# Mars Global Climate Model (GCM)

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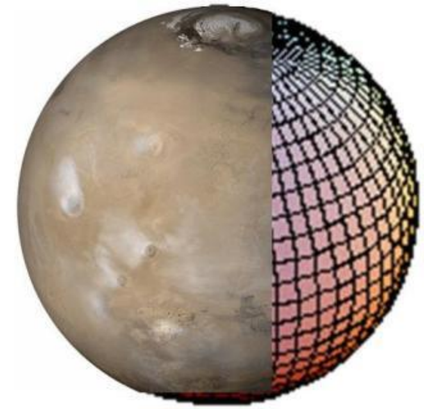
and the MCD/GCM team

# The LMD Mars Global Climate Model

- 1st version developped in the early 1990s (Hourdin et al. 1993) ⇨ *Reference publication Forget et al.* (1999)
- Now applied to all aspect of Mars atmospheric Sciences: Toward a "Mars System Model"

# The LMD/IPSL « Mars system simulator »



**Atmospheric Dynamics**

**Exosphere Atm. Escape**
*(Latmos, LMD)*

**$CO_2$ Cycle**
*(LMD, Latmos IDES)*

**Mars GCM**

**Thermosphere Ionosphere**
*(IAA, LMD, Latmos)*

**Mesoscale Model / LES**
*(LMD)*

**Dust cycle**
*(Oxford U., LMD, LISA, Latmos)*

**Photo-Chemistry**
*(Latmos, IAA)*

**Water Cycle**
*(LMD, Latmos)*

**Radon Cycle**

**Climate variations & paleoclimates**
*(LMD, Brown U, IDES.)*

**Volcanic eruption simulations (with Brown University)**

**HDO cycle**
*(Latmos, Lesia)*

**Ancient Mars**
**(- 3 à -4 Gyr**
***(avec Harvard University Obs. Royal de Belgique)***

*l'Andalousie)*

**« Mars Climate database »**
- Reference tool for the Scientific and Space Engineer community
- Version « pro » on DVD-ROM ordered par ~250 teams from ~20 countries
- Interactive website

# The LMD Mars Global Climate Model

- 1st version developped in the early 1990s (Hourdin et al. 1993) ⇨*Reference publication Forget et al.* (1999)
- Now applied to all aspect of Mars atmospheric Sciences: Toward a "Mars System Model"
- The GCM is constantly improved.
  - The current version is the outcome of 8 years of intense development to renew the model…
  - Validation with several datasets

  ⇨Used to produce a new Mars Climate Database version 5 (see talk on Thursday by Ehouarn Millour)

# Basic characteristics of the Mars Global Climate Model :

**1) LMDZ final Dynamical Core (Grid point Model)**

## 2) Radiative transfer:

- **TIR $CO_2$ wide band model (Hourdin 1991) + NLTE model (Lopez-Valverde 2011)**
- **NIR $CO_2$ (NLTE)**
- **EUV absorption**
- **Aerosols: Toon et al. 1989**

***6) Dust transport and distribution : see below***

## 3) Subgrid scale dynamics

- **Turbulence: Mellor and Yamada 2.5 Scheme**
- **Convection : see below**
- **Gravity waves (orographic) + low level drag:** Prametrisation of impact on the main flow

## 5) Volatile:

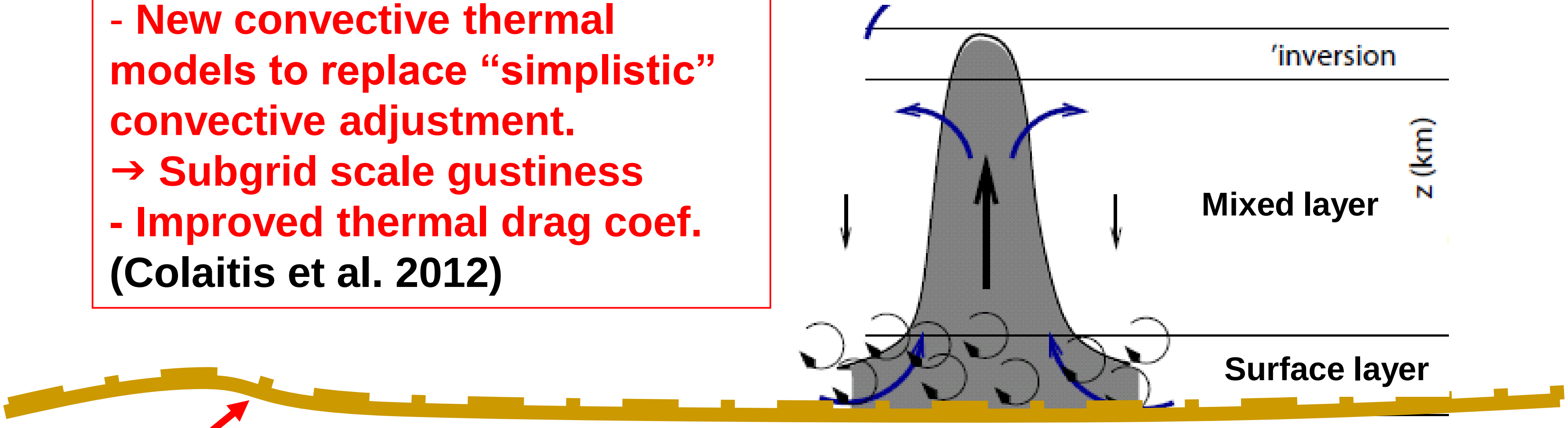
- **$CO_2$ cycle: see below**
- **$H_2O$ cycle: see below**

**4) Surface and subsurface thermal balance**

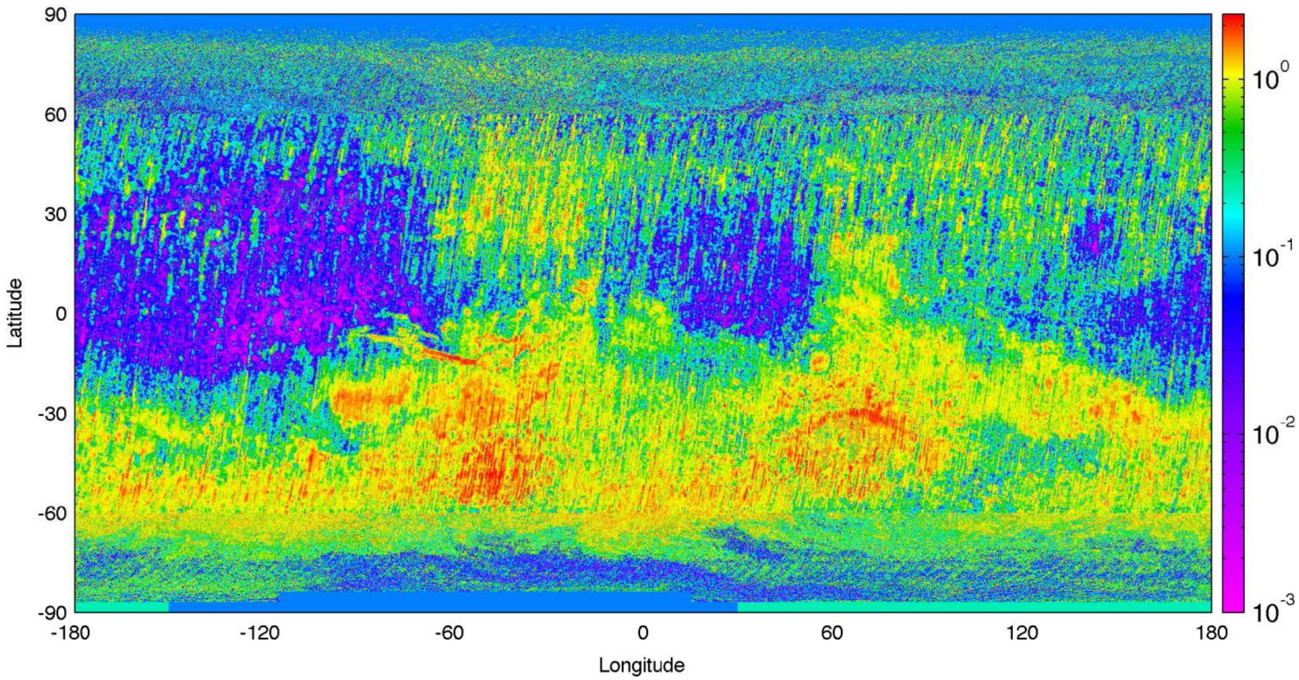
*Forget and Lebonnois (2013) In “ComparativeClimatology of Terrestrial Planets” book, Univ of Arizona press 2013*

# Improved Dynamics, Convection and Turbulence Model

- New convective thermal models to replace "simplistic" convective adjustment.
→ Subgrid scale gustiness
- Improved thermal drag coef.
(Colaitis et al. 2012)

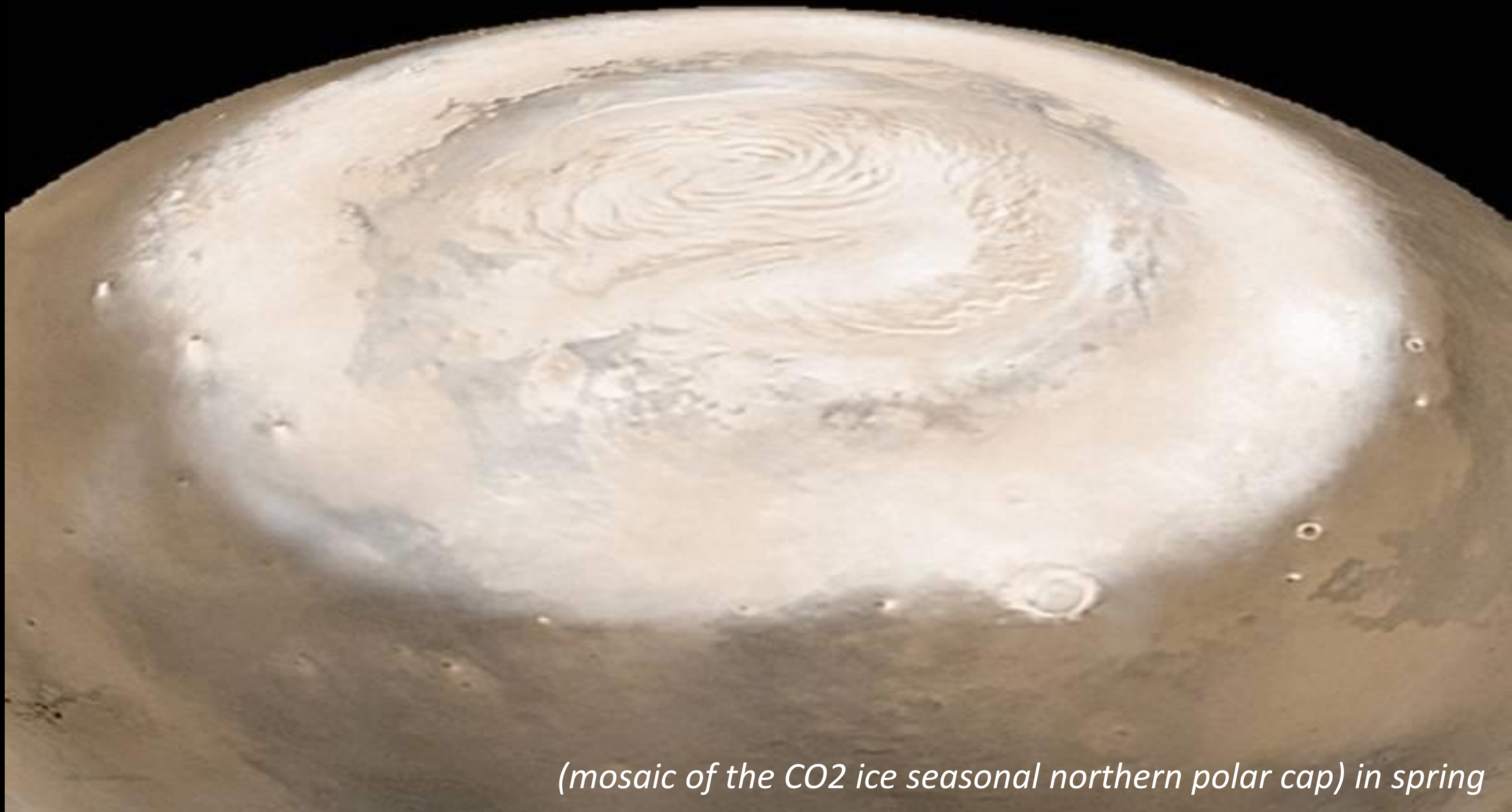



New Roughness Length "$z_0$" Map derived from Extended Martian Rock Abundance Data
*(Hebrard et al. 2011)*



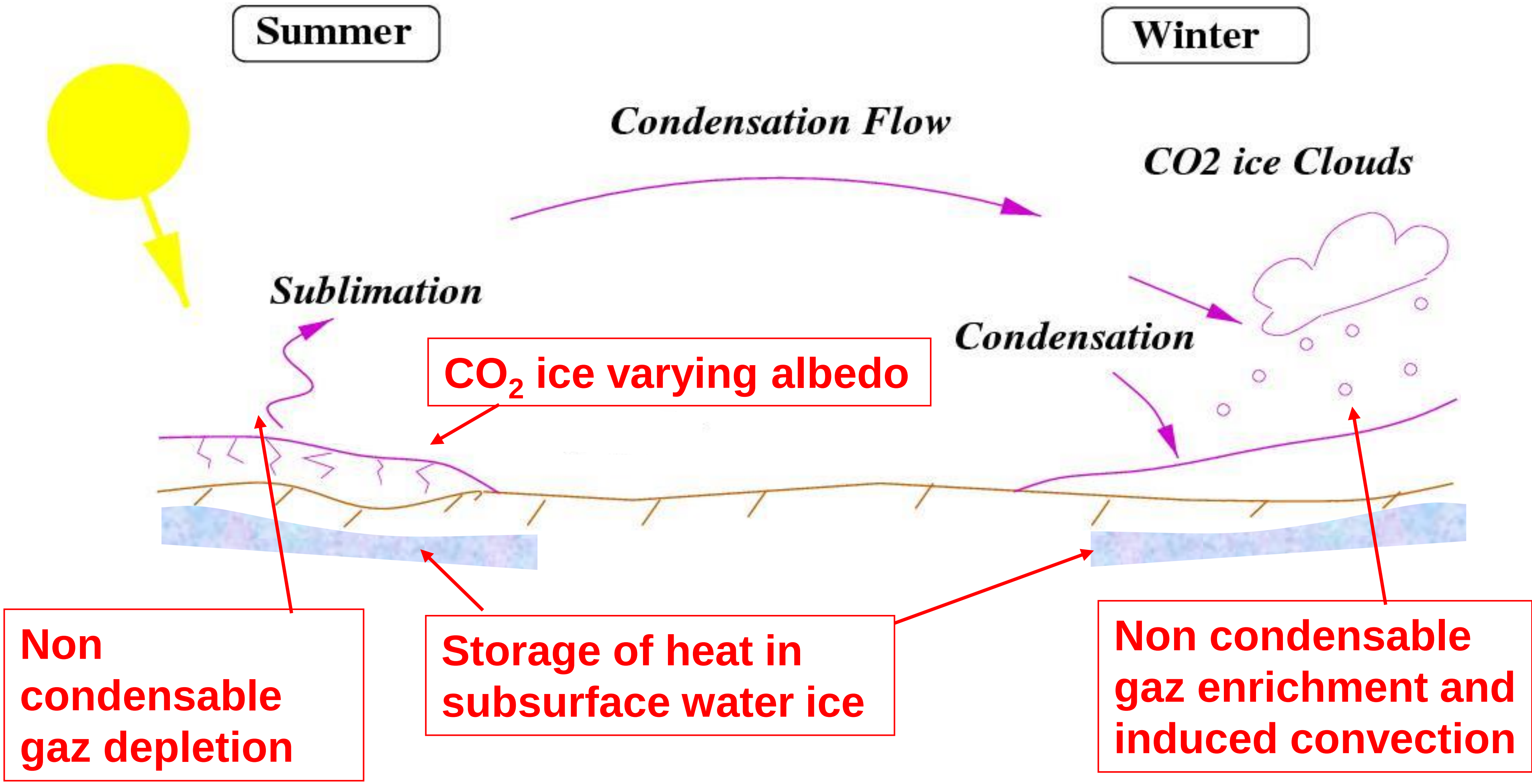
## $CO_2$ の循環

# 炭酸ガスの氷の層



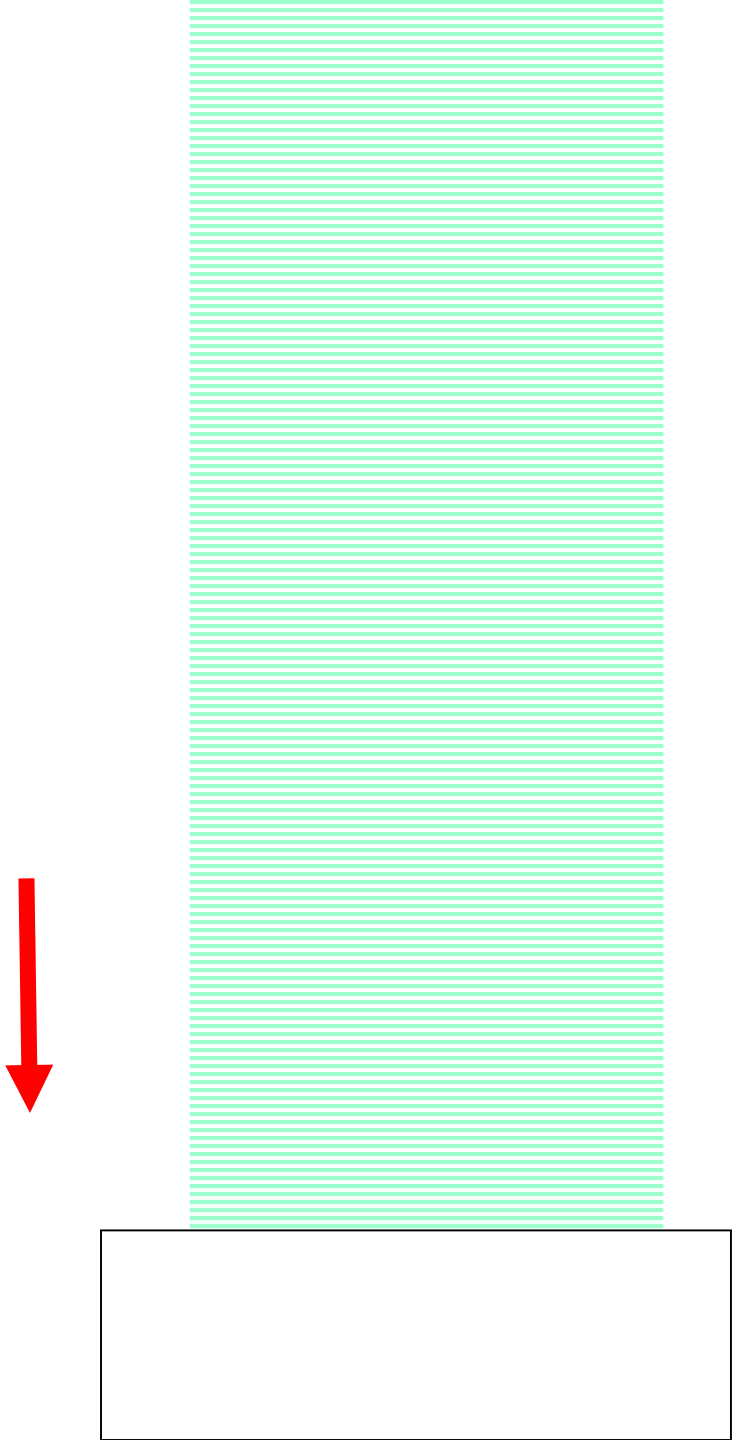
*(mosaic of the CO2 ice seasonal northern polar cap) in spring*

# Improved $CO_2$ cycle

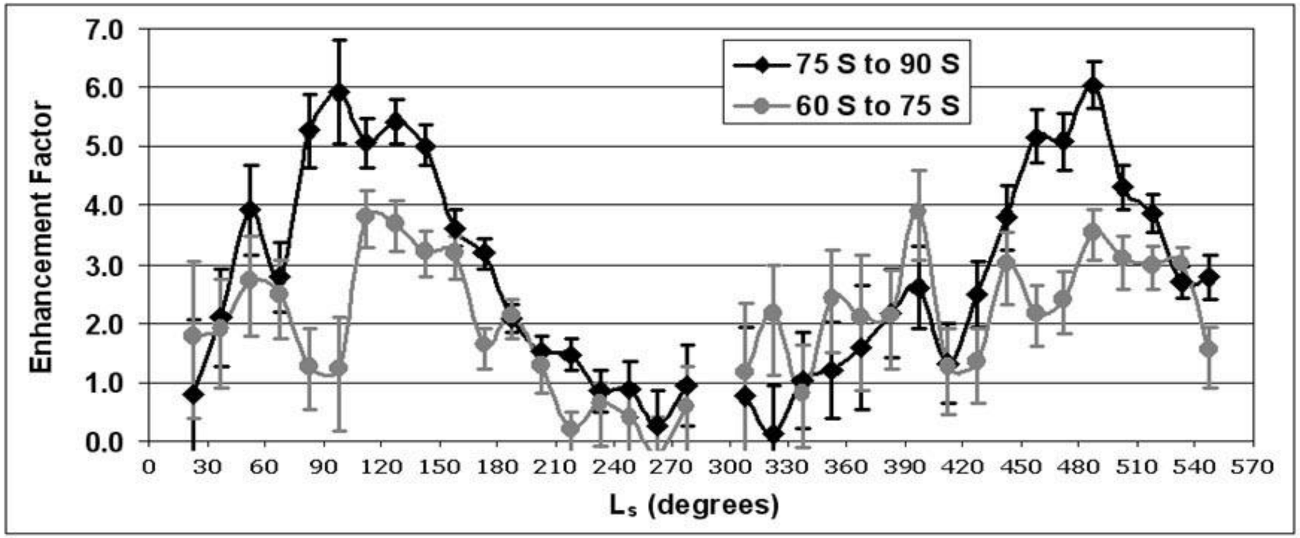


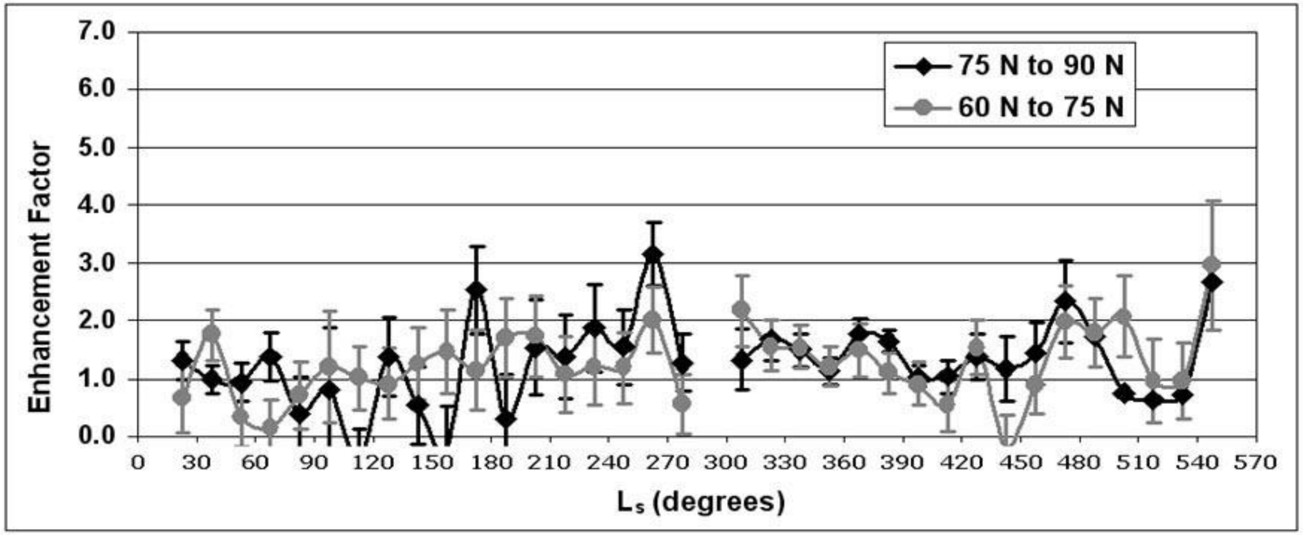
Surface condensation of CO2

Near Surface enrichment of other gases



# Argon enhancement observed by Mars Oddyssey GRS



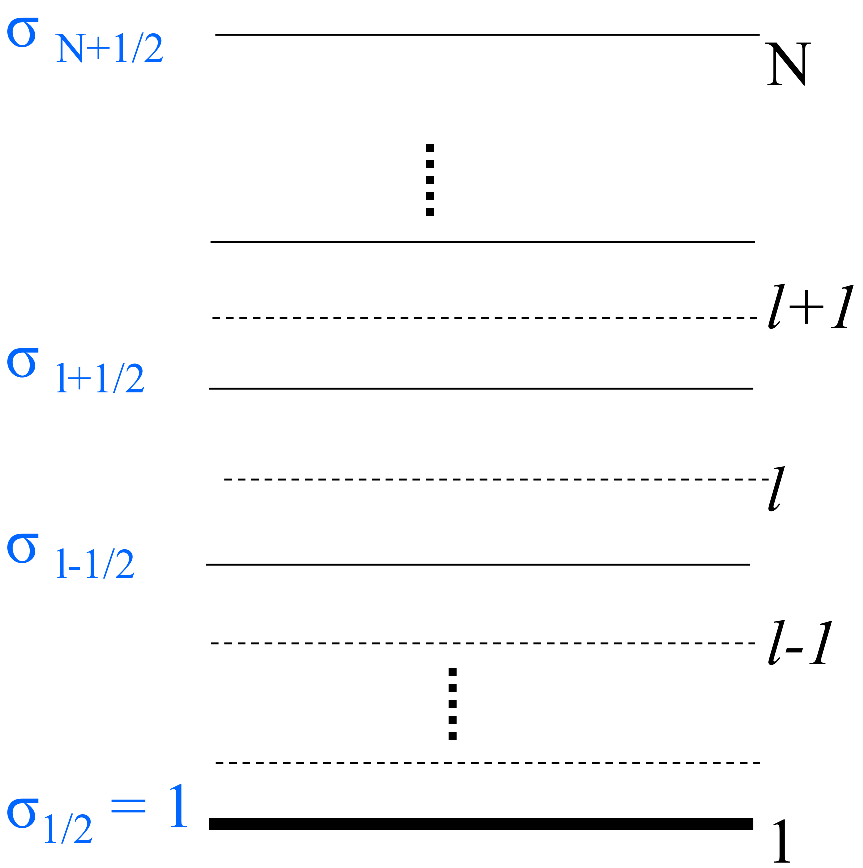

Sprague et al. Granada 2006

# Computation In a discretized world (GCM)

- In « hyprid coordinate » $\sigma = p/ps \rightarrow p$

⇨ each model layer is define by its boundary

$\sigma_{l+1/2}$ $\sigma_{l-1/2}$



Surface condensation of CO2

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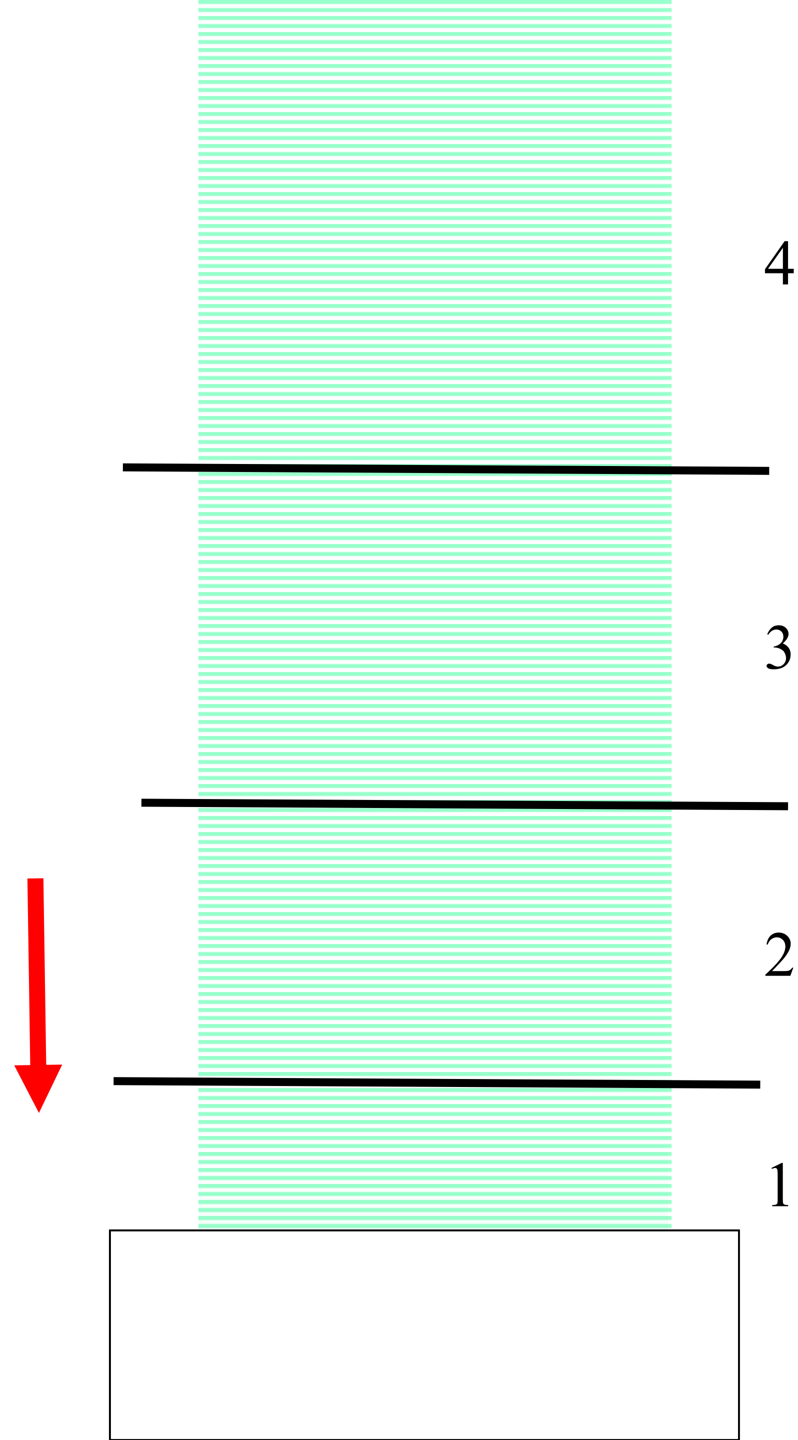


# Mixing and convection induced by non-condensible gas enrichment

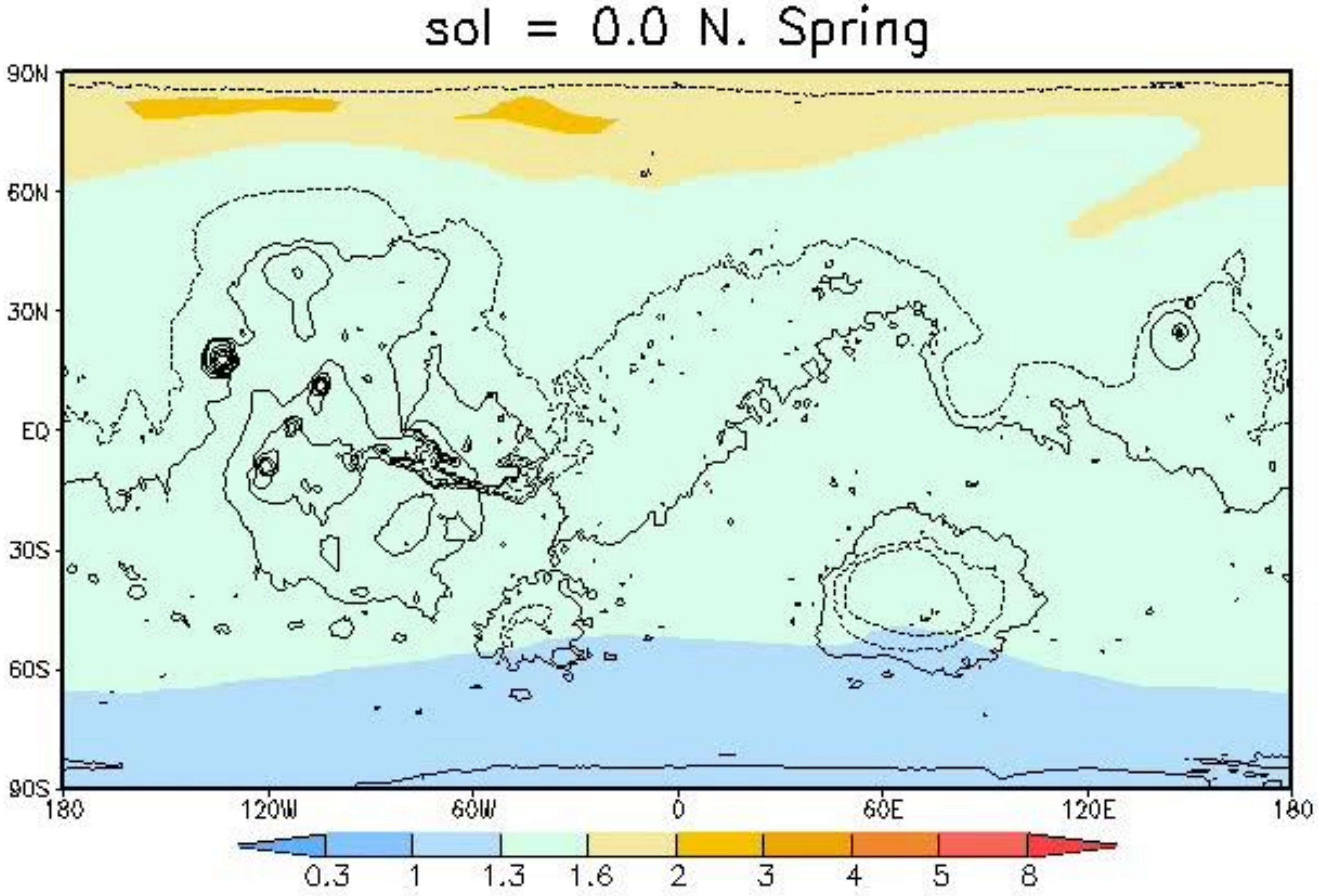
- $CO_2$ : $m$ = 44.0E-3 kg mol-1
- Non-condensible gas ($N_2$, Ar) are lighter:

  ⇨ $m$ = 32.37E-3 kg mol -1 (*Hess, 1979*)
- Induce convection near the surface !
- Density changes ( $\rho = Pm/(8.314\ T)$ ) :

  *$\Delta m$ gradient equivalent to a temperature gradient*

  $\Delta T = m/T\ \Delta m$

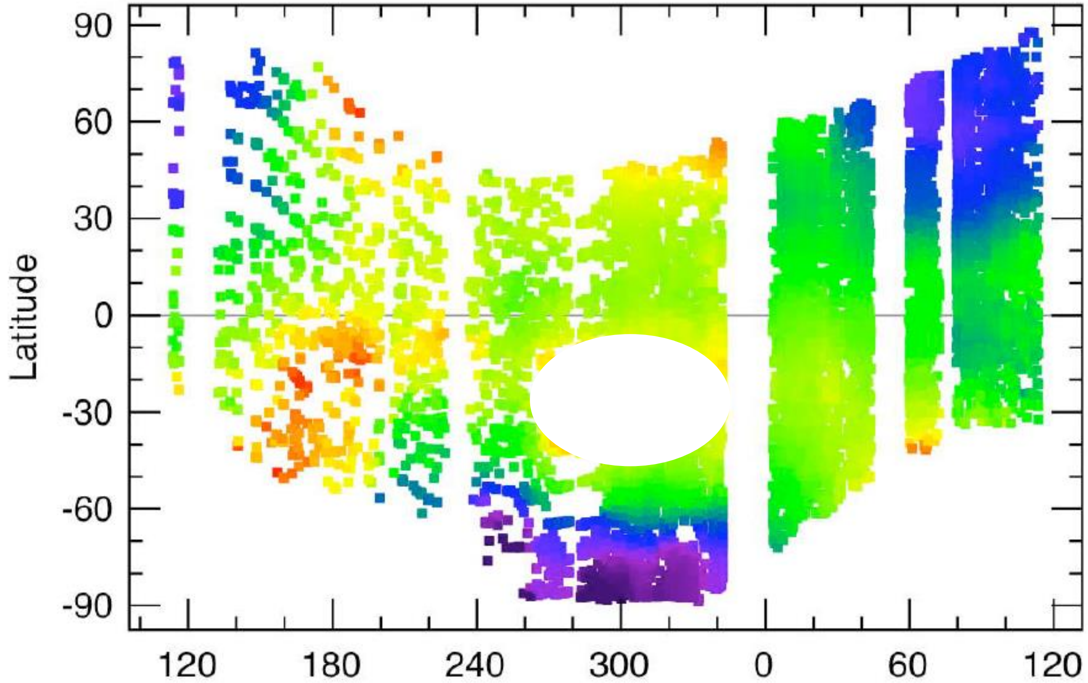
# Argon column averaged mixing ratio (%)



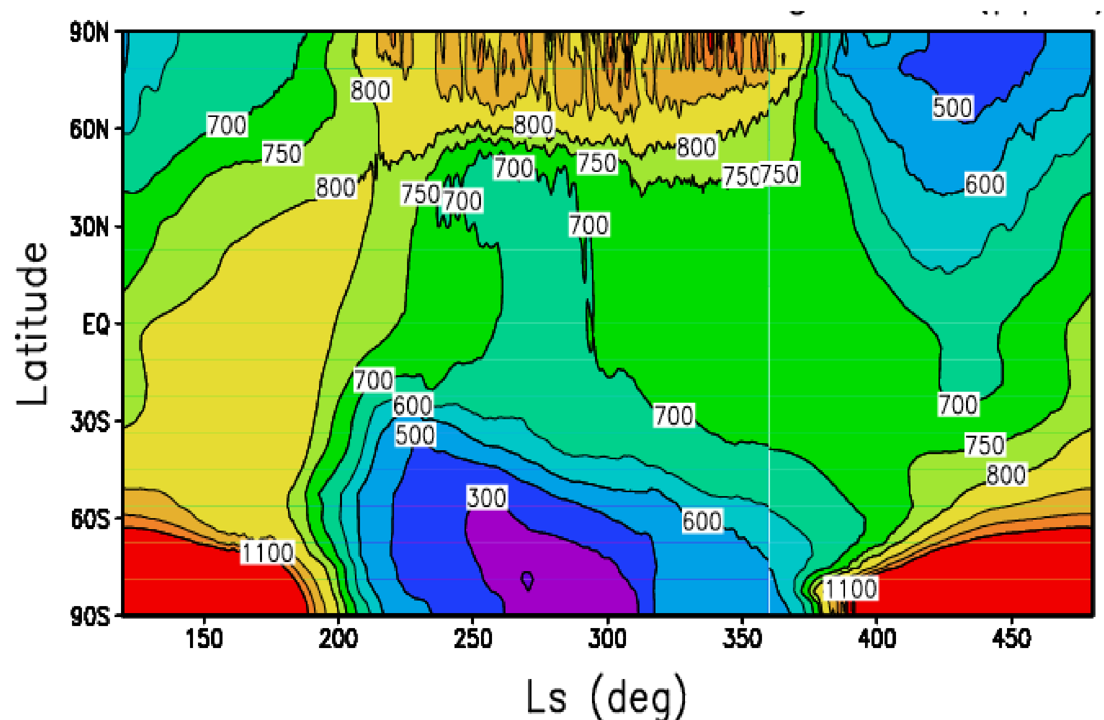
# Observation of CO by CRISM (ppm)

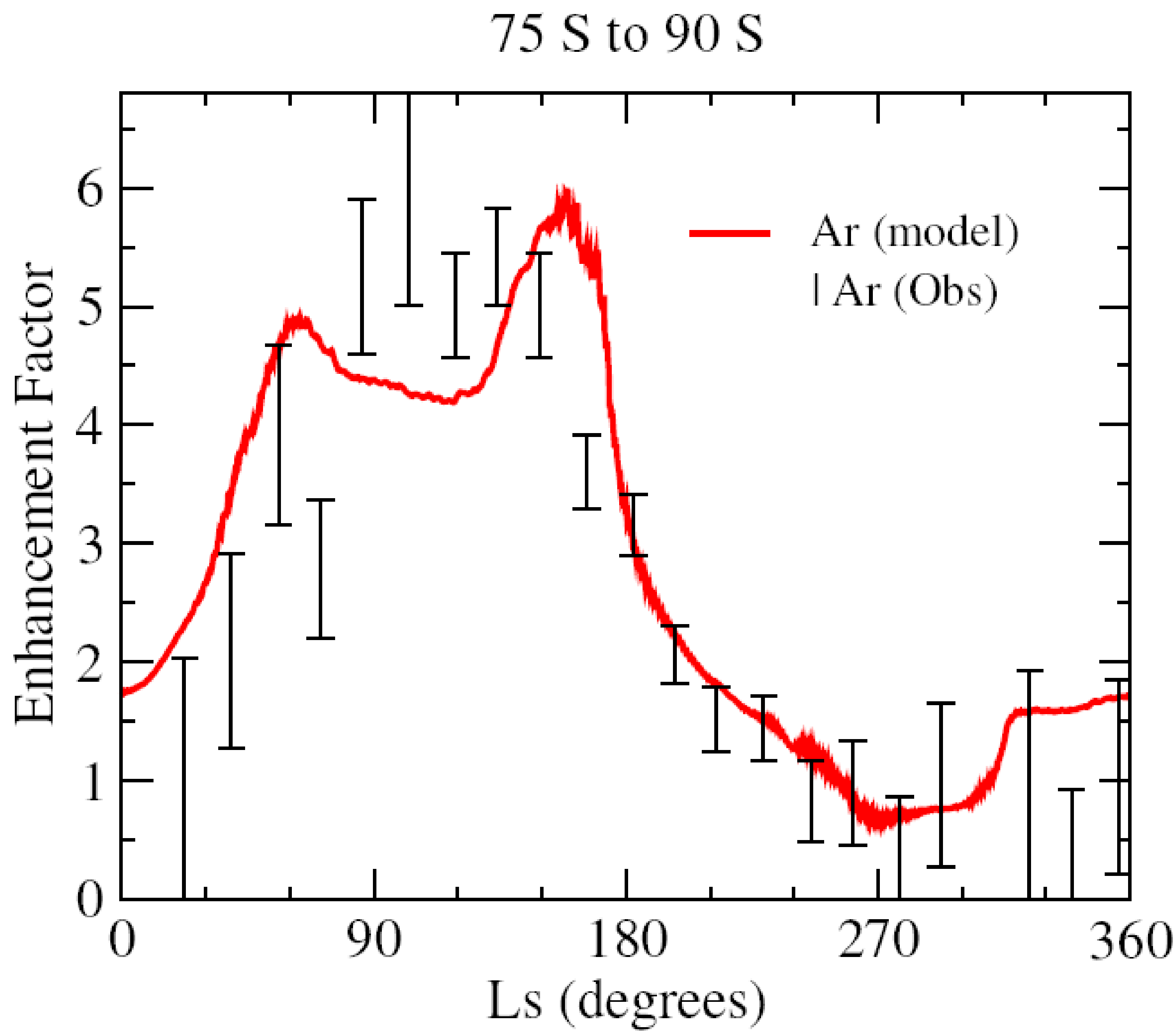
*(Mike Smith 2008)*

Observations

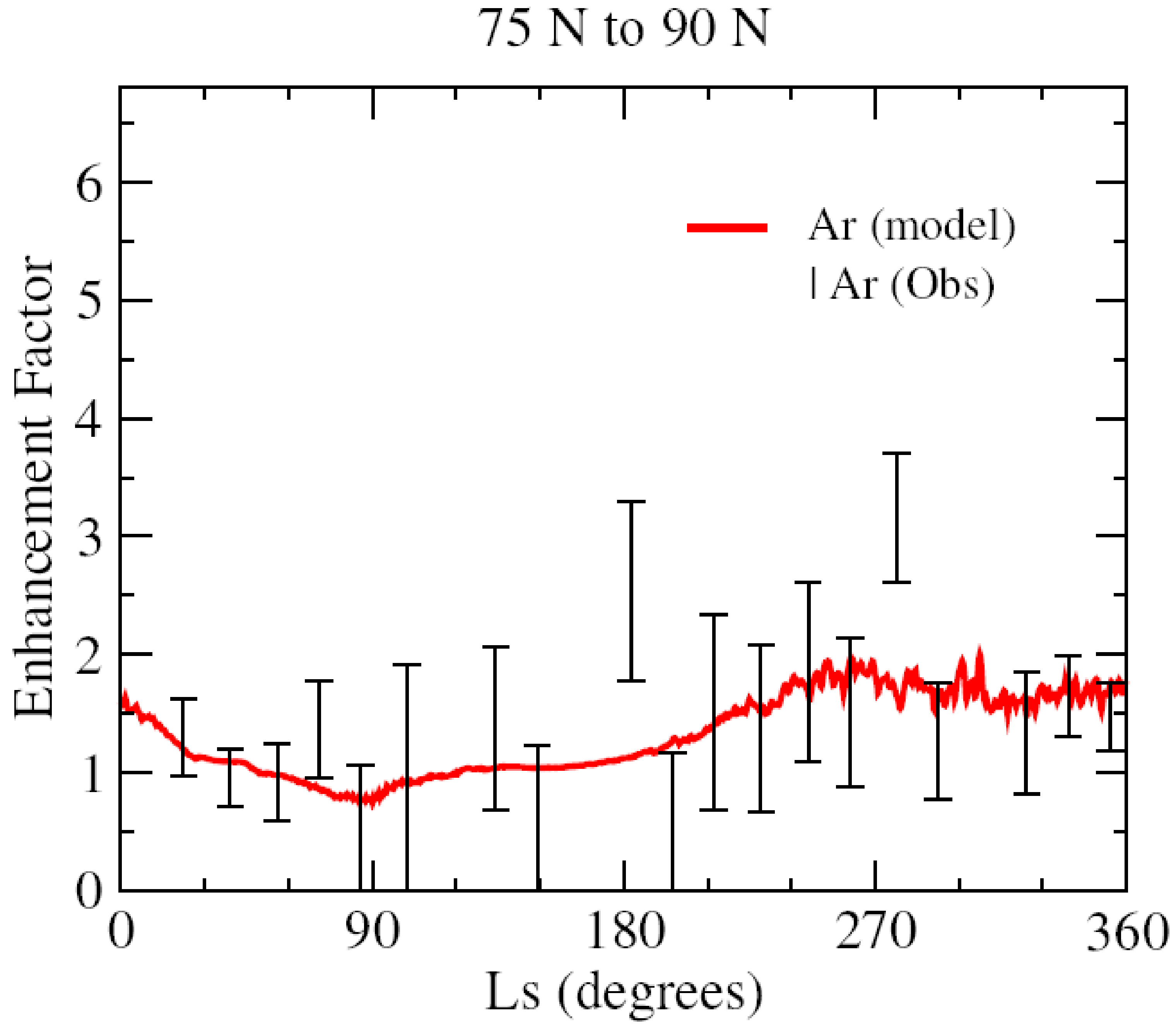



Model





75 S to 90 S
Enhancement Factor
Ls (degrees)
Ar (model)
Ar (Obs)
0
1
2
3
4
5
6
0
90
180
270
360


75 N to 90 N
Ar (model)
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0
1
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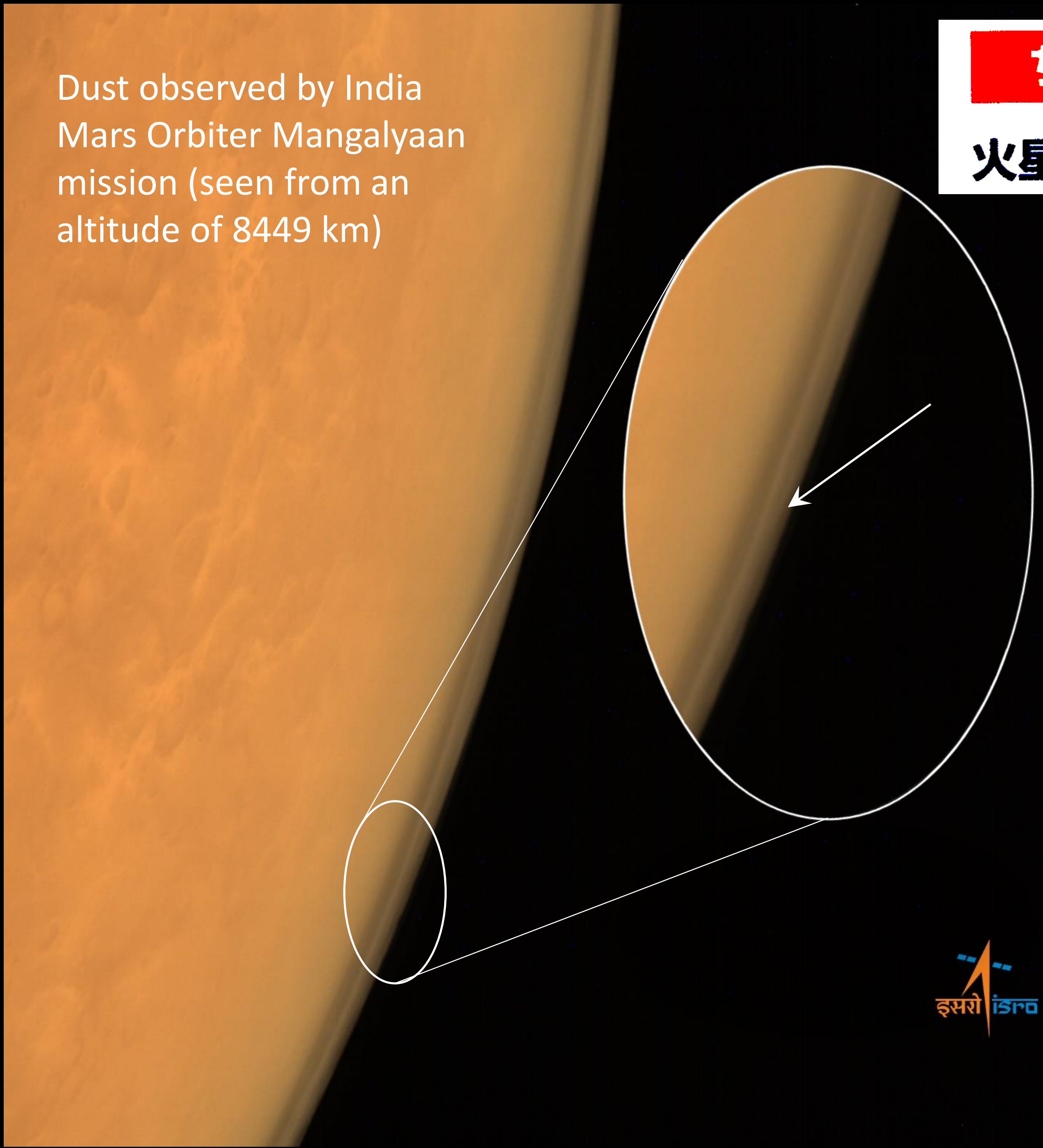
270
360

