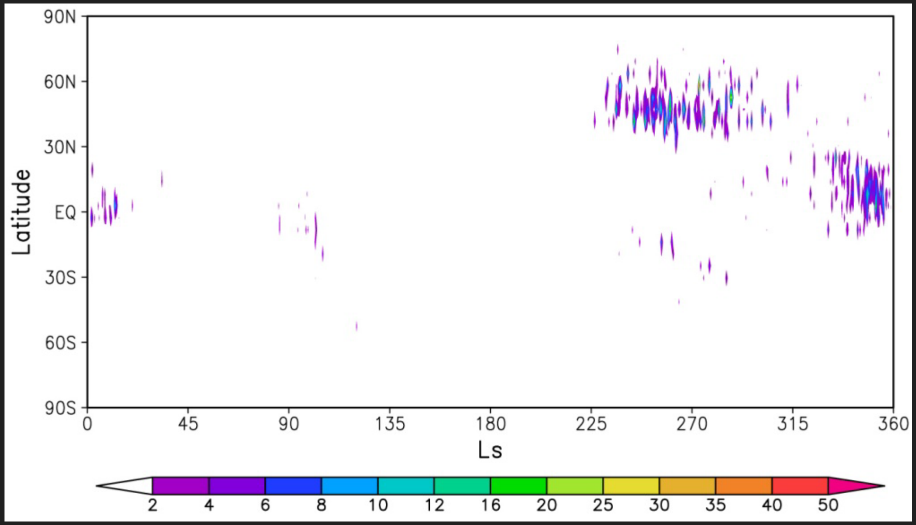
$$v_{sed} = \frac{2\rho g r^2}{9\eta}\left[1+\frac{\lambda}{r}\left\{A+B\exp\left(-\frac{Cr}{\lambda}\right)\right\}\right]$$

η: Dynamic viscosity
λ: Mean free path length
r: CO_2 ice radius
ρ: Density of CO_2 ice (=1600 kg m^{-3})
A, B, C: Dimensionless empirical constants;
A=1.15, B=0.497, C=0.92 for CO_2 air [Rader, 1990]

Definition of CO_2 ice radius (very simple)

$$r\,(z) = r_0 \exp(-z/h)$$

r_0: Radius at 0m height (=50μm) [e.g. Hayne et al., 2012]
h: Particle radius scale height (=20km)
→1μm at ~78km height, which is consistent with the observations of mesospheric CO_2 ice clouds [e.g. Määttänen et al., 2010]



(presented in Paris workshop, 2011)

Seasonal-latitudinal cross-section of simulated zonal-mean CO_2 ice cloud distributions at 1Pa(~64km) [ppm of mass]

Consistent with the observations [Määttänen et al., 2010; McConnochie et al., 2010]

CO_2 snowfalls in winter polar atmosphere [Kuroda et al., 2013, GRL]

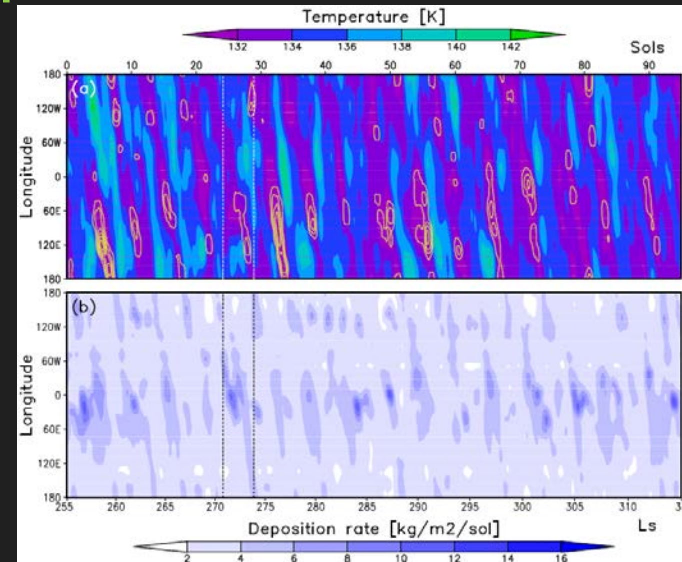
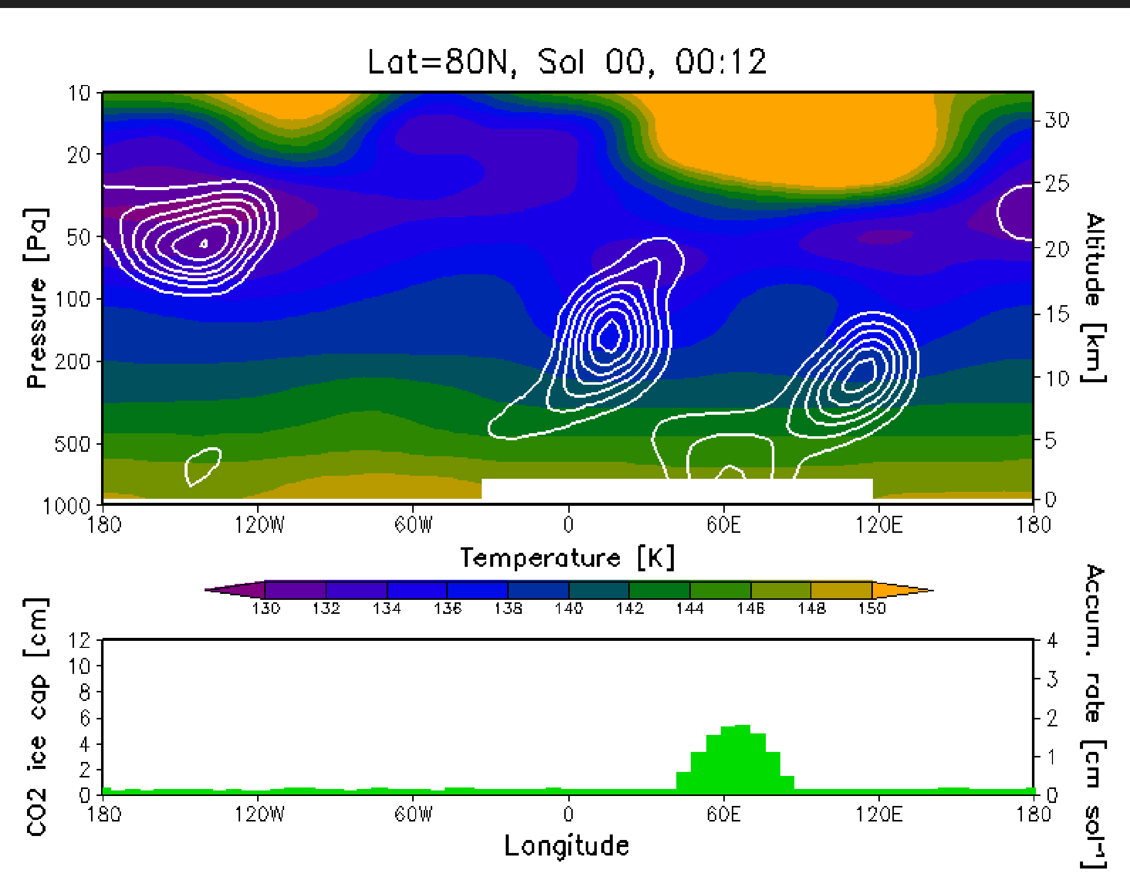
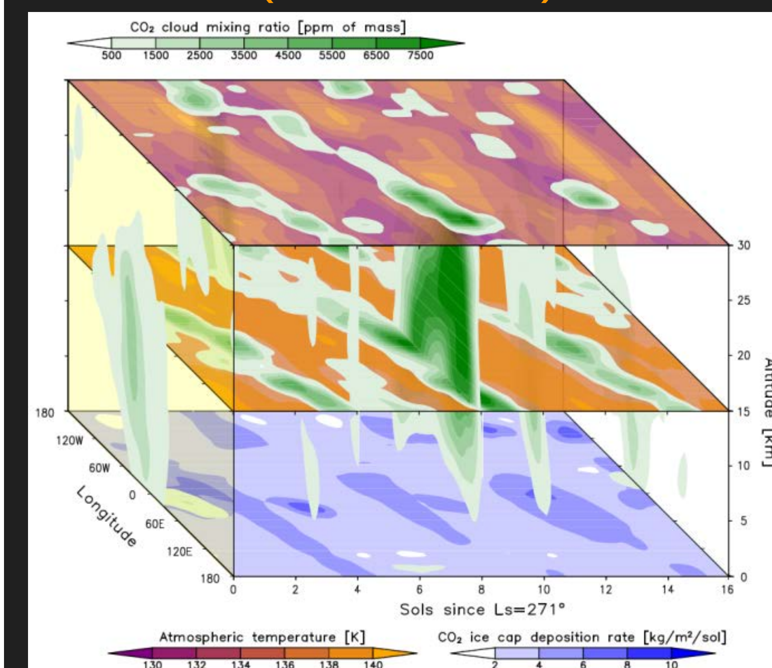