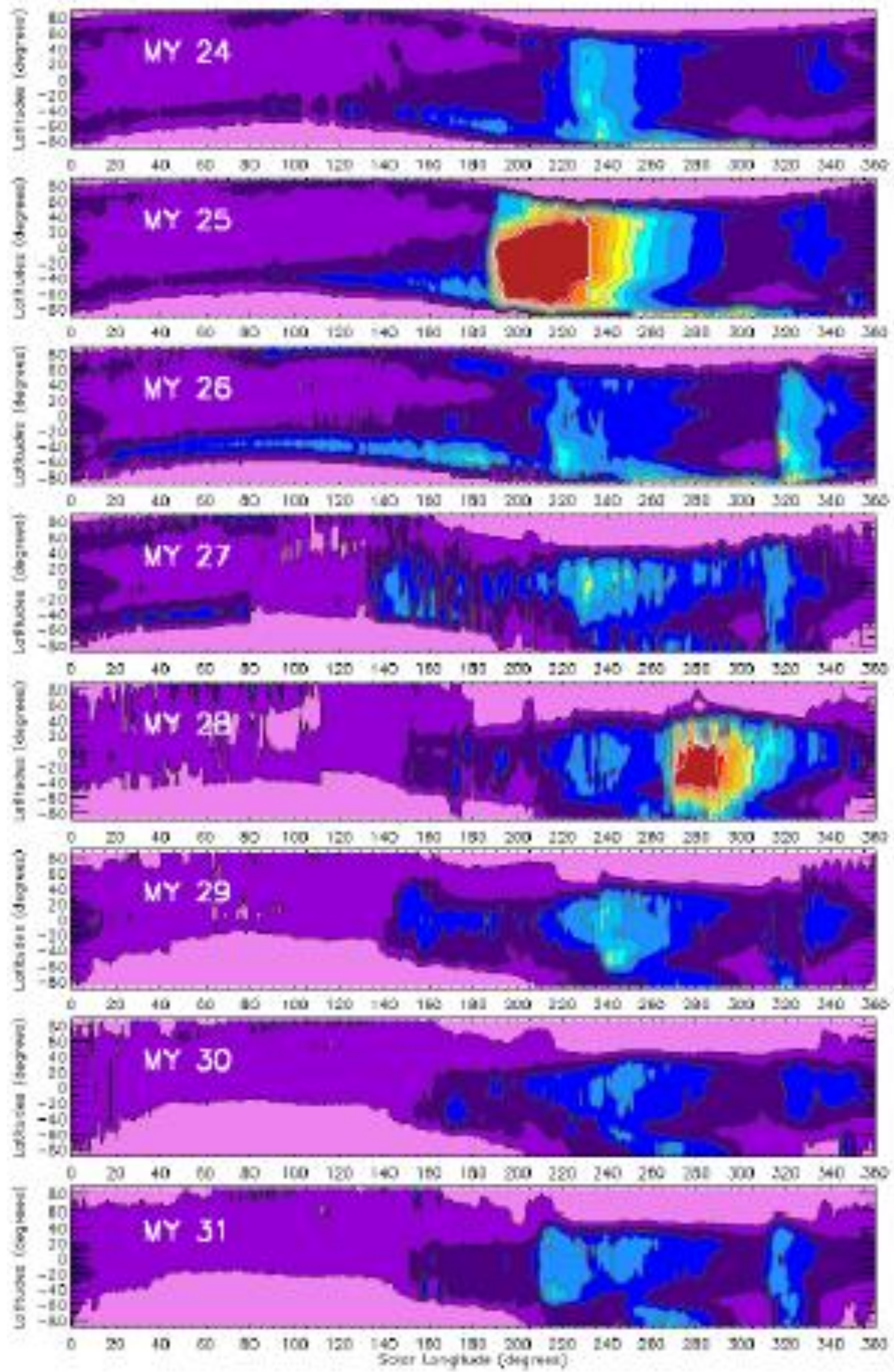
## ちりの循環

**火星大気に浮遊するちり**

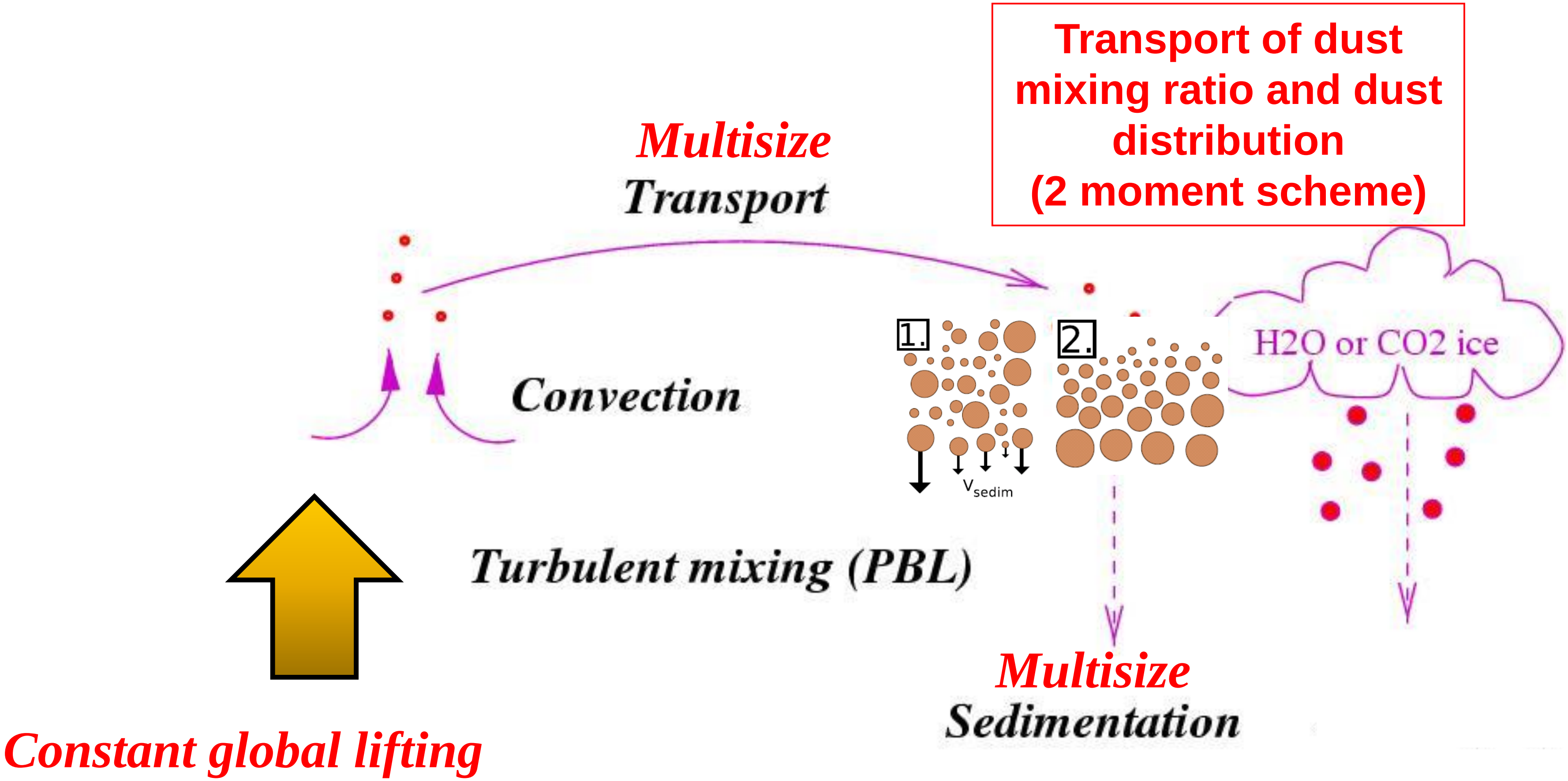


DUST SCENARIOS
Zonal mean of reconstructed column dust opacities for martian year 24-31


*Montabone et al. 2015 (Icarus)*

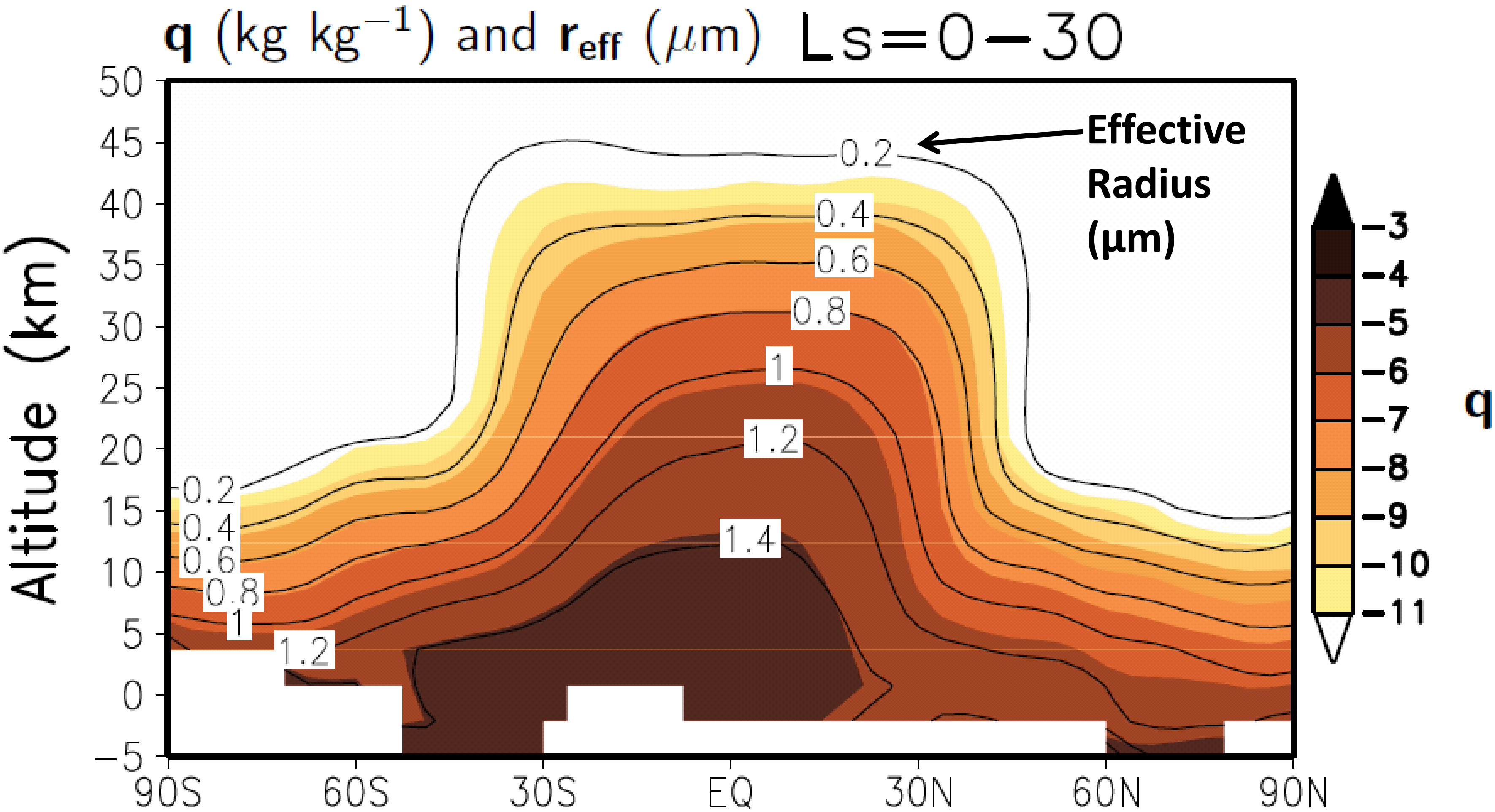


# Improved "dust model" to simulate observed Martian years (MY24 – MY31)




*(Madeleine et al. 2011)*

## Transported dust mixing ratio and size distribution (2 moment scheme)




*Madeleine et al. 2011*

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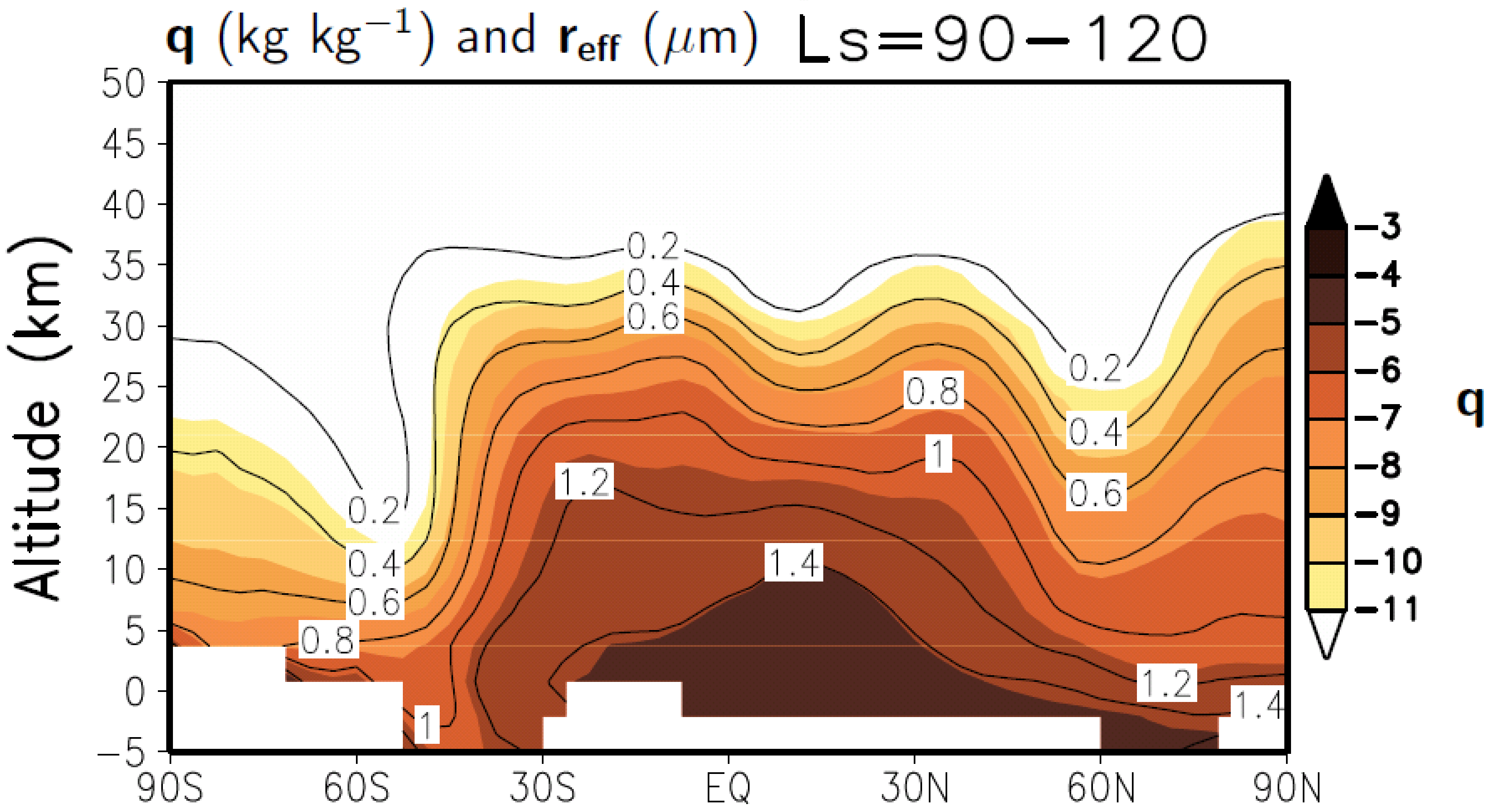


*Madeleine et al. 2011*

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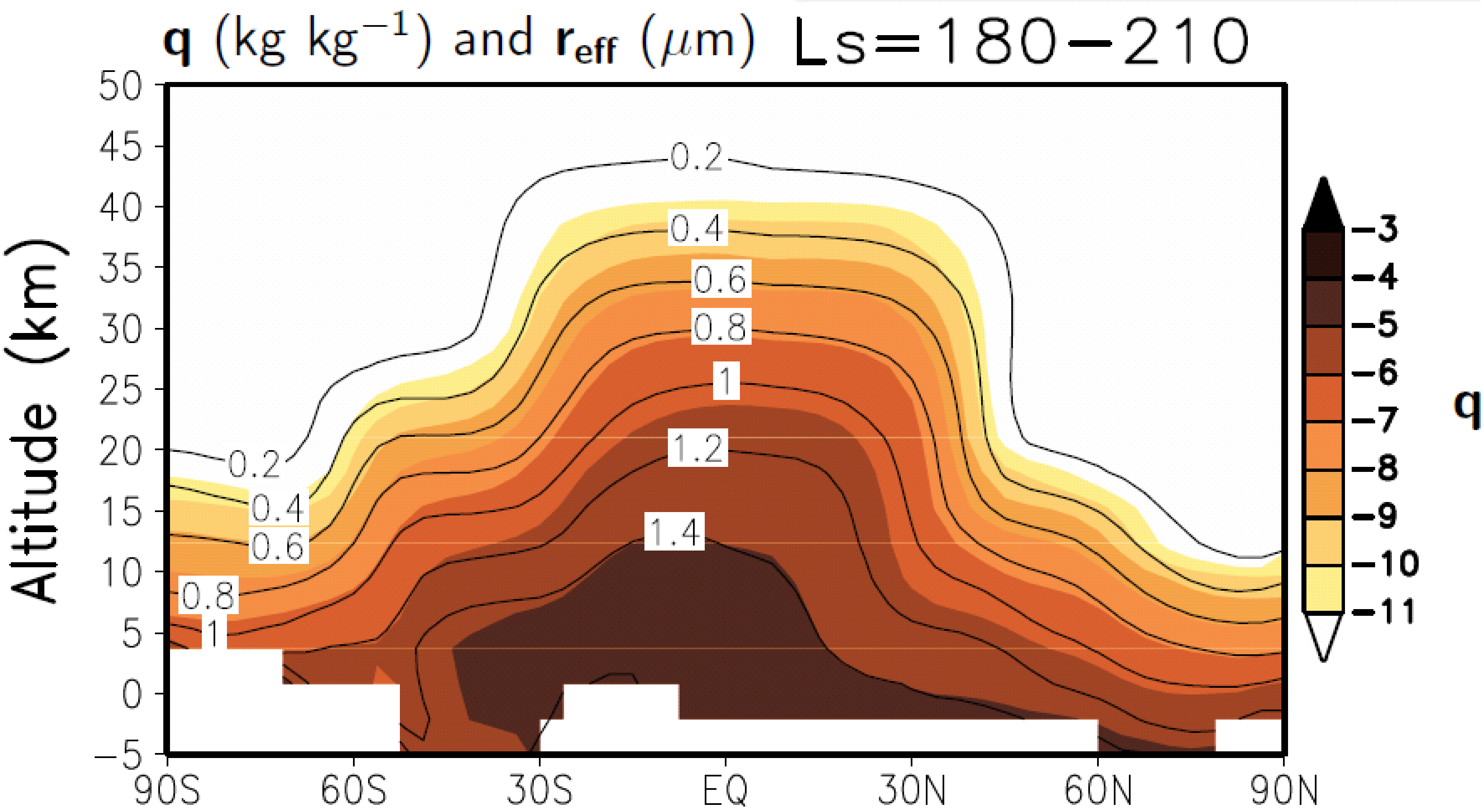


*Madeleine et al. 2011*

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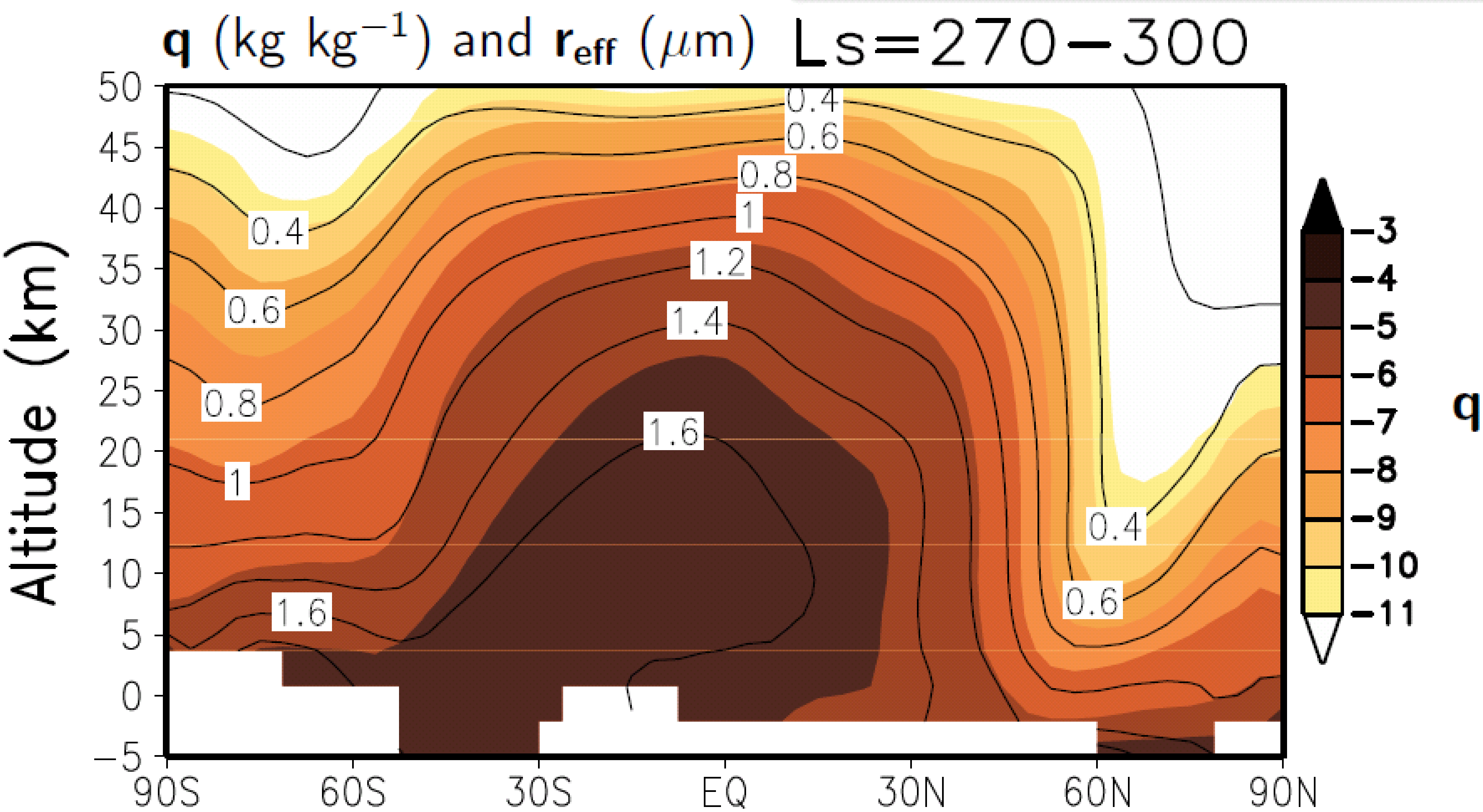
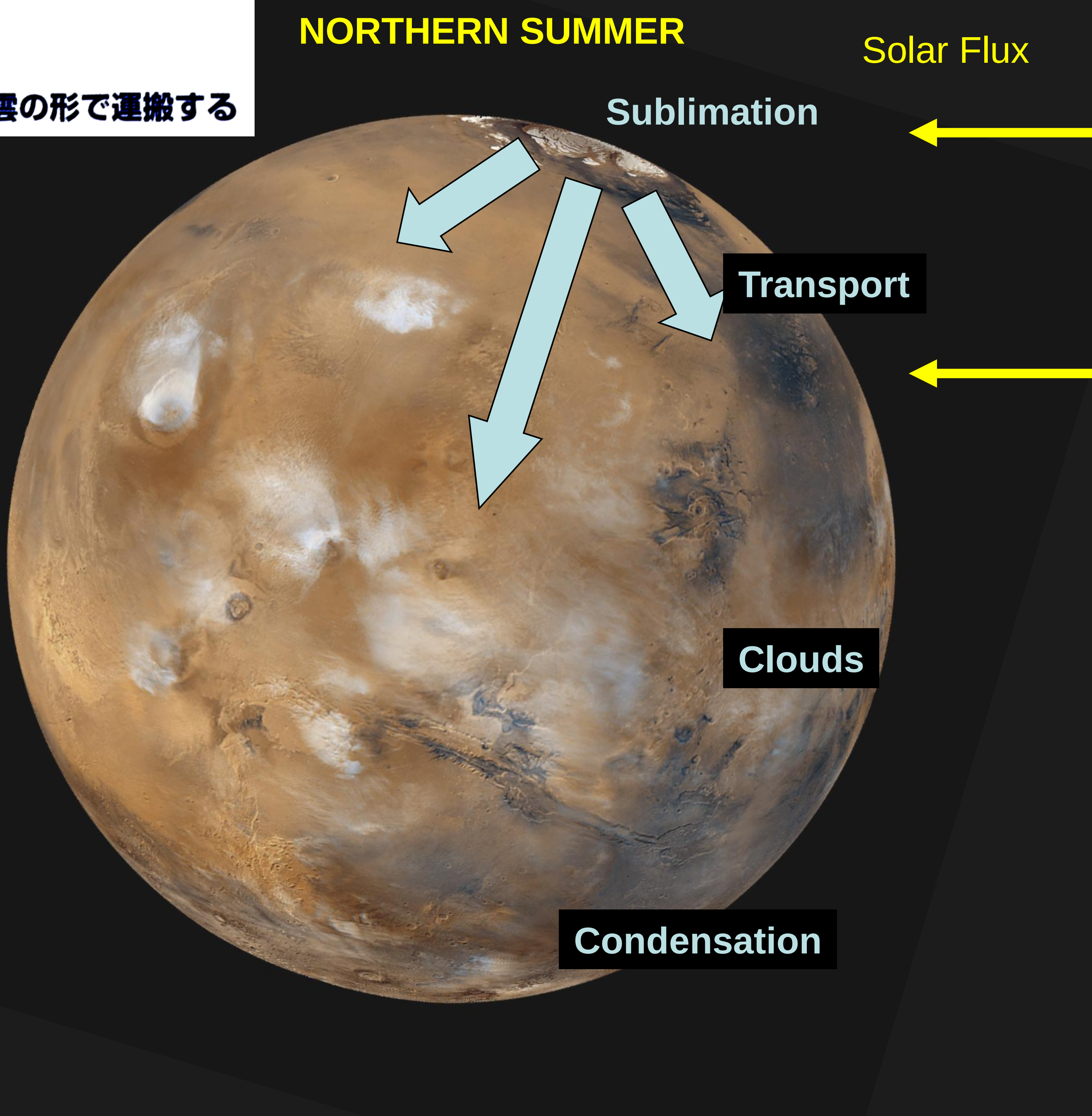


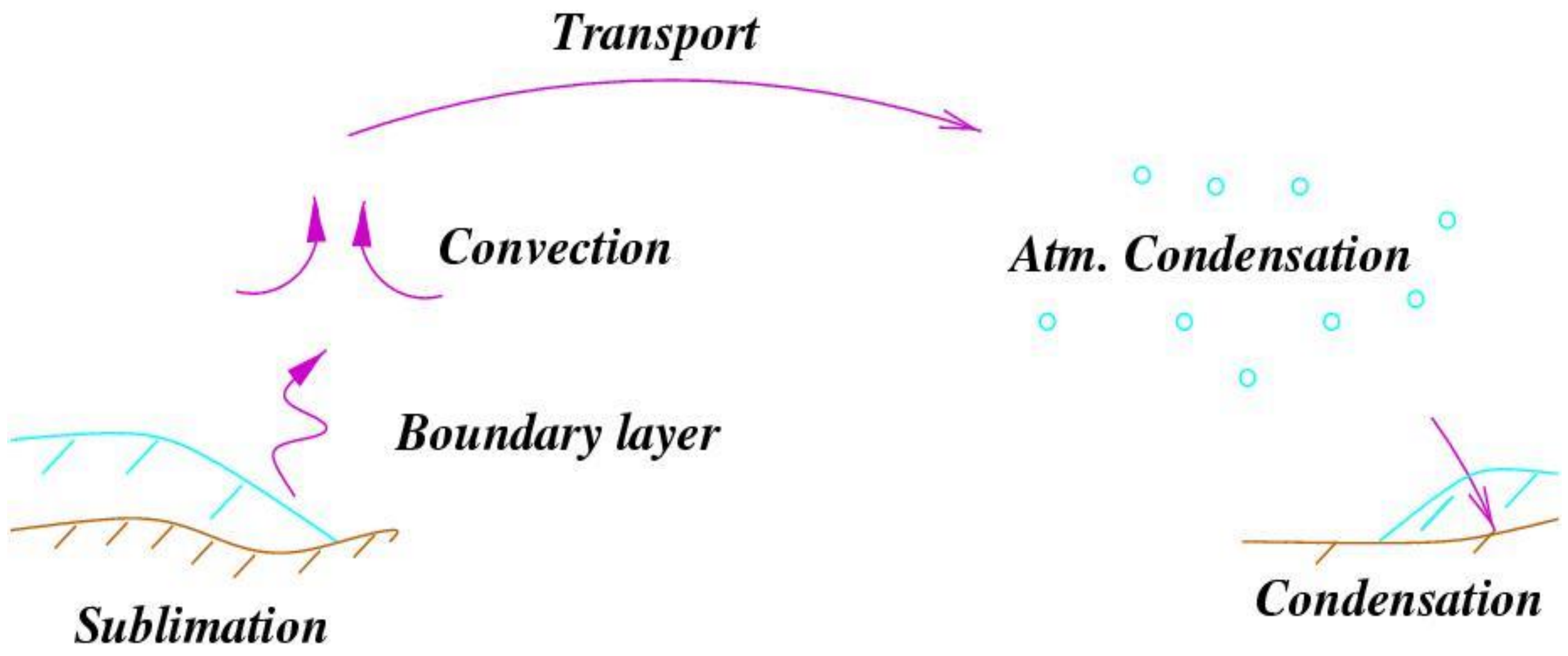

*Madeleine et al. 2011*

水循環

火星大気は水を水蒸気や雲の形で運搬する



# Modelling water cycle and clouds



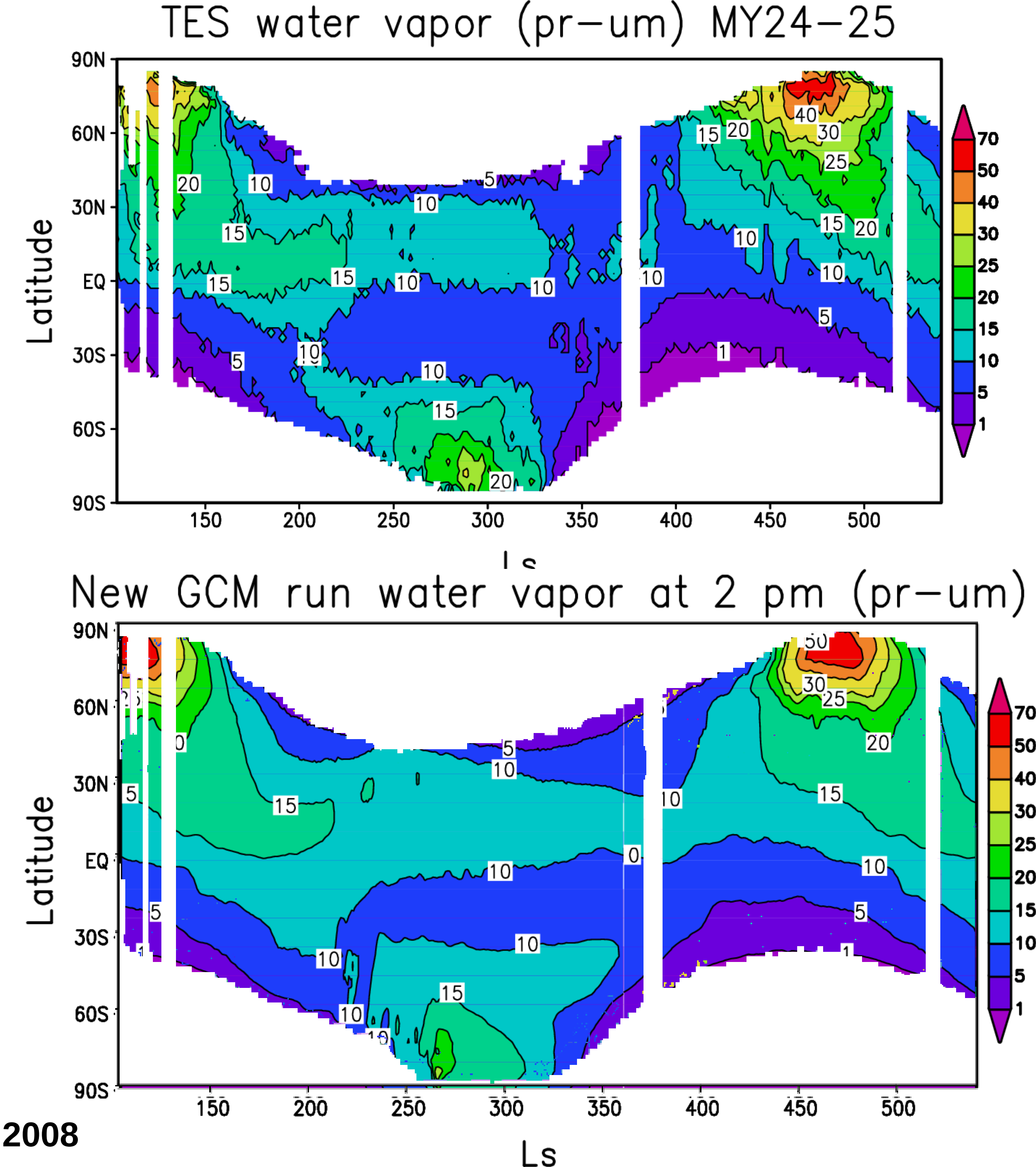
# EARLY GCMS SIMULATION of Mars water cycle: 1) water vapor

OBSERVATION

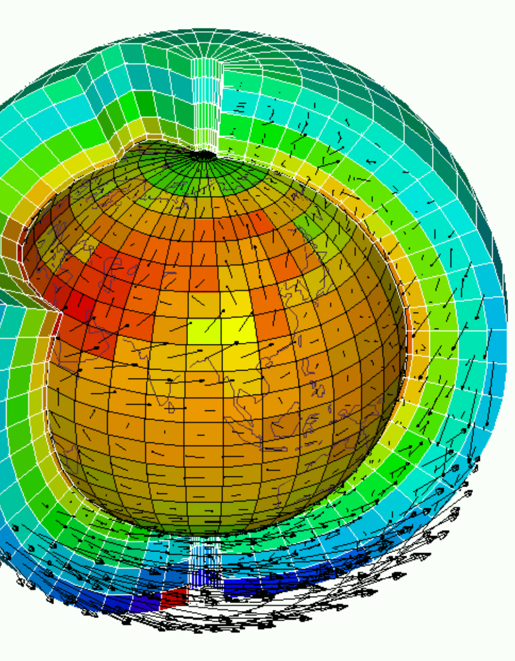
(TES, Smith 2007)

MODEL

(LMD GCM)




Montmessin et al. 2004, Forget 2008



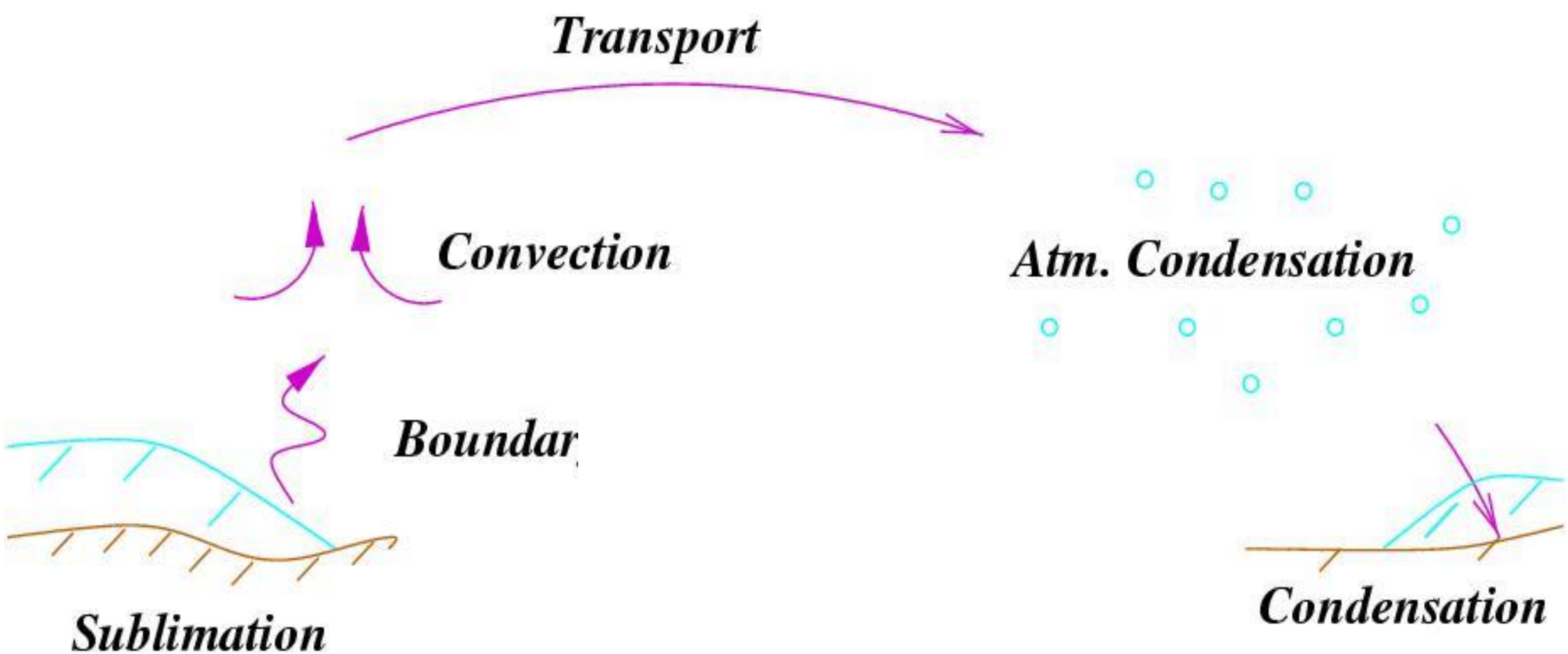
Did these « simple » GCM simulations explain the entire water cycle ?

No ! :

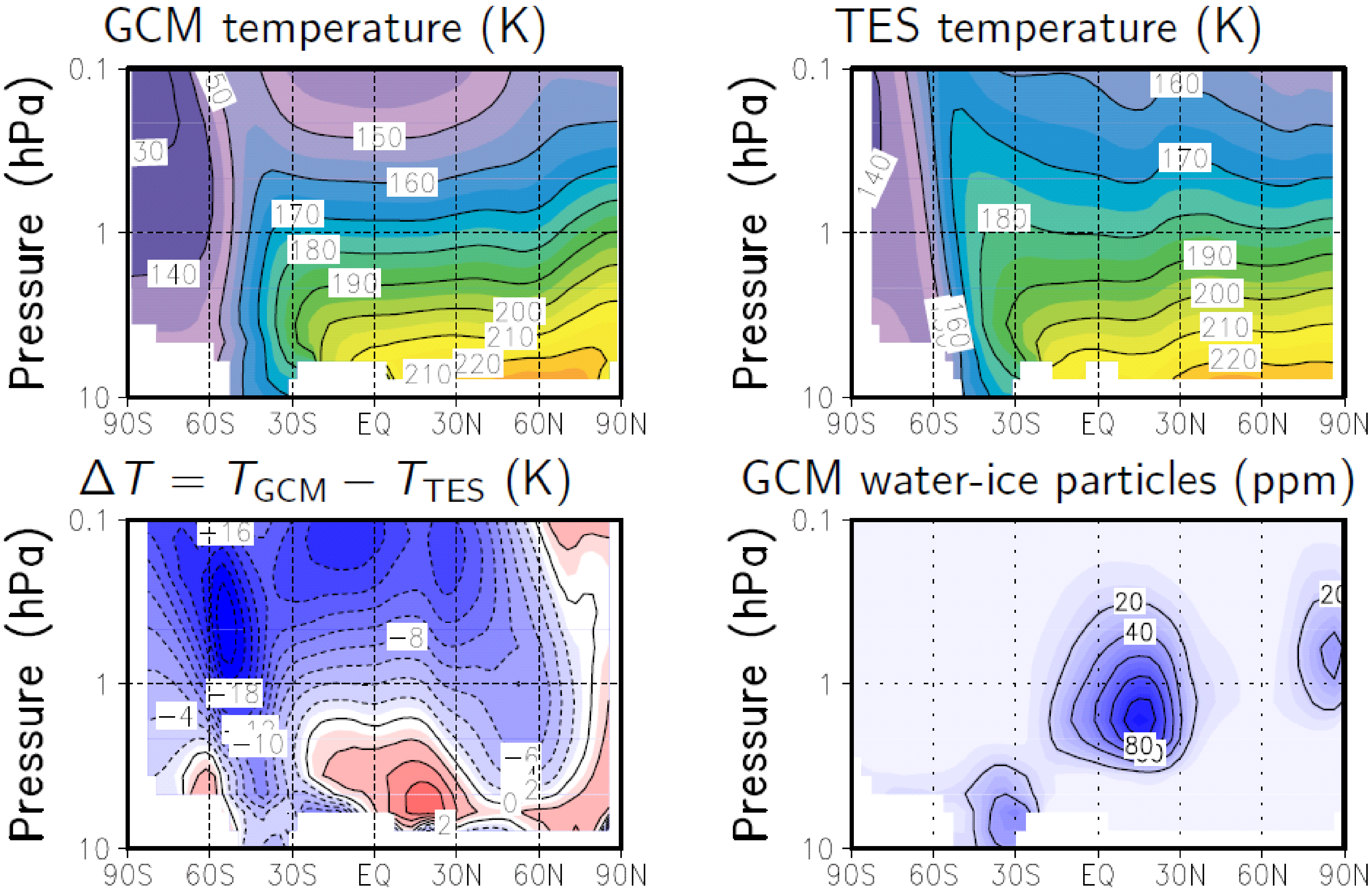
• Unrealistic temperatures => one must take into account the radiative effect of water ice clouds

• Unrealistic water vapor vertical distribution
*(e.g. Fouchet et al. 2007; Maltagliatti et al. 2012)*

⇨ Need for improved cloud microphysic

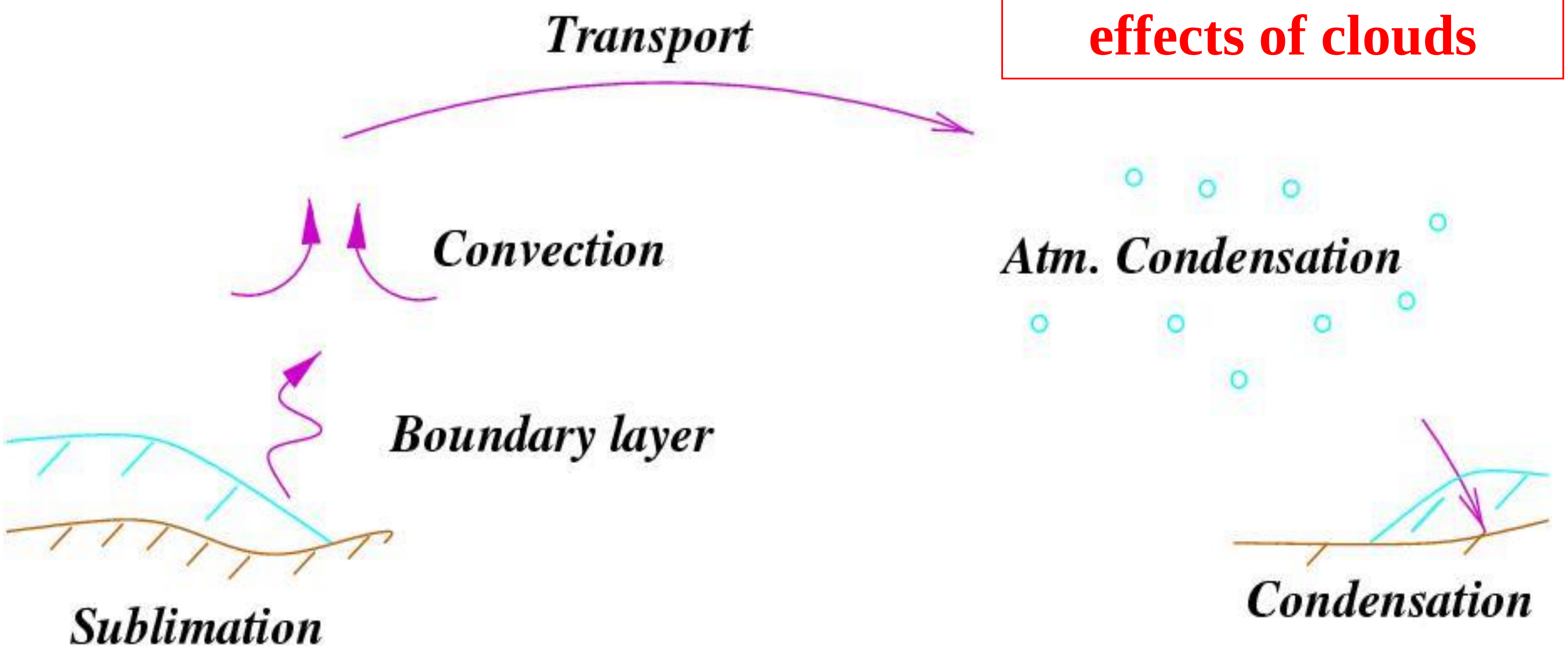


# Temperature without active clouds ($L_s = 90°$)



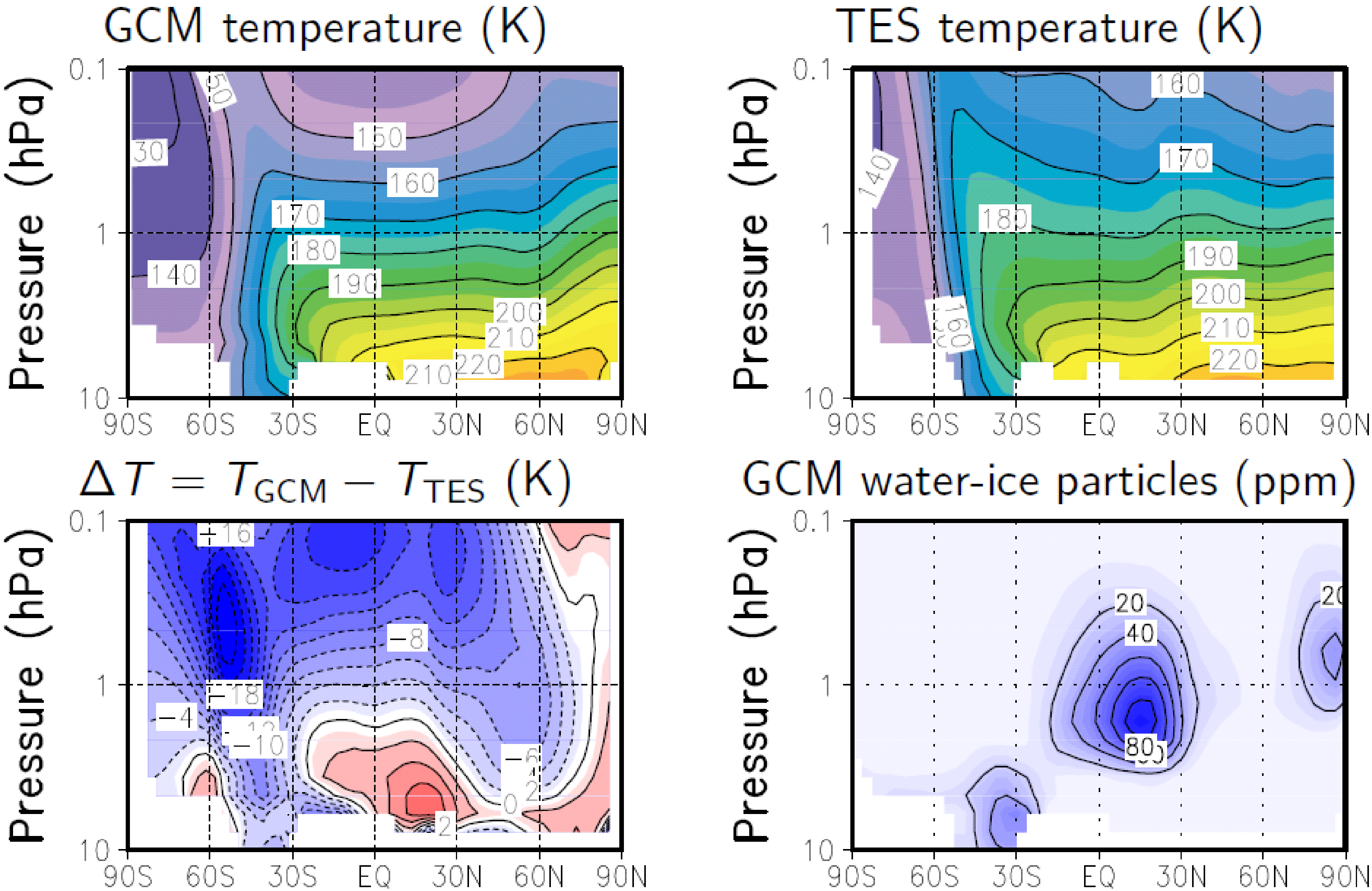
# Water cycle and clouds

**Step#1 :IR and solar walength radiative effects of clouds**

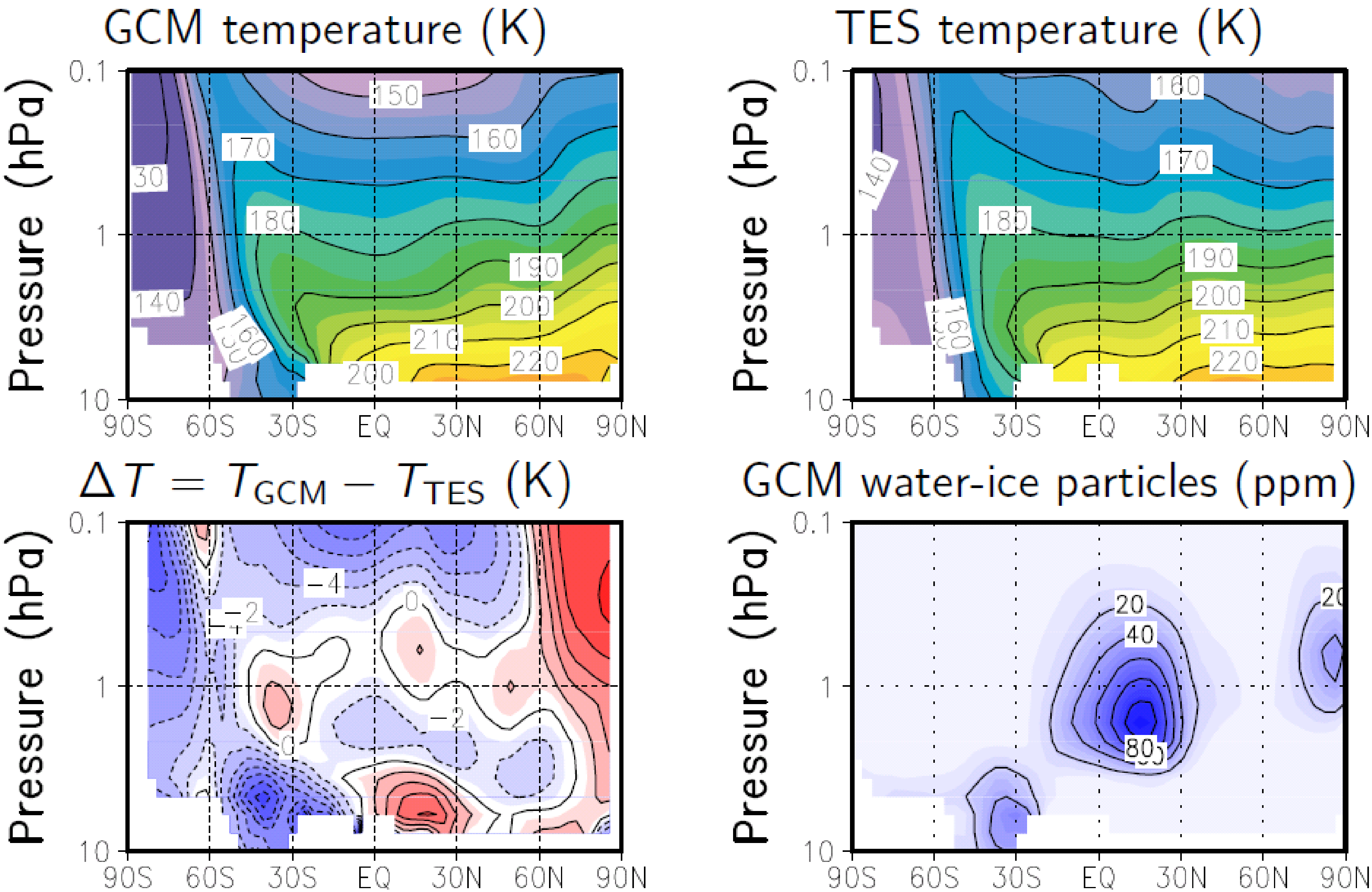



Madeleine et al. (2011)

# Temperature without active clouds ($L_s = 90°$)



# Temperature when clouds are active ($L_s = 90°$)



# Radiatively active Water ice clouds in a GCM

**Temperatures** → **Water vapor**

↓

**Water ice clouds**

Destabilizing
feedback

...