Figure on the paper
(a) 25km height snowfall
(b) surface accumulation rate at 80°N

(Animation)



(3-D feature)



Radiation (from my Ph.D. thesis, 2006)

- CO_2: Absorption and emission in the infrared wavelength (15µm, 4.3µm) and near-infrared solar absorption (the non-LTE effect is not considered)
- Dust: Absorption, emission and scattering in 0.2-200µm

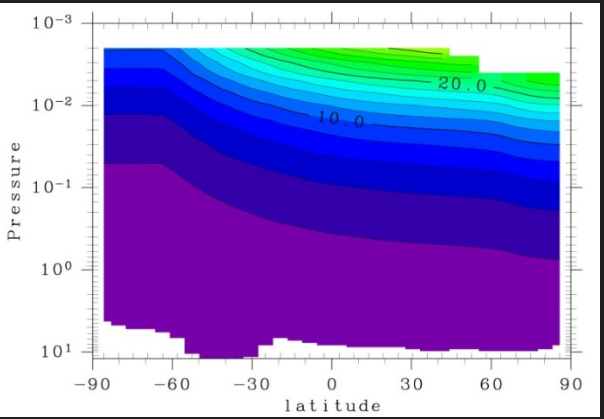
- CO_2 infrared: mstrnX [Sekiguchi and Nakajima, 2008]
- CO_2 NIR heating: from Forget et al. [1999, 2003]

At pressure $p_0 = 700$ Pa and for a mean Mars-Sun distance $r_0 = 1.52$ AU, the heating rate (per martian day) corresponding to a zero solar zenith angle ($\mu = 0$) is taken to be $\partial T/\partial t(p_0, r_0, 0) = 1.1956$ K day^{-1} The heating rate at other pressures p, Mars-Sun distance r, and zenithal angle μ is then computed as follows:

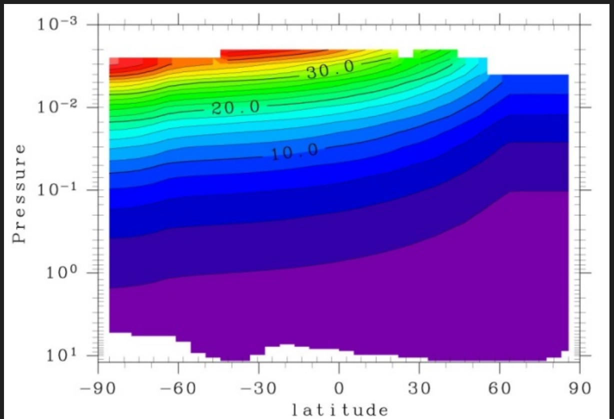
$$\frac{\partial T}{\partial t}(p, r, \mu) = \frac{\partial T}{\partial t}(p_0, r_0, 0) \times \frac{r_0^2}{r^2} \sqrt{\frac{p_0}{p} \tilde{\mu}}\ (1 + \frac{p_1}{p})^{-b} \quad (1)$$

with $p_1 = 0.0015889$ Pa, $b = 1.9628$ and $\tilde{\mu}$ the cosine of the solar zenith angle corrected for atmospheric refraction (we use $\tilde{\mu} = [(1224\mu^2 + 1)/1225)]^{1/2}$).

Ls=90°



Ls=270°



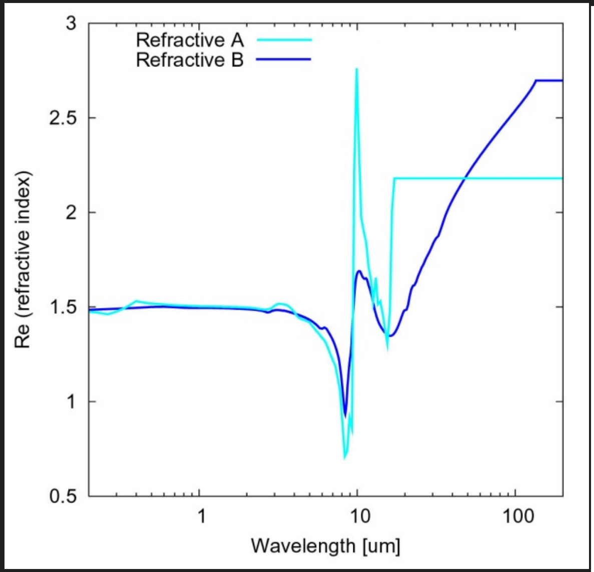
[Forget et al., 2003, Granada workshop]

Heating rate by CO_2 NIR solar absorption [K/sol]

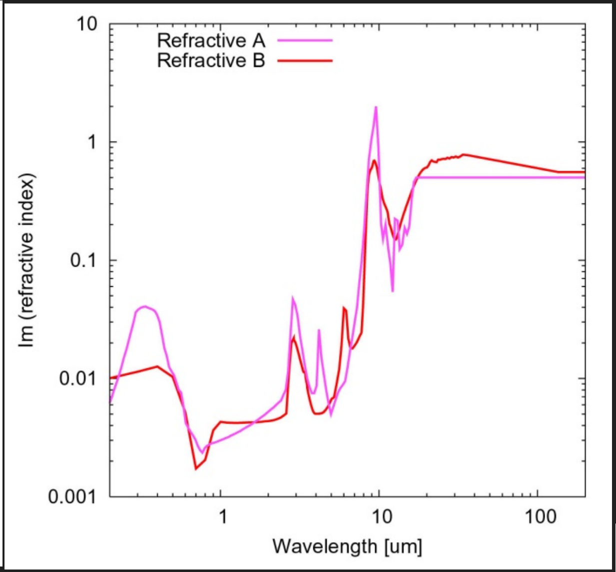
Dust radiation

Assuming the refractive index and particle size distribution based on the observations of Martian dust

Real



Imaginary



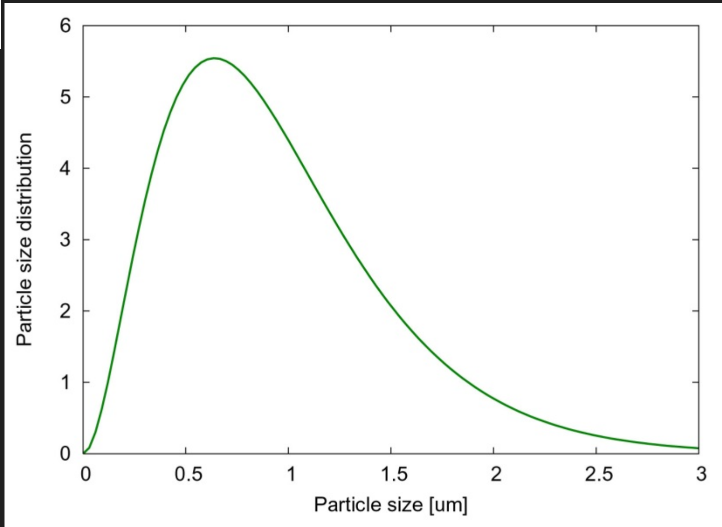
Refractive index: from Wolff and Clancy [2003] (Refractive B)