Inactive Clouds

Active Clouds

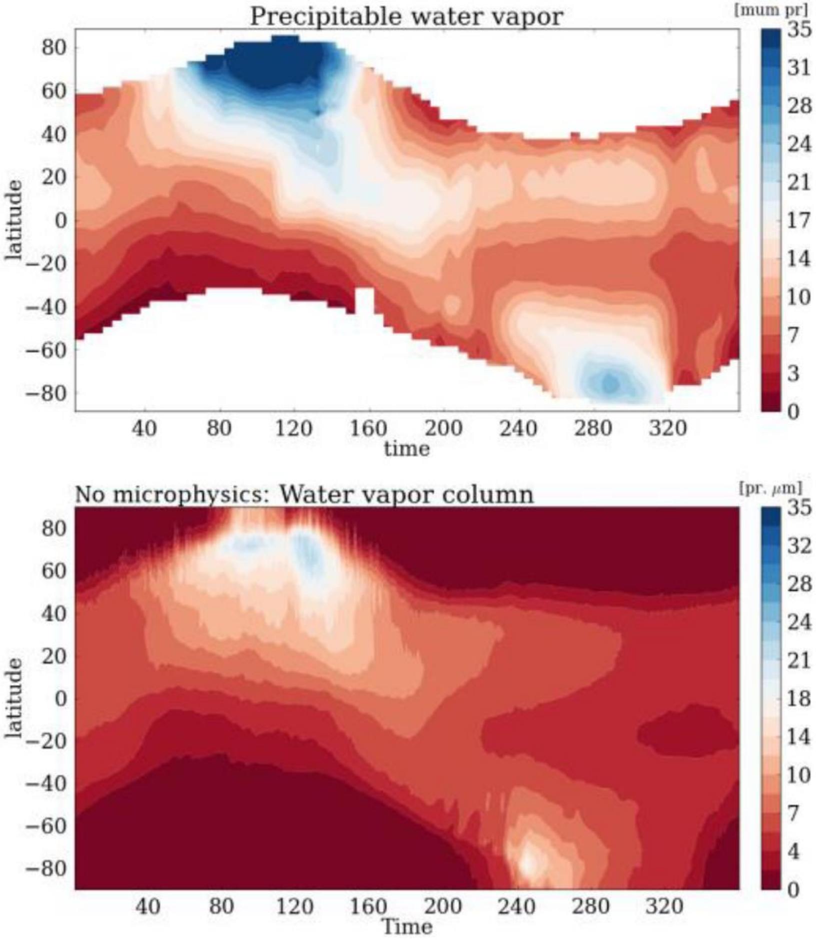
*Illustration off the difficulties ; fromThomas Navarro*

# Water vapor seasonal cycle

(Martian Year 26)

**MGS/TES Observations**

**GCM simulations without microphysics**

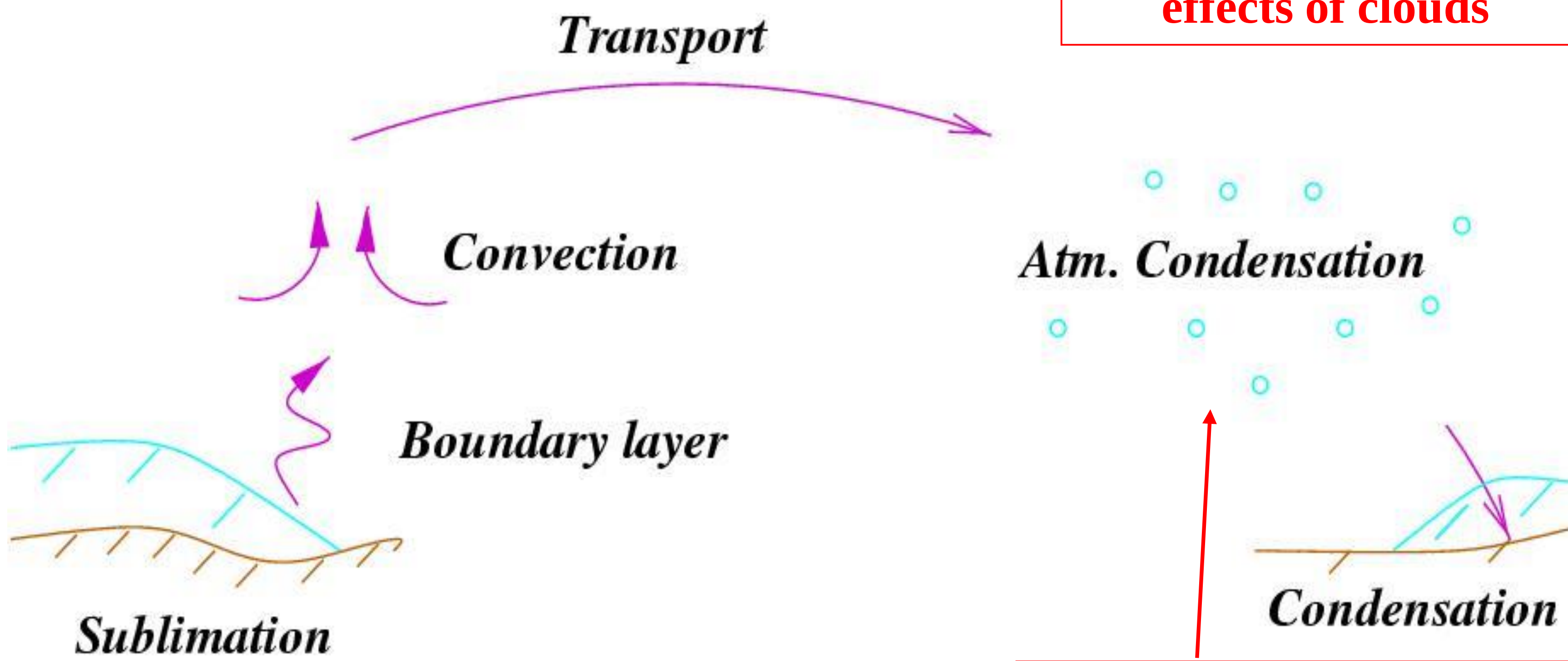



**Solar Longitude Ls (°)**

*Alizee pottier*

# Improving water cycle and clouds

**Step#1 :IR and solar walength radiative effects of clouds**




**Step # 2: Improved cloud Microphysics (nucleation, growth, dust scavenging )**

# Water vapor seasonal cycle

(Martian Year 26)

**MGS/TES Observations**

**GCM simulations without microphysics**

**GCM simulations <u>with</u> microphysics**

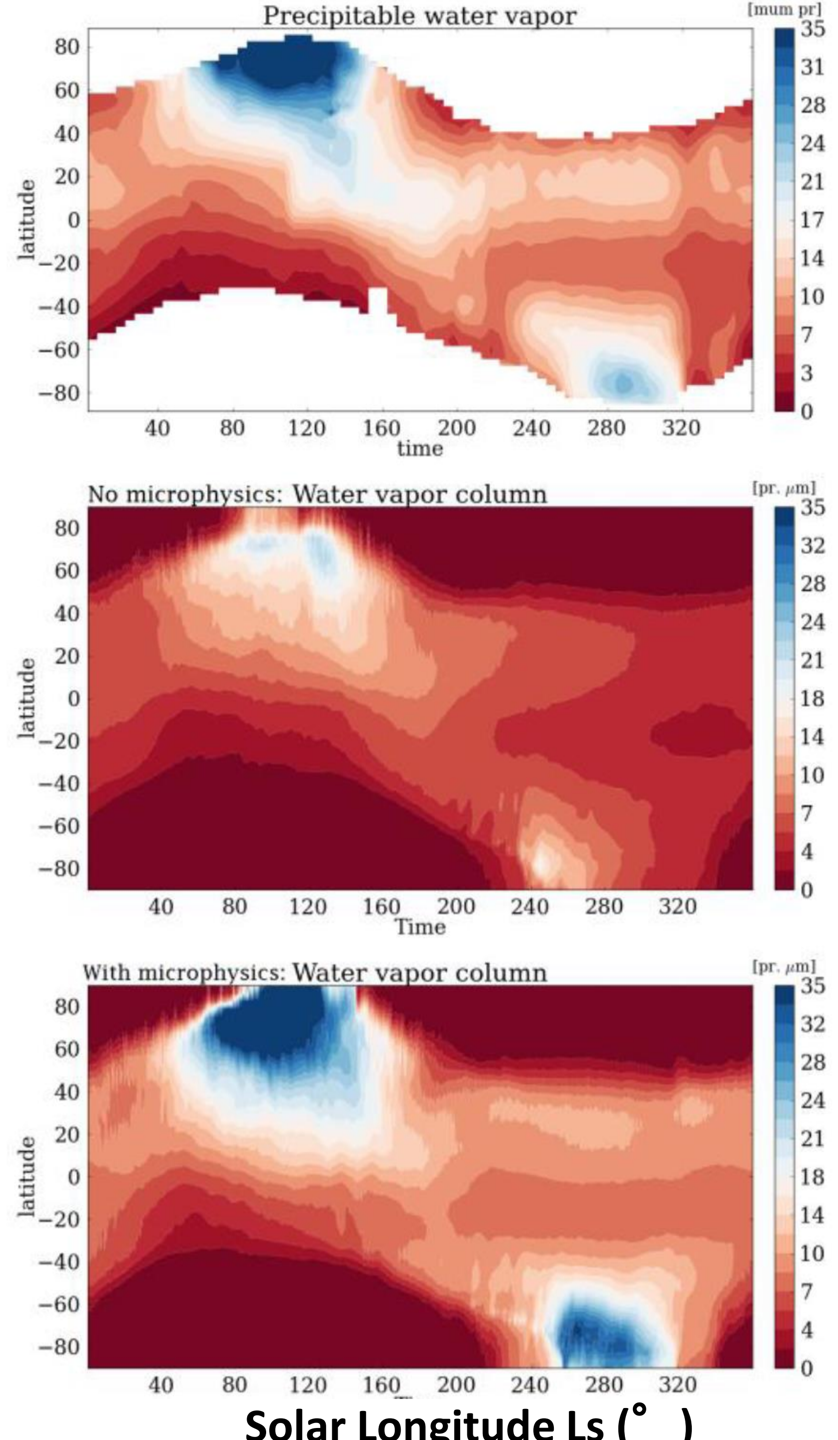
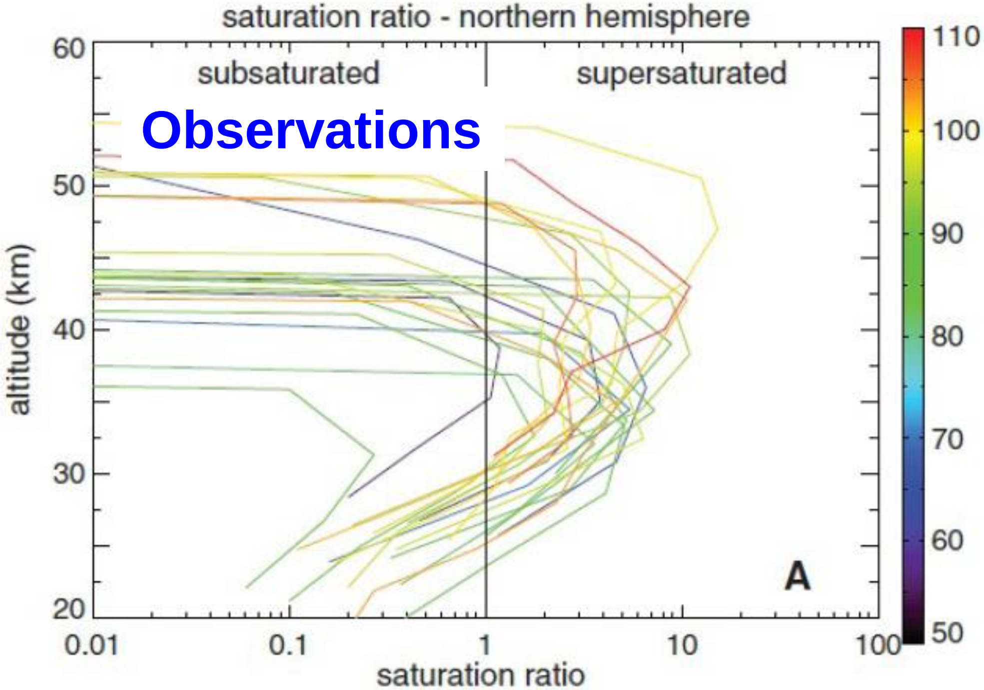
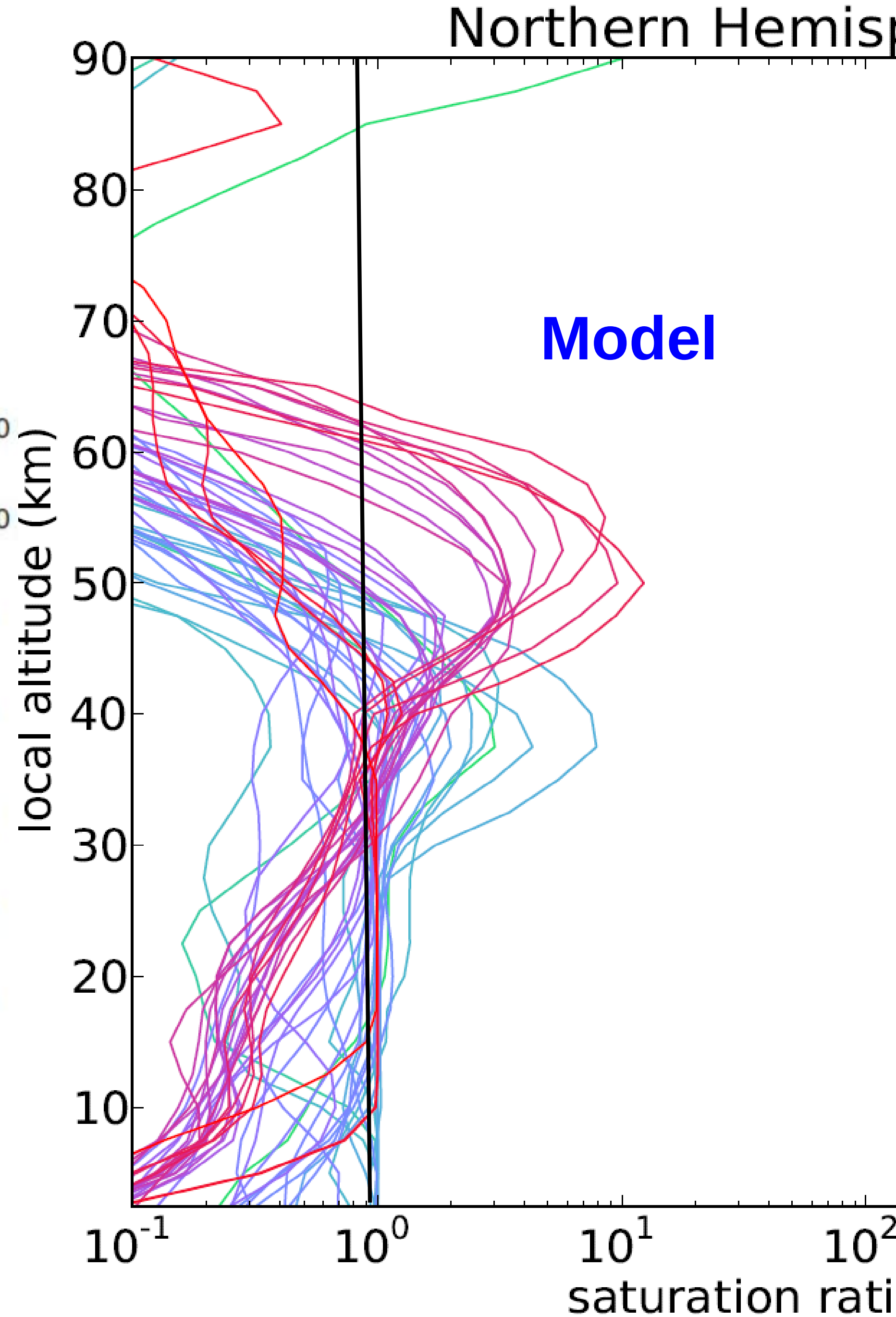



*Figure by Alizee Pottier*

**Water vapor profiles with improved microphysics: comparison with SPICAM solar occultation data**

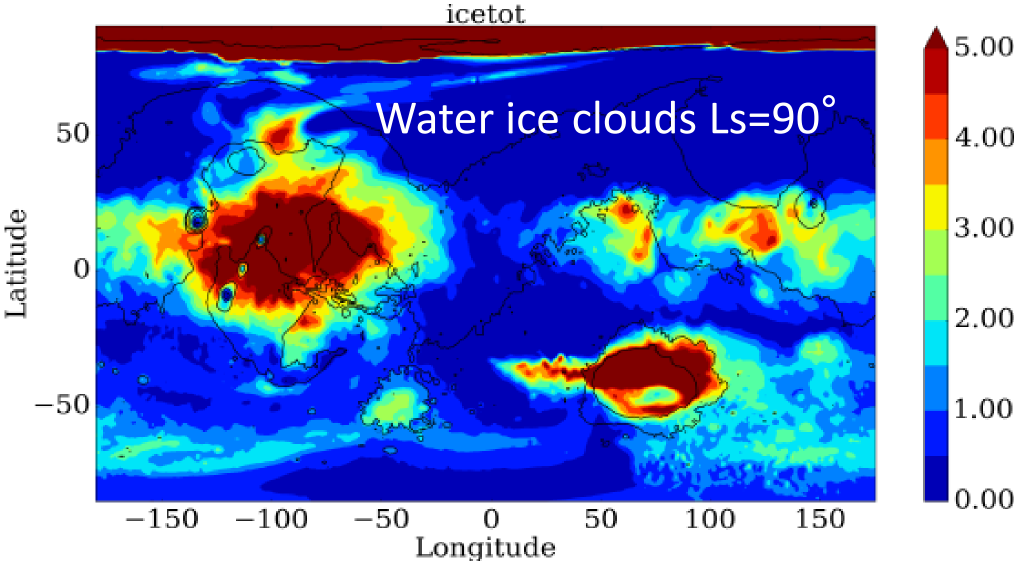



Maltagliati et al. 2011, Science

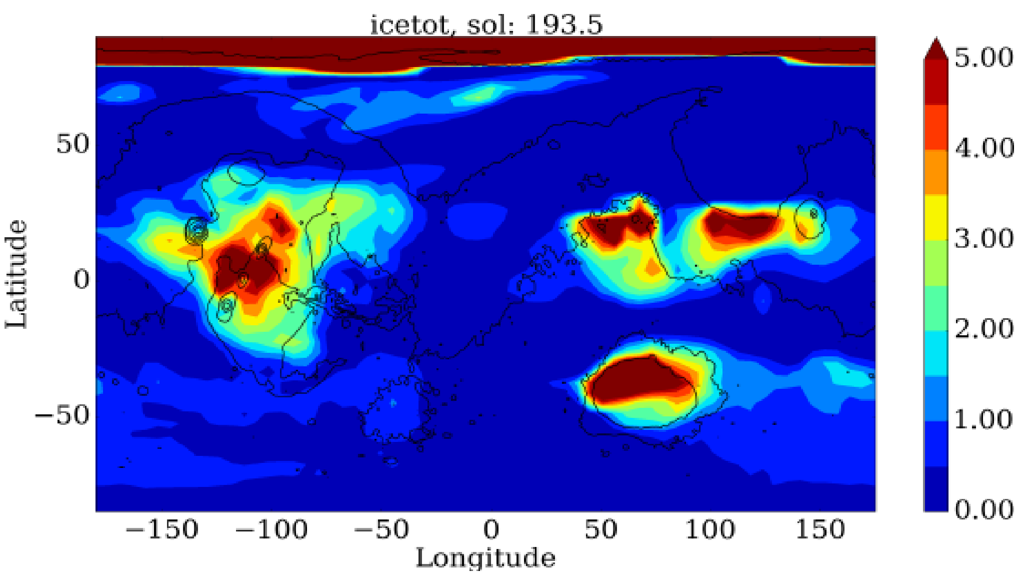


# High resolution (1° x1° ) water cycle sims

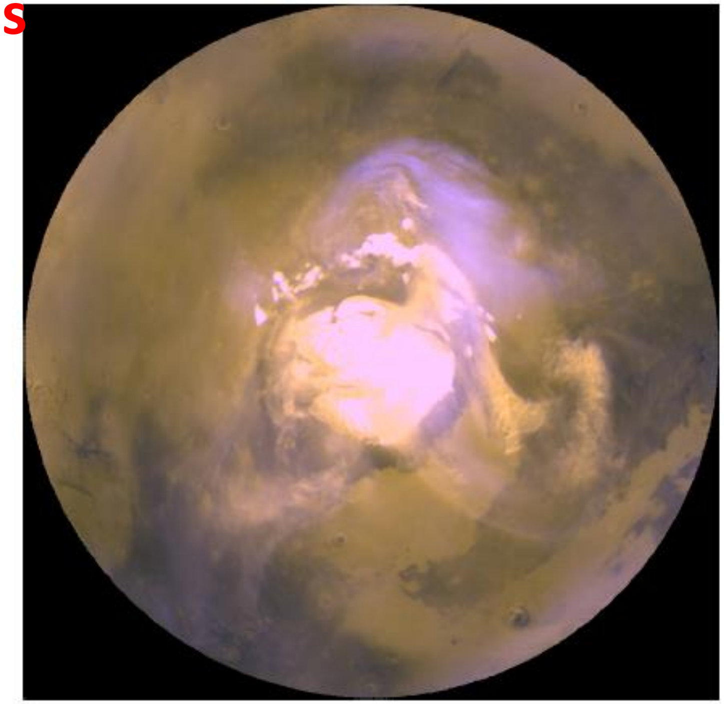
*(Pottier et al. 2015)*

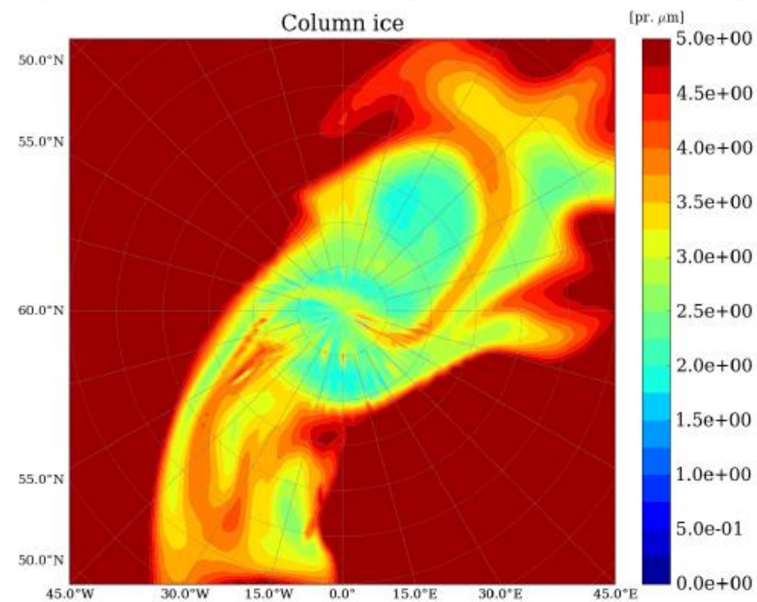



(a) High resolution model




(b) Low resolution model

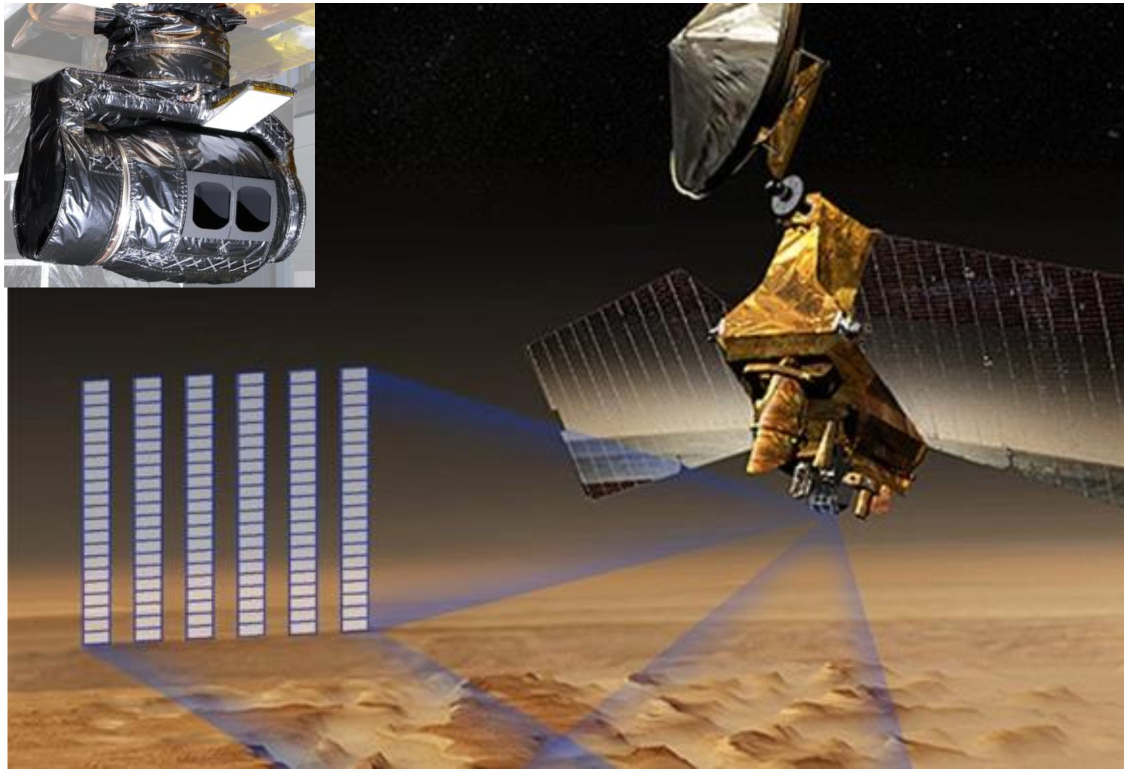





- Spiralling clouds at the north pole, $L_s = 152°$ (MC

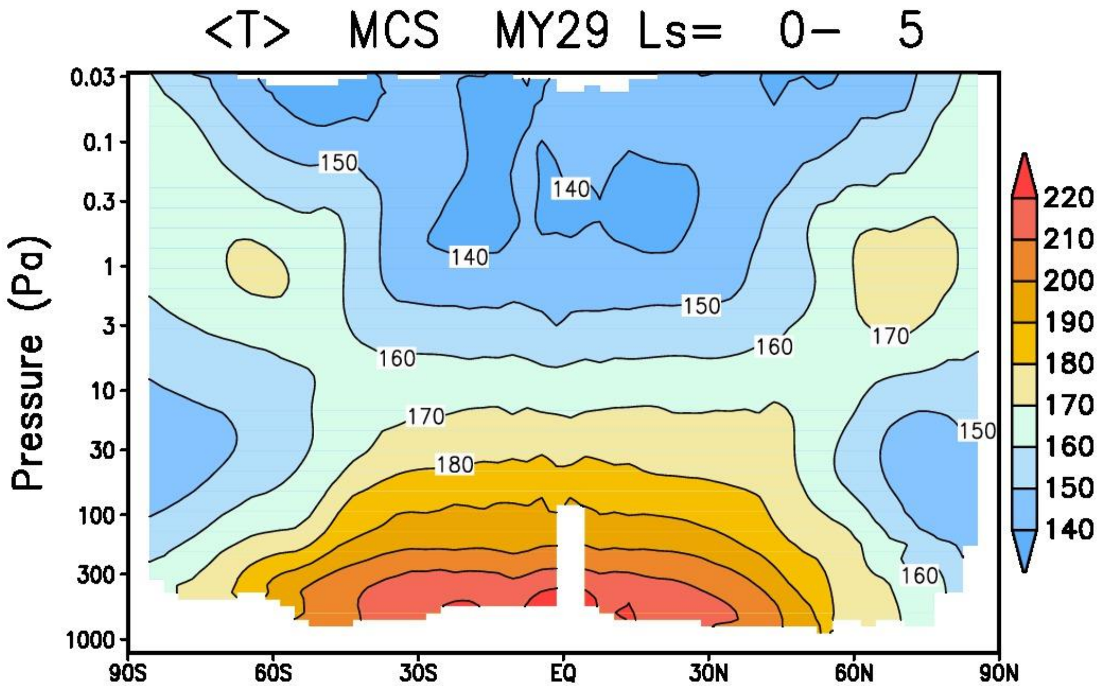
# Comparison with Mars Climate Sounder

- Comparison with Binned Mars Climate Sounder data (*Luca Montabone*)
- Bin sizes: Ls: 5° lat: 3° lon 7.5°
- Today : Martian Year 29

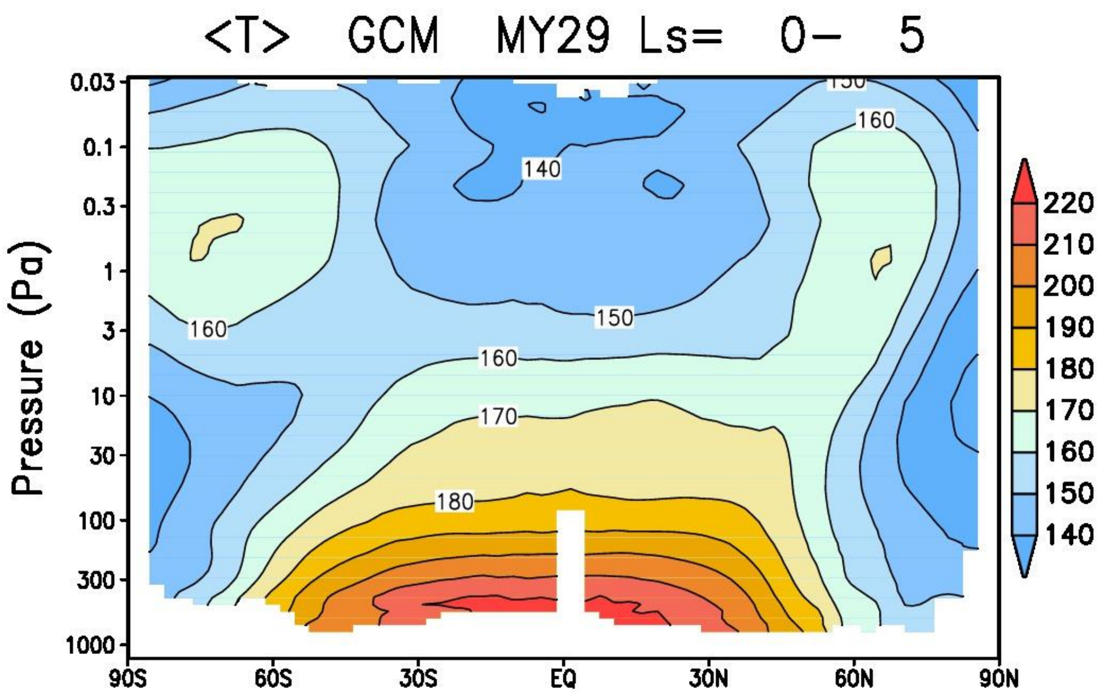


Zonal mean temperatures

$\frac{1}{2}$ (Tday + Tnight)



<T> MCS MY29 Ls= 0- 5
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
140
140
150
160
160
170
170
180
150
160
220
210
200
190
180
170
160
150
140

<T> GCM MY29 Ls= 0- 5
Pressure (Pa)
0.03
0.1
0.3
1
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10
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90S
60S
30S
EQ
30N
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90N
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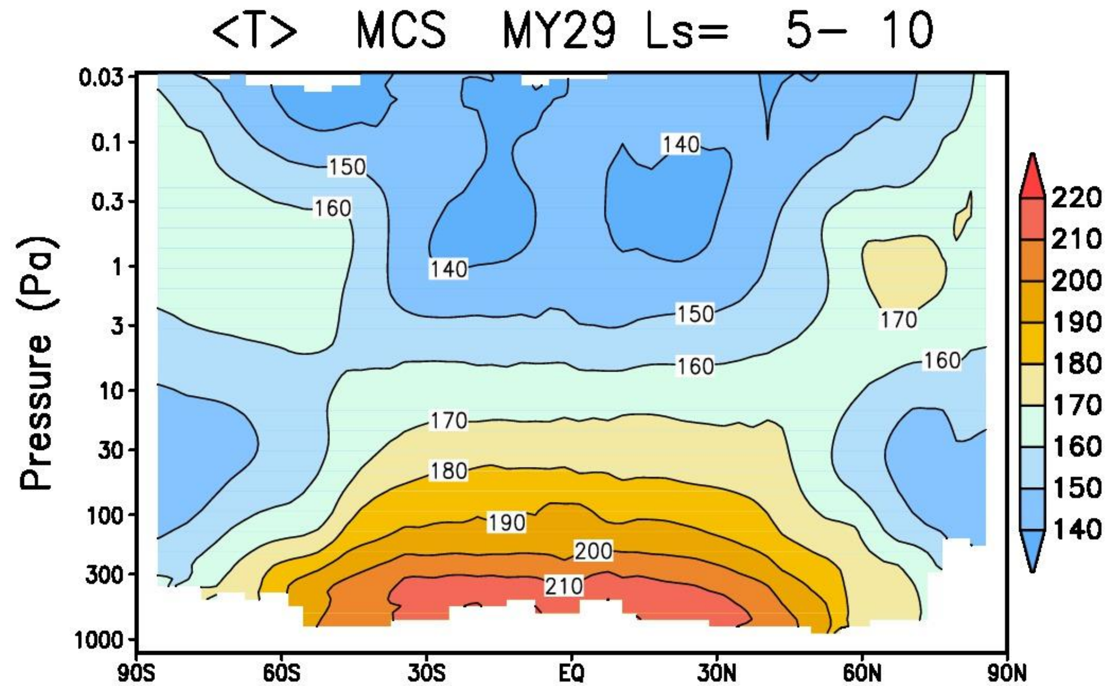
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Pressure (Pa)
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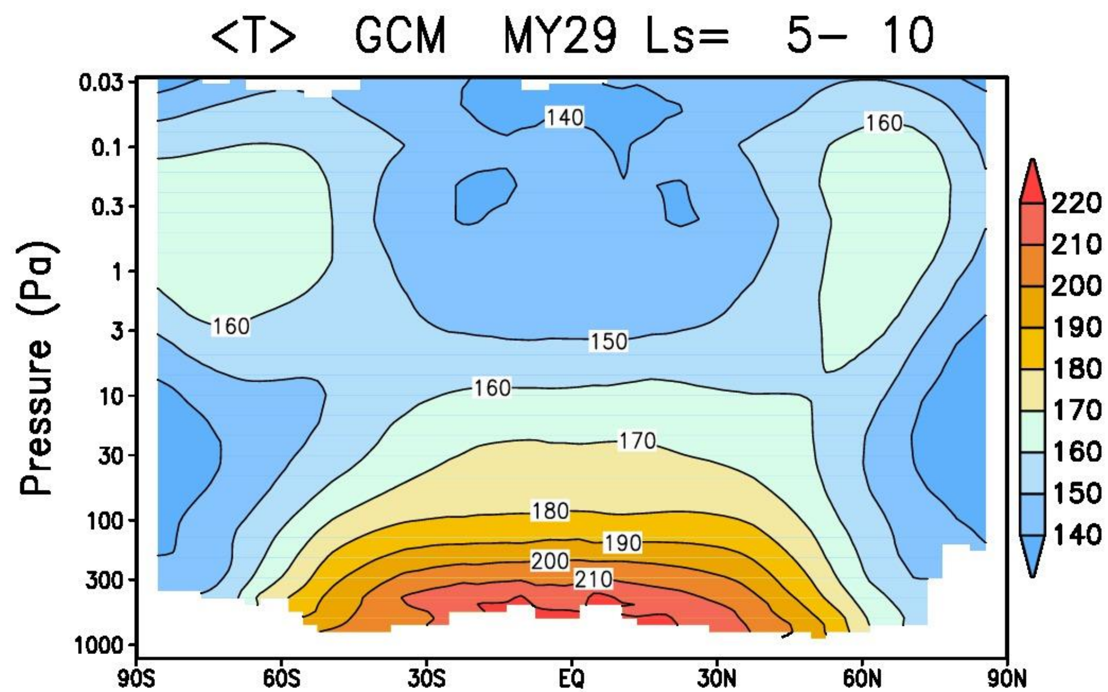
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Pressure (Pa)
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EQ
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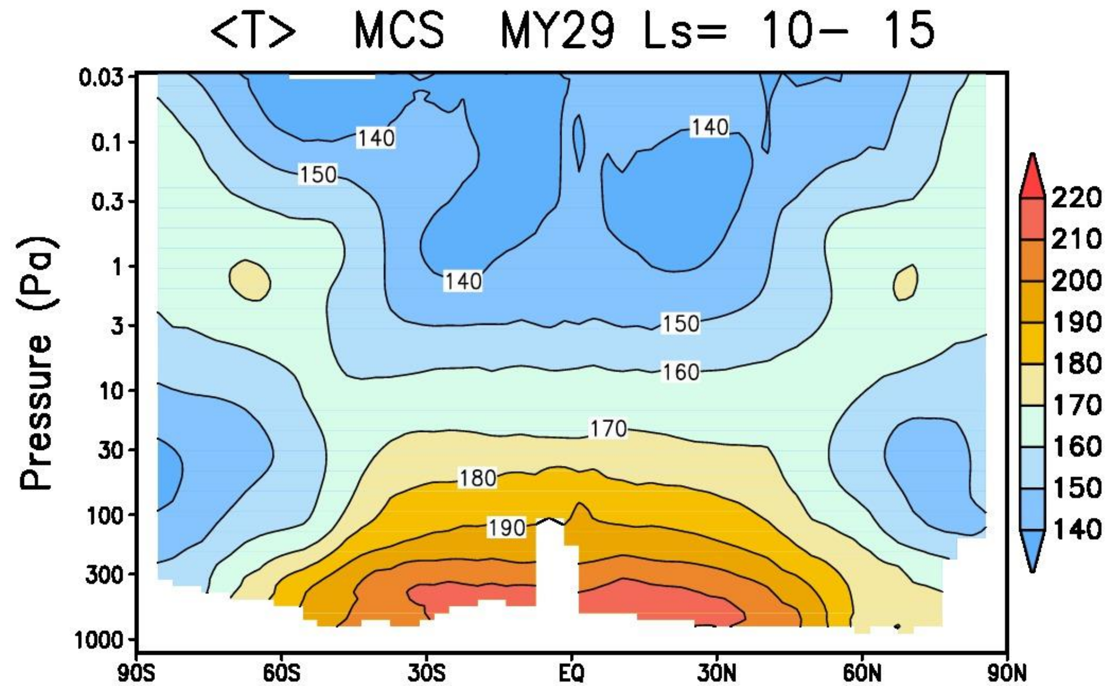
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3
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90N
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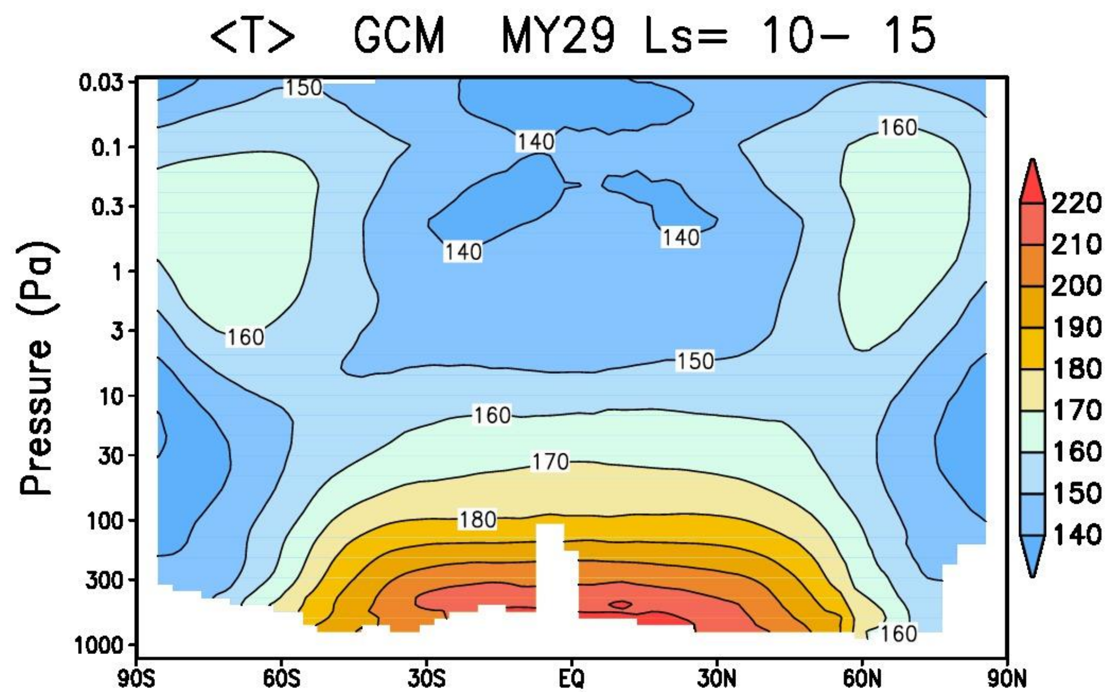
<T> GCM MY29 Ls= 10- 15
Pressure (Pa)
0.03
0.1
0.3
1
3
10
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100
300
1000
90S
60S
30S
EQ
30N
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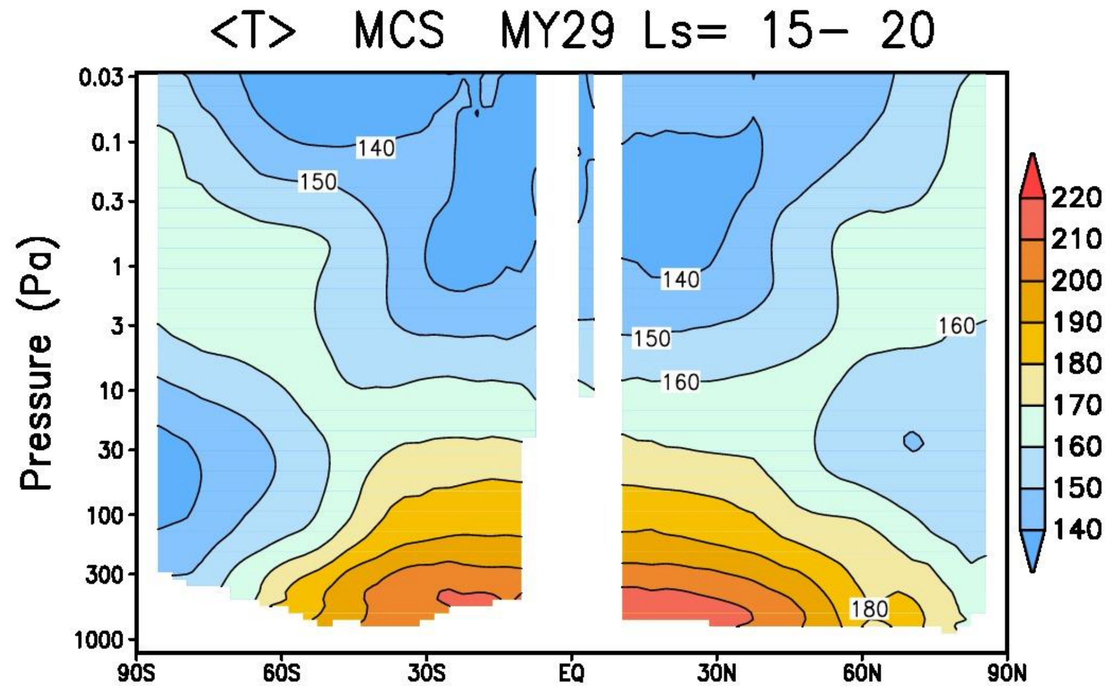
<T> MCS MY29 Ls= 15- 20
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
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150
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200
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150
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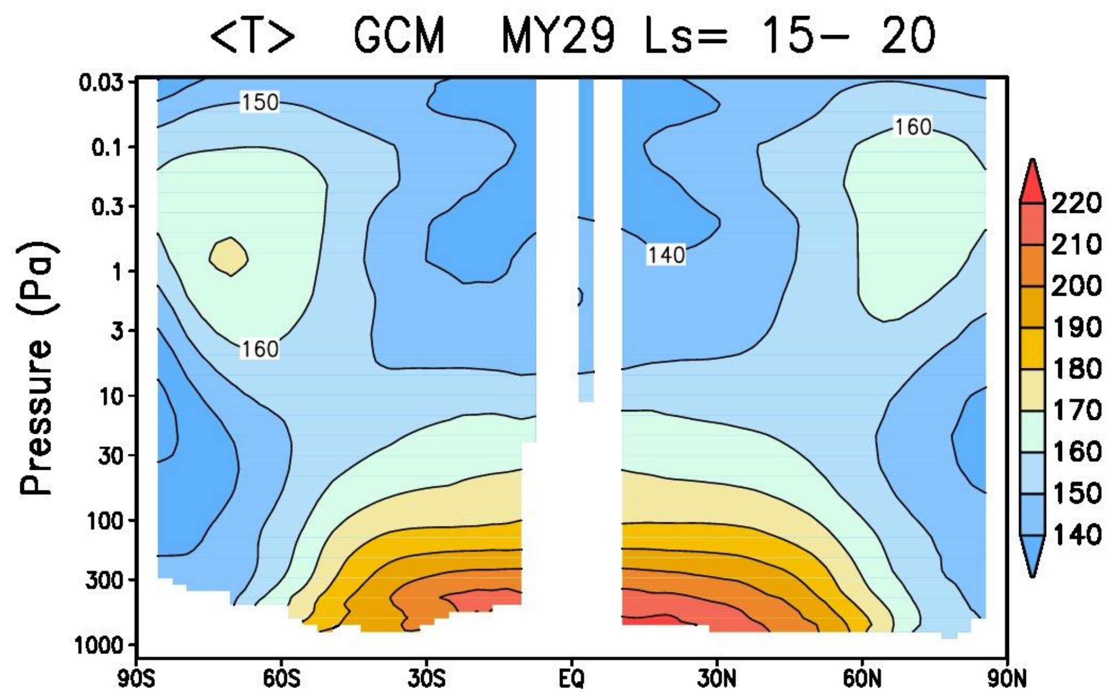
<T> GCM MY29 Ls= 15- 20
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
140
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210
200
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170
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150
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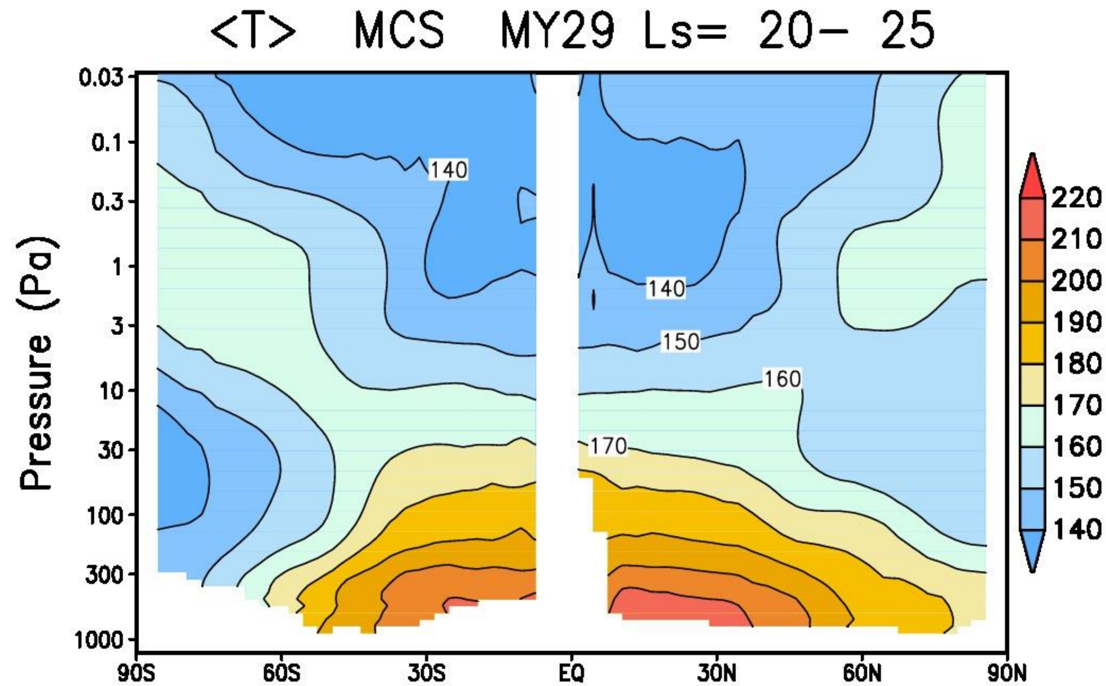
<T> MCS MY29 Ls= 20- 25
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
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150
160
170
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210
200
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170
160
150
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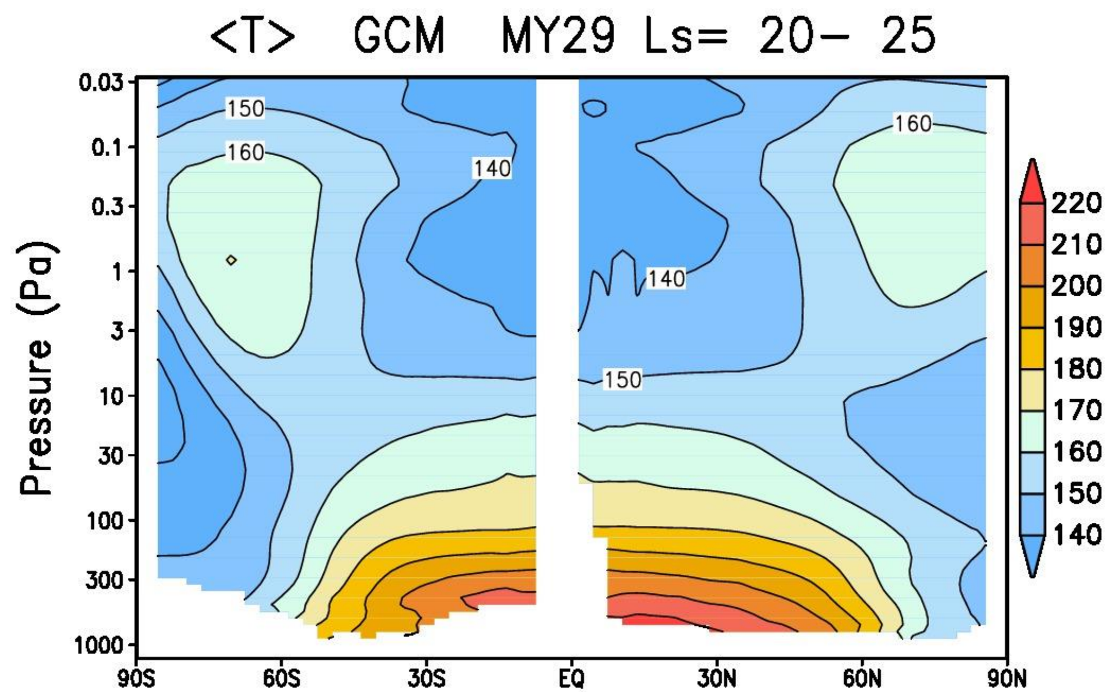
<T> GCM MY29 Ls= 20- 25
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
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140
150
160
220
210
200
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180
170
160
150
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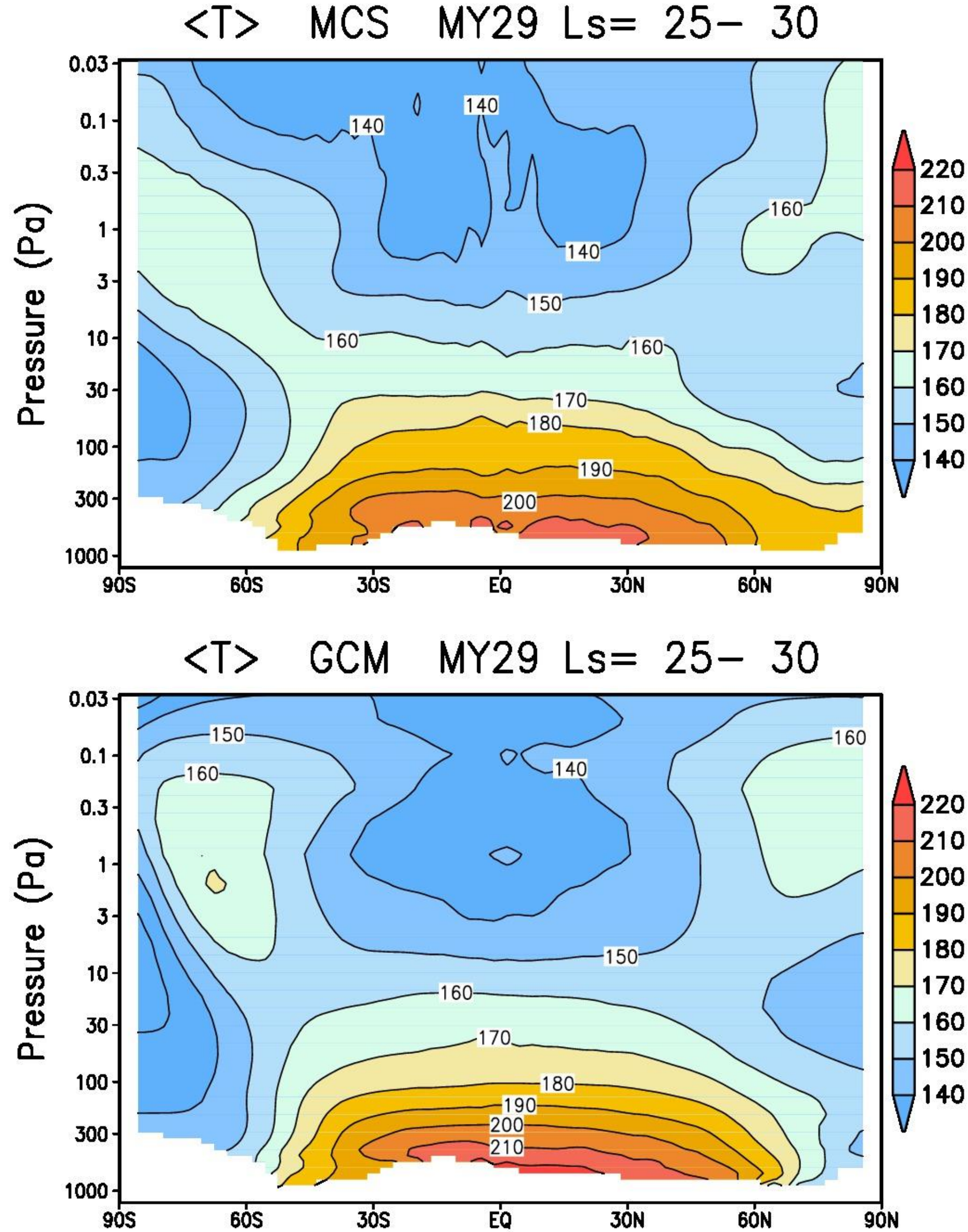

<T> MCS MY29 Ls= 25- 30
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220
<T> GCM MY29 Ls= 25- 30
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
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180
190
200
210
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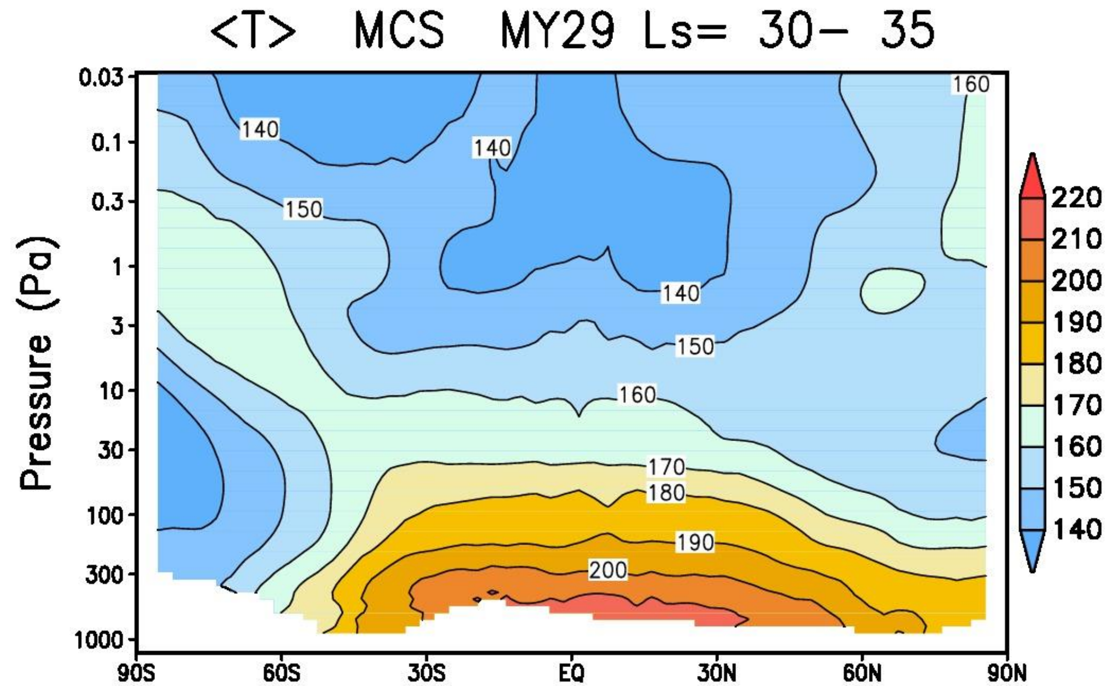
<T> MCS MY29 Ls= 30- 35
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
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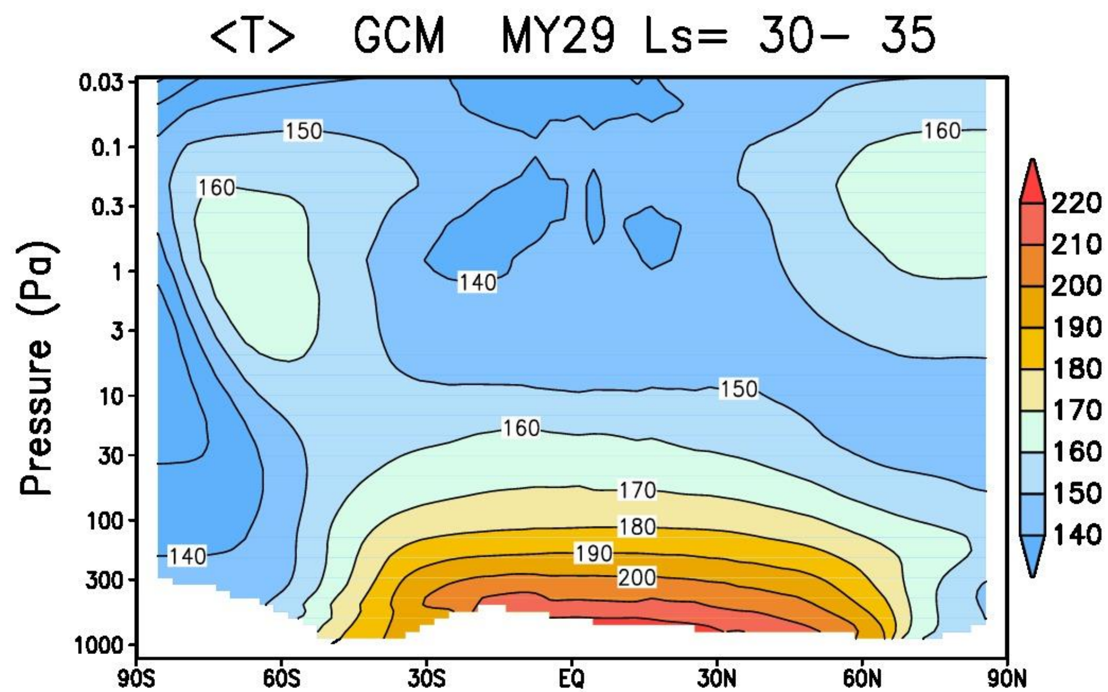
<T> GCM MY29 Ls= 30- 35
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
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150
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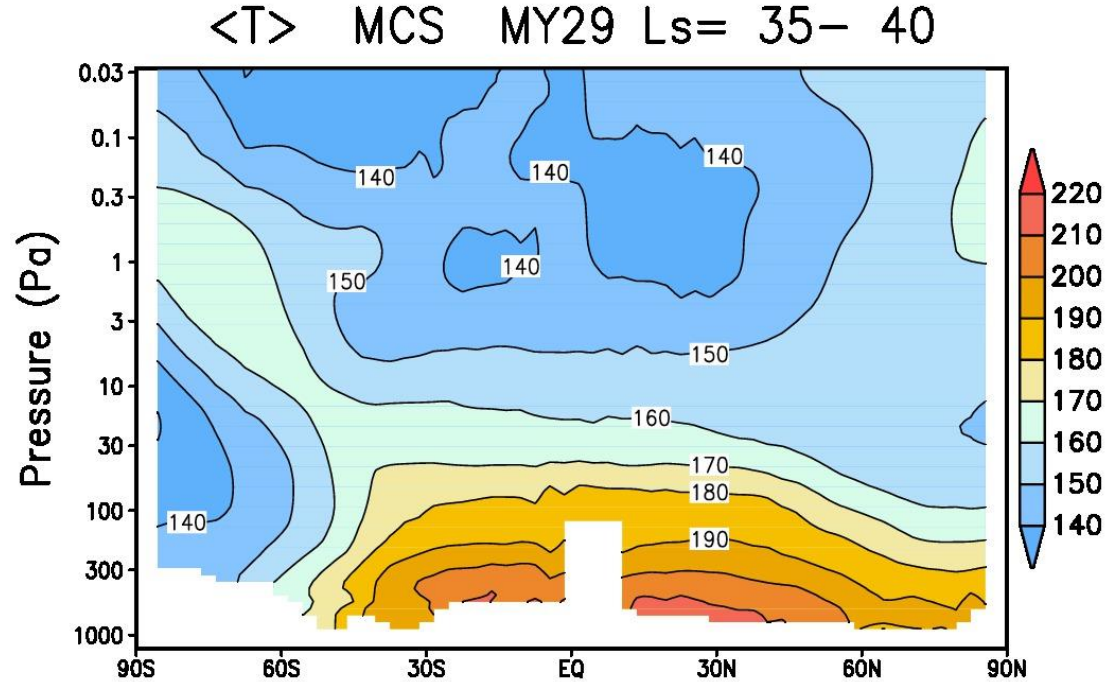
<T> MCS MY29 Ls= 35- 40
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
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180
170
160
150
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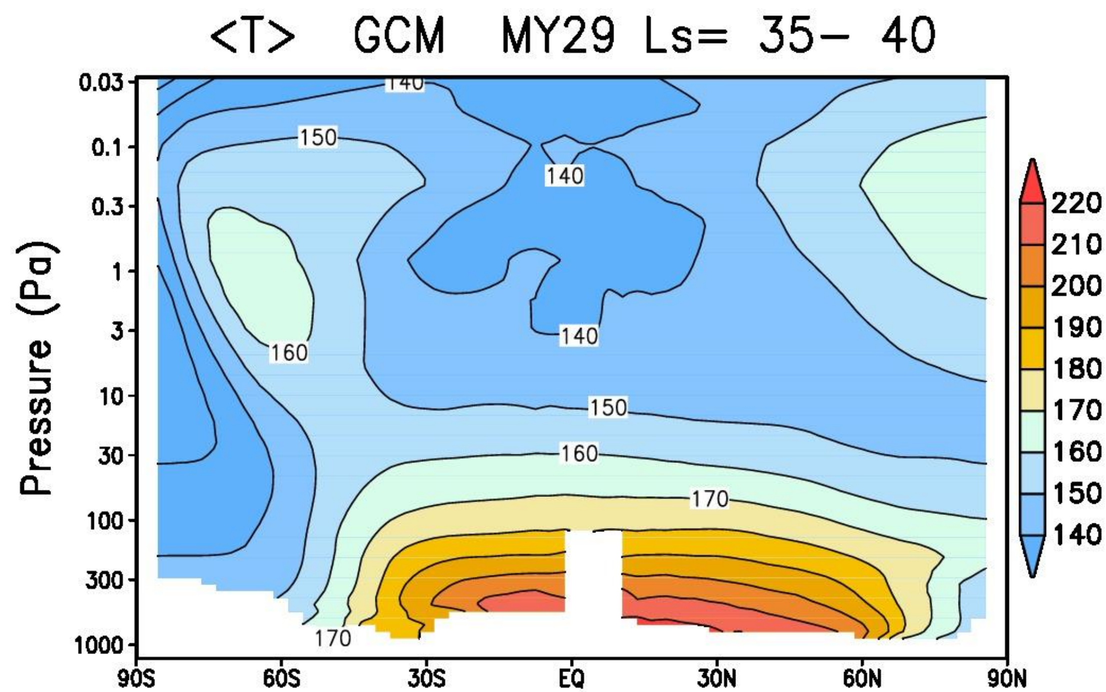
<T> GCM MY29 Ls= 35- 40
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
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150
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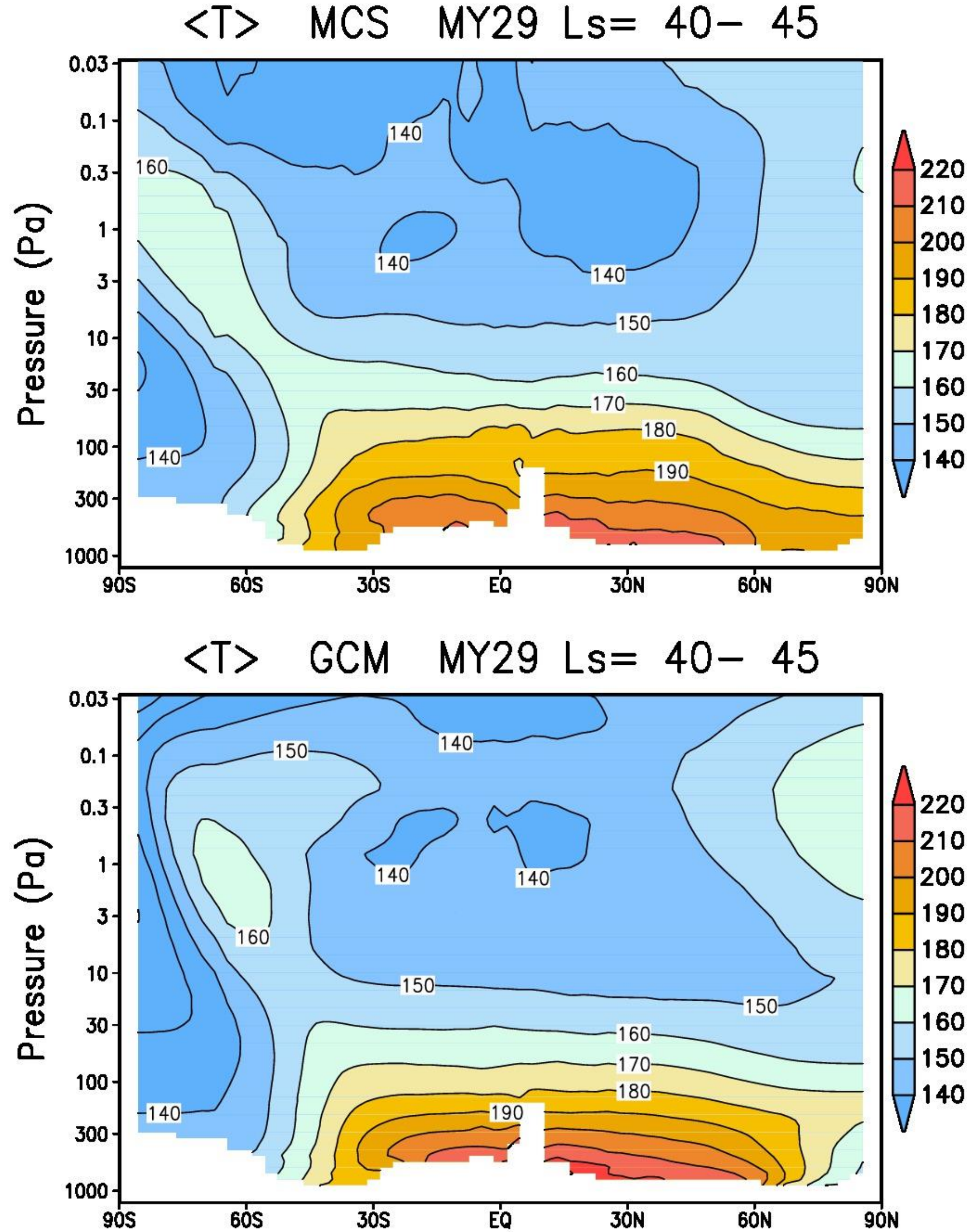
<T> MCS MY29 Ls= 40- 45
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
220
210
200
190
180
170
160
150
140
<T> GCM MY29 Ls= 40- 45
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
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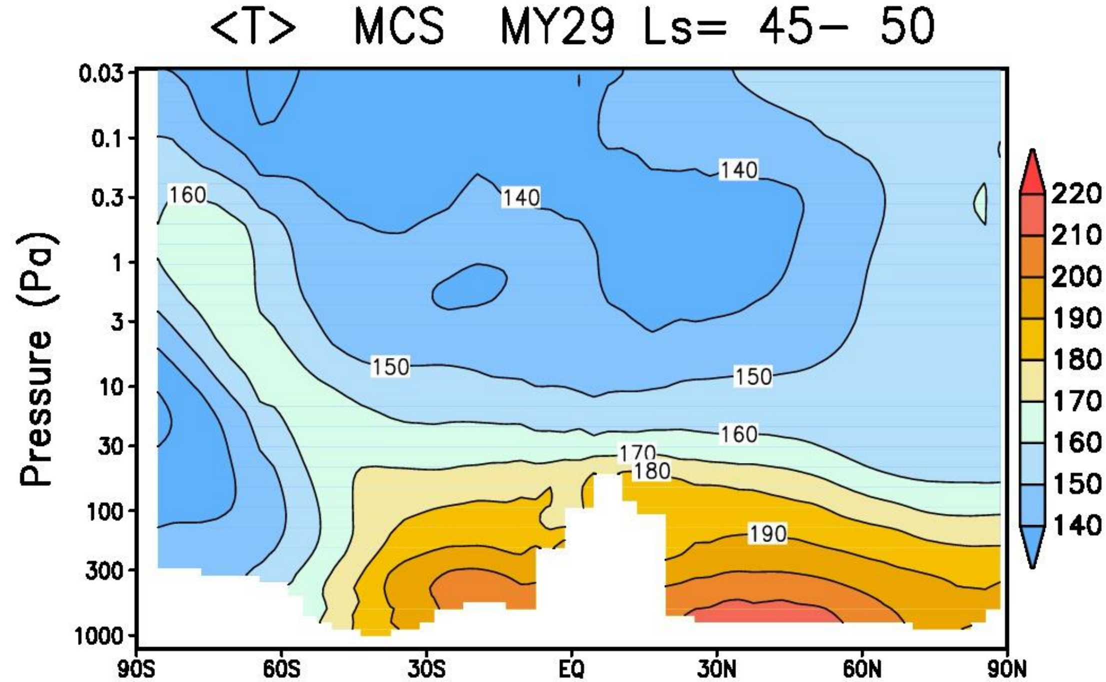
<T> MCS MY29 Ls= 45- 50
Pressure (Pa)
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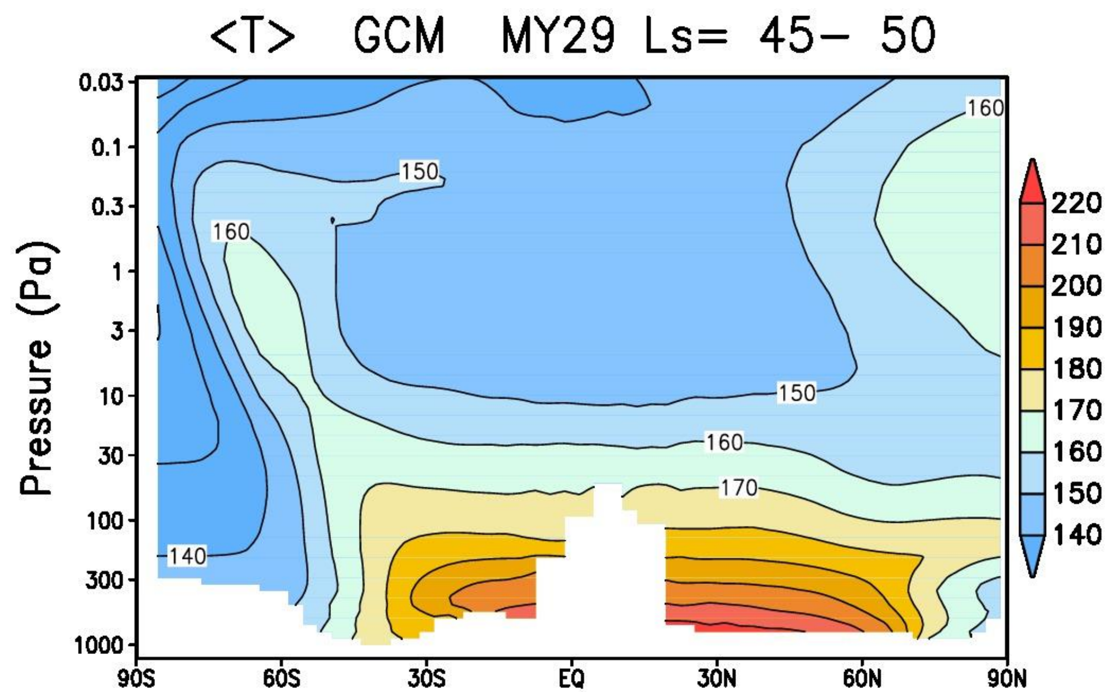
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
220
210
200
190
180
170
160
150
140


<T> GCM MY29 Ls= 45- 50
Pressure (Pa)
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0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
220
210
200
190
180
170
160
150
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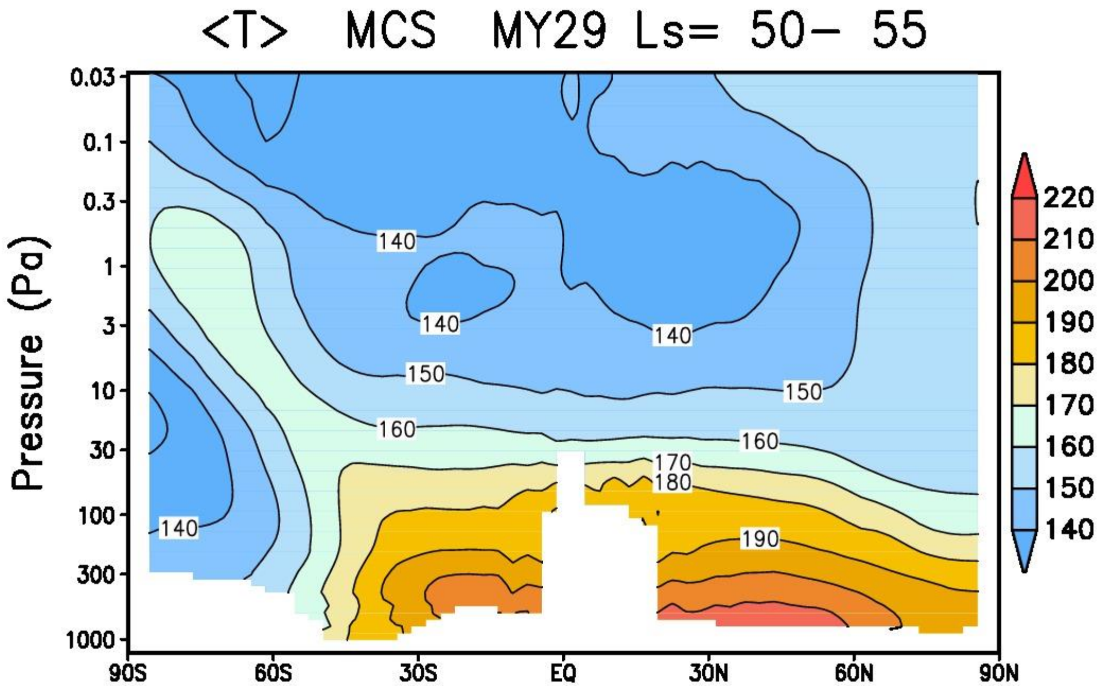
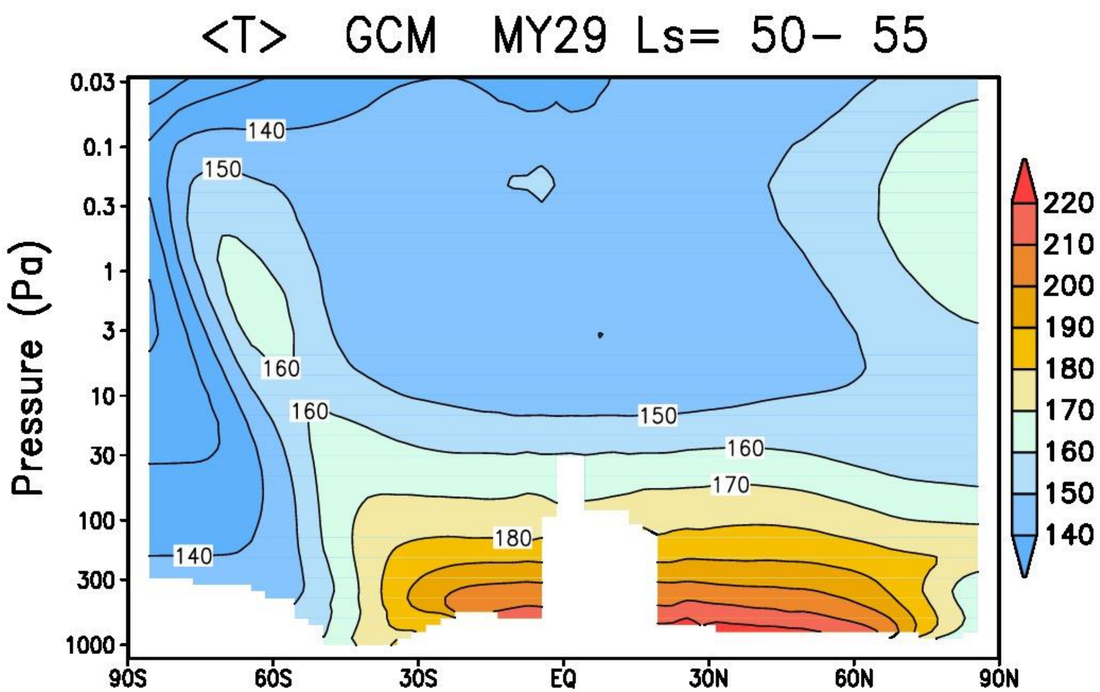
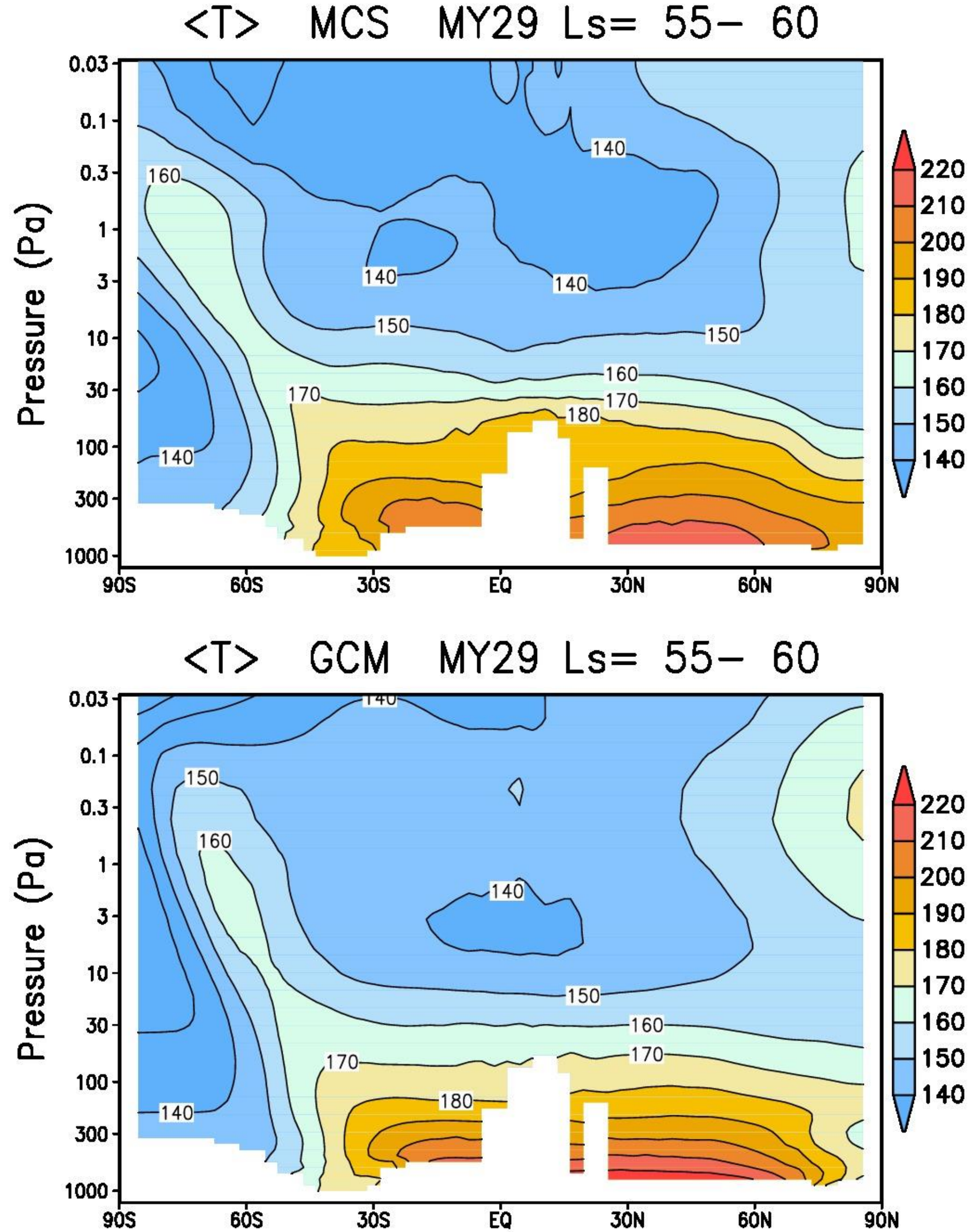

<T> MCS MY29 Ls= 50- 55
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220


<T> GCM MY29 Ls= 50- 55
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220



<T> MCS MY29 Ls= 55- 60
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
220
210
200
190
180
170
160
150
140
<T> GCM MY29 Ls= 55- 60
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
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220
210
200
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170
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150
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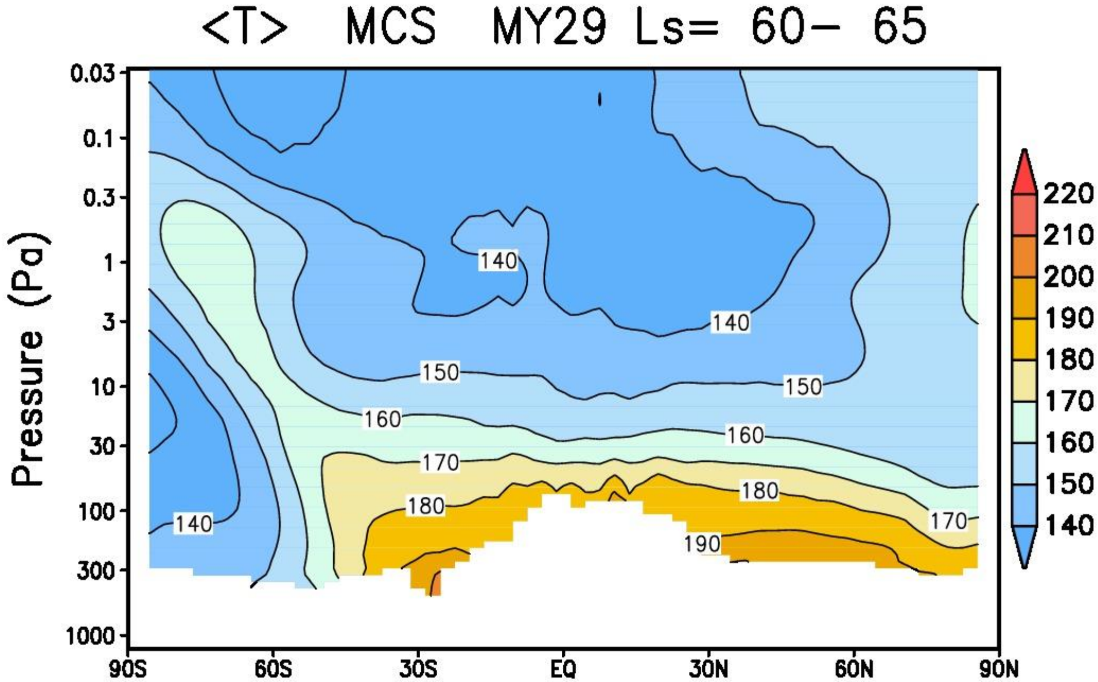
<T> MCS MY29 Ls= 60- 65
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
220
210
200
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150
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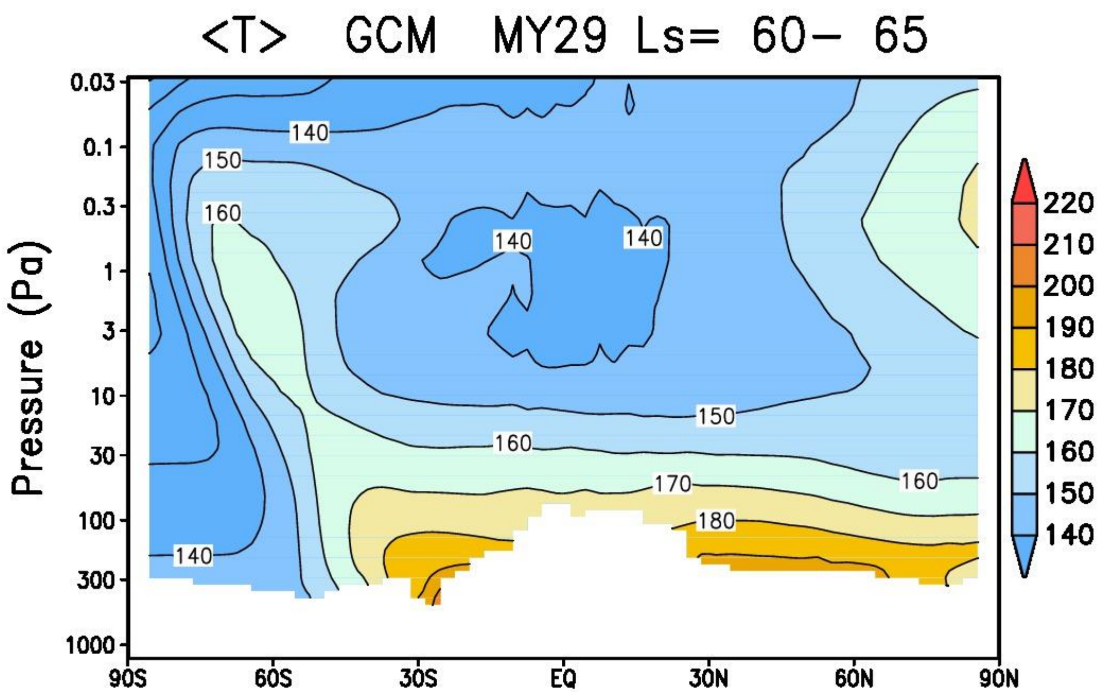
<T> GCM MY29 Ls= 60- 65
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
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220
210
200
190
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170
160
150
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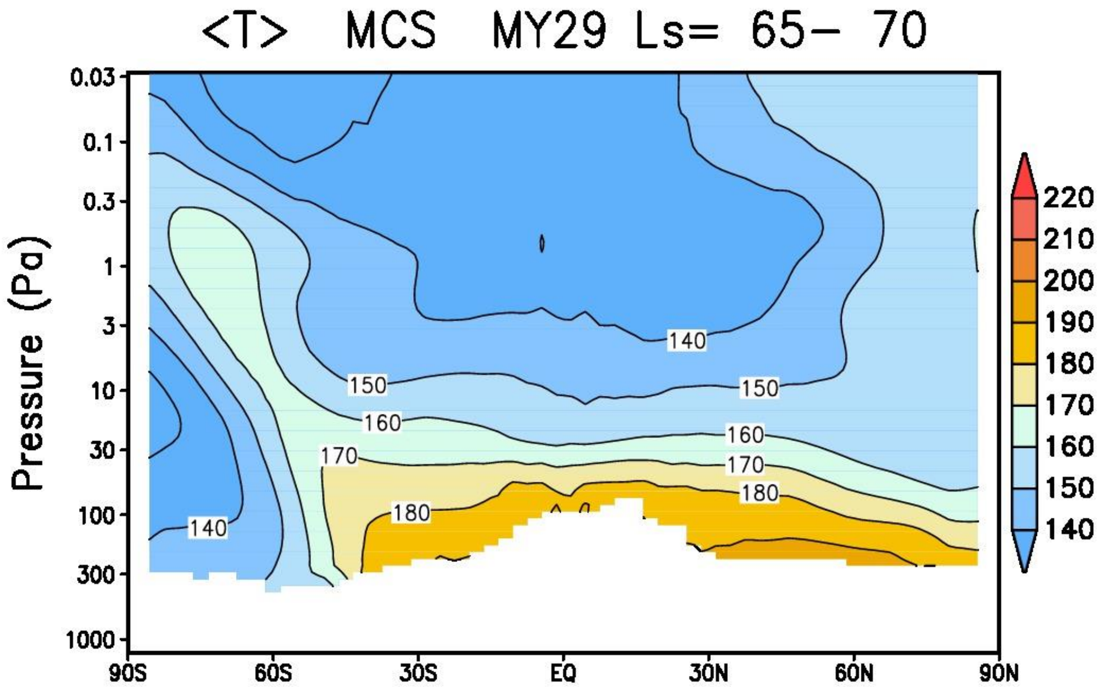
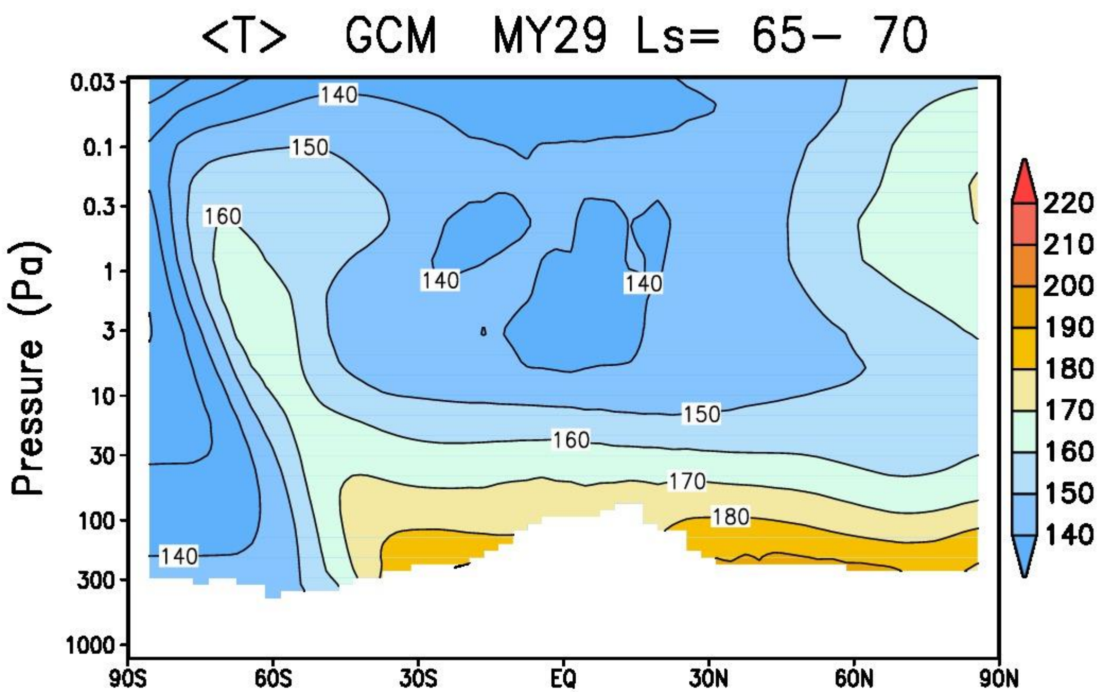

<T> MCS MY29 Ls= 65- 70
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
220
210
200
190


<T> GCM MY29 Ls= 65- 70
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
220
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200
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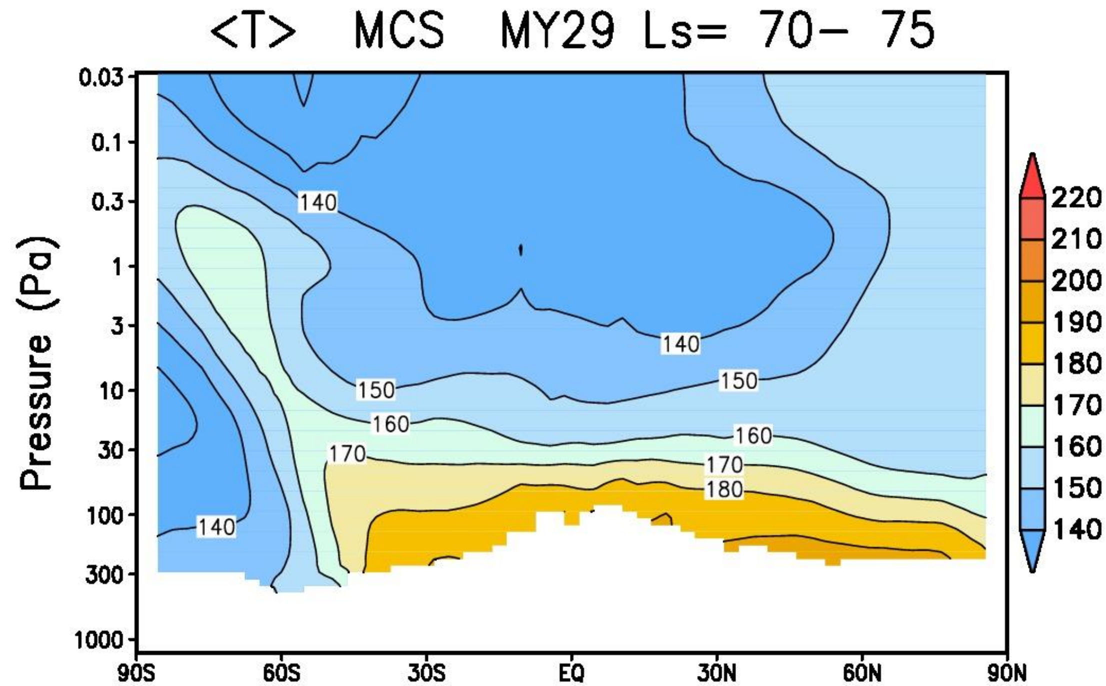
<T> MCS MY29 Ls= 70- 75
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
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170
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200
210
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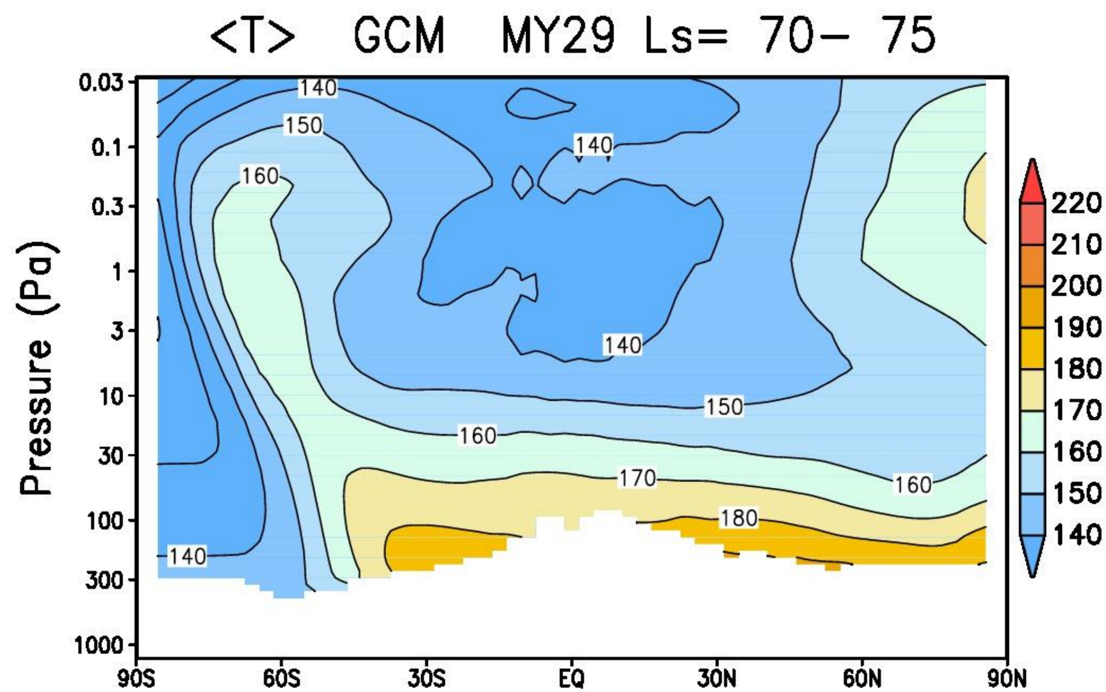
<T> GCM MY29 Ls= 70- 75
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
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210
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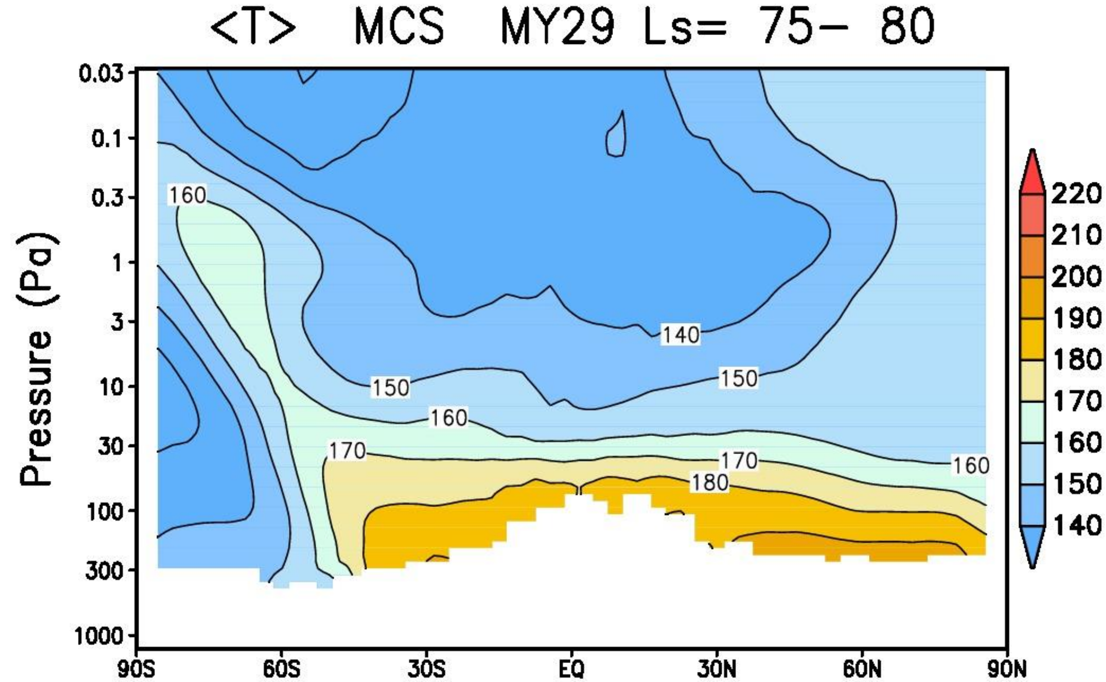

<T> MCS MY29 Ls= 75- 80
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
140
150
150
160
170
170
180
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220
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170
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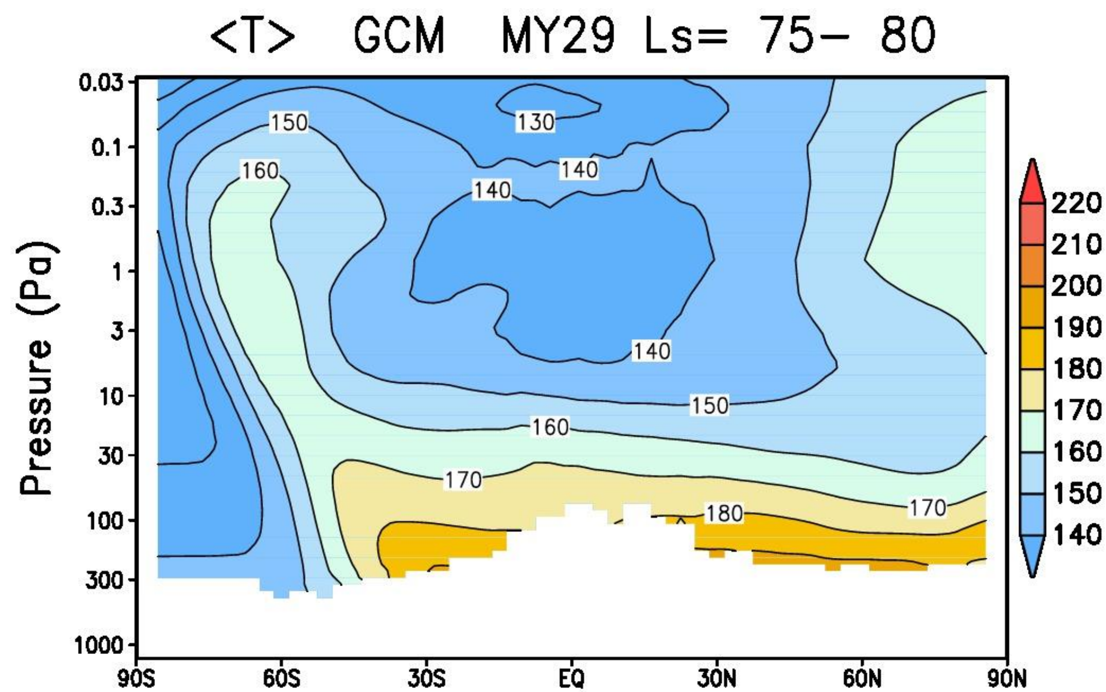