Refractive A: old standards [Ockert-Bell et al., 1997; Toon et al., 1977; Forget, 1998]

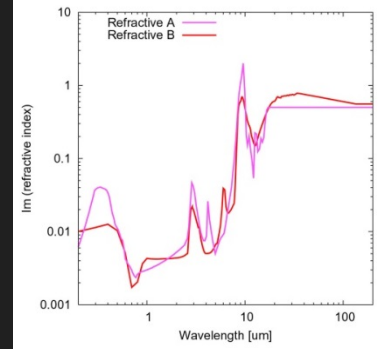
Particle size distribution: from Tomasko et al. [1999] (r_{eff}=1.6 μm, v_{eff}=0.2 μm)

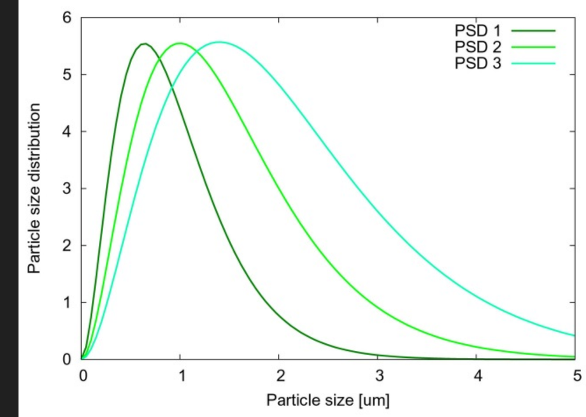
(Modified Gamma function)

$$n(r) = cr^{(1-3\nu_{eff})/\nu_{eff}} \exp\left[-r/r_{eff}\nu_{eff}\right]$$



Sensitivity test of dust parameters on the heating rate and temperature

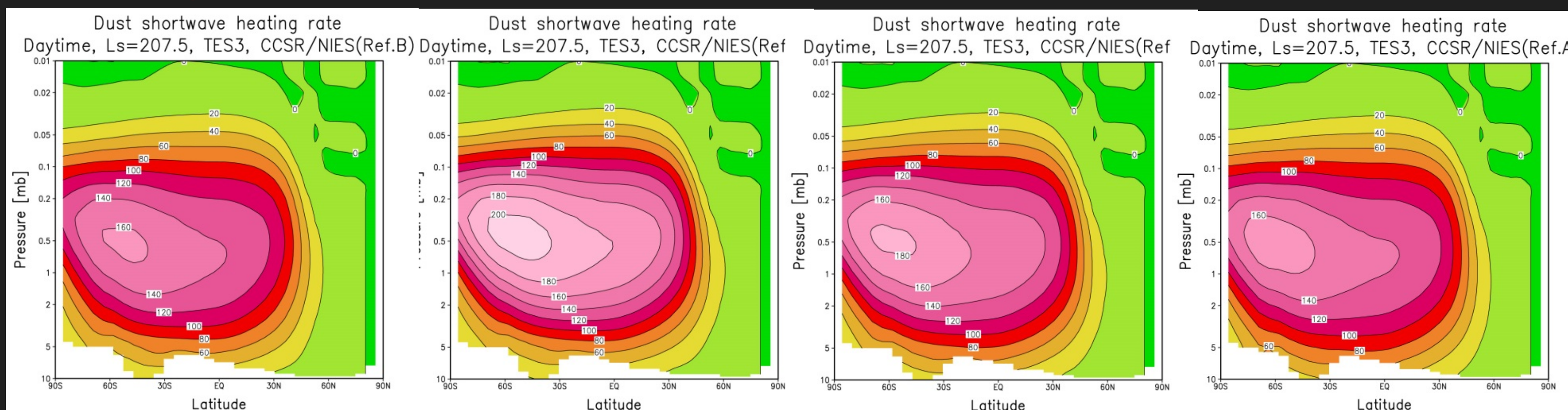




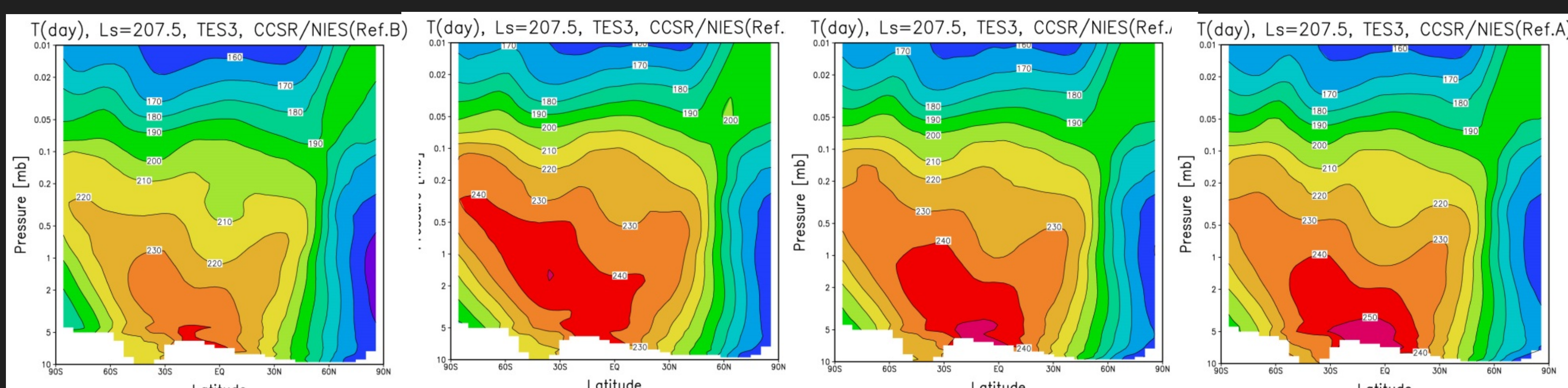
τ_{dust}~2.2, Ls=207.5° (assuming MY25 storm), daytime

Refractive B, PSD 1 | Refractive A, PSD 1 | Refractive A, PSD 2 | Refractive A, PSD 3

Heating rate in <4μm [K/sol]

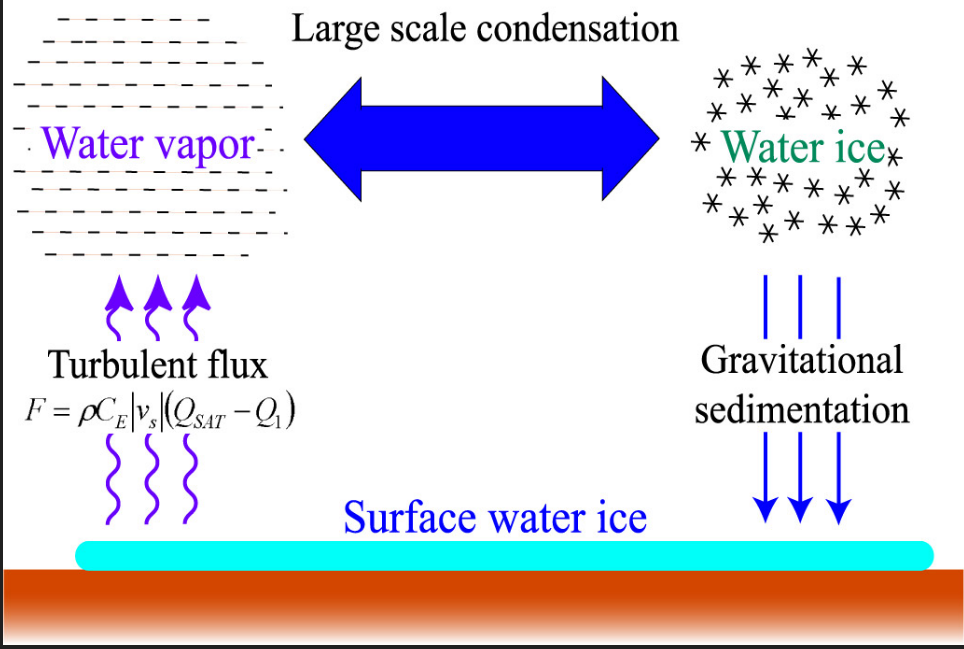


T [K]



Water cycle (since 2008)

- Based on the large scale condensation (supersaturated water vapor condenses to the water ice)
- Implementation of the gravitational sedimentation (modifies Stokes' law, same as CO_2 ice)
- Accumulation of surface water ice, including the change of surface albedo (absorption by the regolith is not assumed)
- Sublimation of surface ice by the turbulent flux



Estimation of water particle size based on Montmessin et al. [2004] (no supersaturation)

$$r_c = \left(\frac{M_c}{(4/3)\pi \rho_i N} + r_0^3 \right)^{1/3}$$

r_c: Radius of water ice
M_c: Water ice mass in the grid/layer
ρ_i: Density of water ice (917 kg m^{-3})
N: Number of dust particles in the grid/layer
r_0: Radius of dust particle (as nuclei)

$$N = \frac{M_d}{(4/3)\pi \rho_d r_0^3}$$

M_d: Mass of dust in the grid/layer
ρ_d: Density of dust (2500 kg m^{-3})

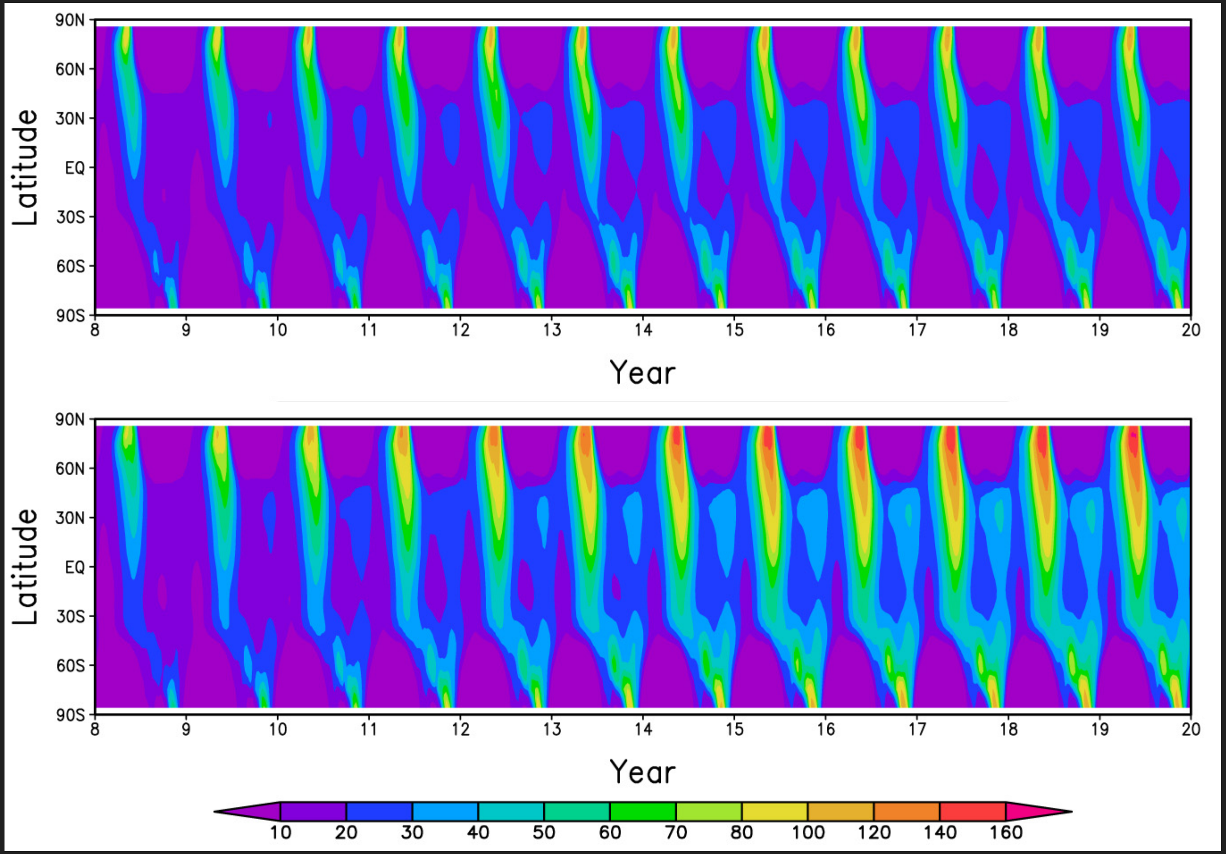
$$r_0(z) = r_{z0} \exp(-z/h)$$

r_{z0}: Radius at 0km height(0.8μm)
h: Scale height of the particle radius (18km)

Water vapor column density
(8-20 Martian years from the isothermal state)

No supersaturation

Assuming 10 times supersaturation (simply the saturation amount of water vapor is set to 10 times of the theoretical value)



In the initial isothermal state, north of 80°N is assumed as the water ice sheet with limitless water, and no water vapor/ice in the atmosphere.

About the possibility of 10-times super-saturation (SPICAM) [Maltagliati et al., 2011]

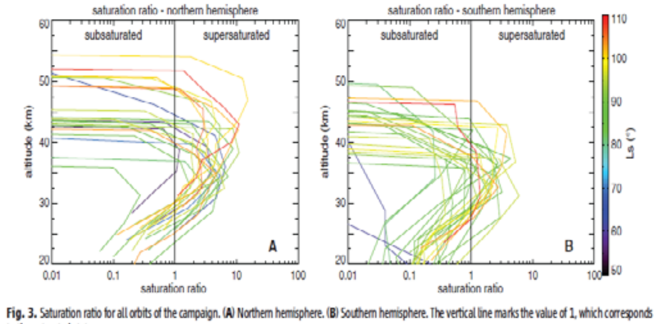
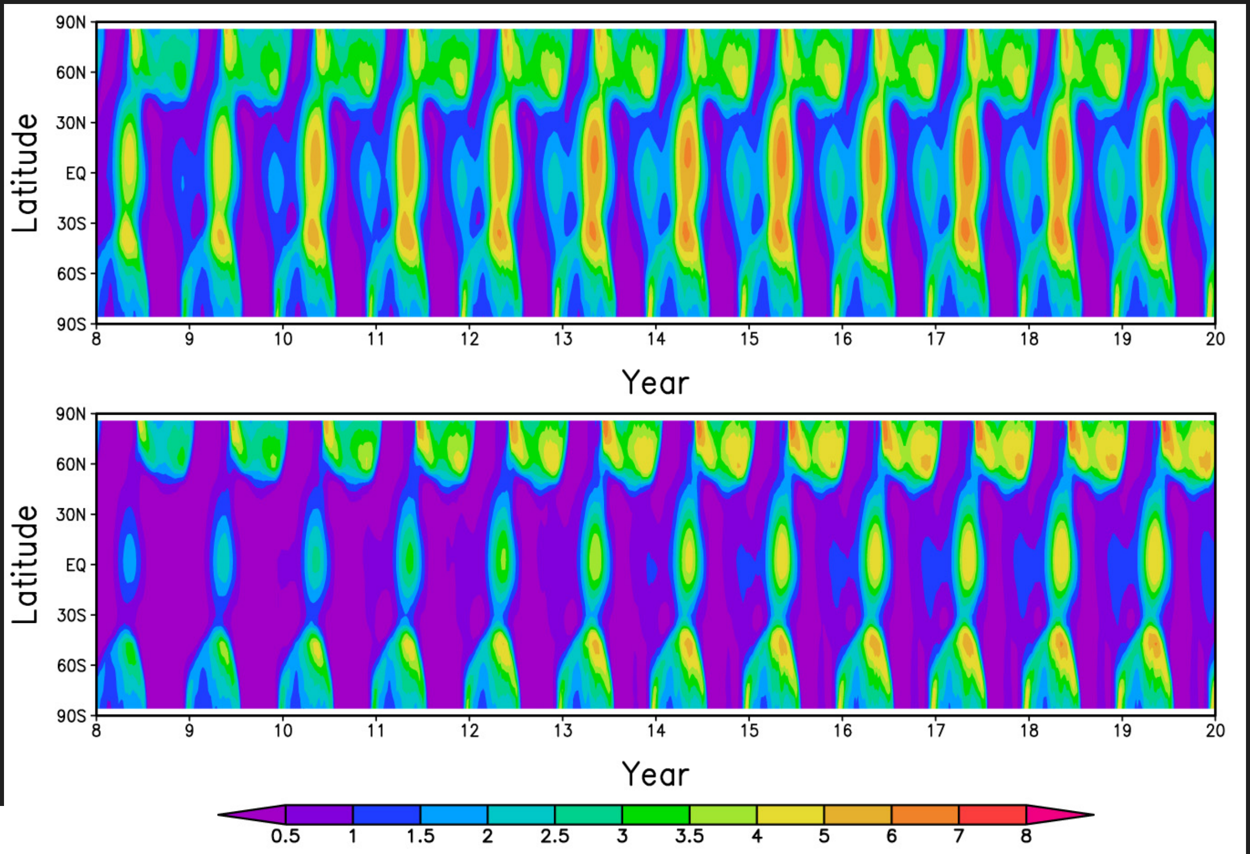