<T> GCM MY29 Ls= 75- 80
Pressure (Pa)
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0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
130
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140
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150
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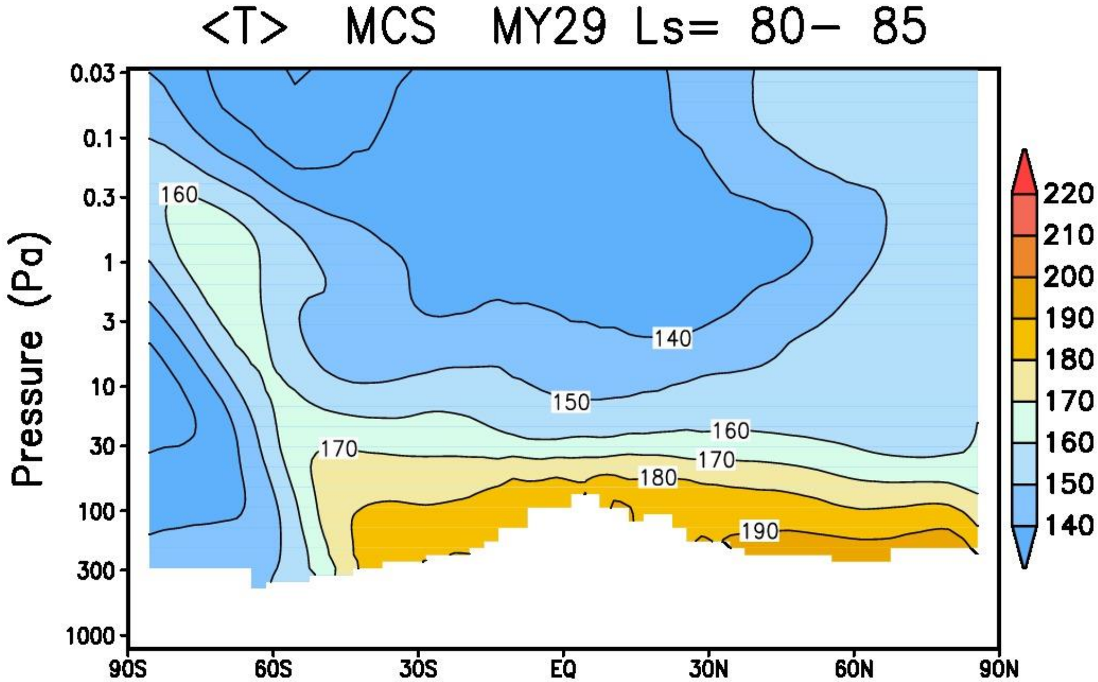
<T> MCS MY29 Ls= 80- 85
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
140
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210
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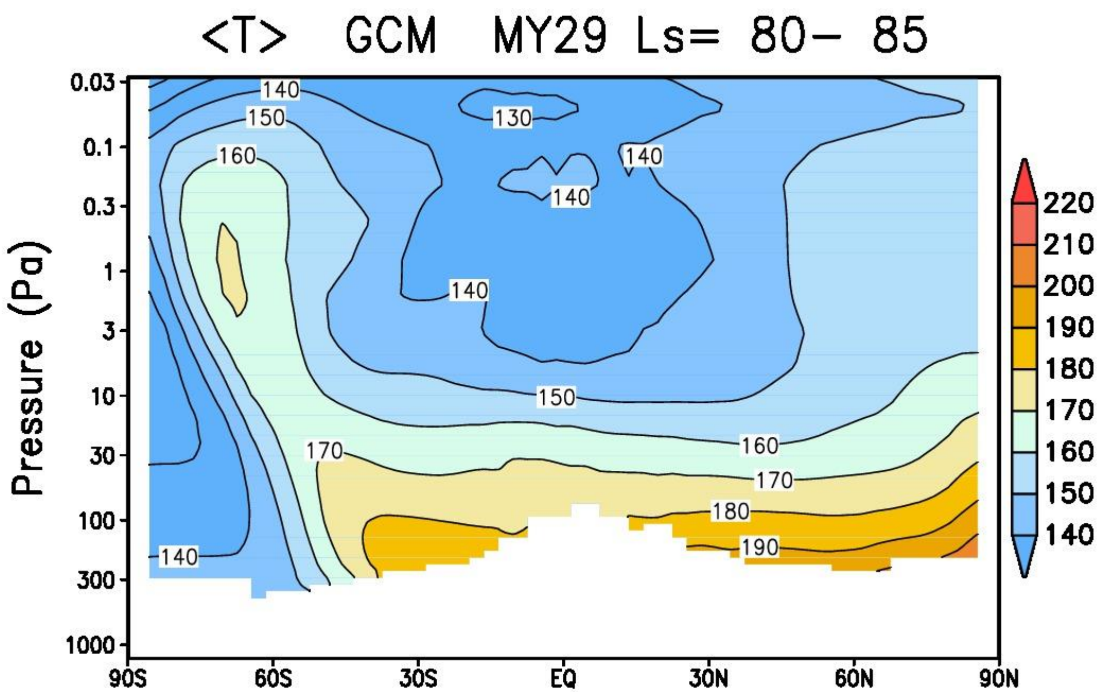
<T> GCM MY29 Ls= 80- 85
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
130
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140
140
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170
180
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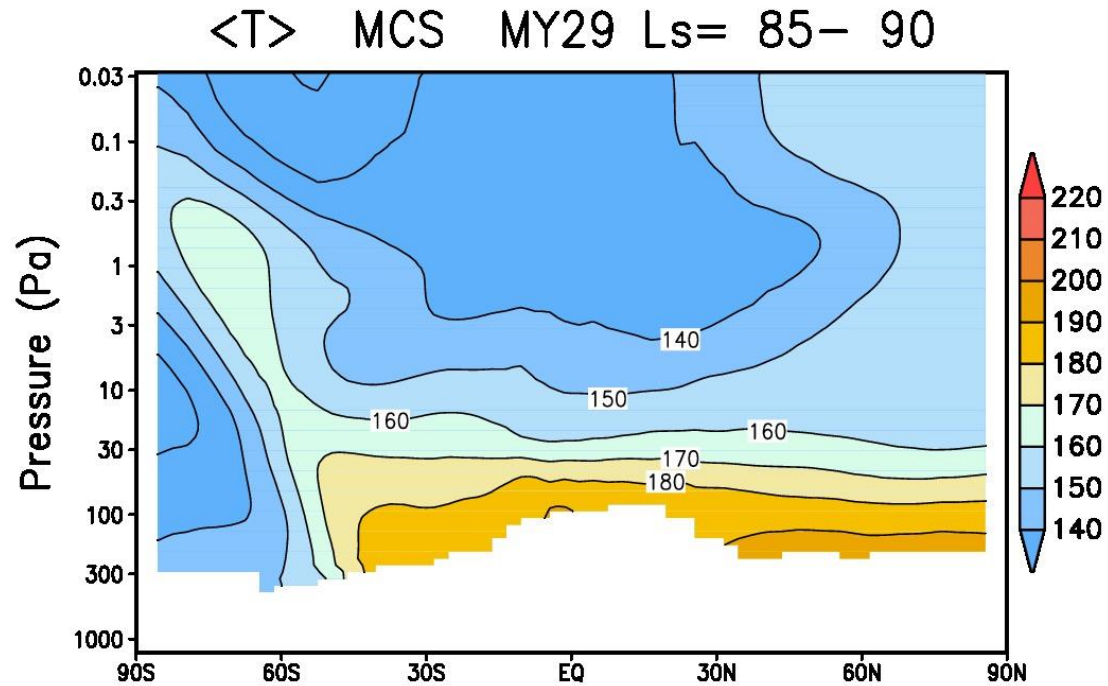
<T> MCS MY29 Ls= 85- 90
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
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220
210
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150
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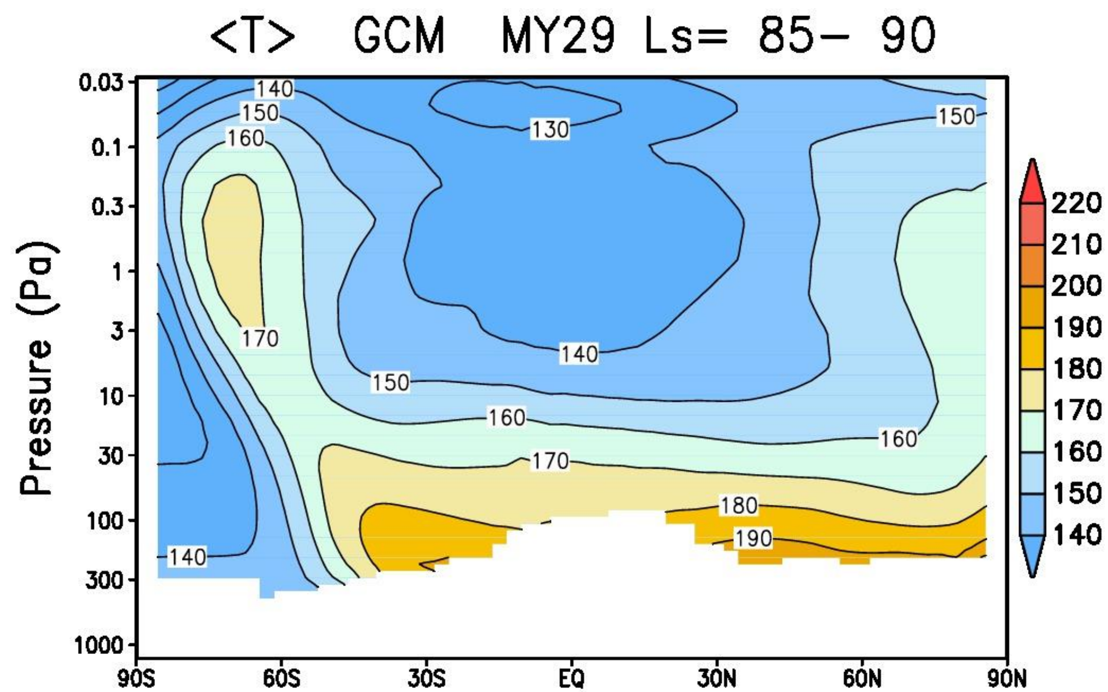
<T> GCM MY29 Ls= 85- 90
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
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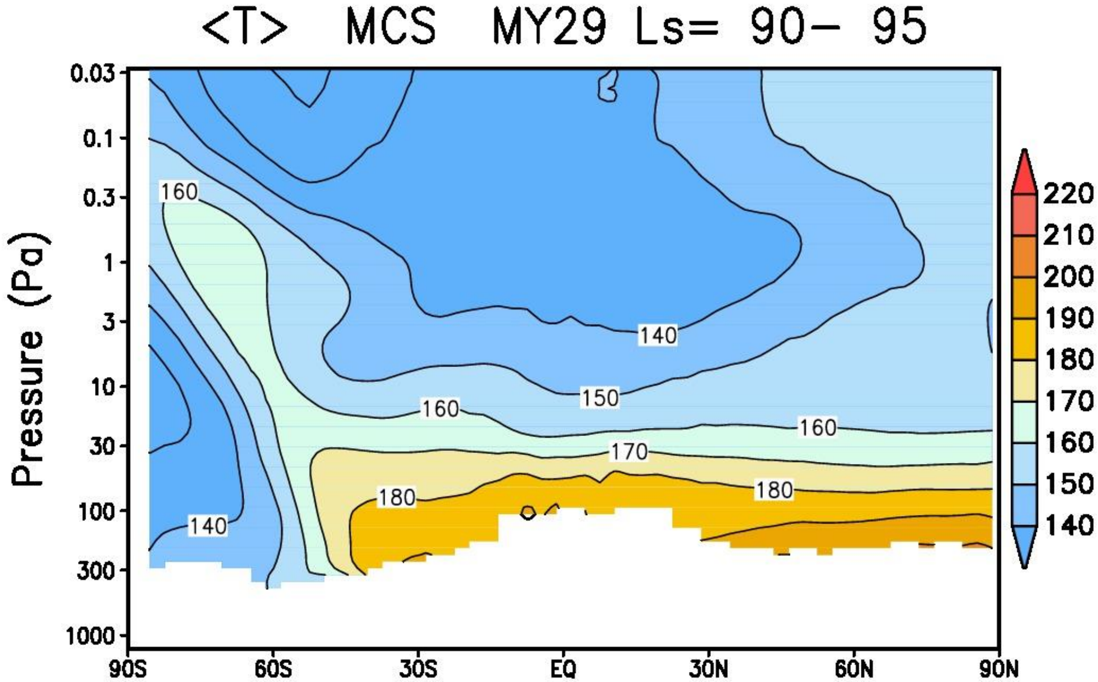
<T> MCS MY29 Ls= 90- 95
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
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30S
EQ
30N
60N
90N
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160
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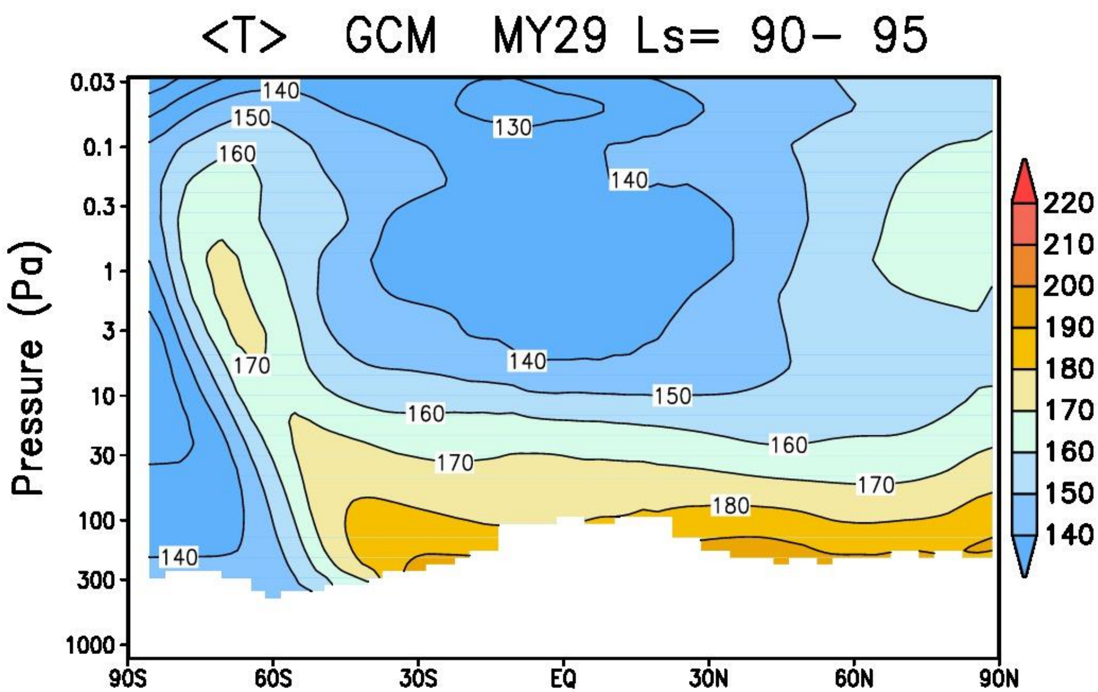
140


<T> GCM MY29 Ls= 90- 95
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
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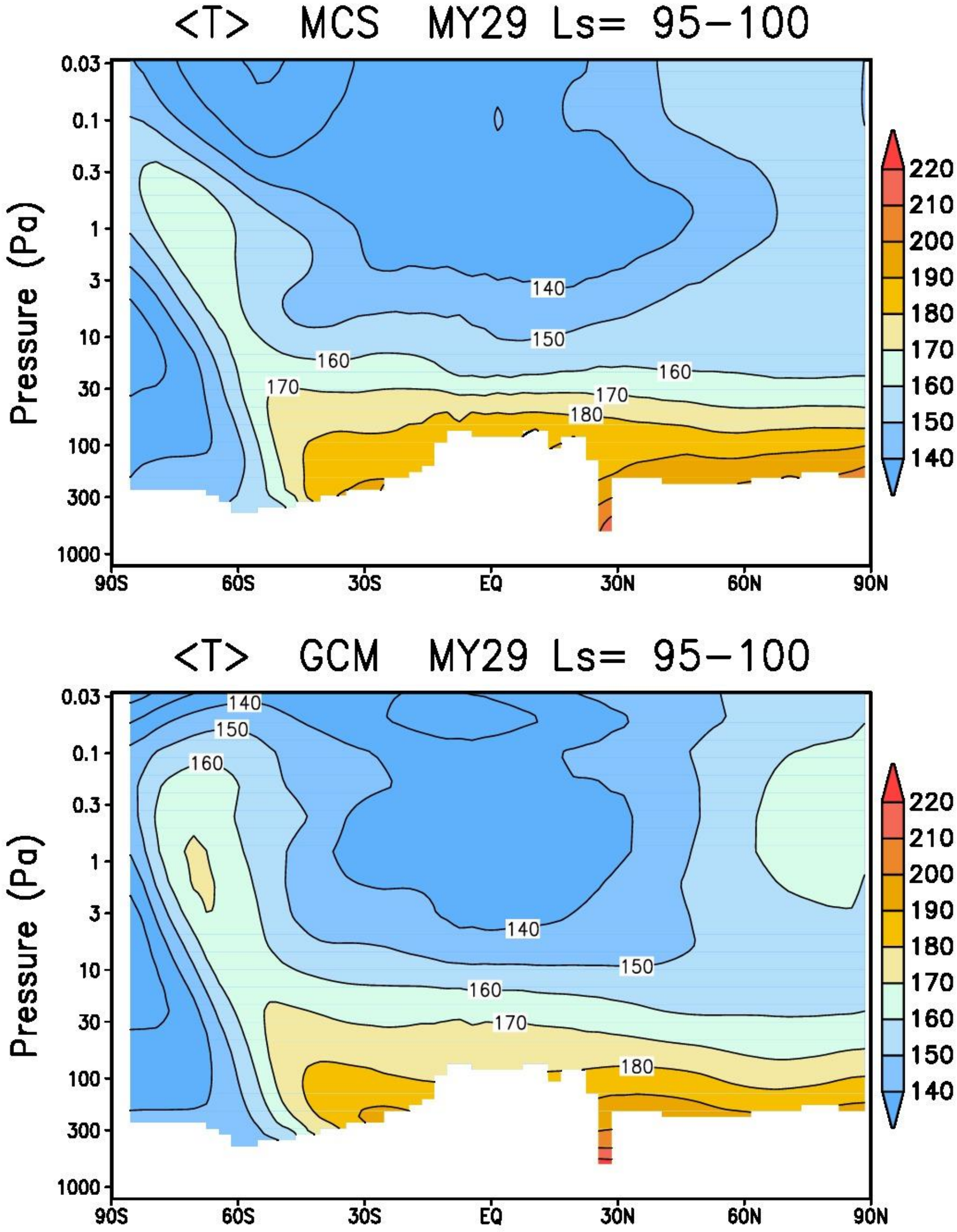
<T> MCS MY29 Ls= 95-100
<T> GCM MY29 Ls= 95-100
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
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210
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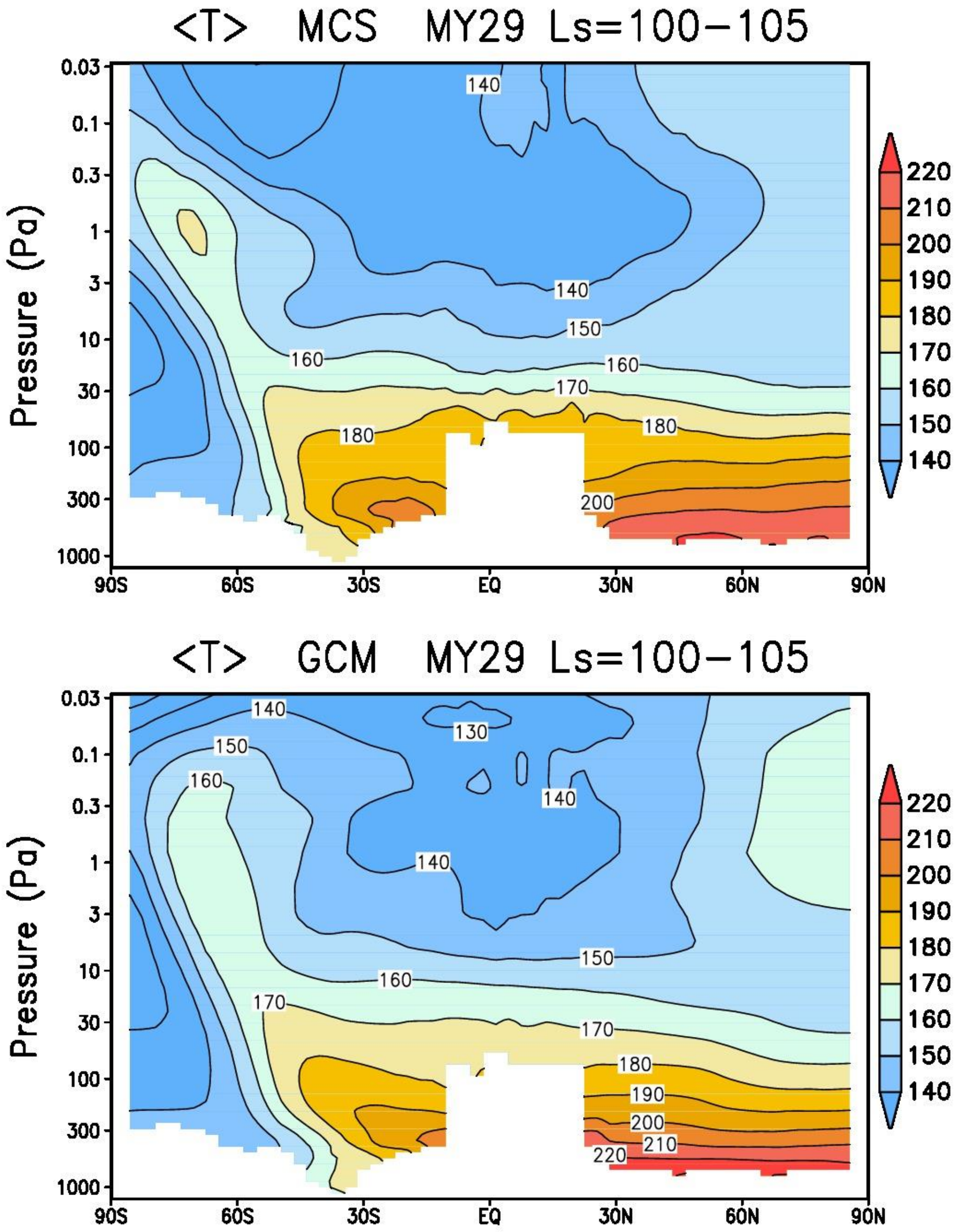

<T> MCS MY29 Ls=100-105
<T> GCM MY29 Ls=100-105
Pressure (Pa)
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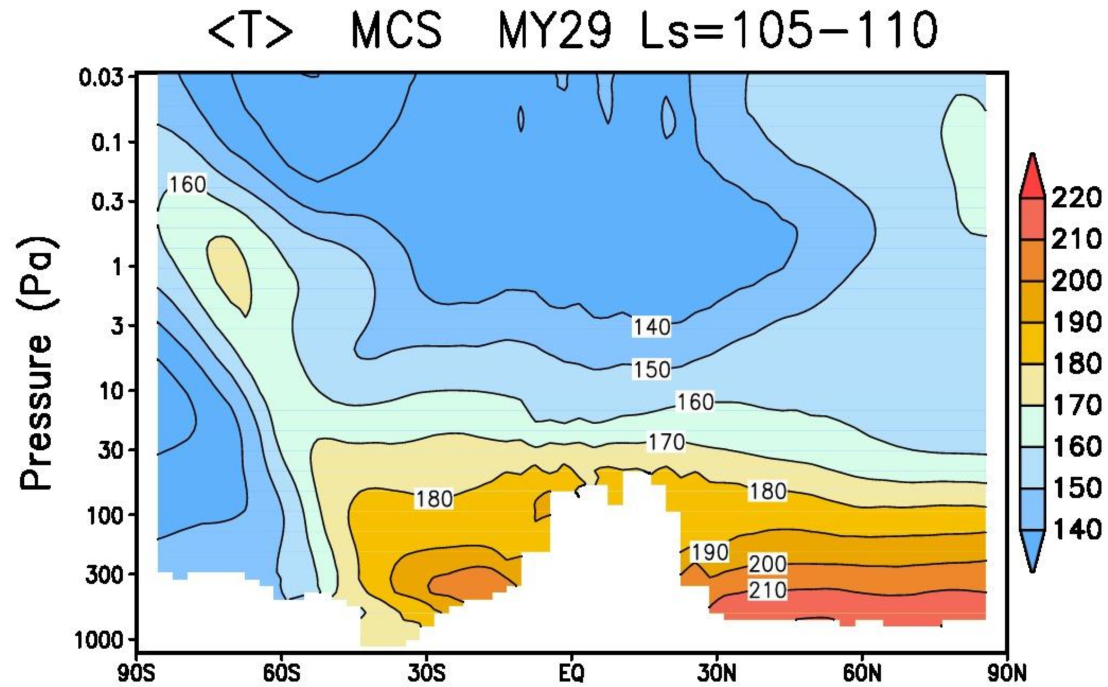
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
220
210
200
190
180
170
160
150
140
130


<T> MCS MY29 Ls=105-110
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
140
150
160
170
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180
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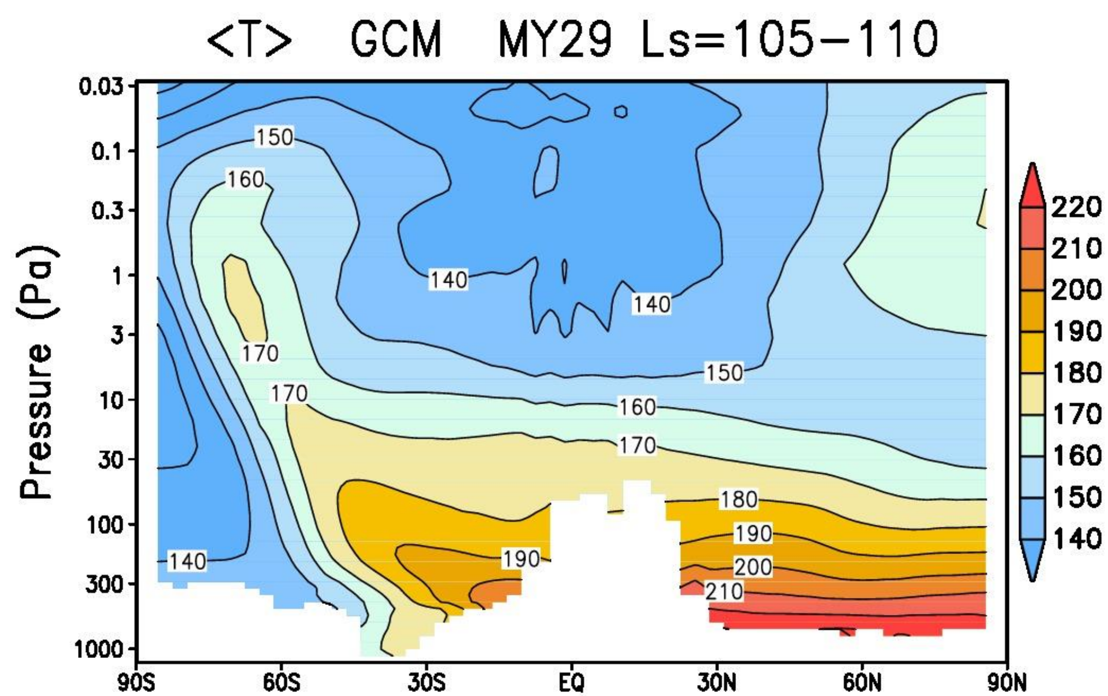
150
140


<T> GCM MY29 Ls=105-110
Pressure (Pa)
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0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
140
140
170
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180
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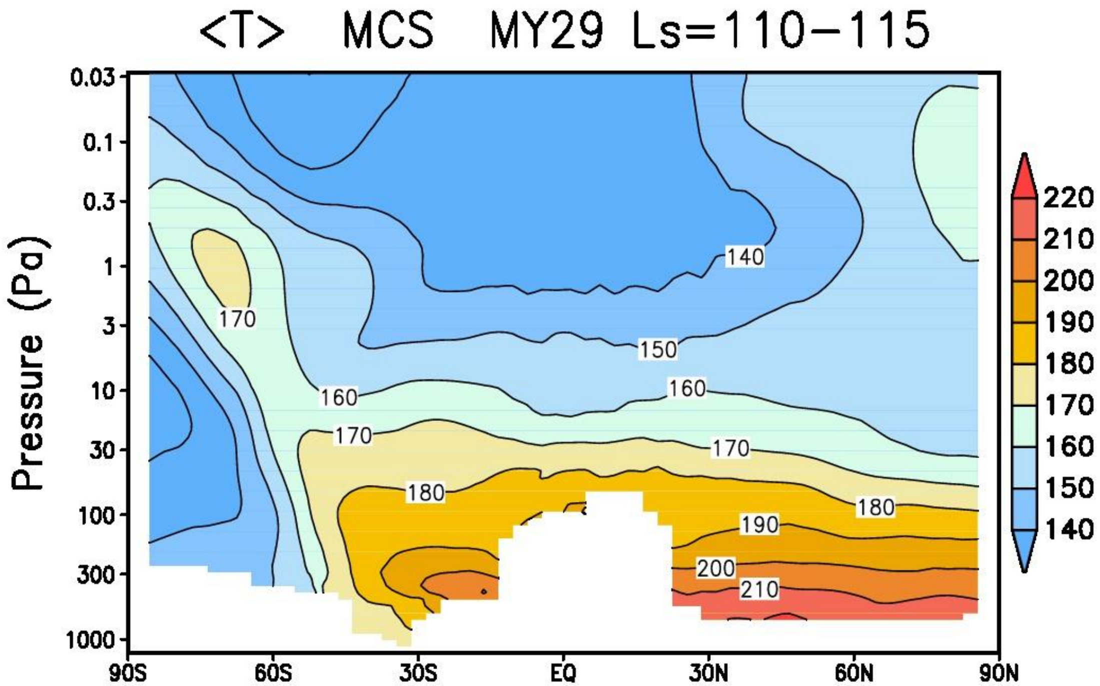
150
140


<T> MCS MY29 Ls=110-115
Pressure (Pa)
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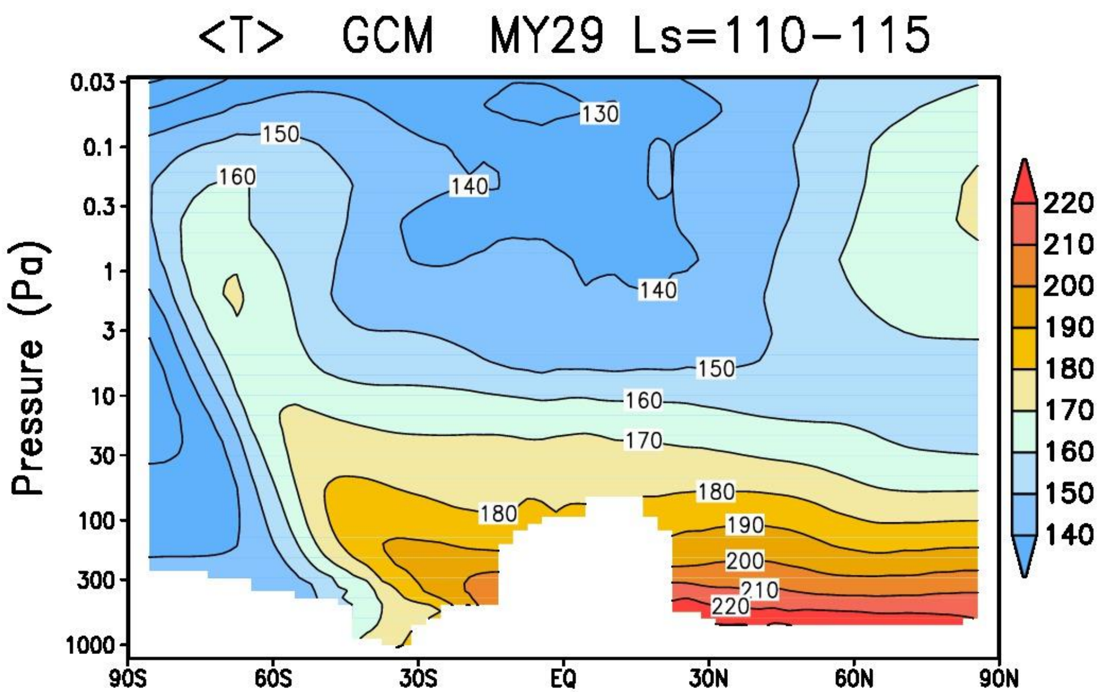
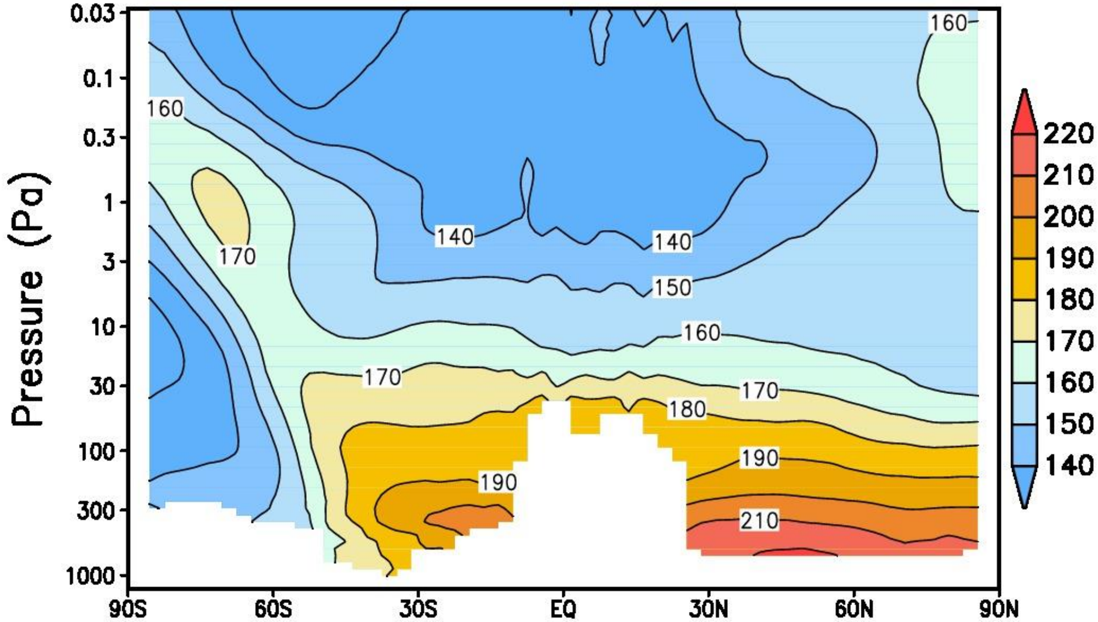
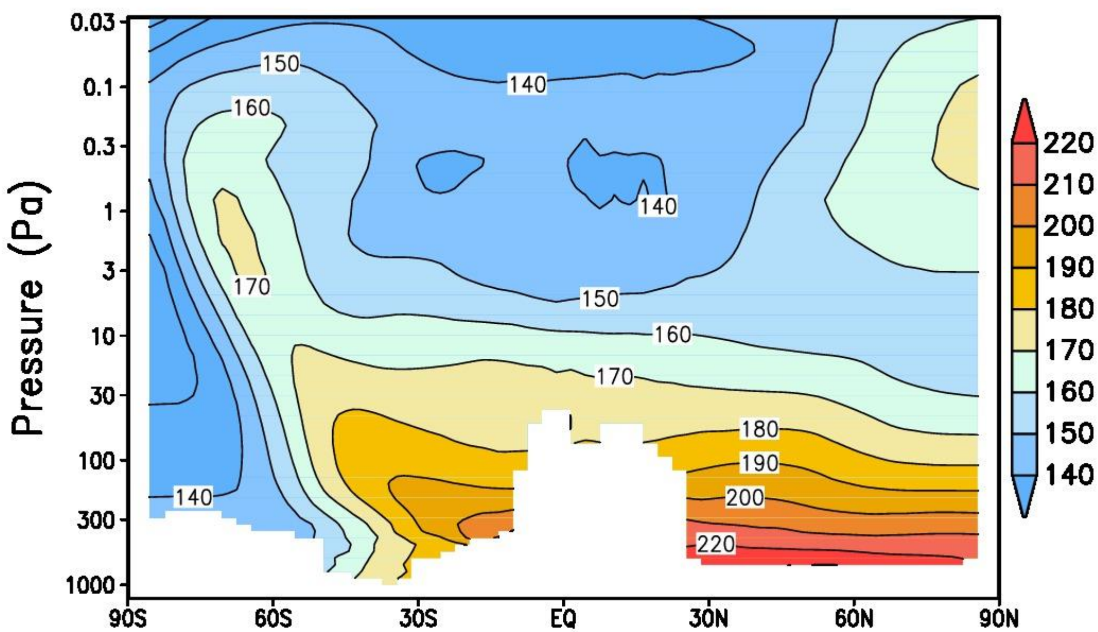
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220

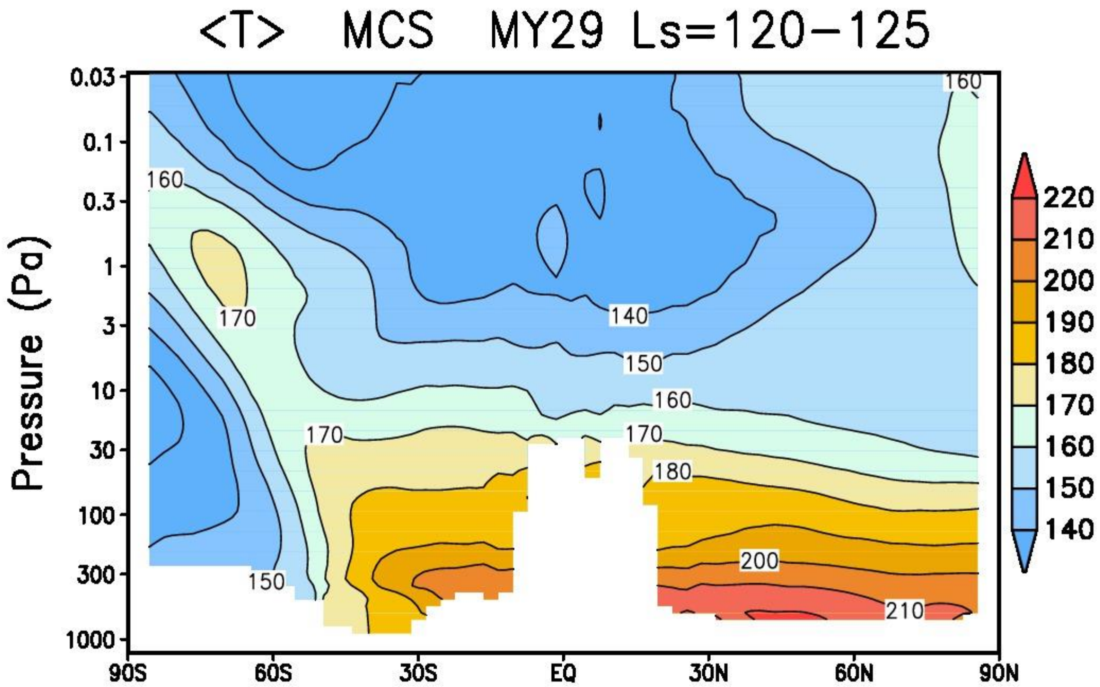

<T> GCM MY29 Ls=110-115
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
130
140
150
160
170
180
190
200
210
220

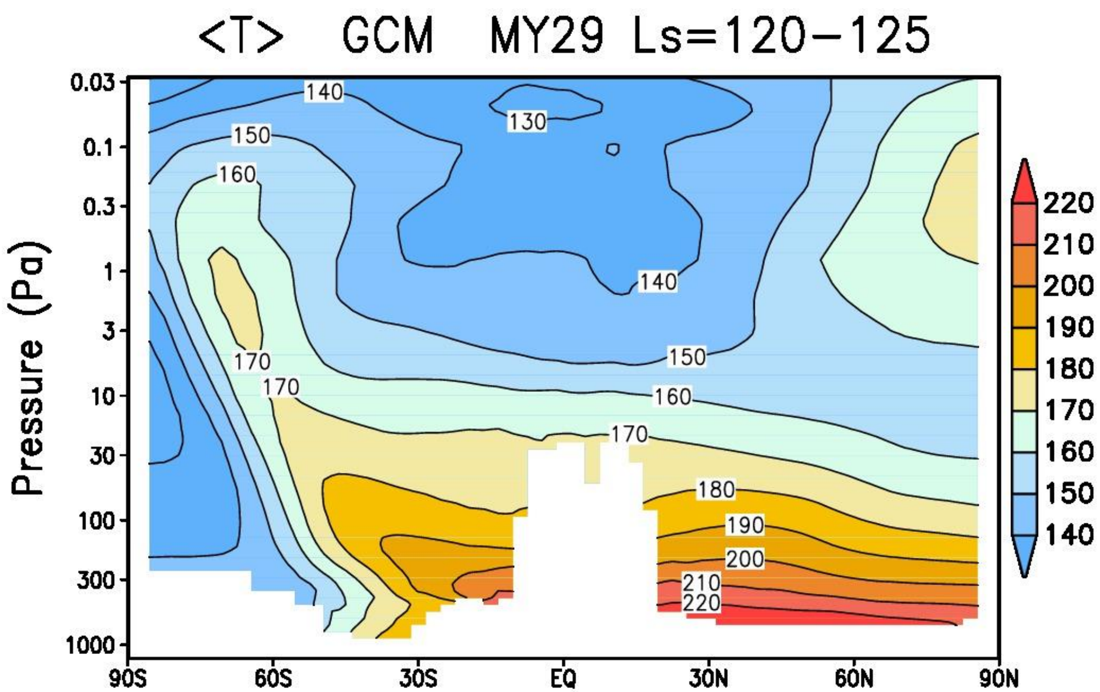
<T> MCS MY29 Ls=115-120

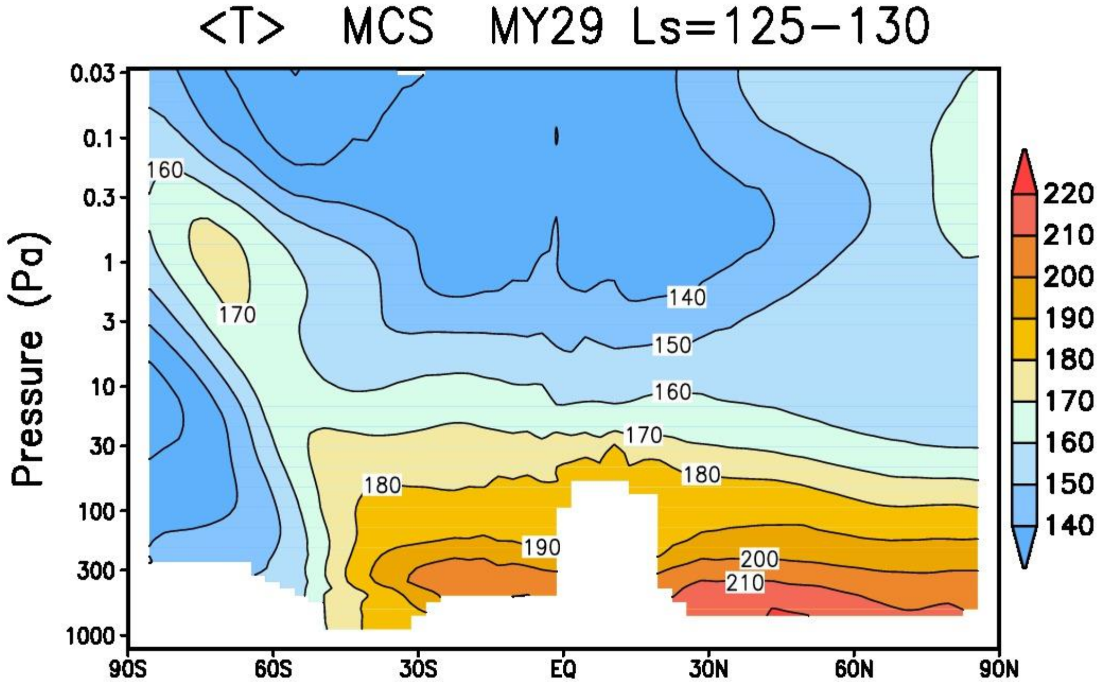


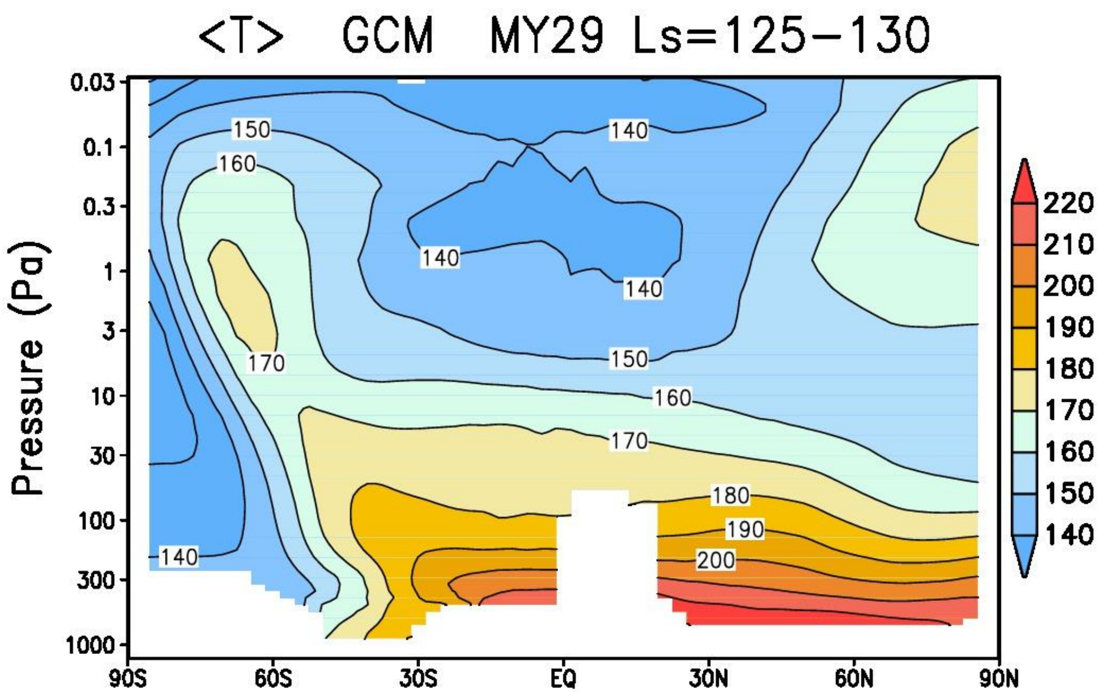

<T> GCM MY29 Ls=115-120

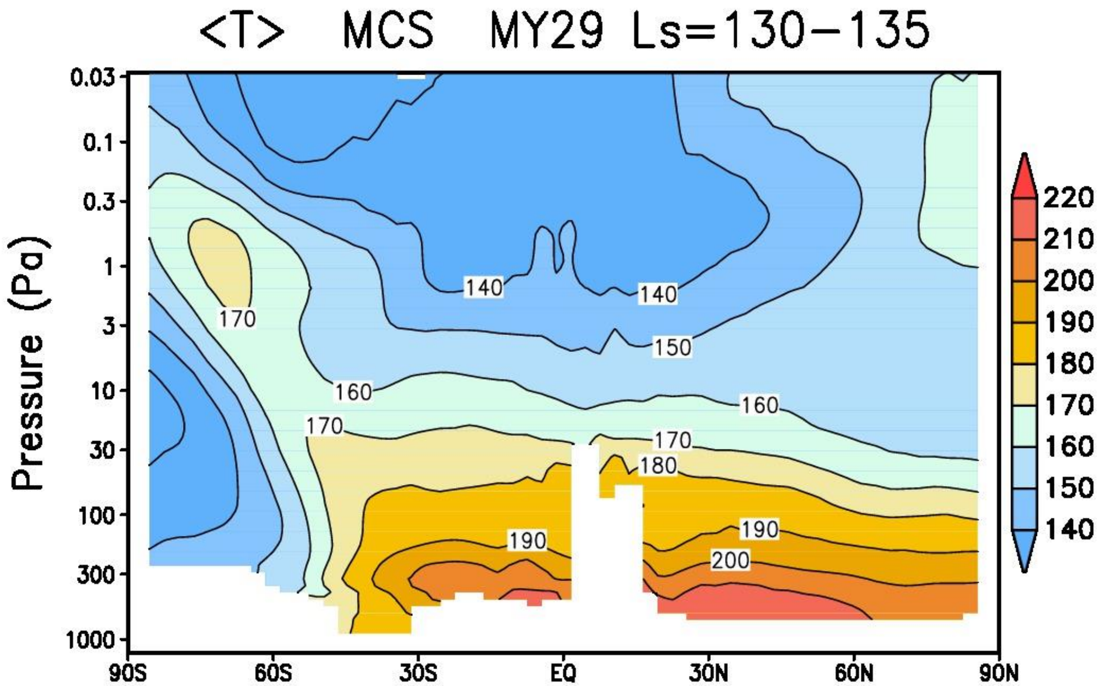


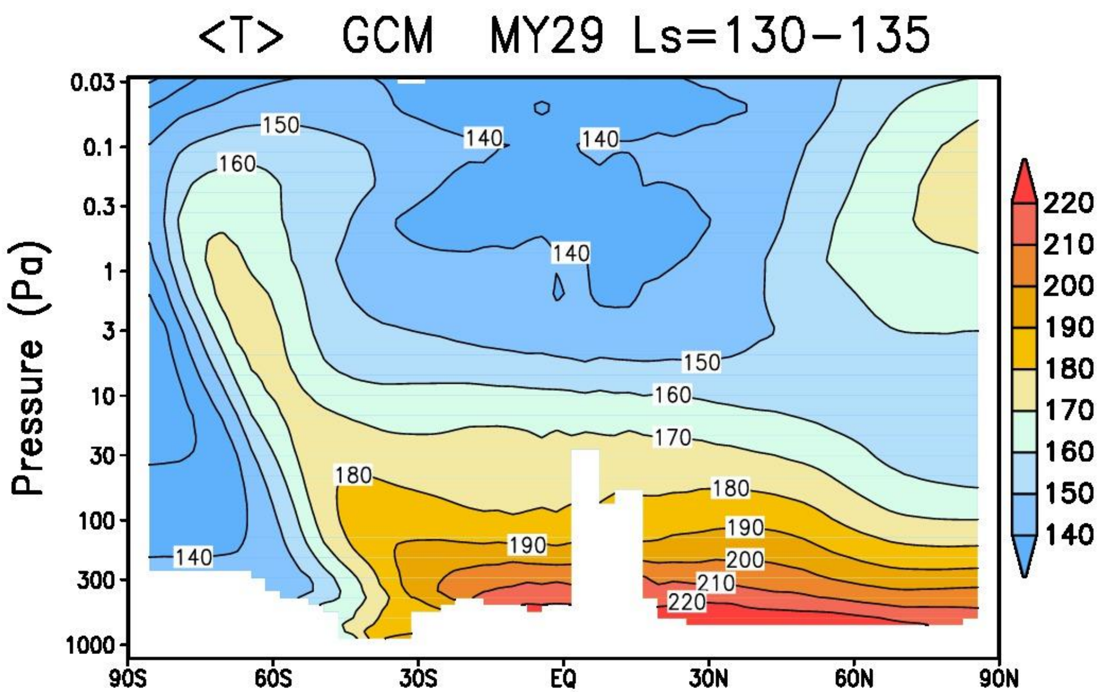

<T> MCS MY29 Ls=120-125
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220

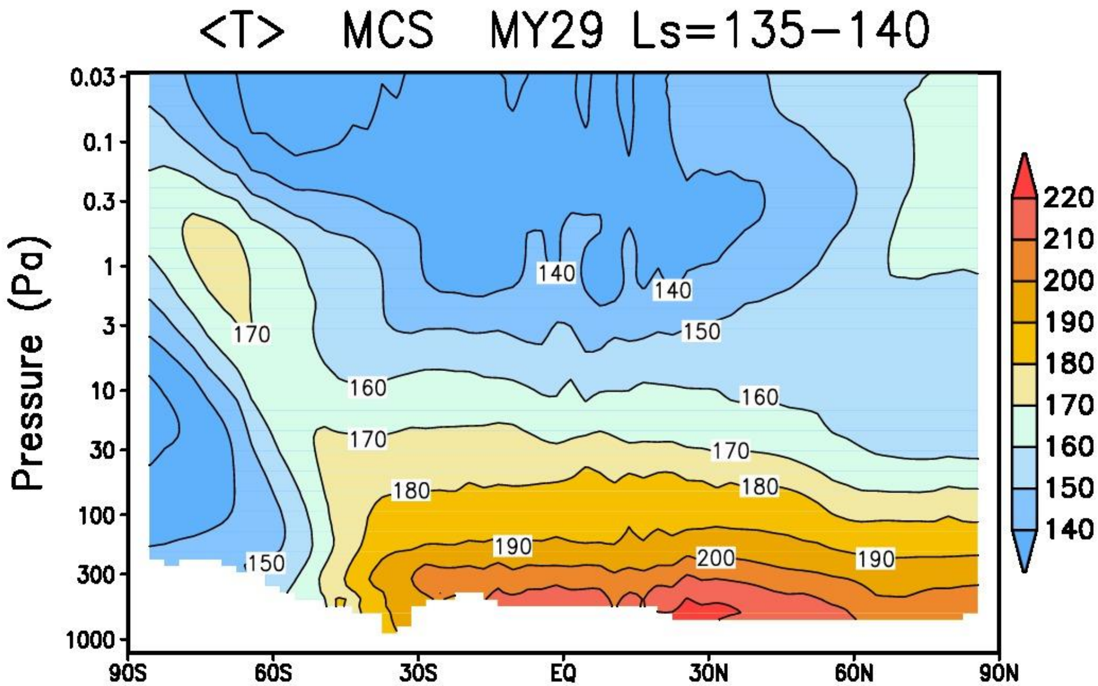

<T> GCM MY29 Ls=120-125
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
130
140
150
160
170
180
190
200
210
220

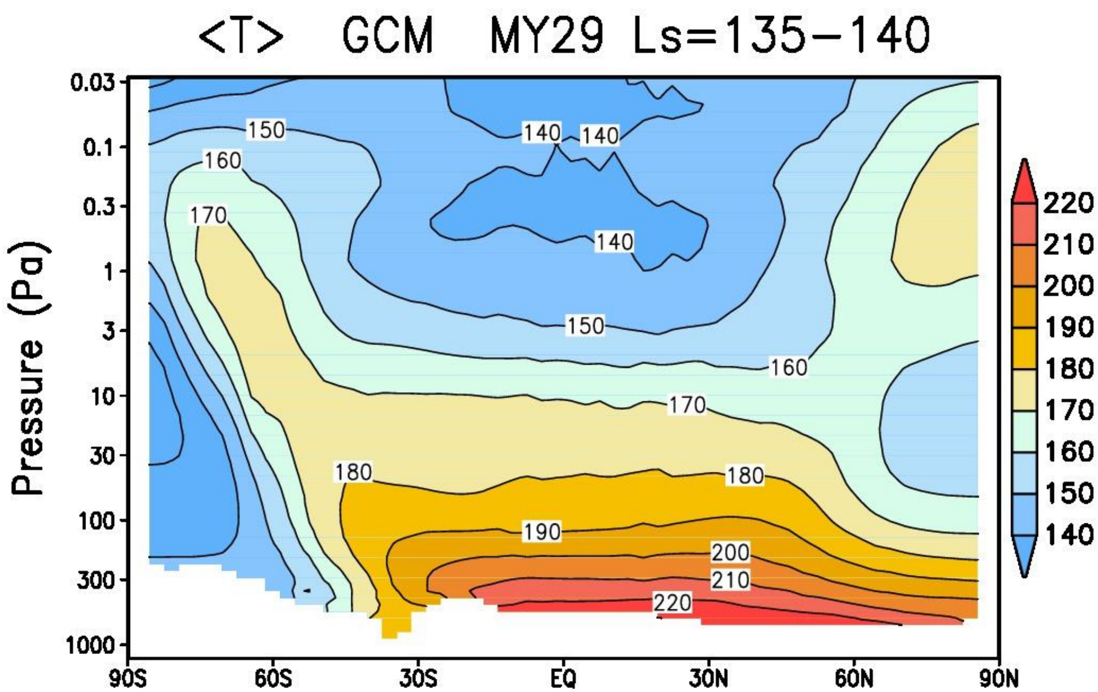

<T> MCS MY29 Ls=125–130
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
170
140
150
160
170
180
180
190
200
210
220
210
200
190
180
170
160
150
140


<T> GCM MY29 Ls=125–130
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
140
140
140
170
150
160
170
180
190
200
140
220
210
200
190
180
170
160
150
140


<T> MCS MY29 Ls=130-135
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220


<T> GCM MY29 Ls=130-135
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220


<T> MCS MY29 Ls=135-140
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
140
150
160
160
170
170
170
180
180
190
200
190
150
220
210
200
190
180
170
160
150
140


<T> GCM MY29 Ls=135-140
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
140
140
140
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160
170
180
180
190
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210
220
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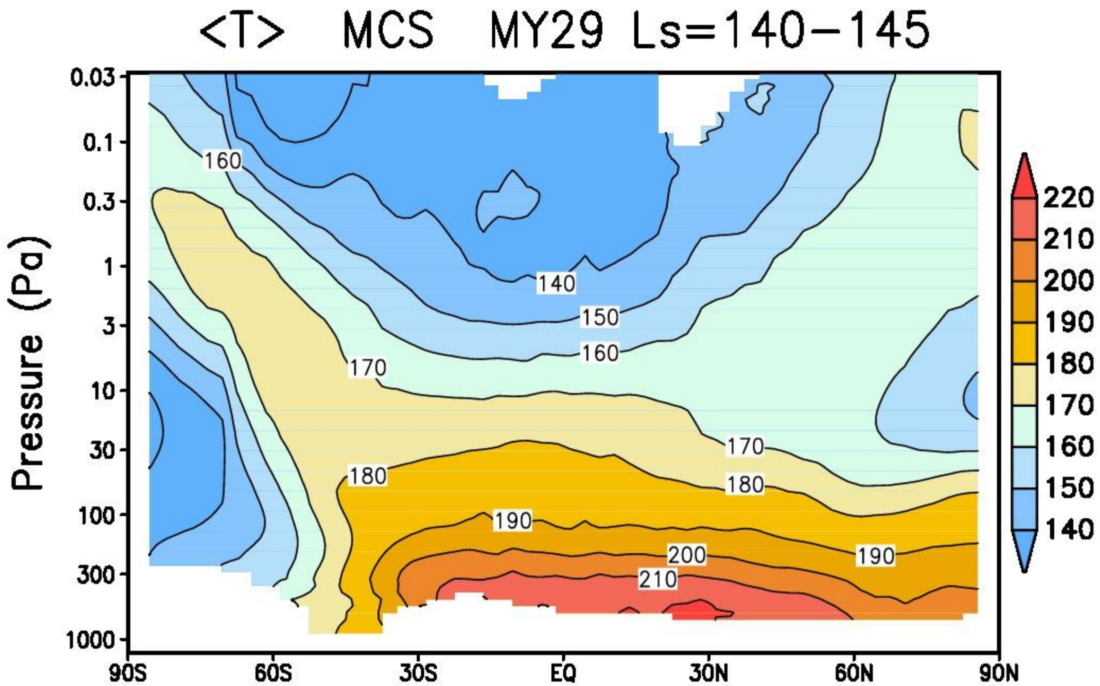
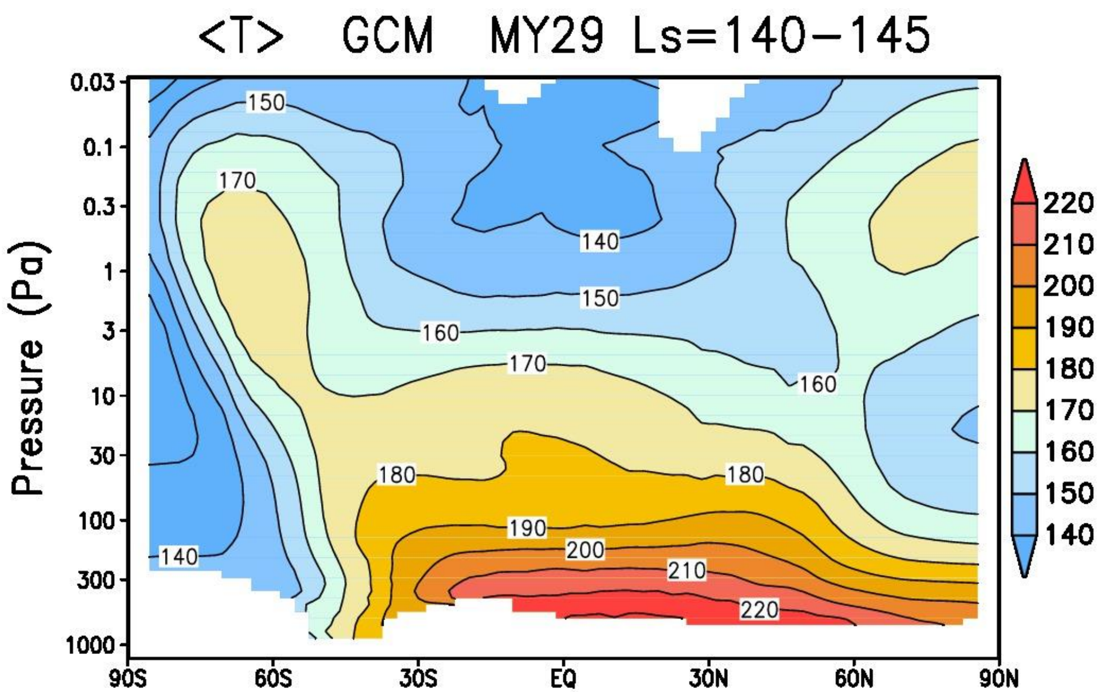
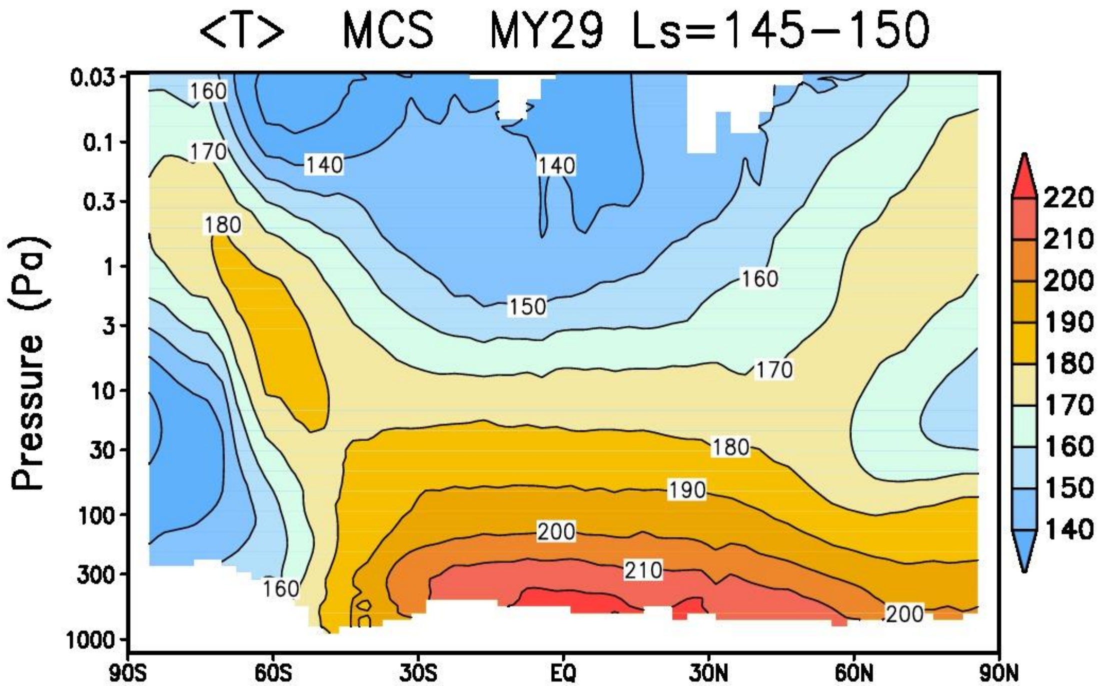
210
200
190
180
170
160
150
140



<T> MCS MY29 Ls=140-145
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
140
150
160
170
170
180
180
190
200
210
190
220
210
200
190
180
170
160
150
140

<T> GCM MY29 Ls=140-145
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
170
140
150
160
170
160
180
180
190
200
210
220
140
220
210
200
190
180
170
160
150
140


<T> MCS MY29 Ls=145-150
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
170
180
140
140
150
160
170
180
190
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160
200
220
210
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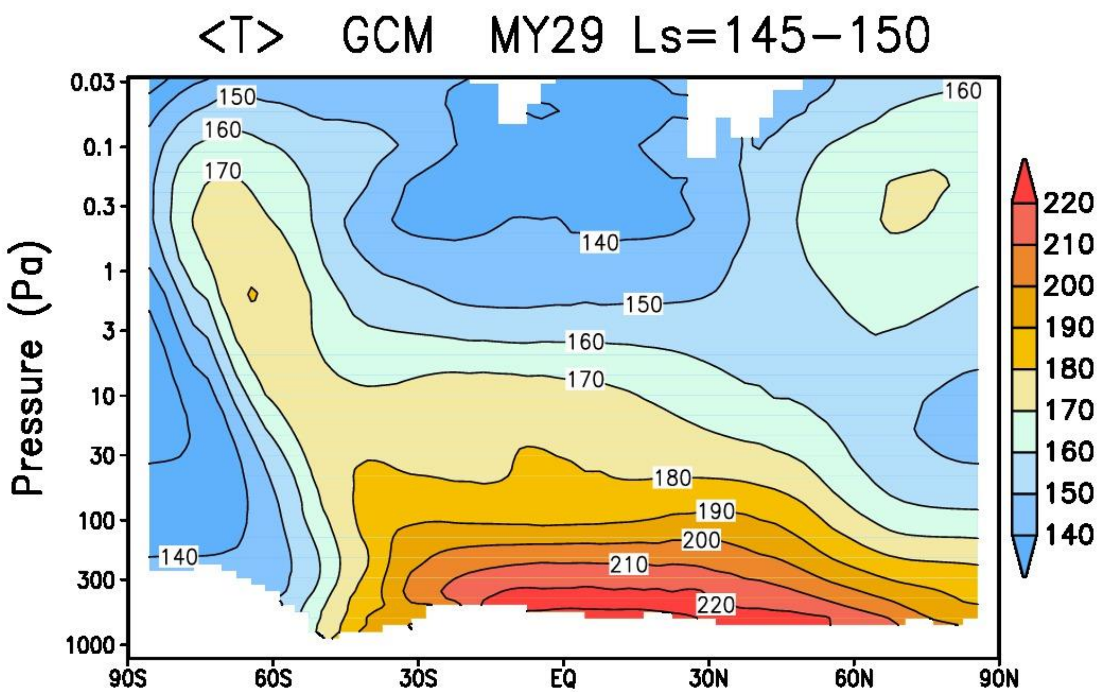
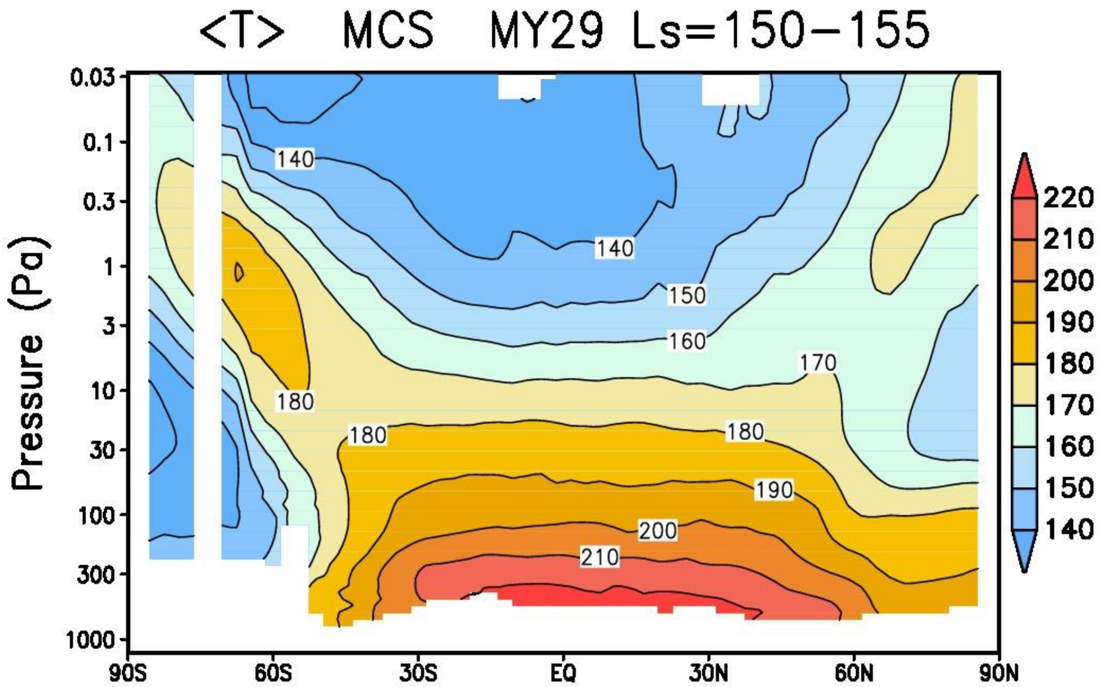
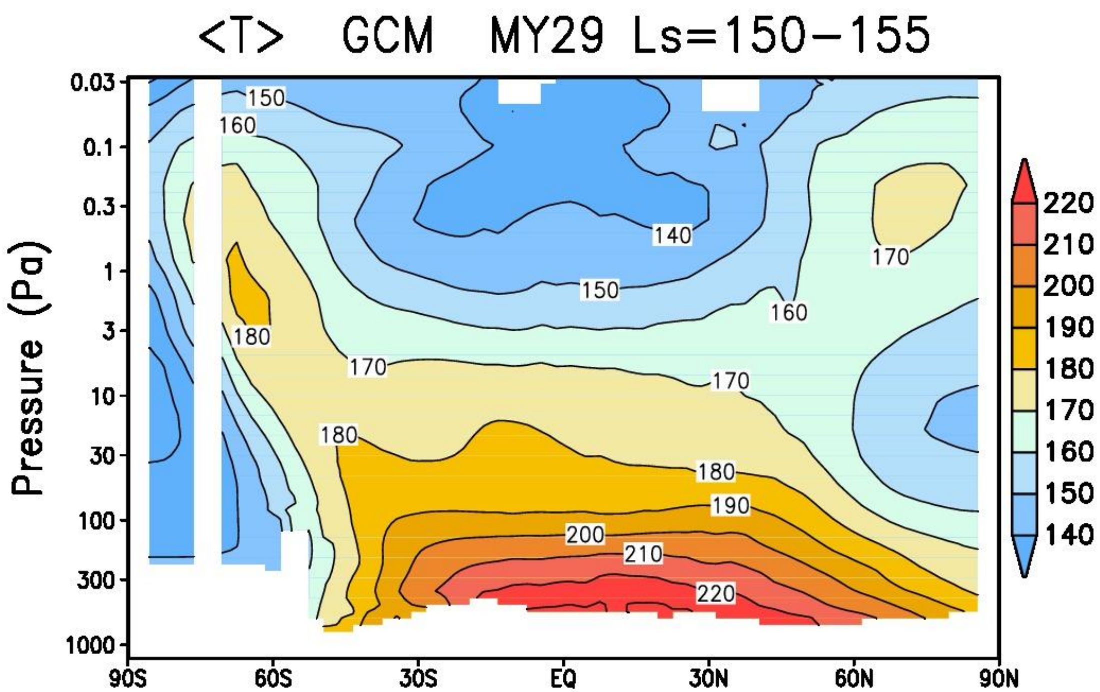
190
180
170
160
150
140


<T> GCM MY29 Ls=145-150
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
140
150
160
170
180
190
200
210
220
140
160
220
210
200
190
180
170
160
150
140


<T> MCS MY29 Ls=150−155
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220


<T> GCM MY29 Ls=150−155
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
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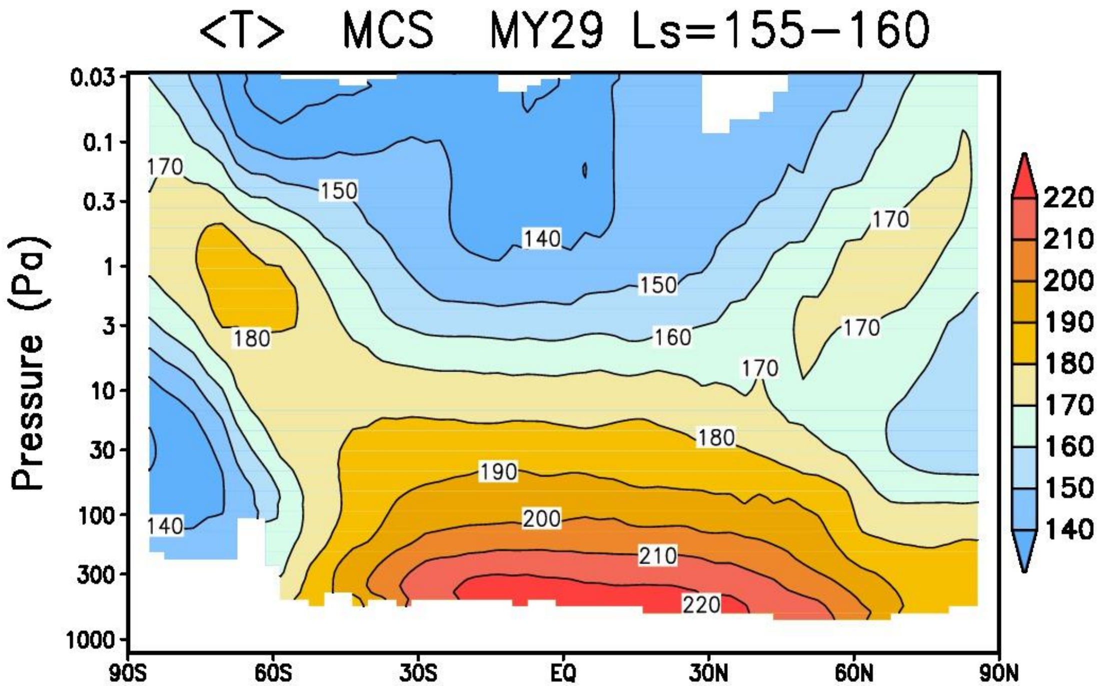
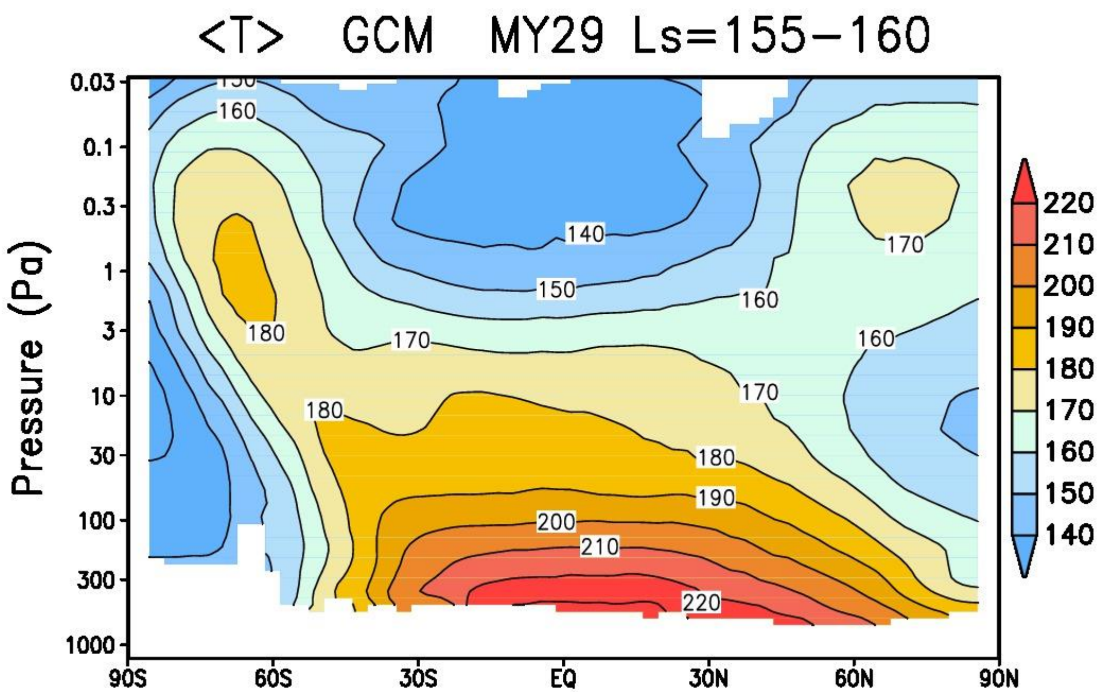
180
190
200
210
220

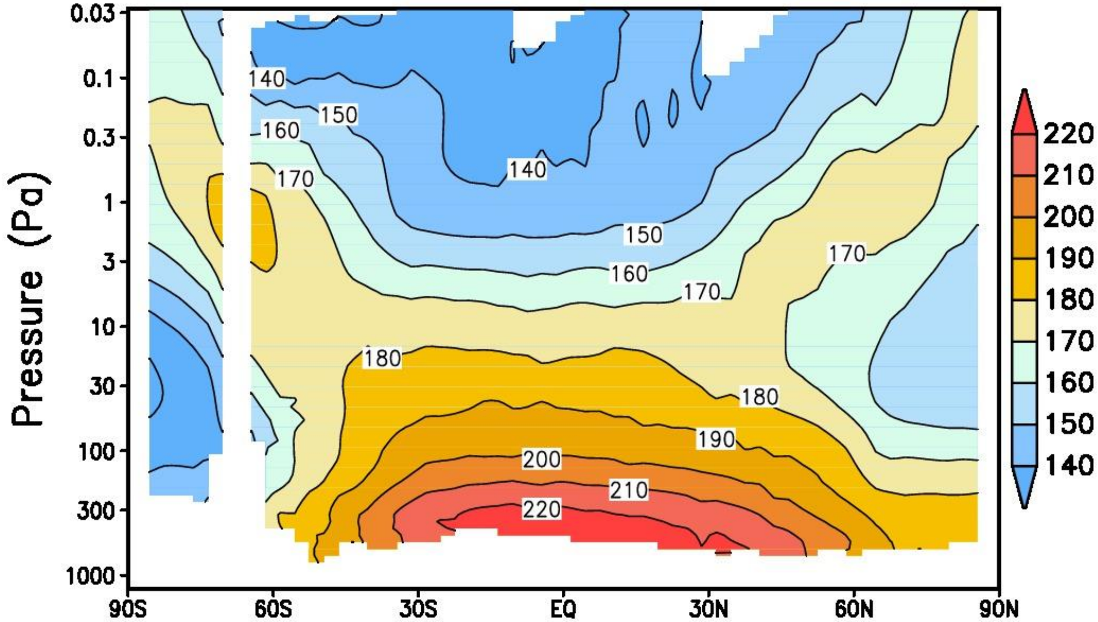


<T> MCS MY29 Ls=155-160
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220

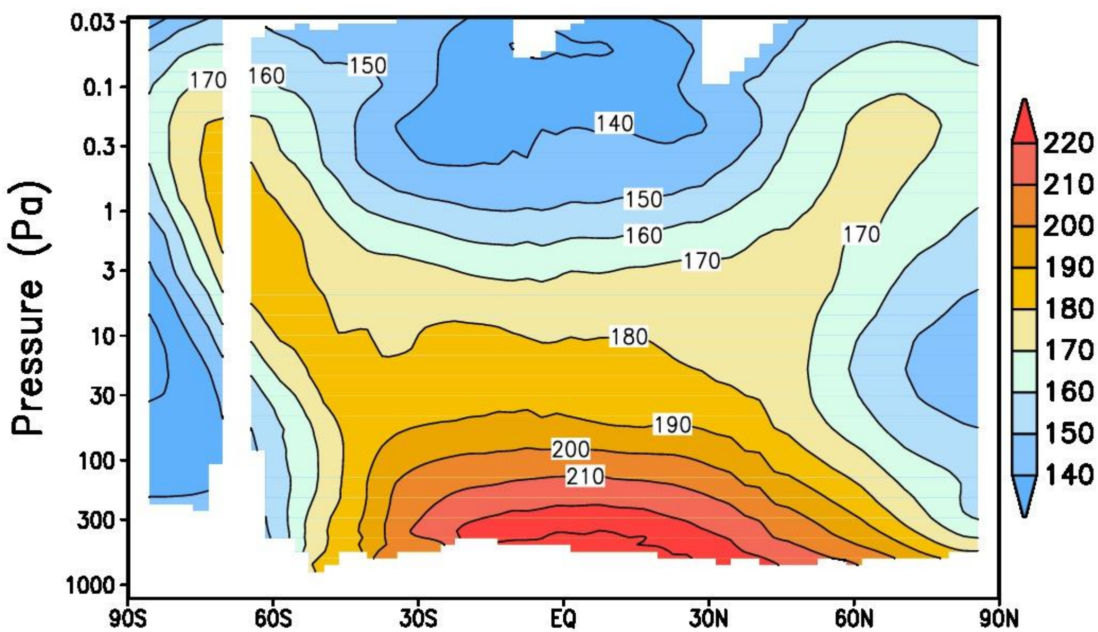



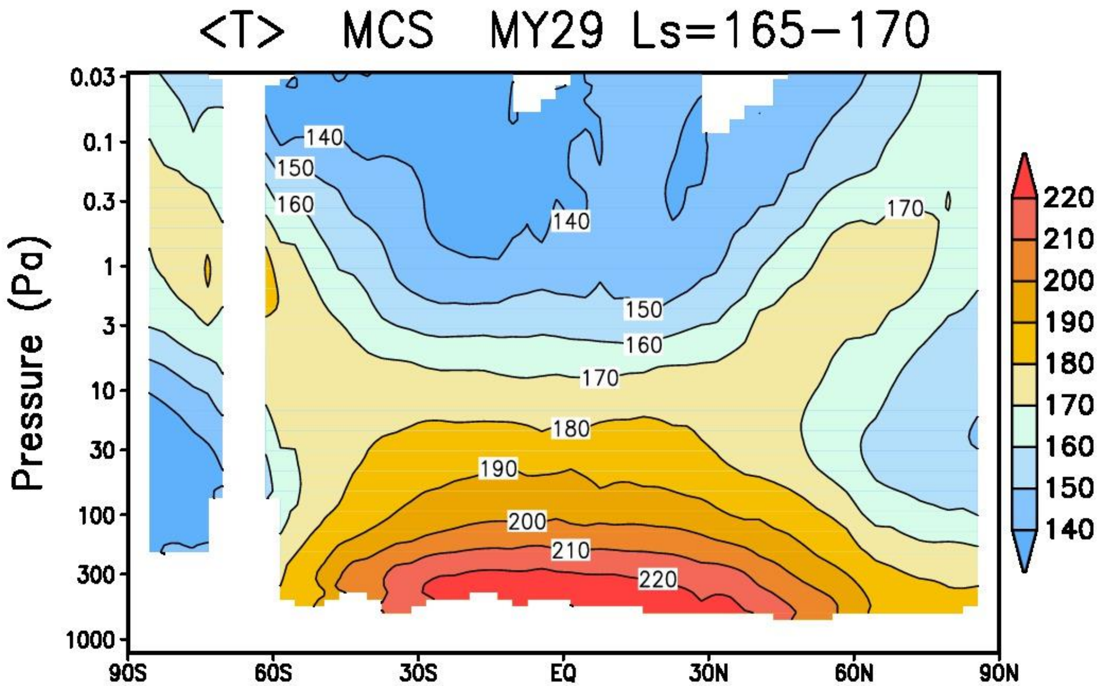
<T> GCM MY29 Ls=155-160
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220

<T>  MCS  MY29 Ls=160–165

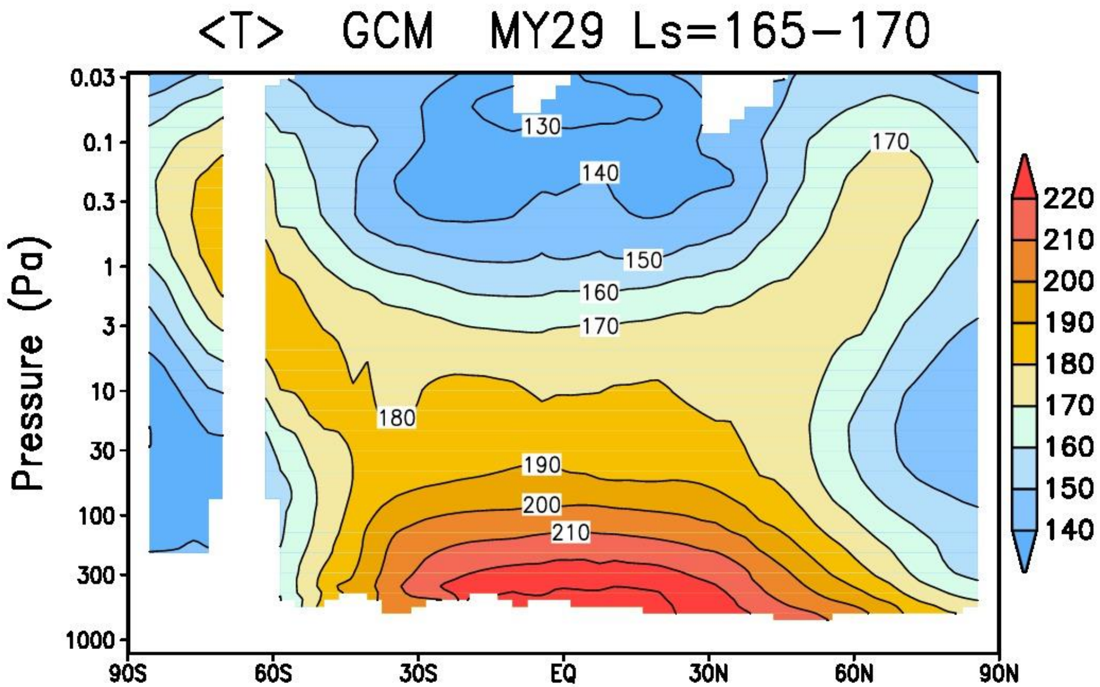



<T>  GCM  MY29 Ls=160–165

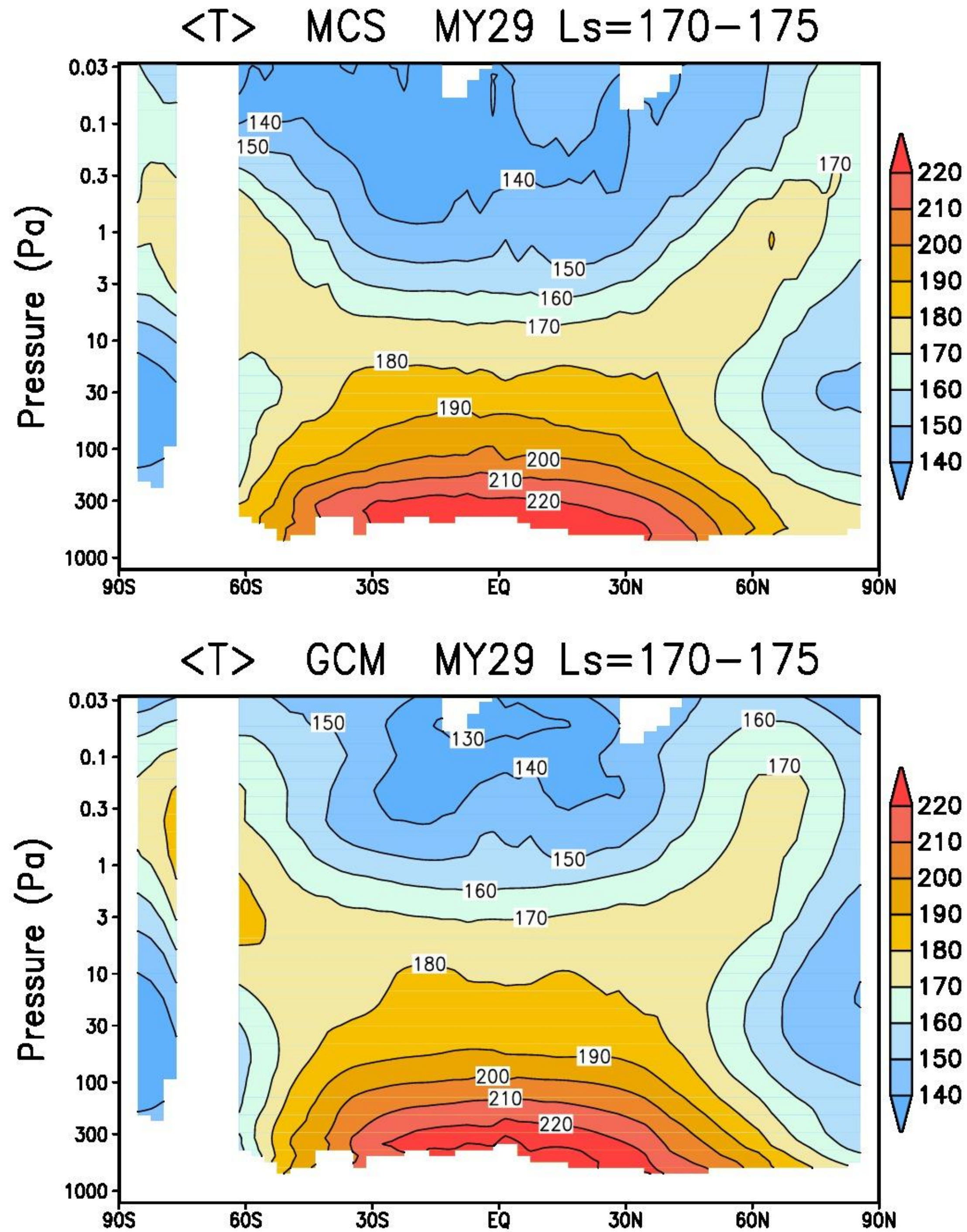


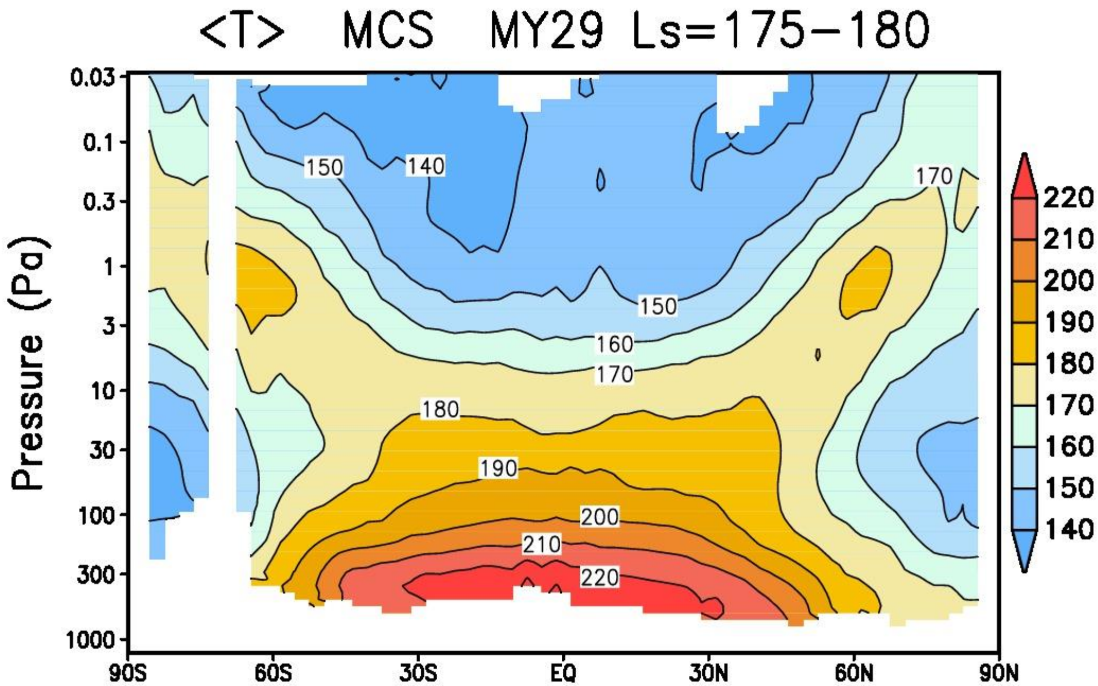


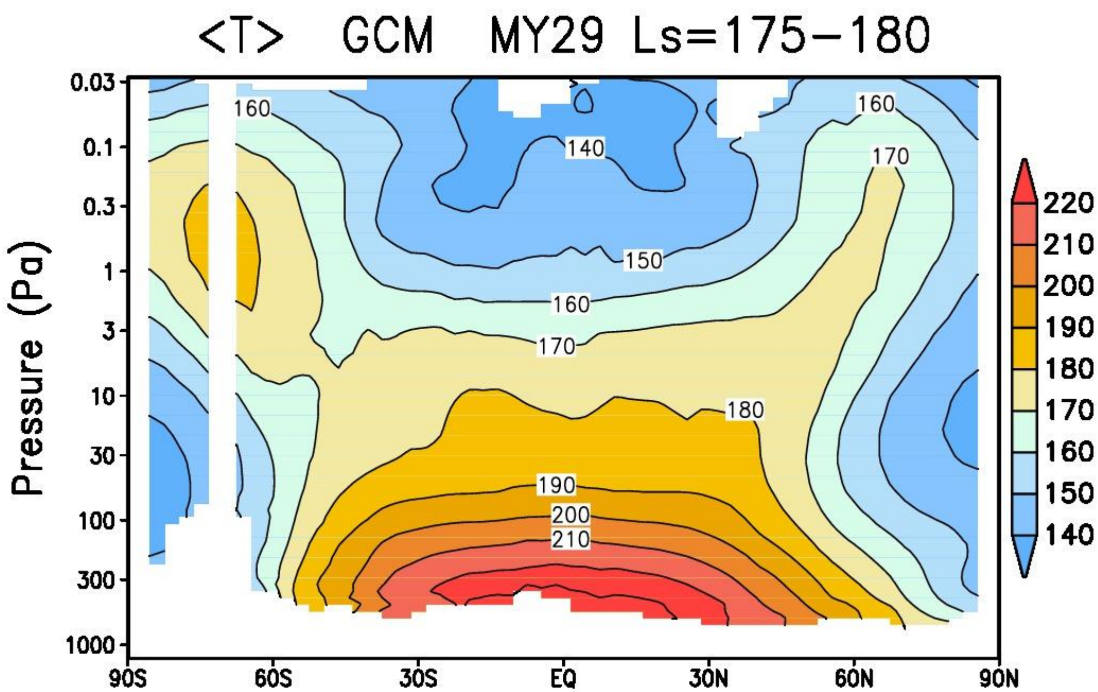
<T> MCS MY29 Ls=165-170
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220

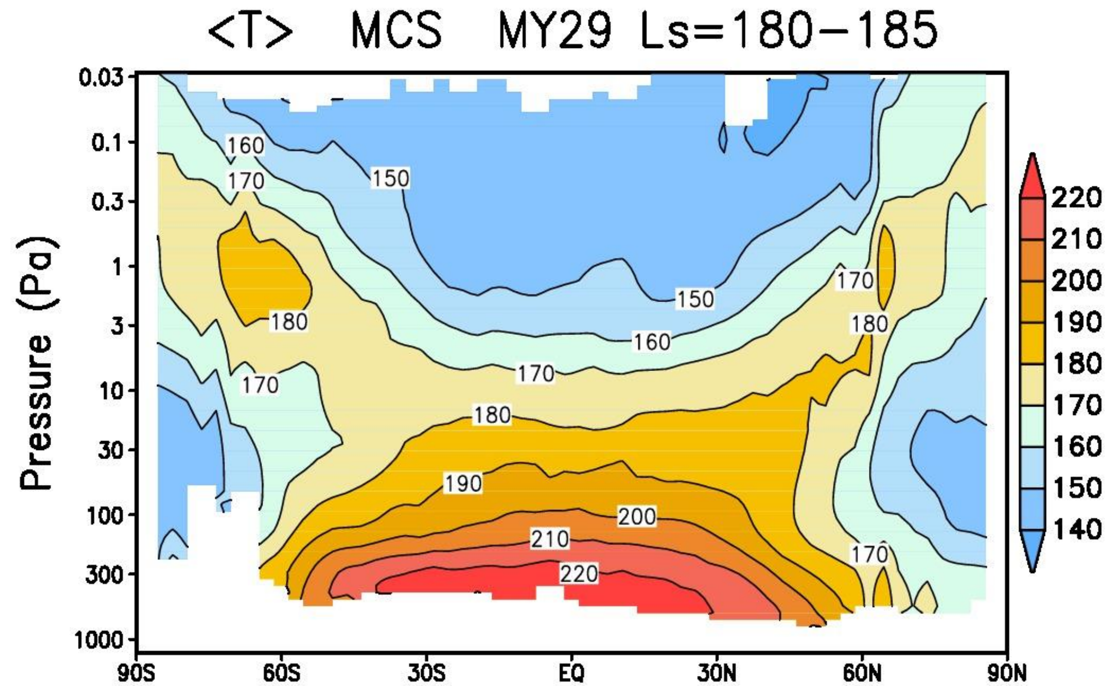



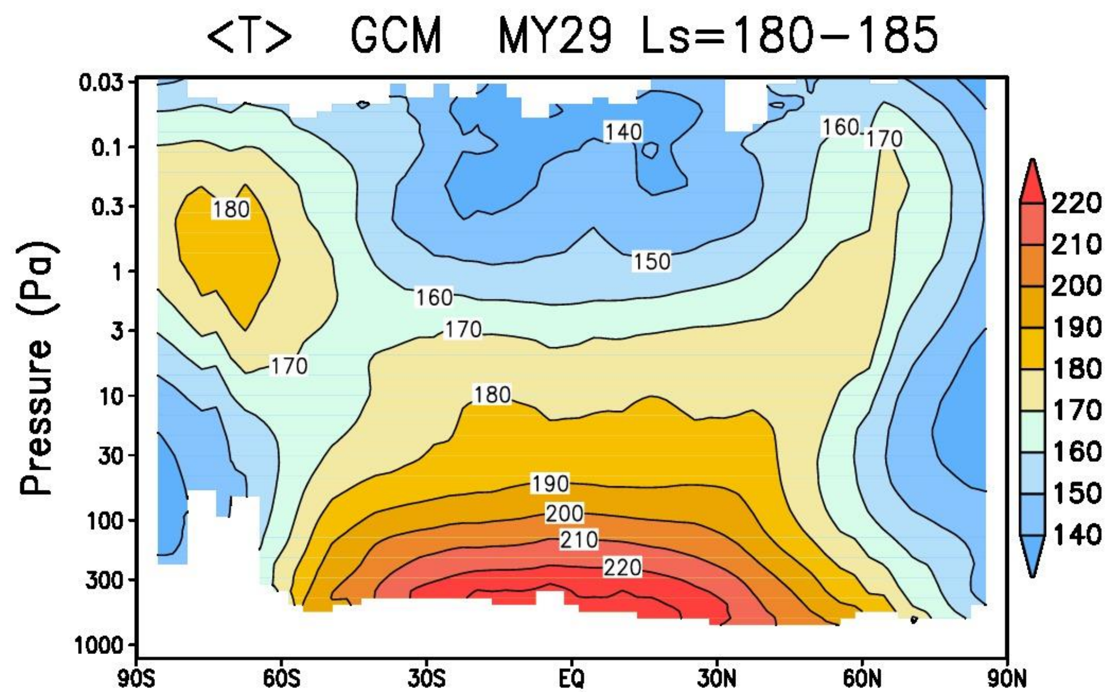
<T> GCM MY29 Ls=165-170
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
130
140
150
160
170
180
190
200
210
220


<T> MCS MY29 Ls=170−175
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220
<T> GCM MY29 Ls=170−175
130

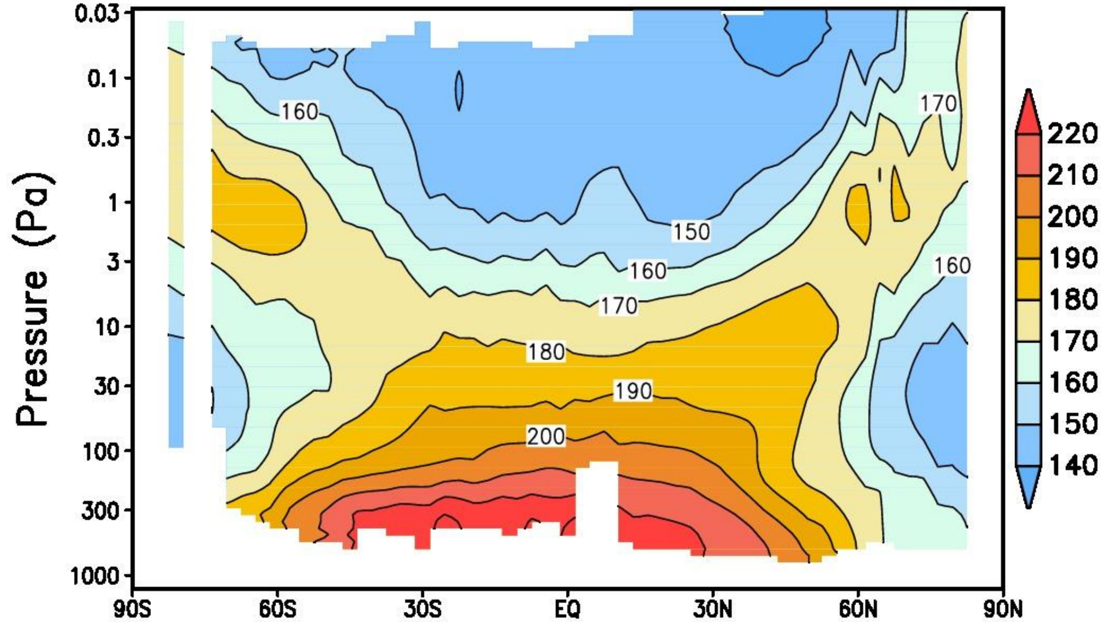

<T> MCS MY29 Ls=175-180
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
140
170
150
160
170
180
190
200
210
220
140
150
160
170
180
190
200
210
220


<T> GCM MY29 Ls=175-180
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
160
140
170
150
160
170
180
190
200
210
140
150
160
170
180
190
200
210
220

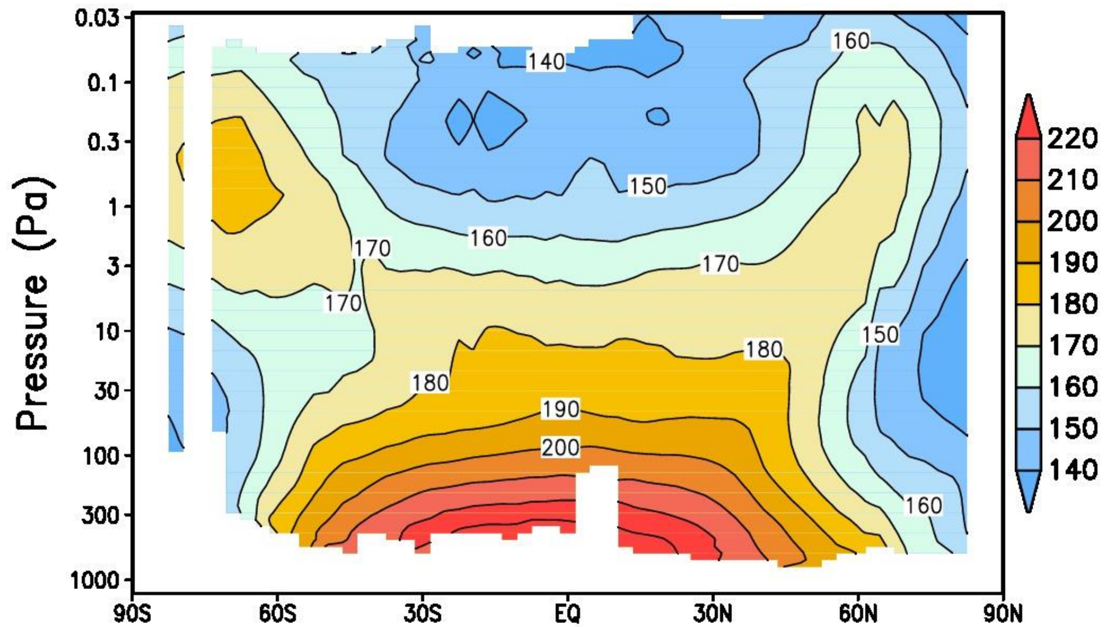

<T> MCS MY29 Ls=180-185
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
220
210
200
190
180
170
160
150
140