Fig. 3. Saturation ratio for all orbits of the campaign. (A) Northern hemisphere. (B) Southern hemisphere. The vertical line marks the value of 1, which corresponds to the saturated state.

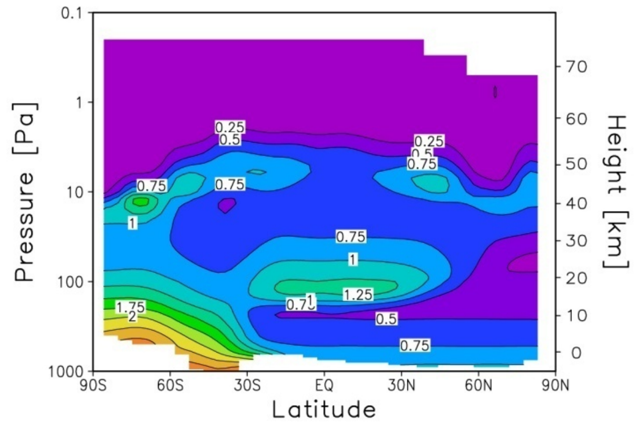
Water ice cloud optical depth
(8-20 Martian years from the isothermal state)

No supersaturation

10 times supersaturation



Water ice radius in Ls=90º (no supersaturation)



Obviously too much, considering the improvements.

HDO/H_2O isotopic fractionation (since 2011)

SMOW(D/H): 1.56×10^{-4}
(Standard Mean Ocean Water)

Merlivat and Nief [1967]'s formula

$$\alpha = \frac{(\mathrm{HDO/H_2O})_{\mathrm{ice}}}{(\mathrm{HDO/H_2O})_{\mathrm{vap}}} = \exp\left(\frac{16289}{T^2} - 9.45 \times 10^{-2}\right)$$

α=1.72: 160K
1.51: 180K
1.37: 200K

Two idealized estimations [Montmessin et al., 2005]

Rapid isotopic Homogenization case (RH): Appropriate for liquid clouds

$$\alpha = \frac{(M^c_{hdo} + dM_{hdo})/(M^c_{h2o} + dM_{h2o})}{(M^v_{hdo} - dM_{hdo})/(M^v_{h2o} - dM_{h2o})}, \quad (1)$$

Rayleigh Distillation case (RD): Appropriate for ice clouds

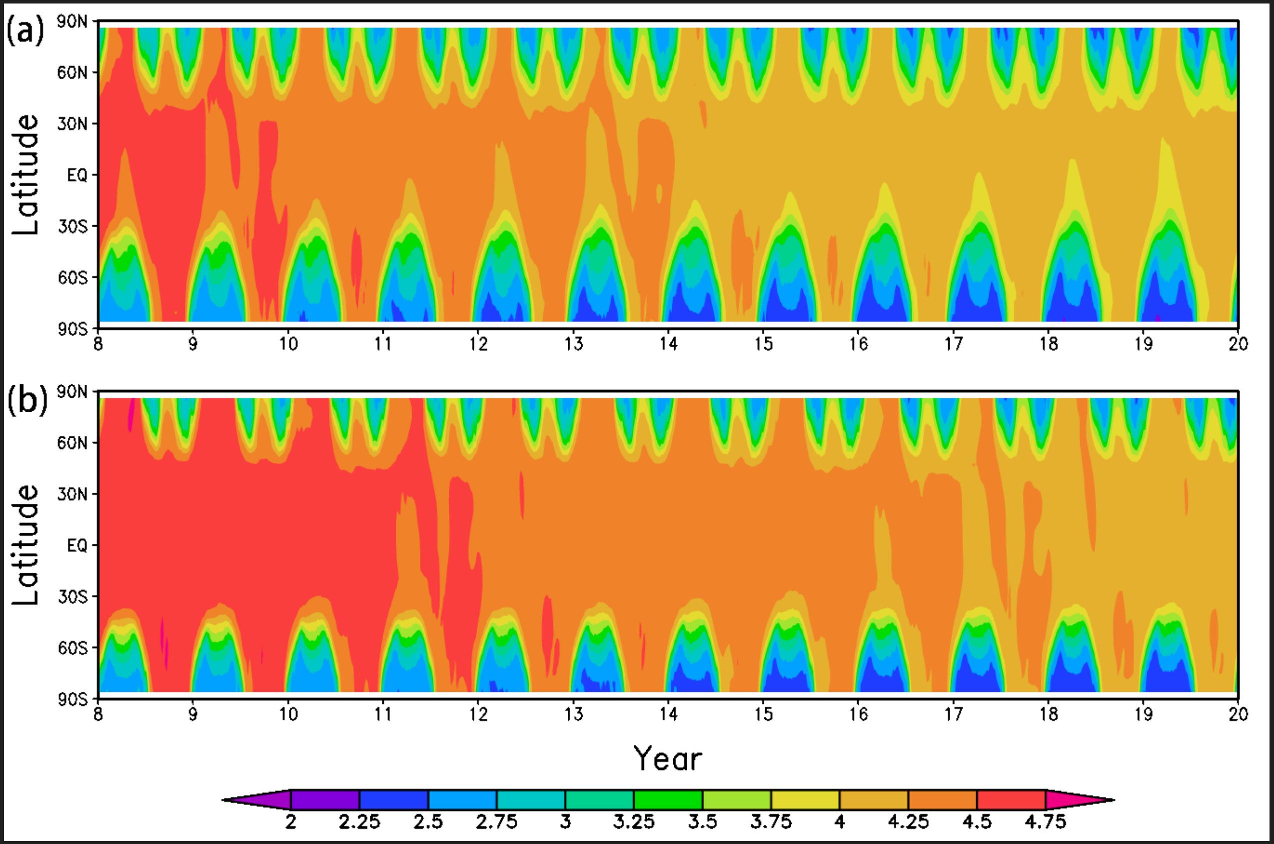
$$\alpha = \frac{dM_{hdo}/dM_{h2o}}{M^v_{hdo}/M^v_{h2o}} \quad (2)$$

(1) is adopted for the fractionation in the atmosphere, and
(2) is adopted for the surface ice.