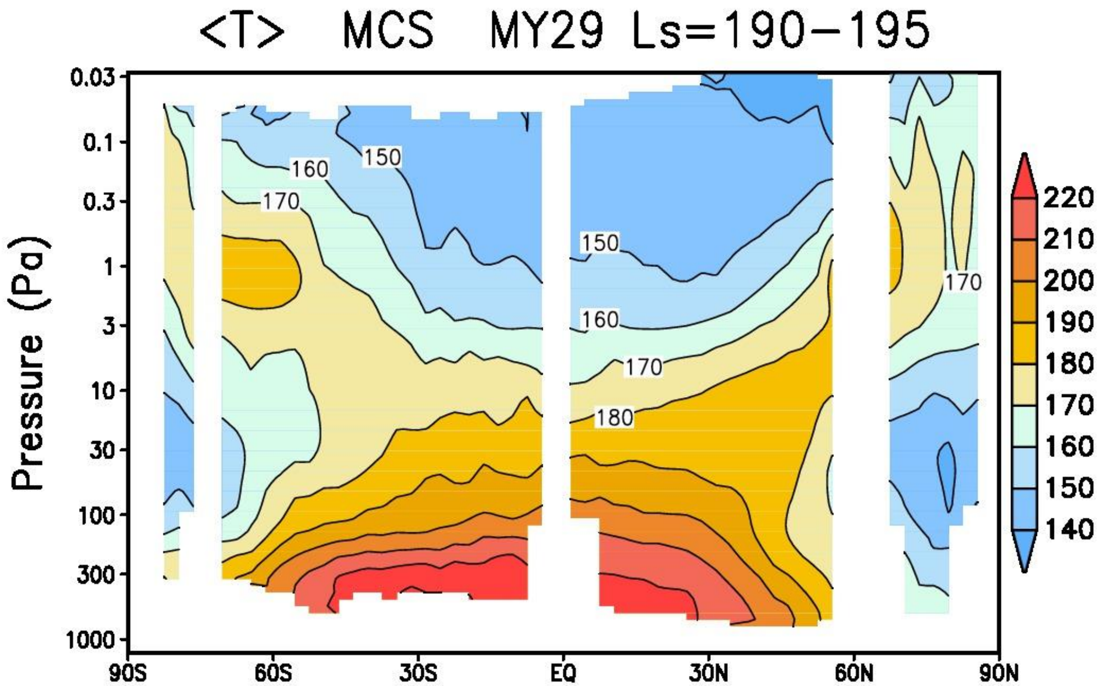

<T> GCM MY29 Ls=180-185
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
220
210
200
190
180
170
160
150
140

<T> MCS MY29 Ls=185-190

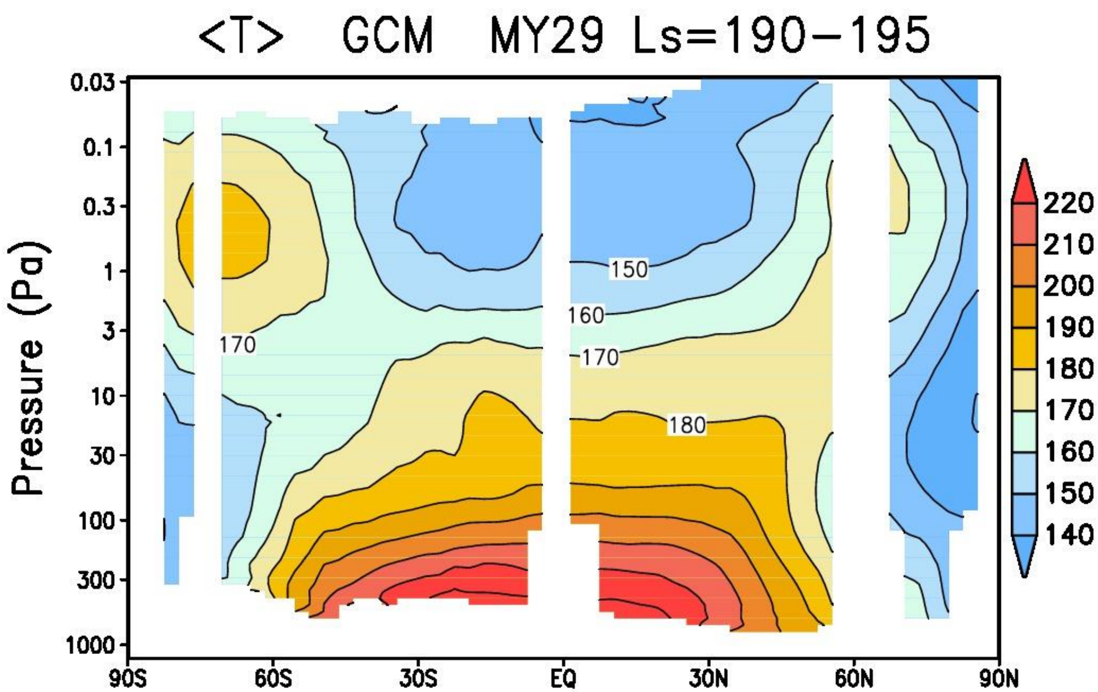



<T> GCM MY29 Ls=185-190

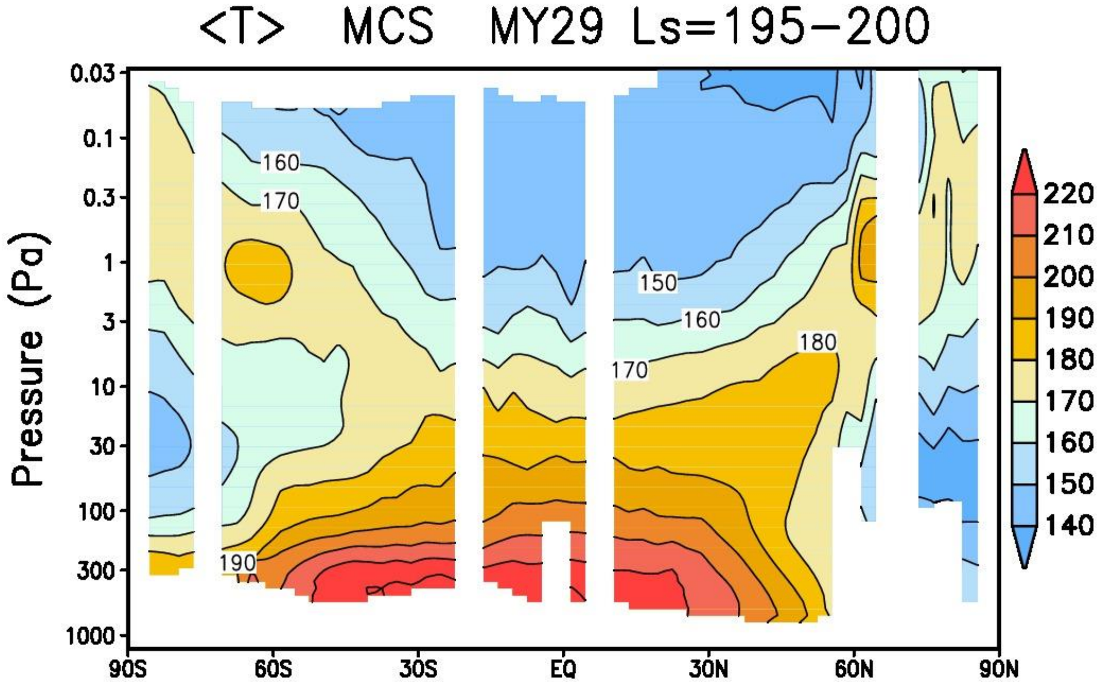


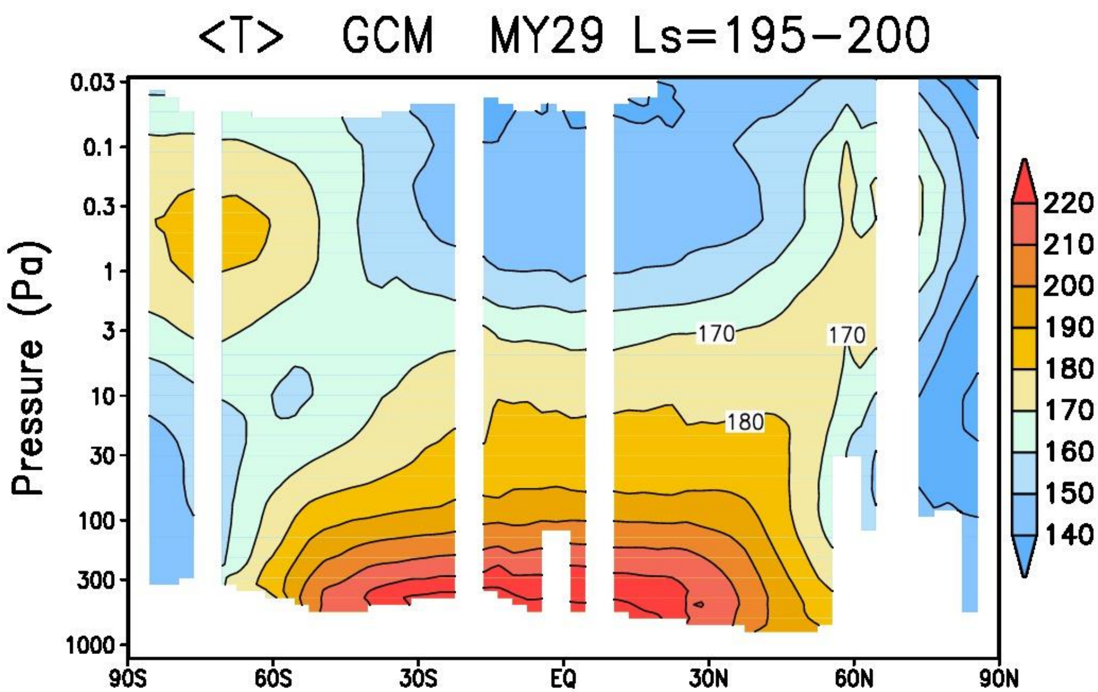


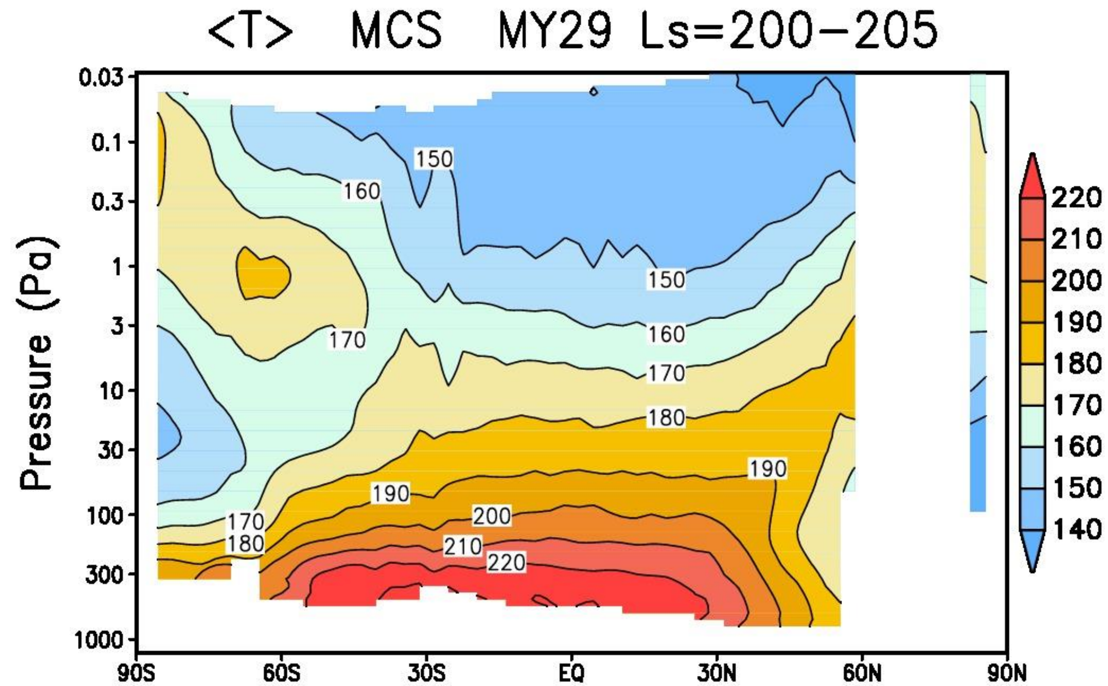
<T> MCS MY29 Ls=190–195
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
220
210
200
190
140

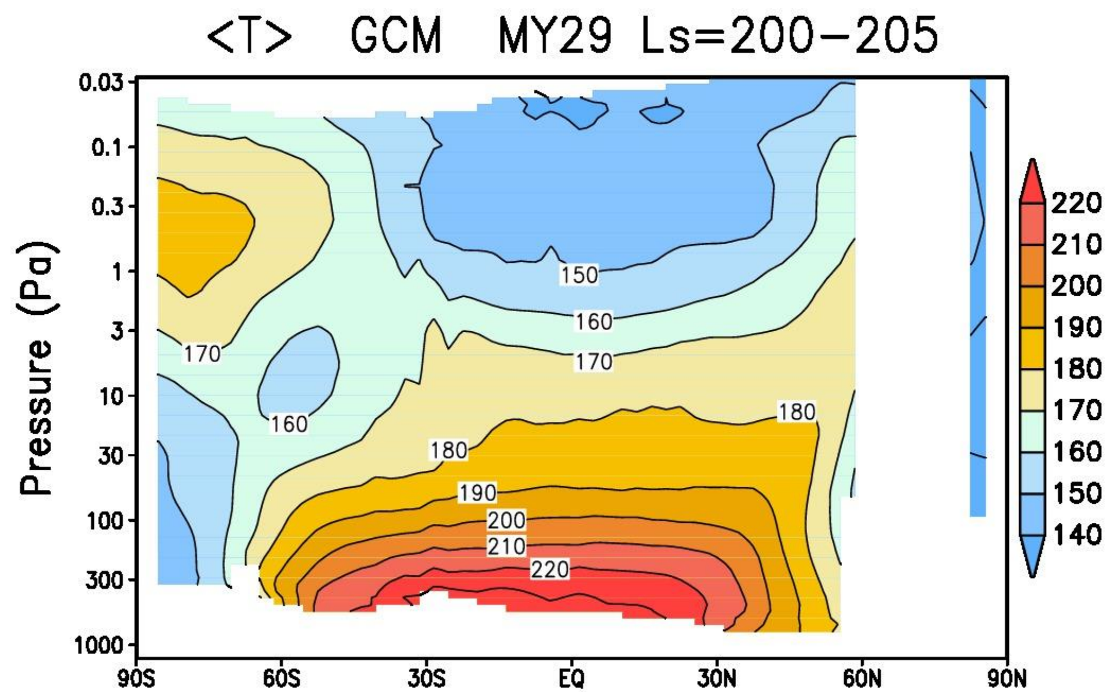



<T> GCM MY29 Ls=190–195
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
220
210
200
190
140

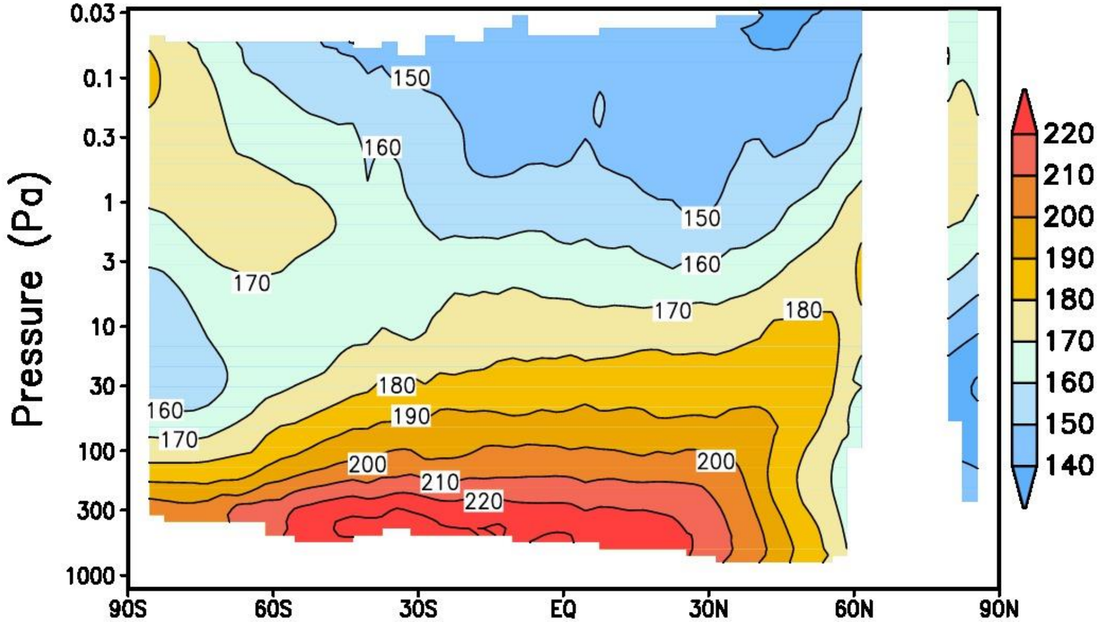

<T> MCS MY29 Ls=195-200
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
170
150
160
180
170
190
220
210
200
190
180
170
160
150
140


<T> GCM MY29 Ls=195-200
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
170
170
180
220
210
200
190
180
170
160
150
140

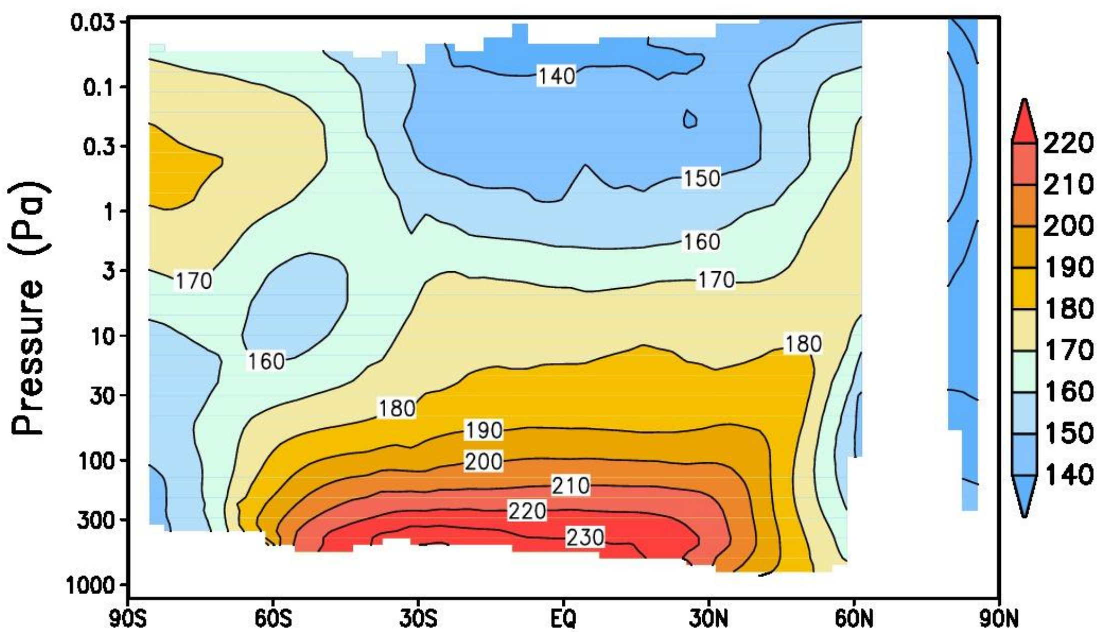

<T> MCS MY29 Ls=200-205
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140


<T> GCM MY29 Ls=200-205
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140

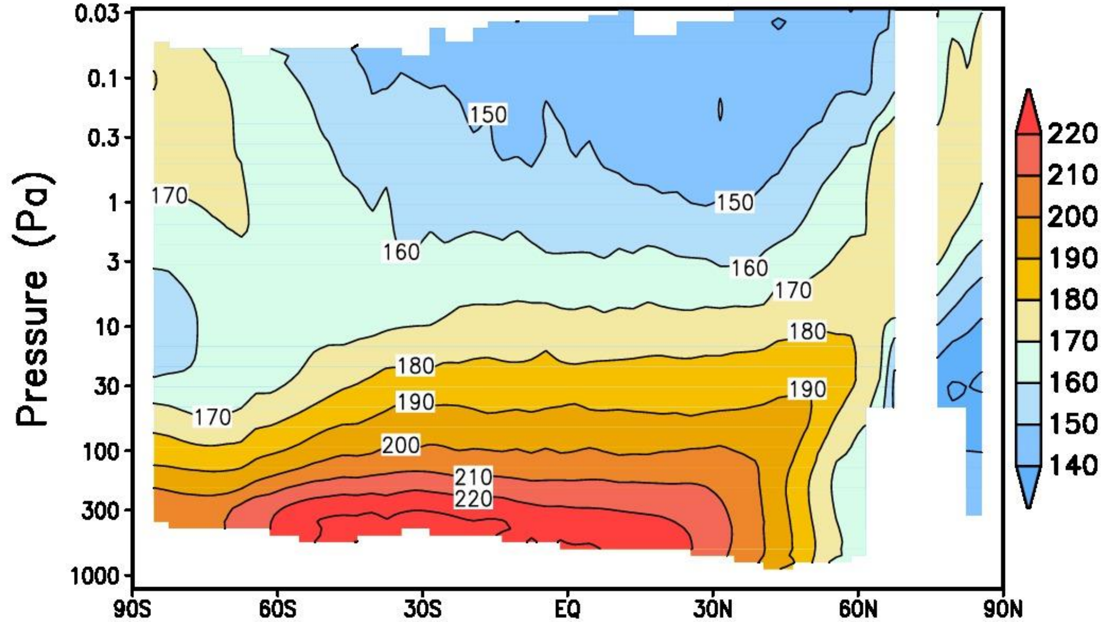
<T> MCS MY29 Ls=205-210



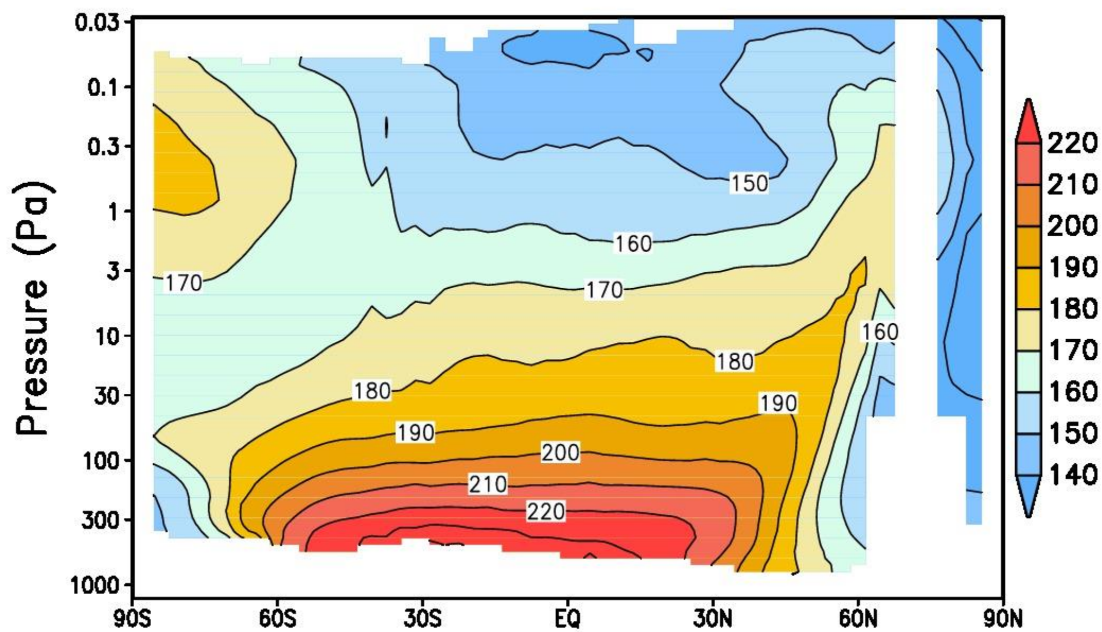

<T> GCM MY29 Ls=205-210

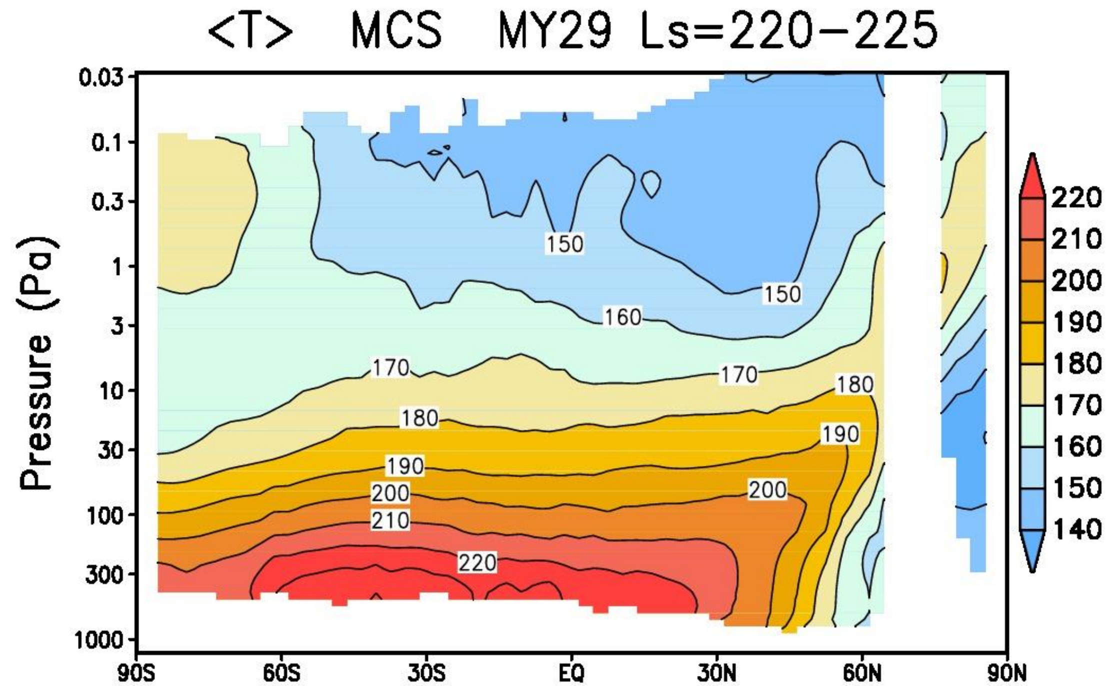


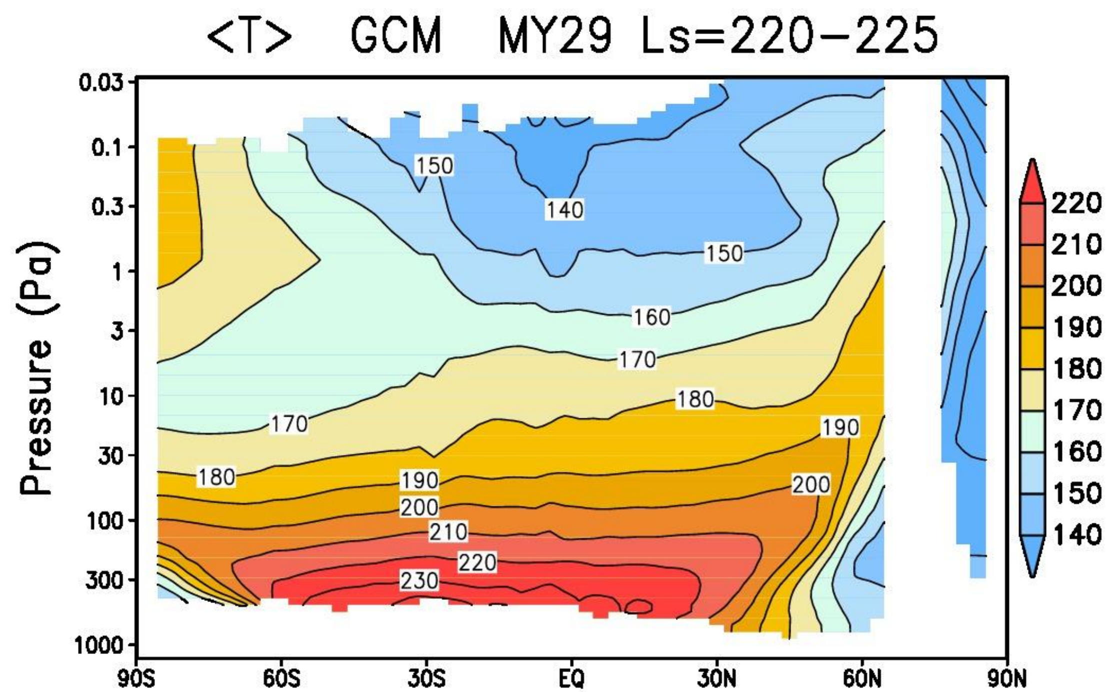
<T> MCS MY29 Ls=210-215

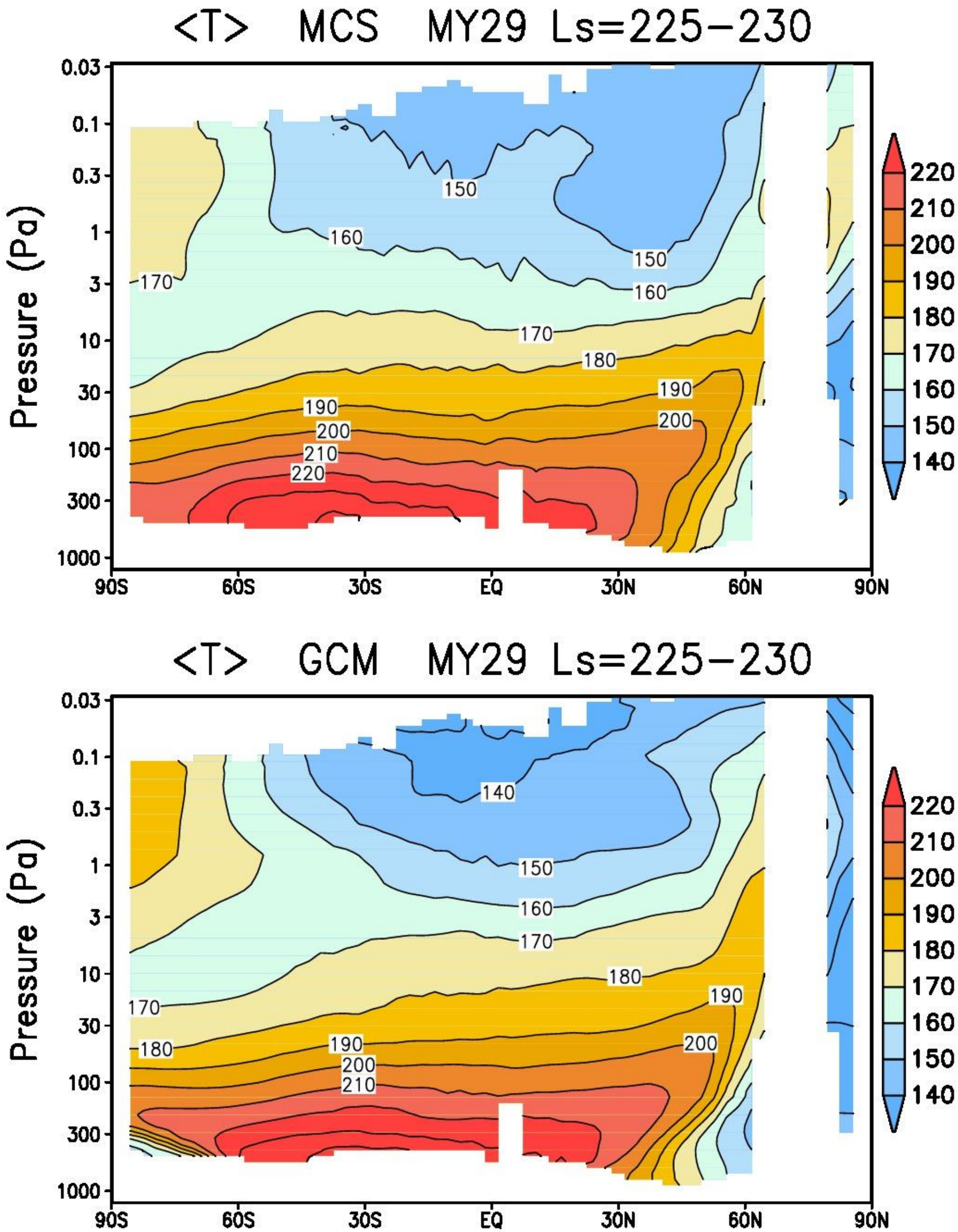


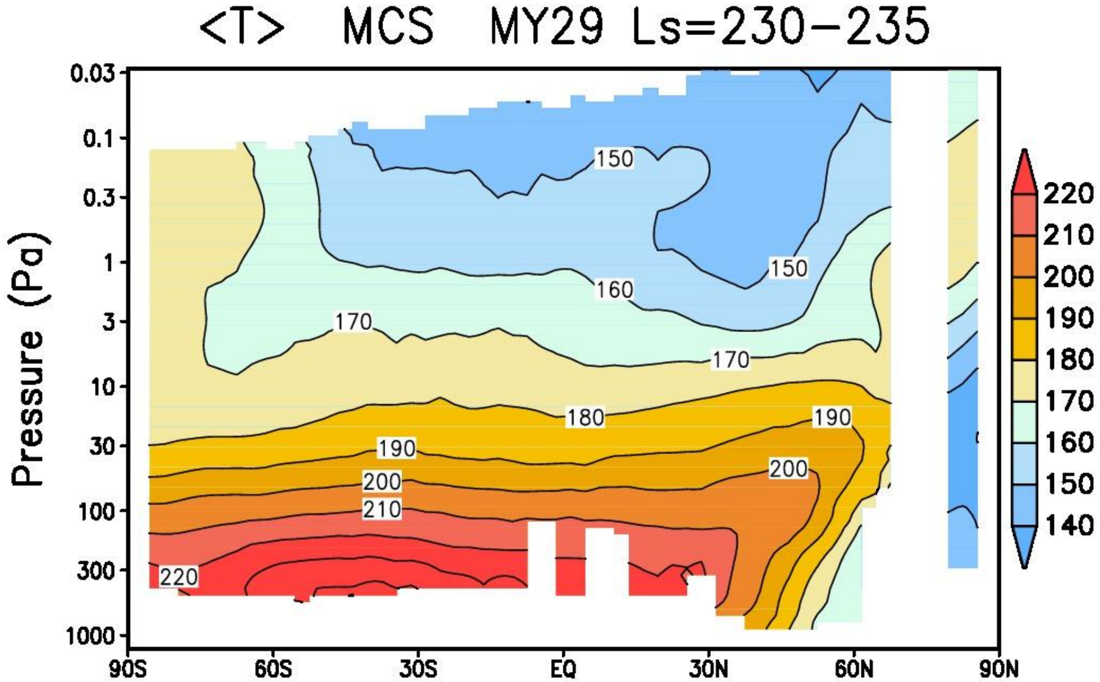

<T> GCM MY29 Ls=210-215




<T> MCS MY29 Ls=220-225
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140


<T> GCM MY29 Ls=220-225
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220
230


<T> MCS MY29 Ls=225-230
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140
<T> GCM MY29 Ls=225-230
Pressure (Pa)


<T> MCS MY29 Ls=230-235
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
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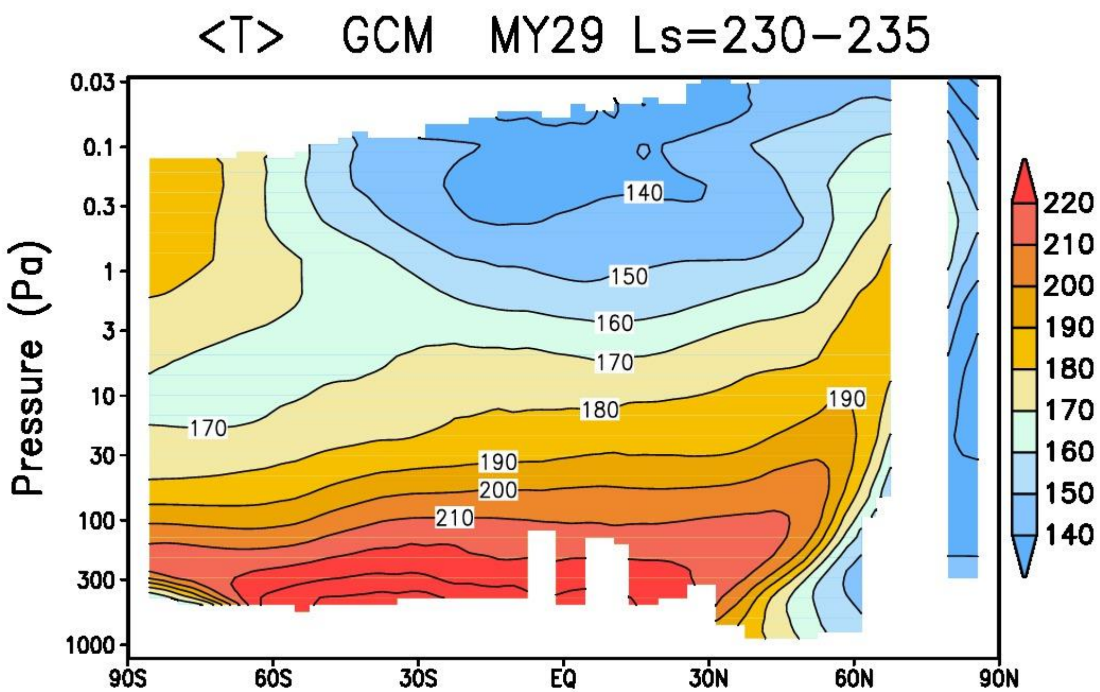
220
140


<T> GCM MY29 Ls=230-235
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
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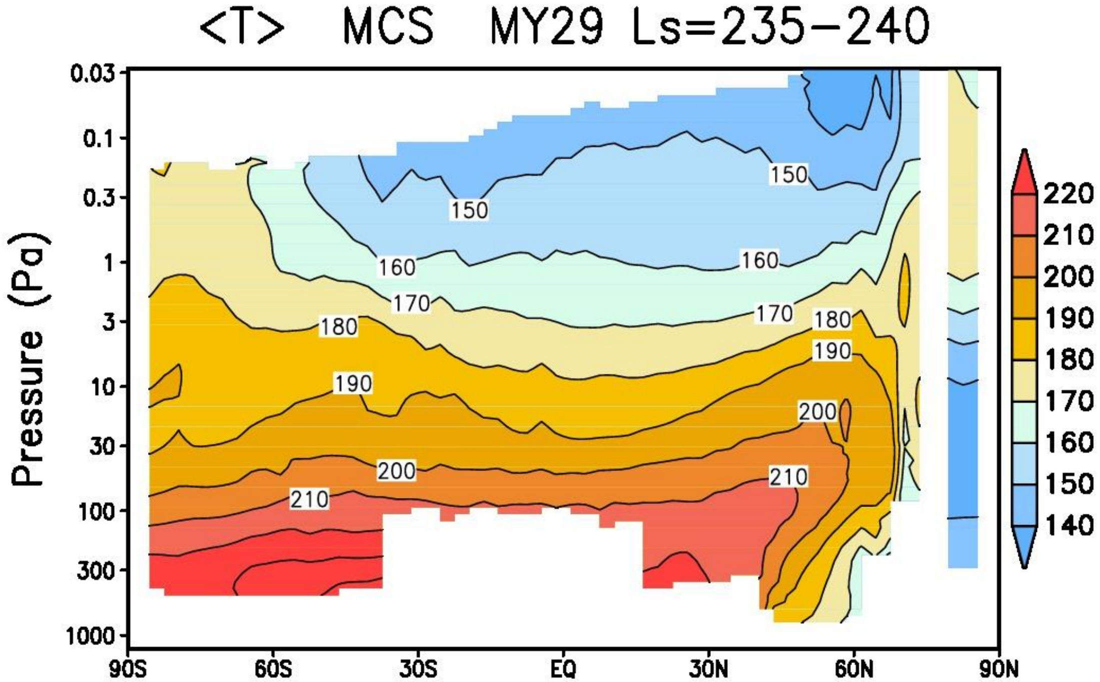
<T> MCS MY29 Ls=235-240
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
150
160
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200
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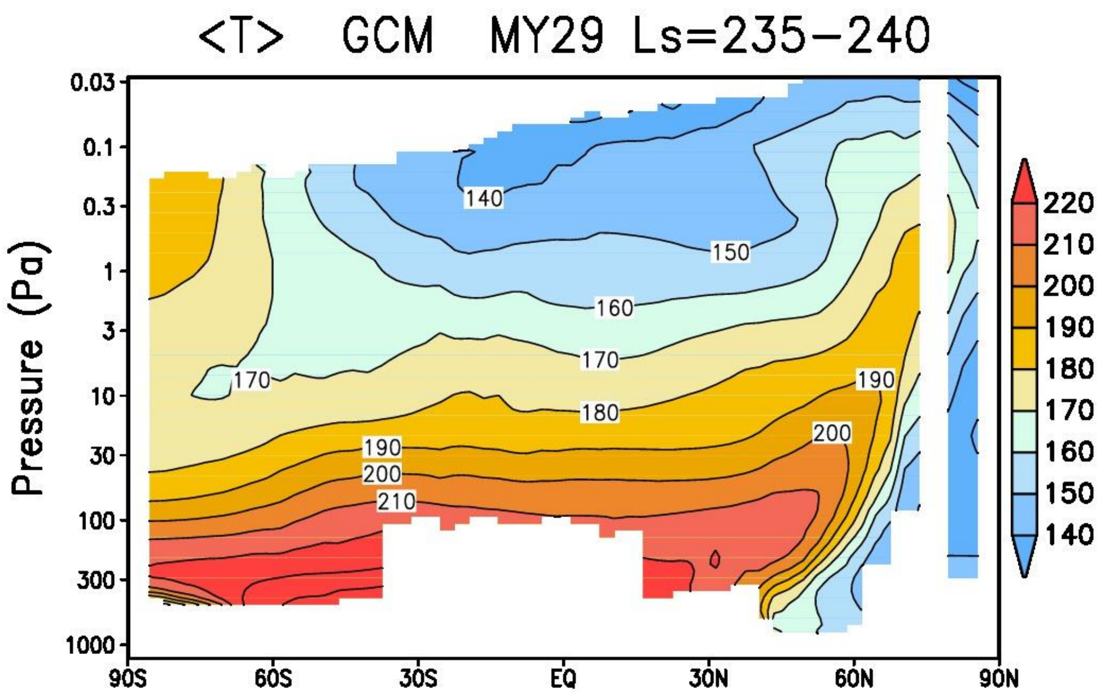
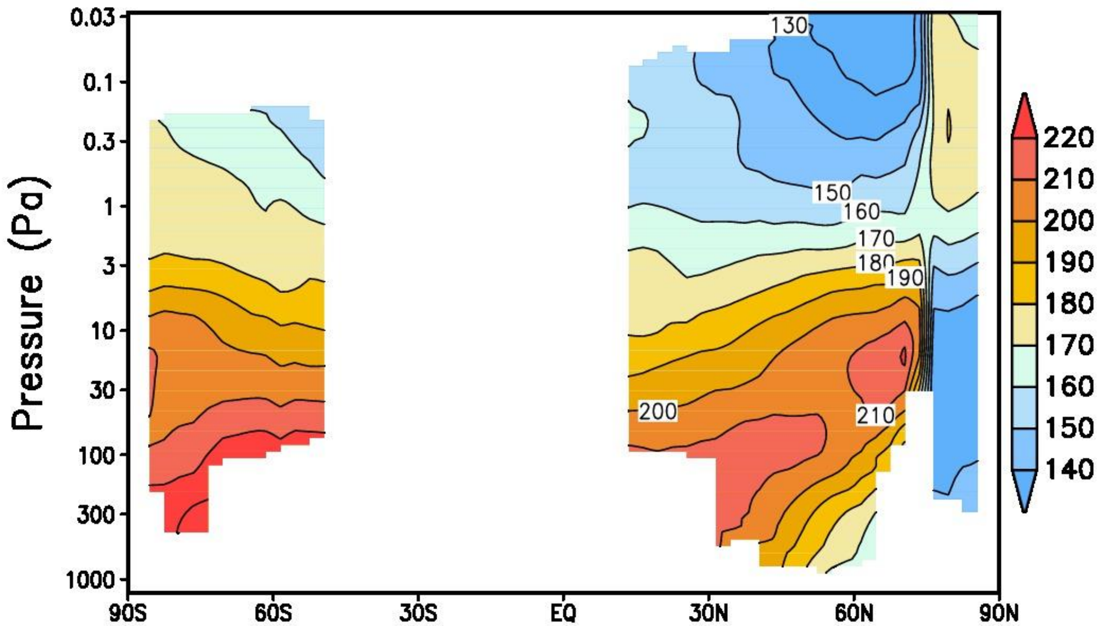
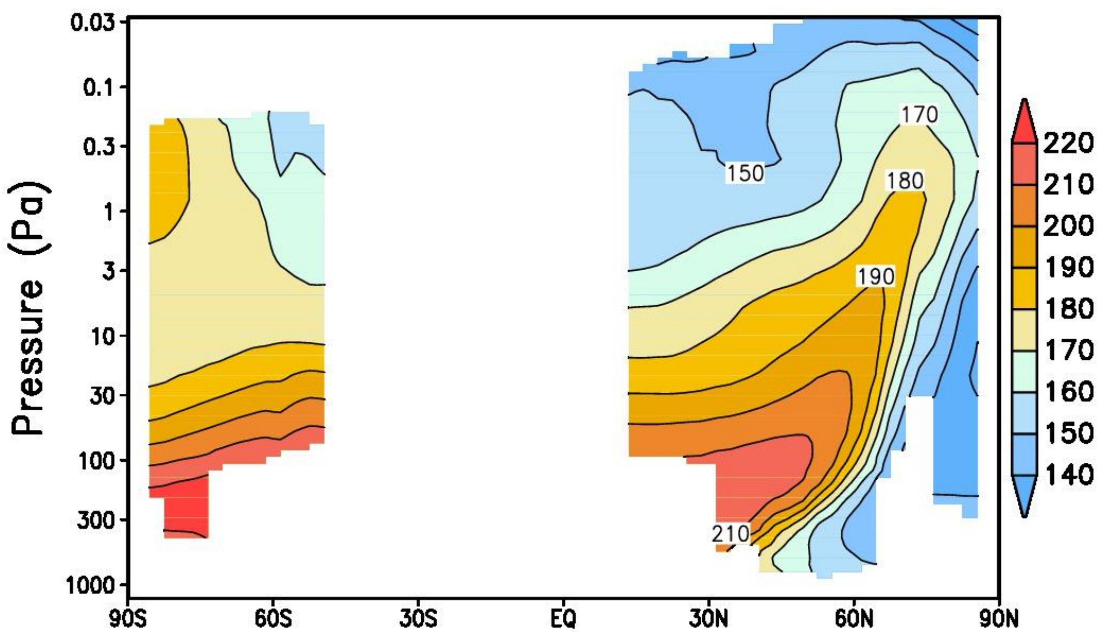
210
200
190
180
170
160
150
140

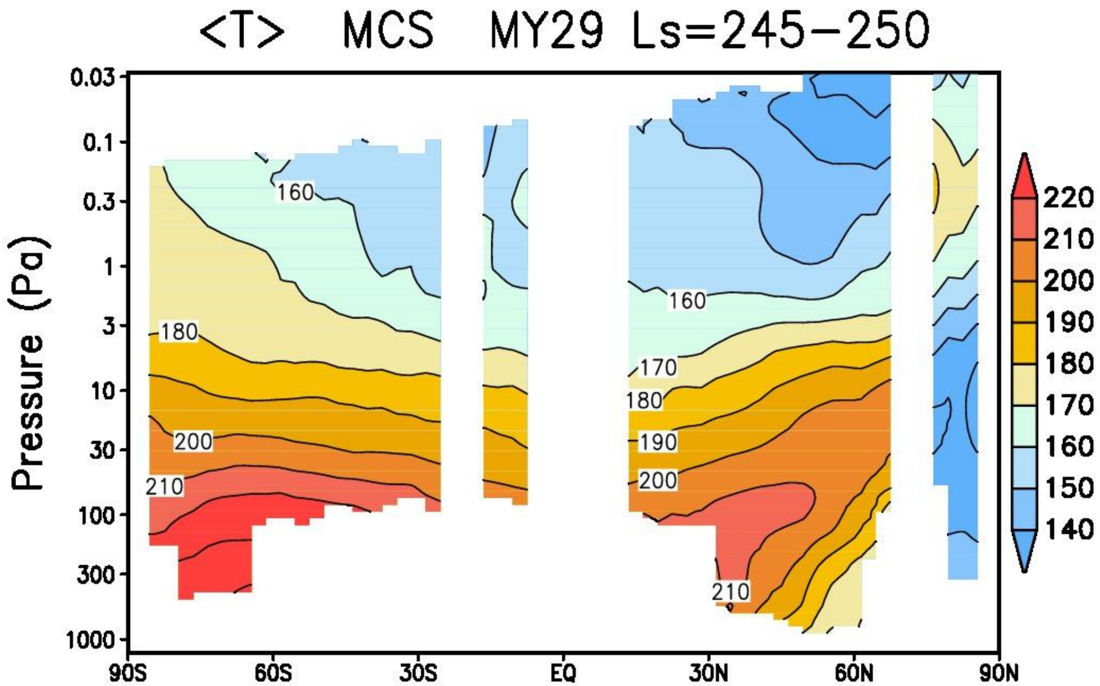

<T> GCM MY29 Ls=235-240
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
170
180
190
190
200
200
210
220
210
200
190
180
170
160
150
140

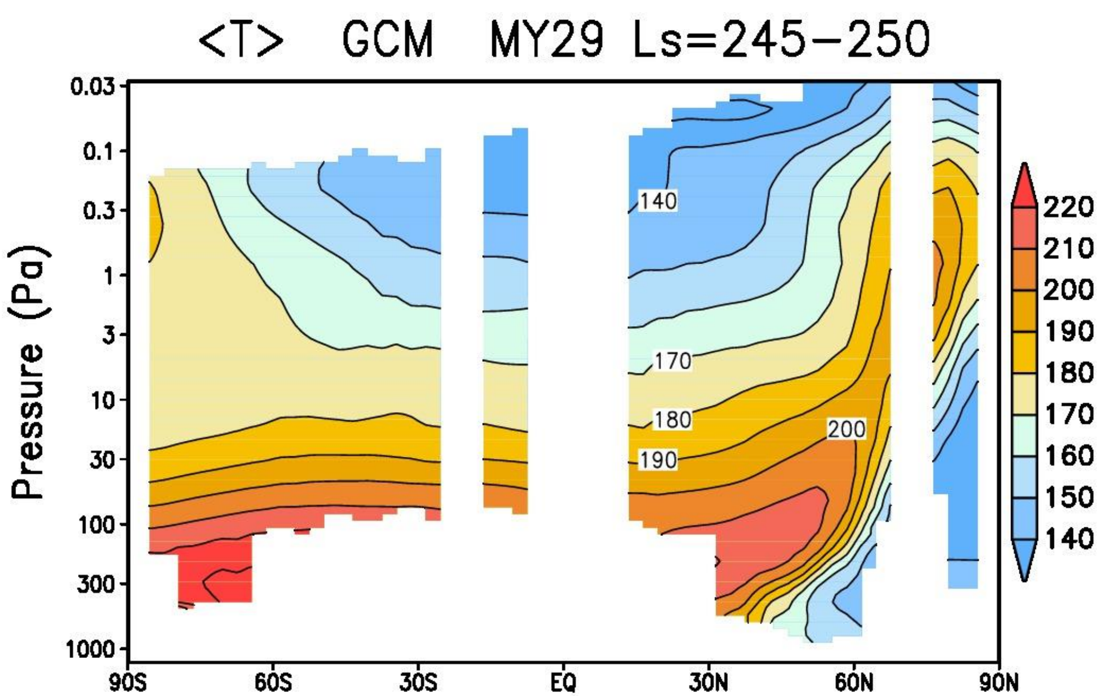
<T> MCS MY29 Ls=240-245

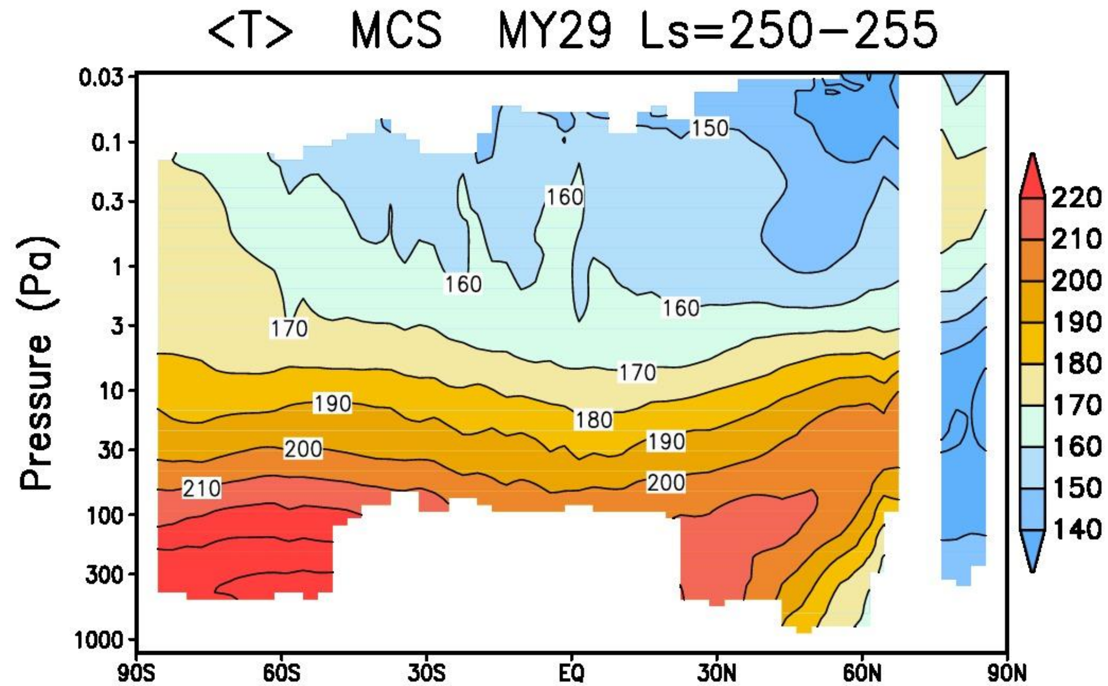



<T> GCM MY29 Ls=240-245




<T> MCS MY29 Ls=245-250
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
180
200
210
170
190
220
150
140