HDO/H_2O ratio in the water vapor column density [vrt. SMOW]

No supersaturation

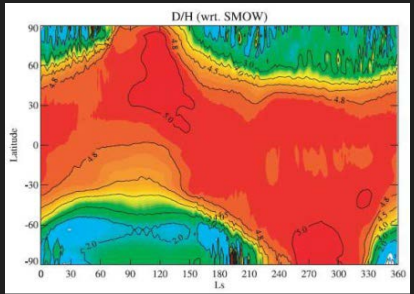
10 times supersaturation



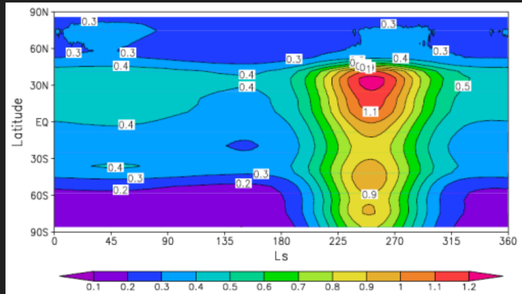
[Kuroda et al., 2012, Mars Recent Climate Change Workshop, NASA/Ames]

In the initial state, the HDO/H_2O ratio of the ice sheet in north of 80° N is set to 5.6 vrt. SMOW, based on the observations for Mars.

[Montmessin et al., 2005]

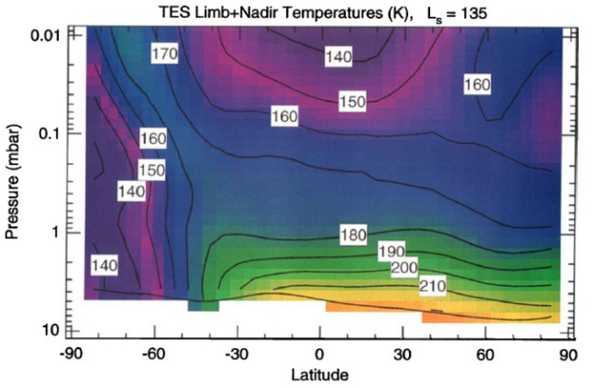


Seasonal-latitudinal change of dust opacity: 0.2~1 in visible



Radiative effects of water ice clouds (since 2015)

These are really preliminary results, which still need a lot of improvements…

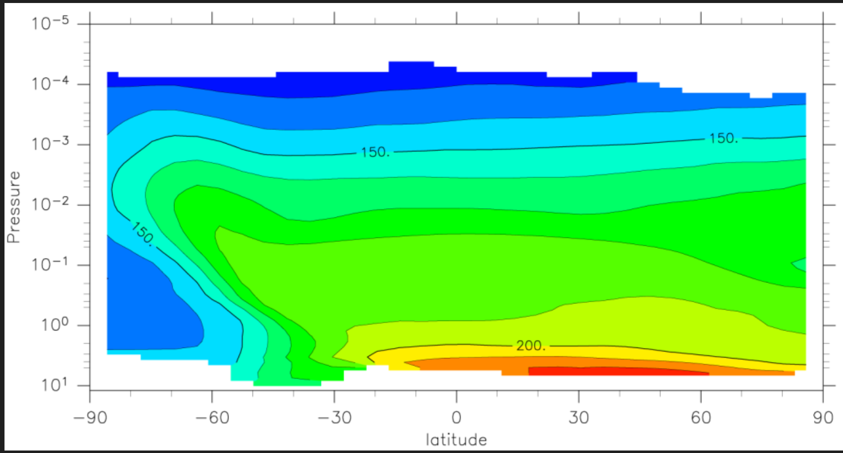


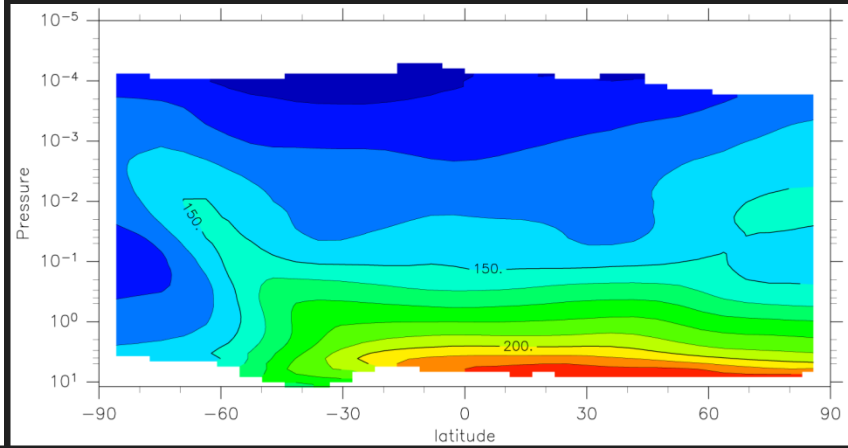
T by MGS-TES [Smith et al., 2001]

With radiative effects

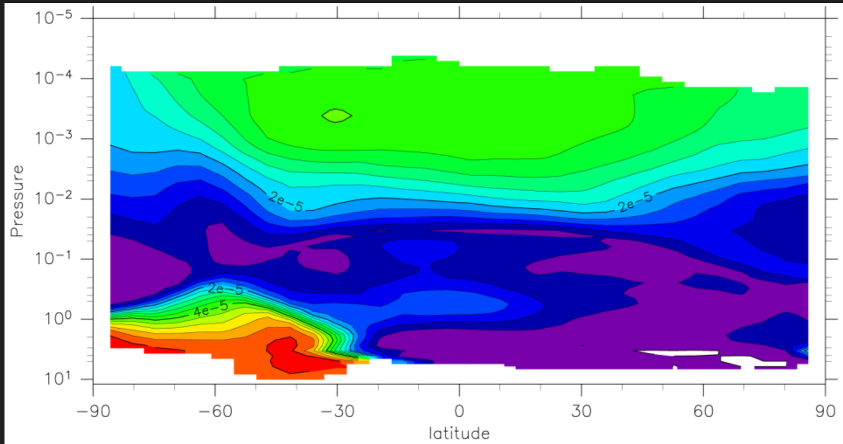
Without radiative effects

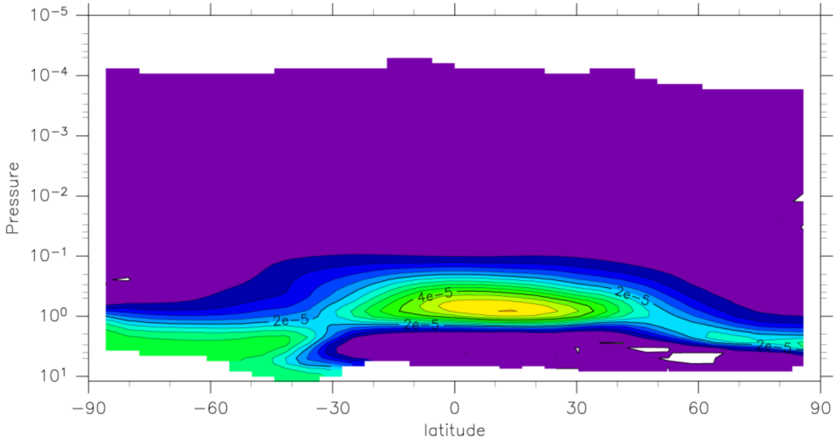
T [K]





Water cloud mass mixing ratio

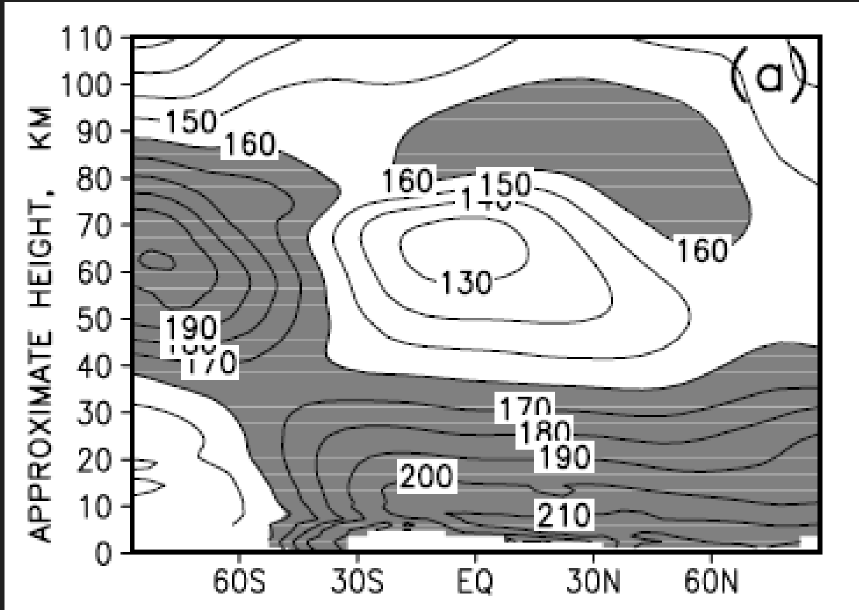




MAOAM-GCM (German)

MAOAM
Martian Atmosphere Observation And Modeling
Max Planck Institut für Aeronomie

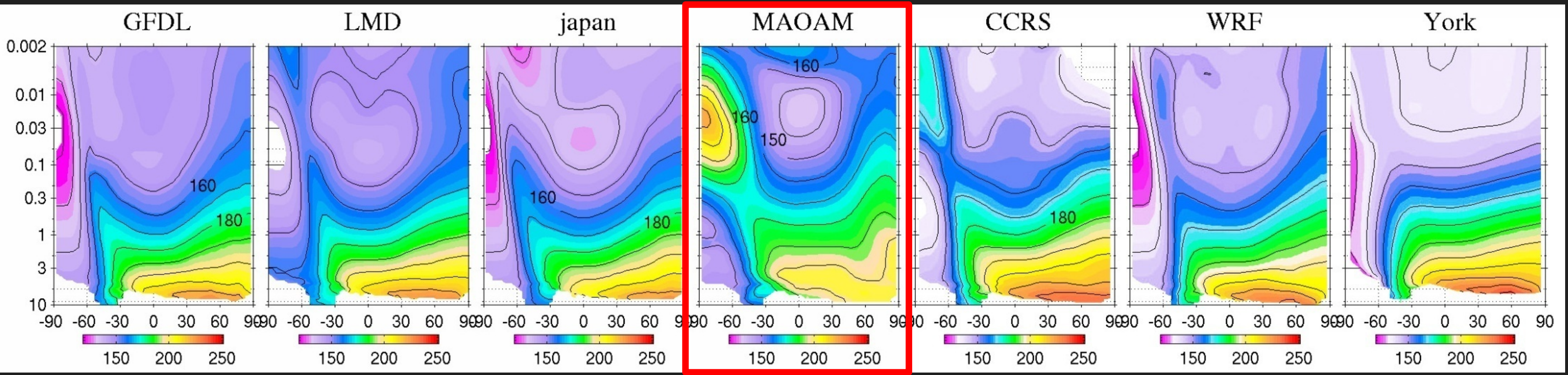
- Project started in April 2002
- Based on COMMA (COlogne Model of the Middle Atmosphere), from surface to ~130km height (lower thermosphere)
- New efficient non-LTE radiation scheme [Feofilov et al., 2006, Granada workshop]
- Kuroda’s contribution: Implementation of a dust radiation scheme
- First paper was published in 2005 (Hartogh et al., JGR)



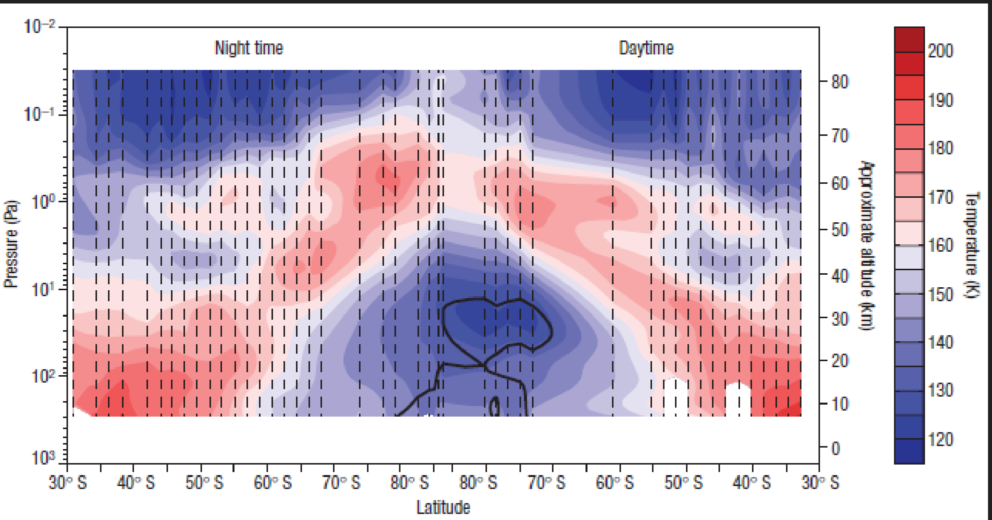
Strong polar warming produced

GCM intercomparison in 2006

(Second workshop on Mars atmosphere modelling and observations @Granada, Spain)



MCS observation [McCleese et al., 2008]



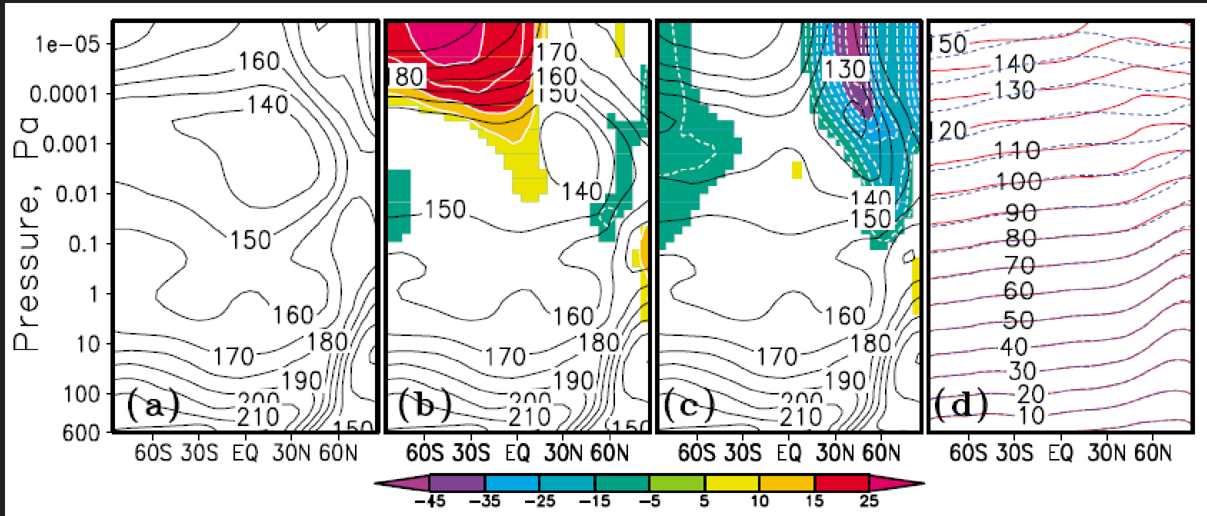
Only MAOAM well reproduced the winter polar warming above ~60 km!

New MAOAM-GCM

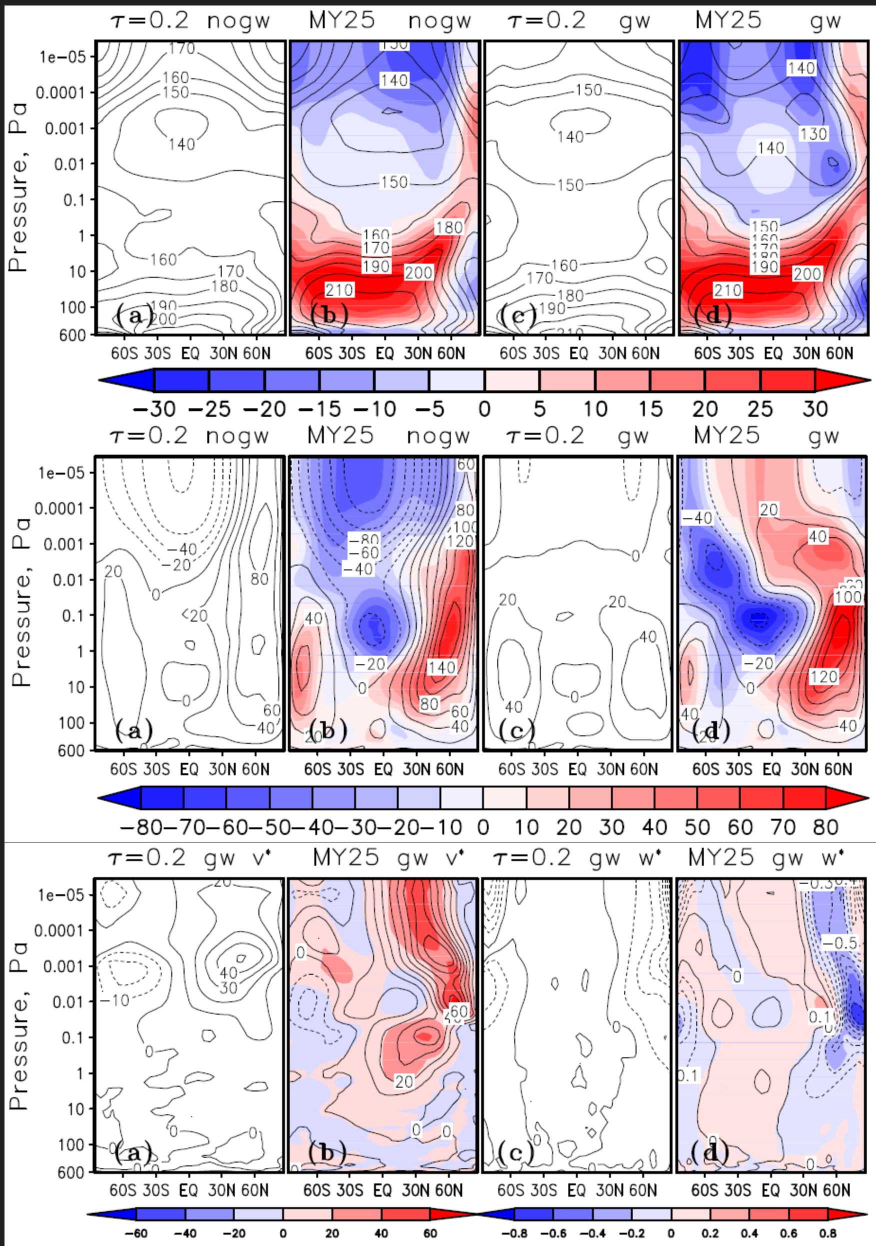
(Medvedev et al., 2011, JGR; Medvedev and Yigit, 2012, GRL; Medvedev et al., 2013, JGR)

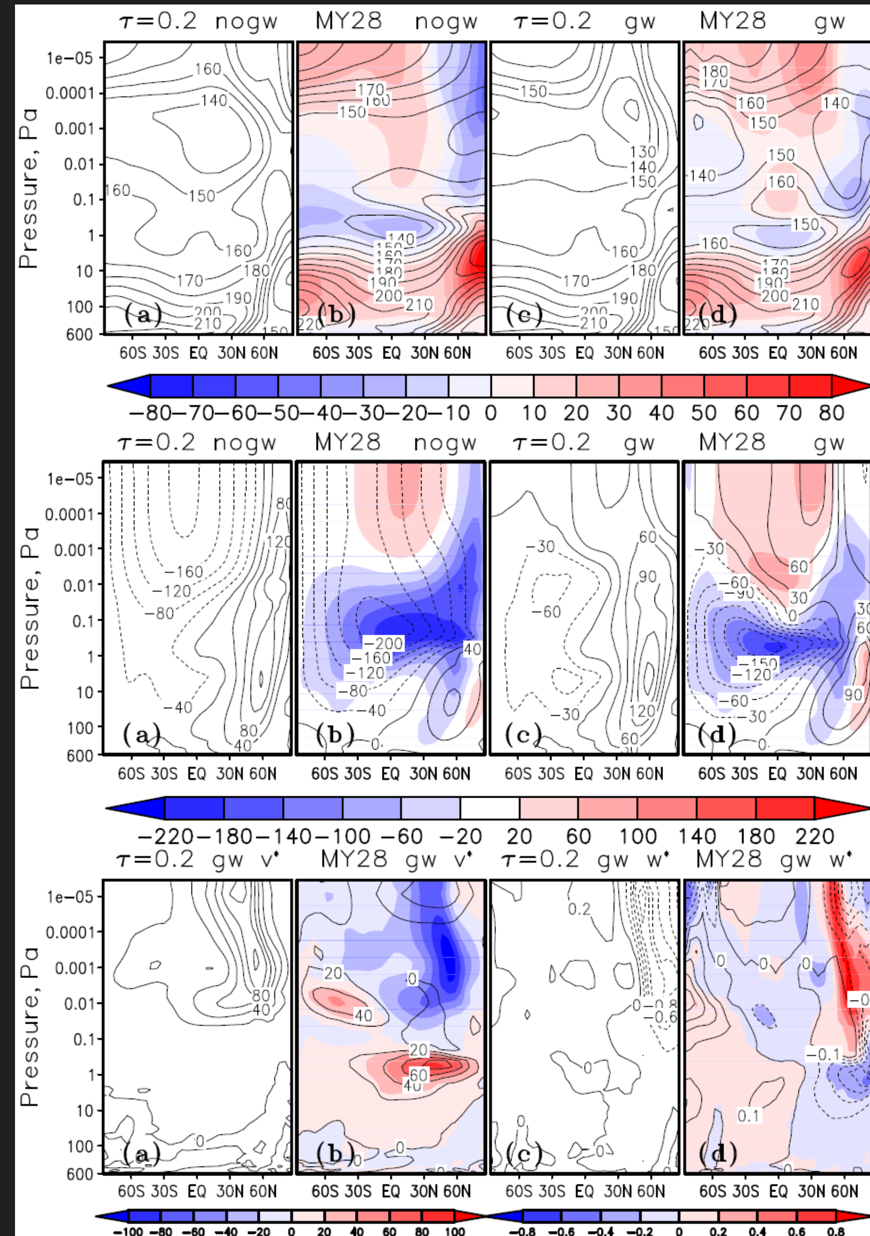
- New dynamical core of Kühlungsborn Mechanistic General Circulation Model (KMCM) with spectral solver
- Horizontal resolution of ~5.6° × 5.6° , 67 hybrid vertical levels up to 150-160 km
- EUV heating is implemented [Torr et al., 1979; Richards et al., 1994]
- Gravity wave drag parameterization (dynamical and thermal effects)

(a) No GW drag
(b) GW drag (only dynamical)
(c) GW drag (dynamical and thermal)
(d) Geopotential height
[Medvedev and Yigit, 2012]



Effects of the global dust storm in MY25 and MY28 on the thermosphere [Medvedev et al., 2013]





Future plans with both MGCMs (and more)

- Radiation scheme of both MGCMs will be common (effects of CO_2 and dust/cloud particles in lower atmosphere, non-LTE effects of CO_2 radiation in middle atmosphere, EUV heating in upper atmosphere)
- DRAMATIC: Implementation of the atmospheric chemistry for the approach to the interactions between lower (water cycle, dust storm) and upper (atmospheric escape) atmospheres
  (DRAMATIC will be the abbreviation of "Dynamics, RAdiation, MAterial Transport, Isotopomer and Chemistry")
- Medvedev and Kuroda participate in the MAVEN science team (IUVS, NGIMS): studies using the obtained data of composition/density profiles are planned
- Development of a Jupiter stratospheric GCM (will be talked on Thursday)
- And so on… (preparing for some publications…)