<T> GCM MY29 Ls=245-250
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
170
180
190
200
220
210
160
150


<T> MCS MY29 Ls=250-255
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
210
200
190
180
170
160
150
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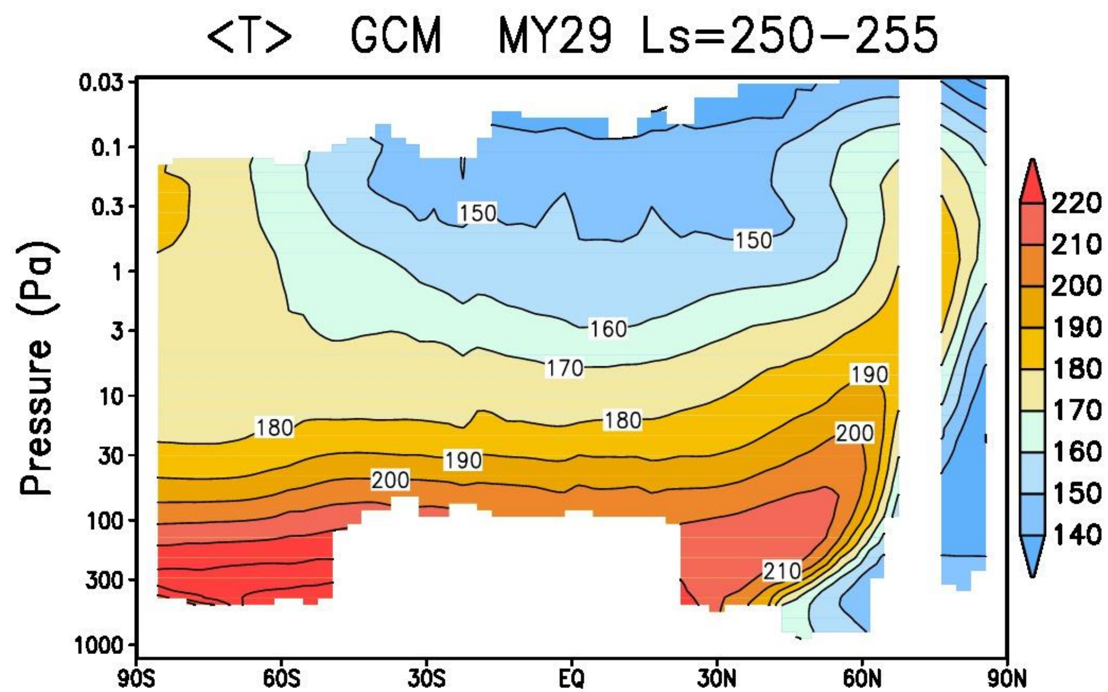
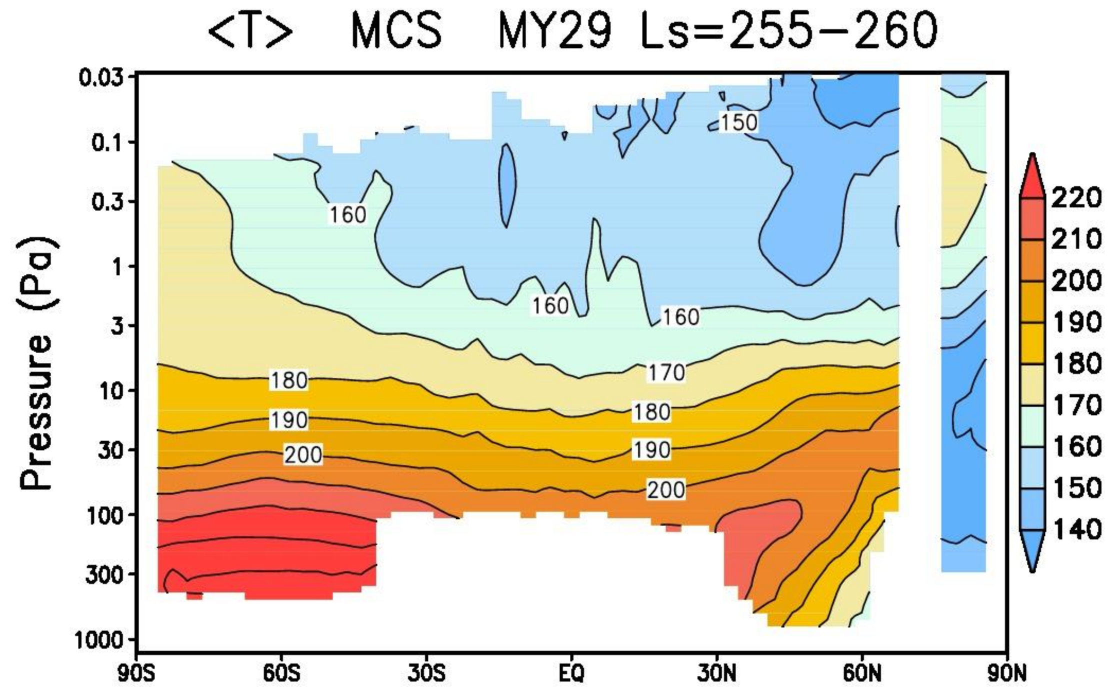

<T> GCM MY29 Ls=250-255
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
210
200
190
180
170
160
150
140


<T> MCS MY29 Ls=255-260
Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
160
160
170
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180
170
160
150
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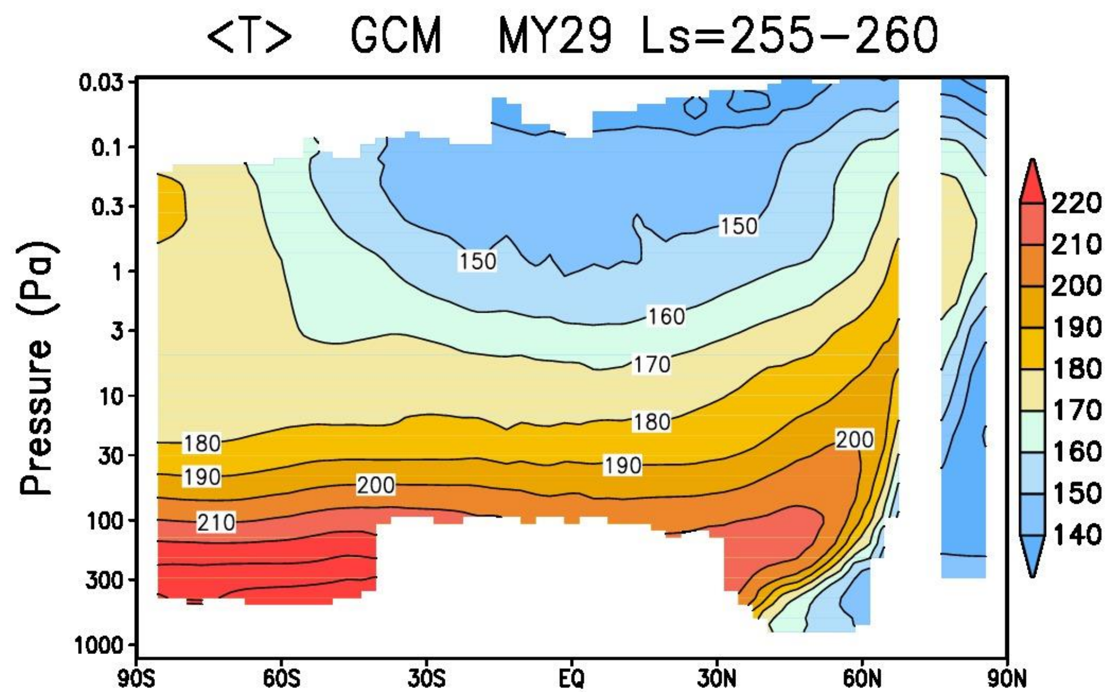
<T> GCM MY29 Ls=255-260
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
150
160
170
180
180
190
190
200
200
210
220
210
200
190
180
170
160
150
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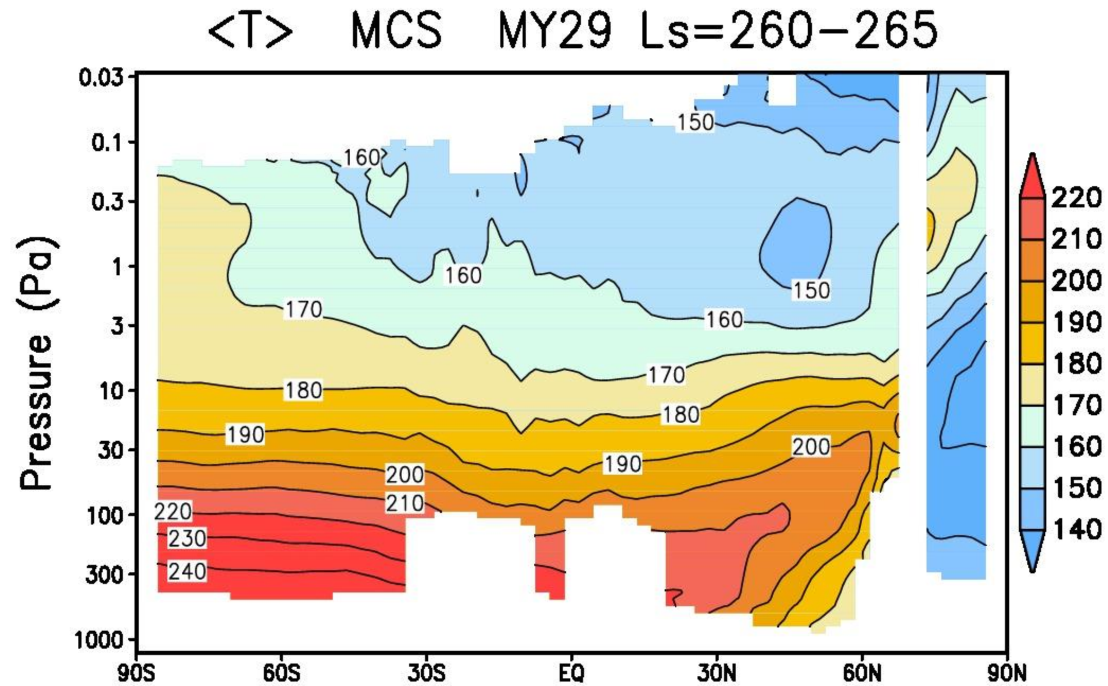
<T> MCS MY29 Ls=260-265
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
230
240
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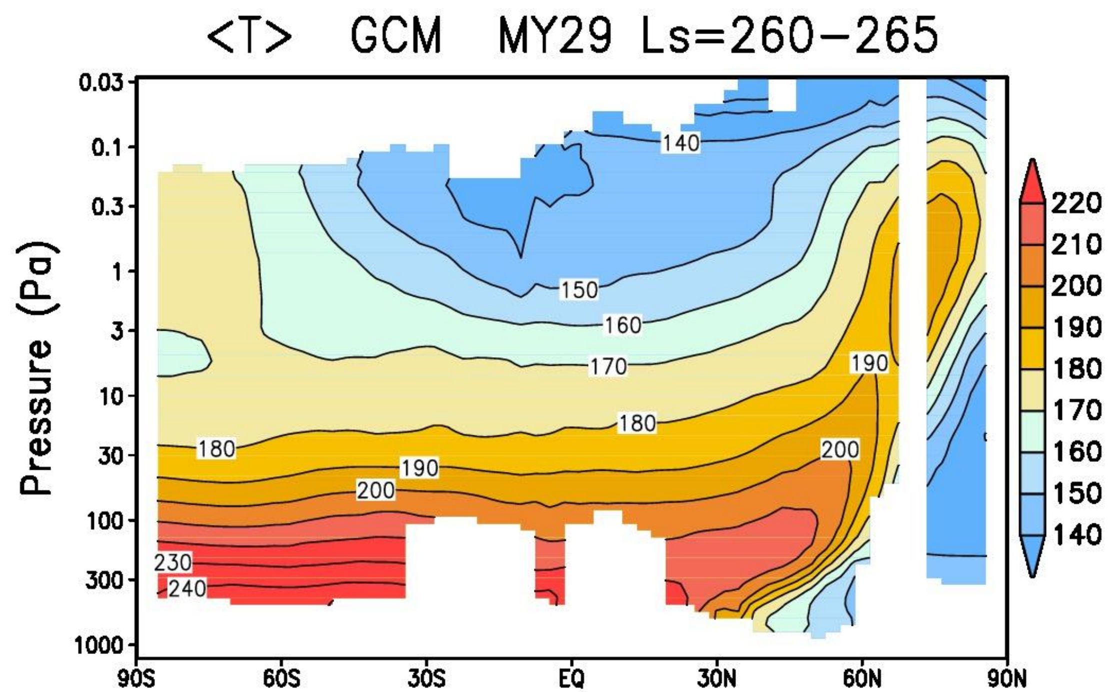
<T> GCM MY29 Ls=260-265
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
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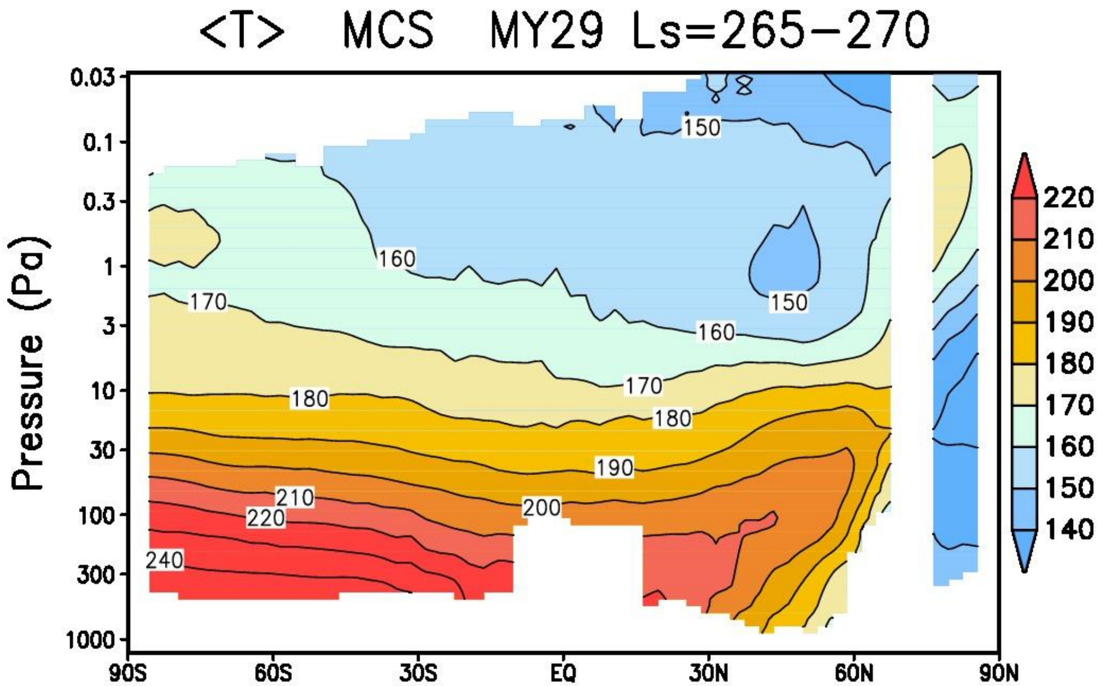
200
210
220
230
240


<T> MCS MY29 Ls=265-270
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
150
170
160
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180
170
160
150
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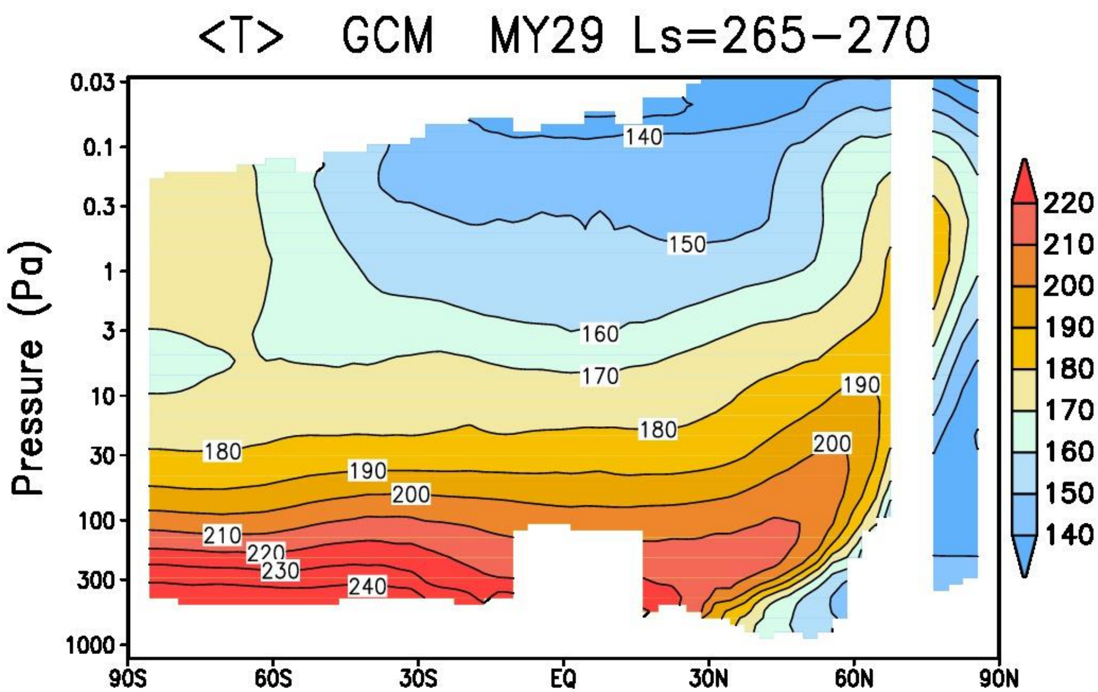
<T> GCM MY29 Ls=265-270
Pressure (Pa)
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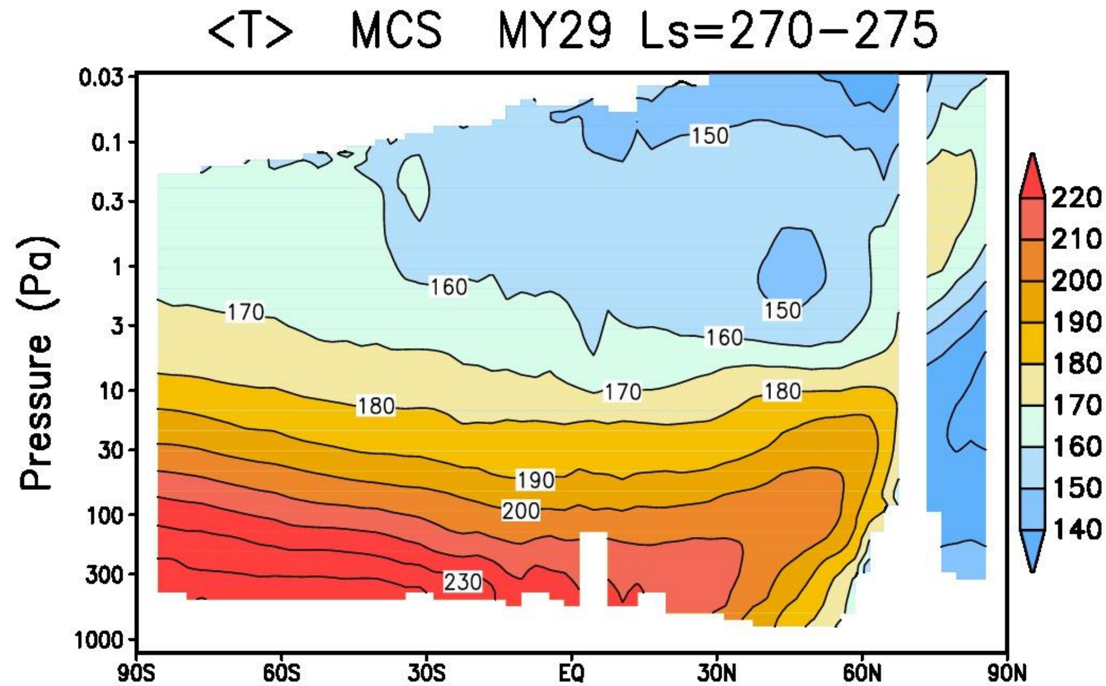
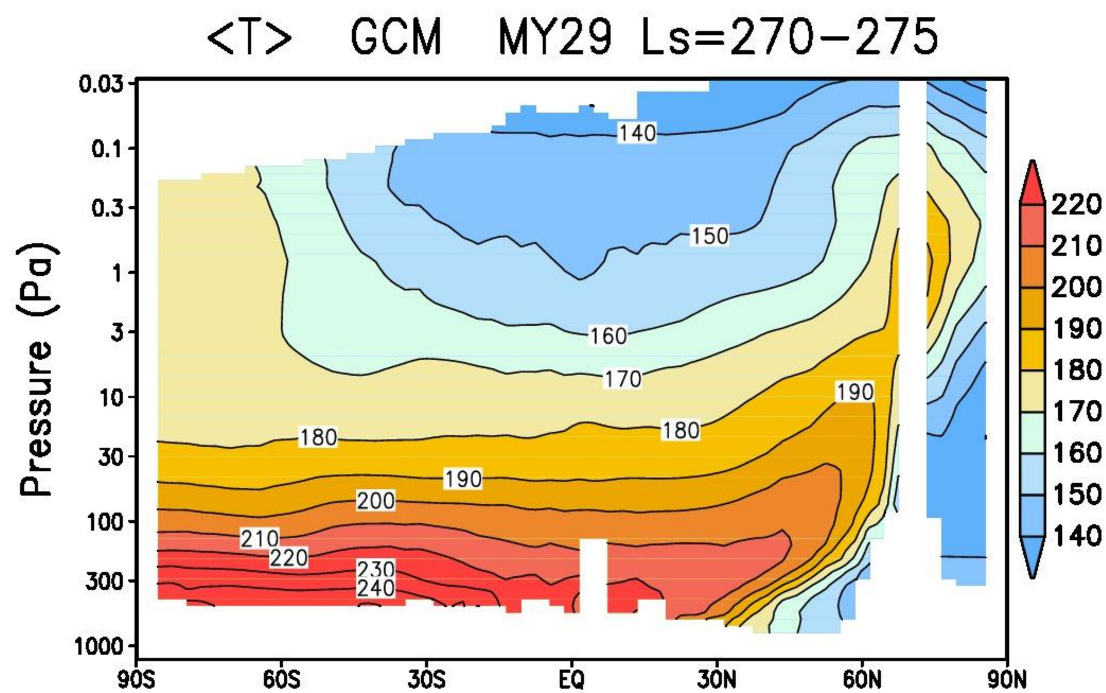
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
190
180
200
180
190
200
210
220
230
240
220
210
200
190
180
170
160
150
140


<T> MCS MY29 Ls=270-275
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
230
220
210
140


<T> GCM MY29 Ls=270-275
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
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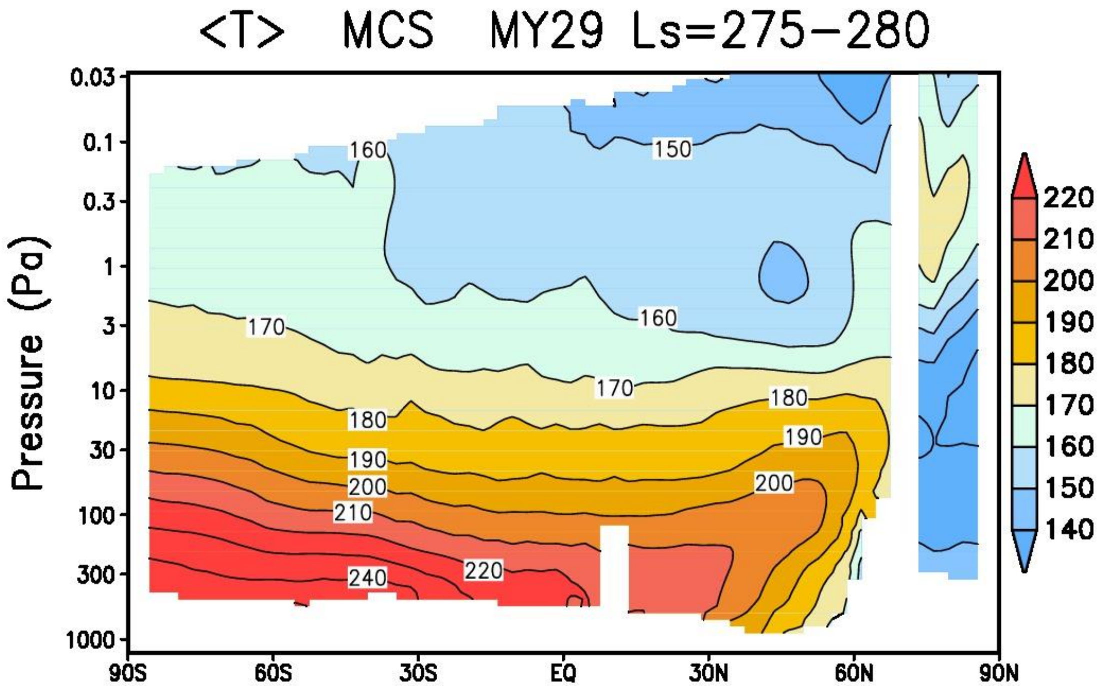
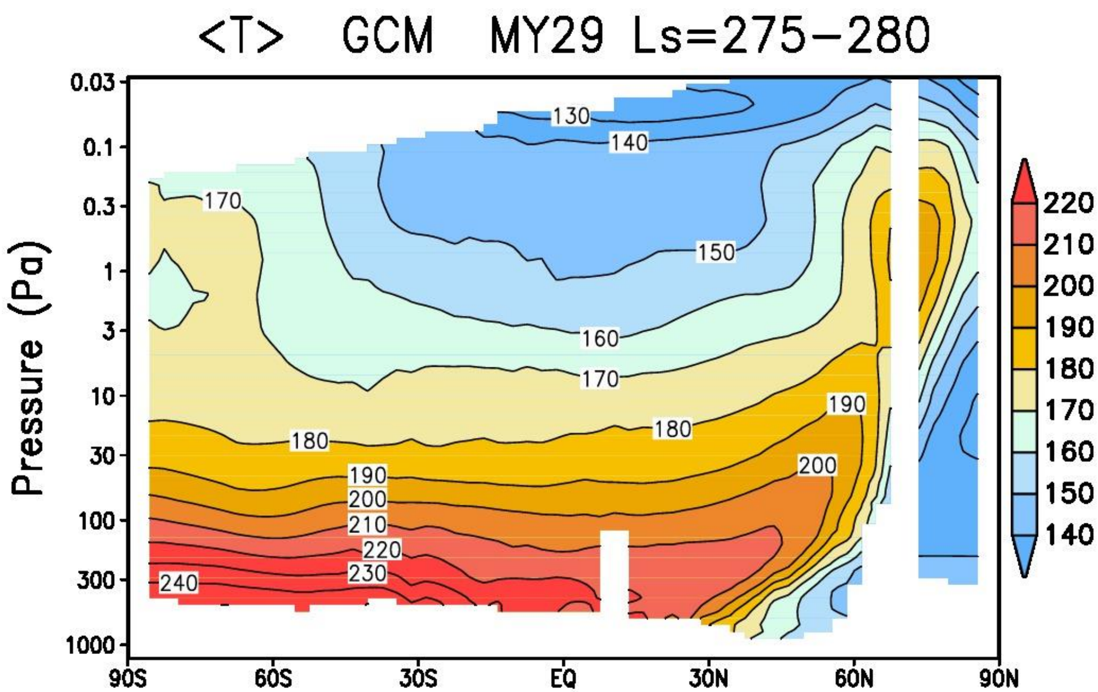
200
210
220
230
240


<T> MCS MY29 Ls=275-280
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
150
160
170
170
180
180
190
190
200
200
210
240
220
220
210
200
190
180
170
160
150
140


<T> GCM MY29 Ls=275-280
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
130
140
170
150
160
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200
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180
170
160
150
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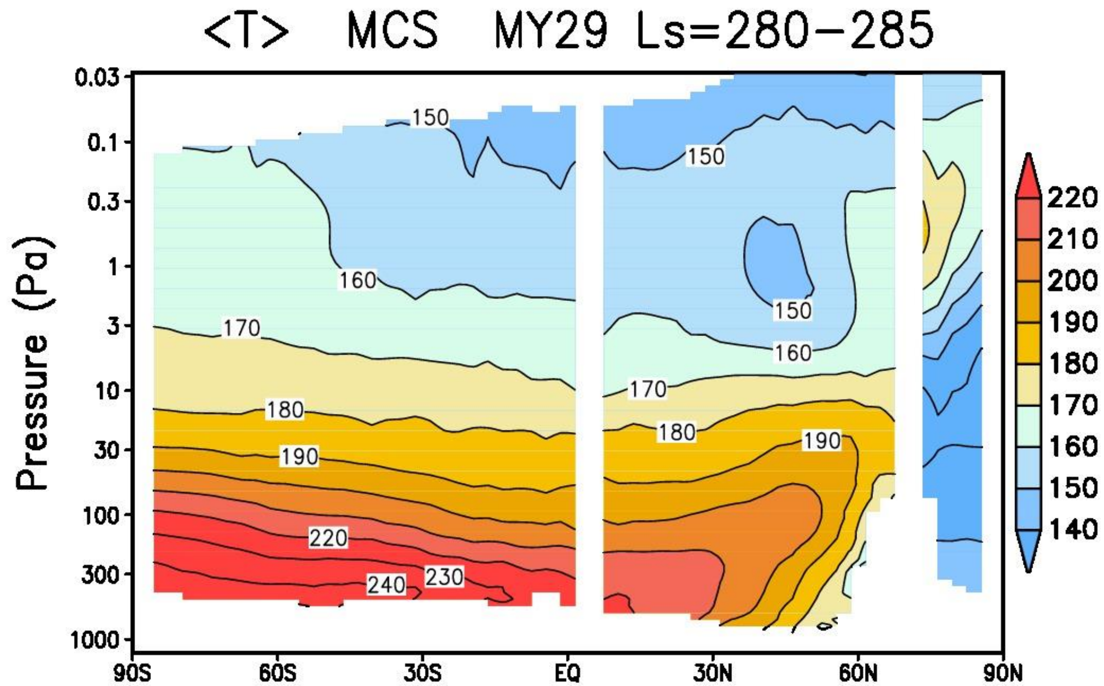
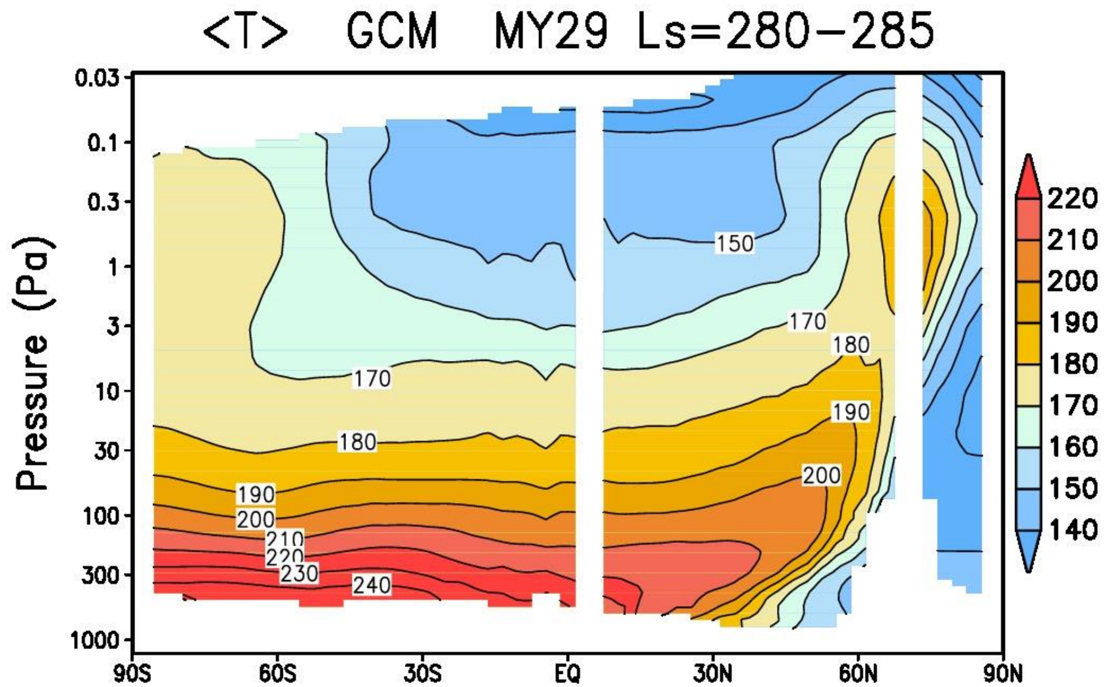

<T> MCS MY29 Ls=280-285
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
220
230
240
140
200
210


<T> GCM MY29 Ls=280-285
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
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200
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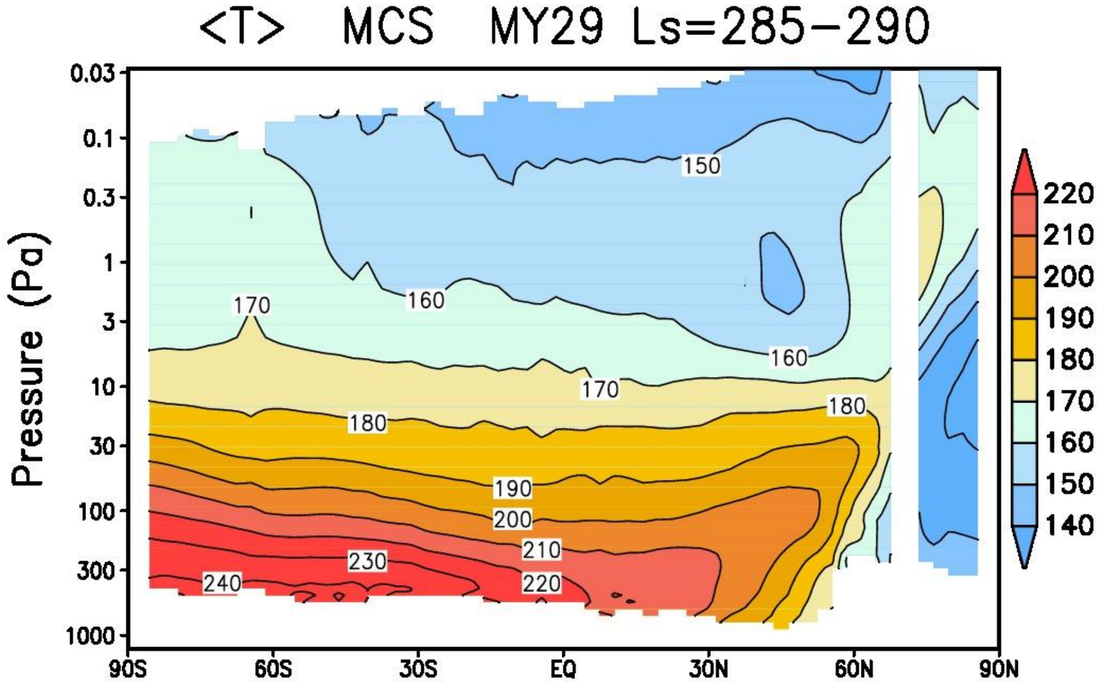
220
230
240



<T> MCS MY29 Ls=285-290
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
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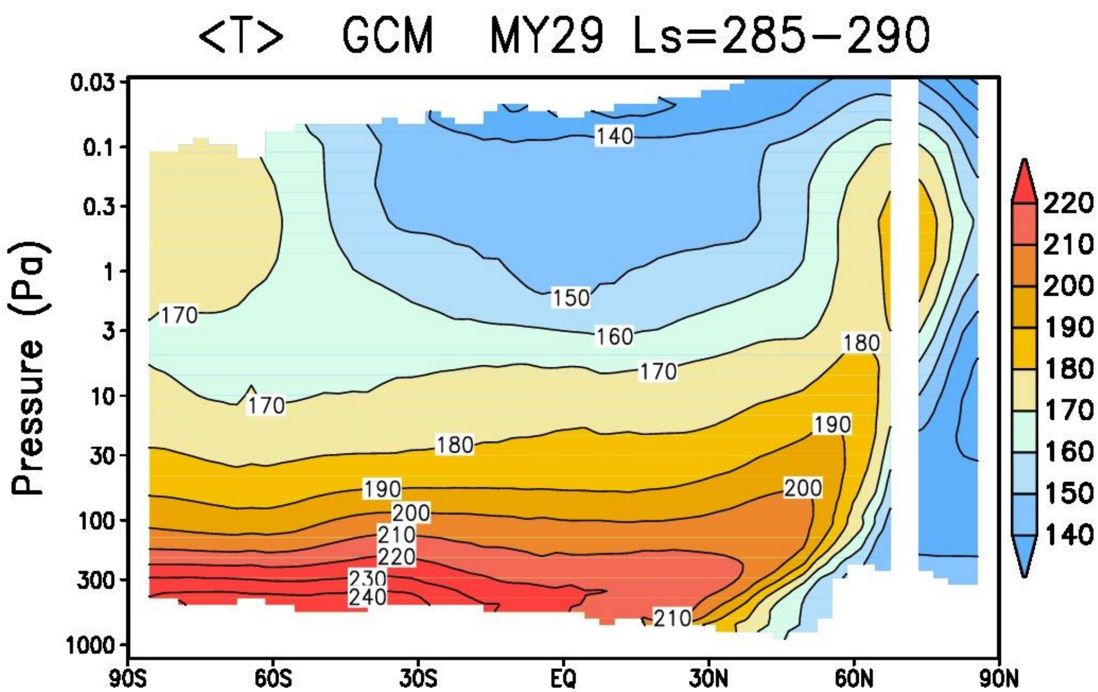
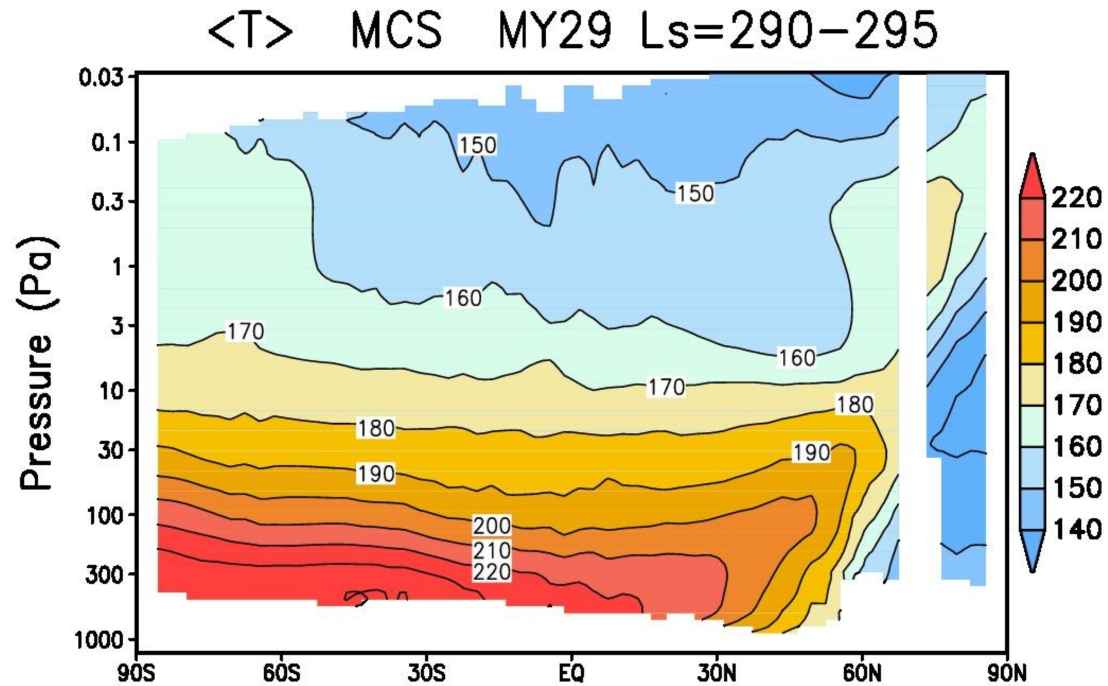
240
140

<T> GCM MY29 Ls=285-290
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220
230
240


<T> MCS MY29 Ls=290-295
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
150
160
160
170
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180
180
190
190
200
210
220
220
210
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180
170
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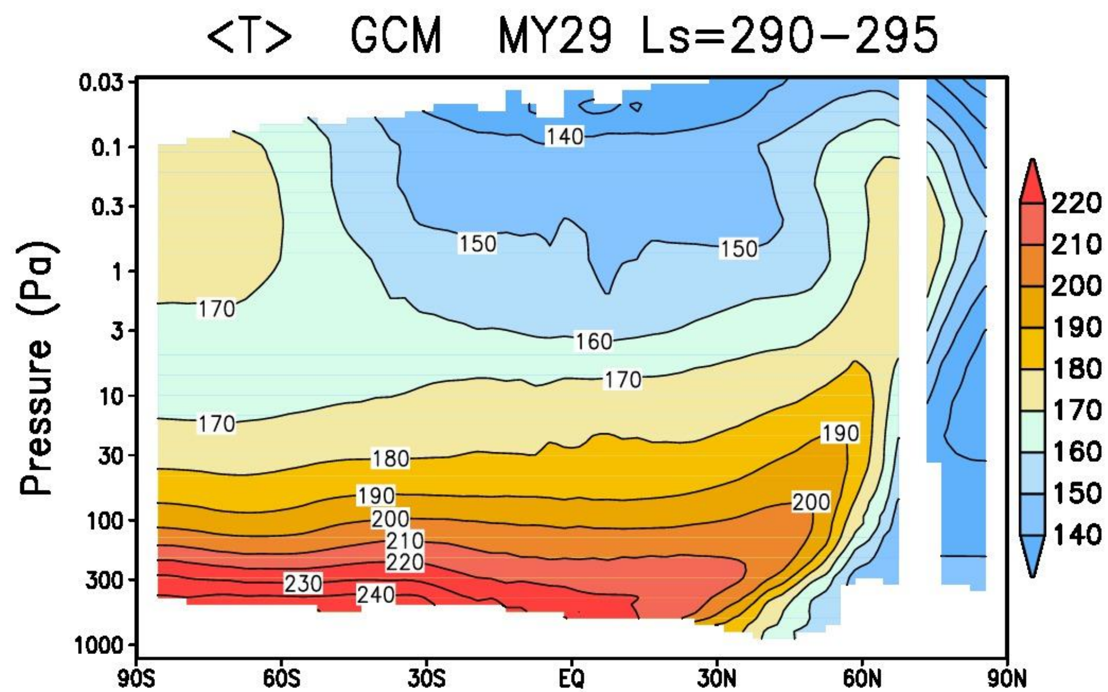
150
140


<T> GCM MY29 Ls=290-295
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
150
160
170
170
170
180
190
190
200
200
210
220
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150
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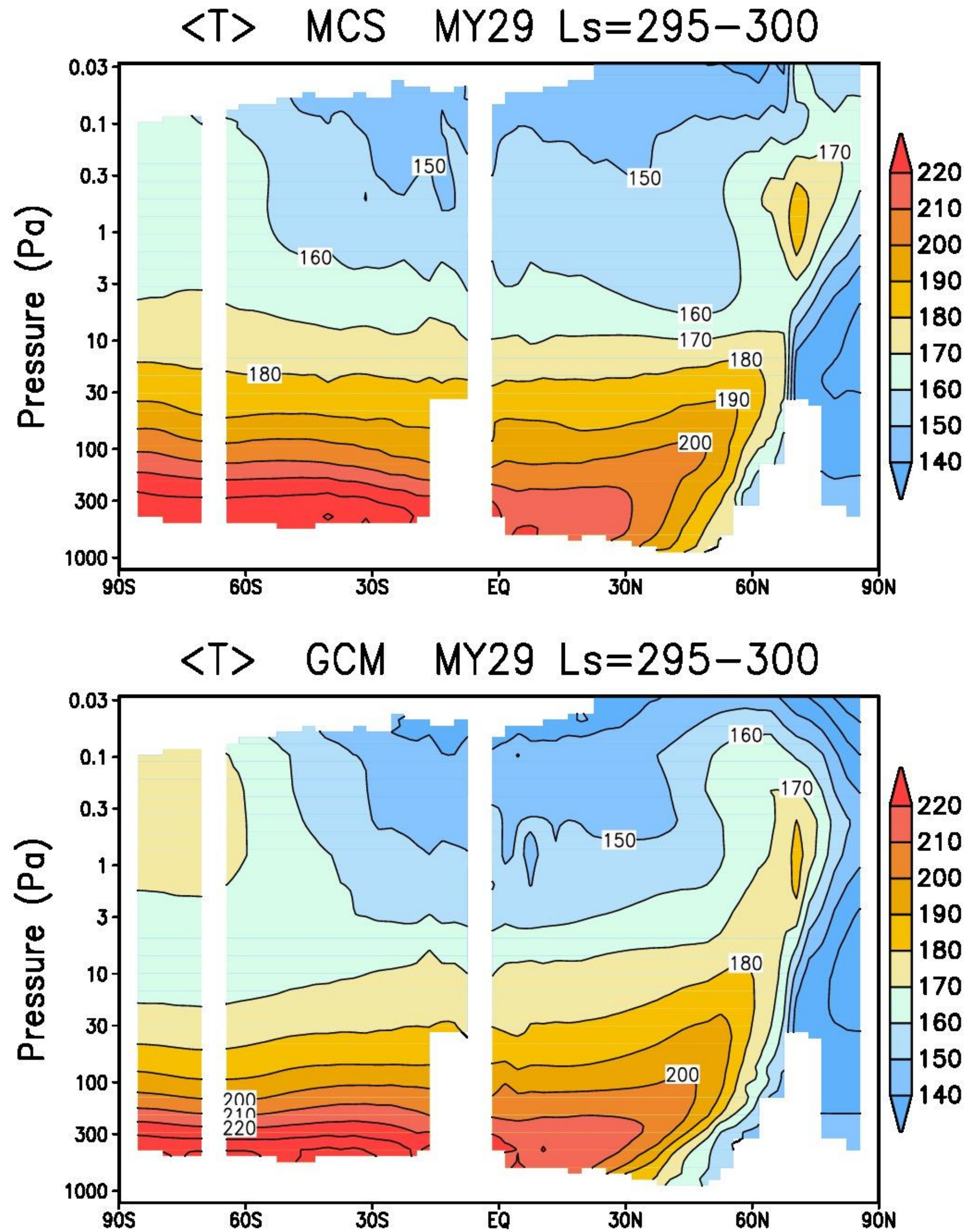
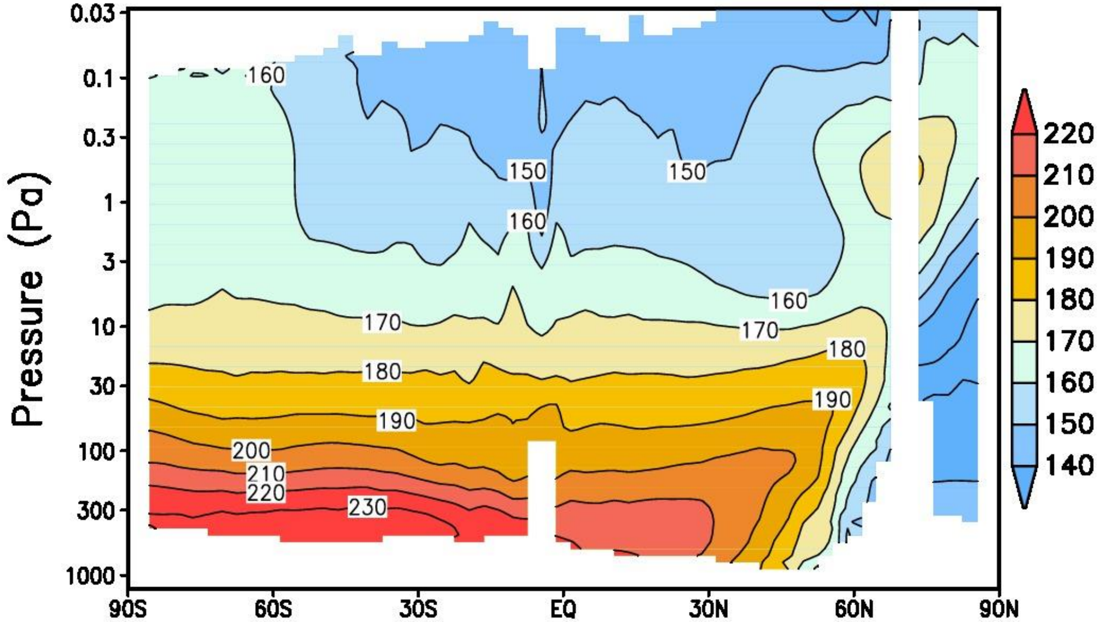
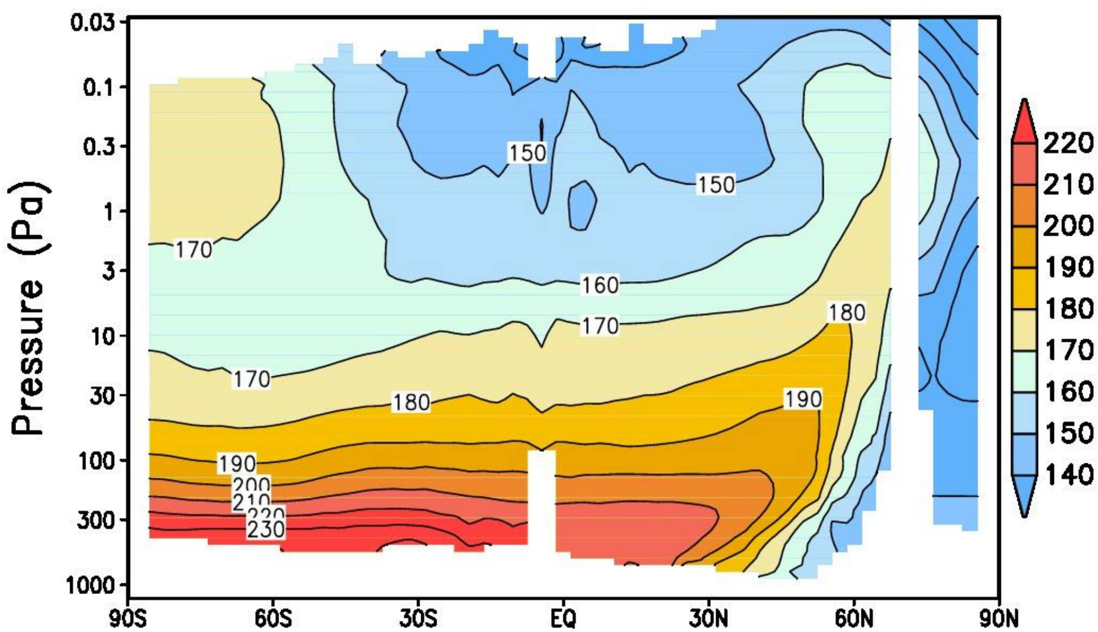
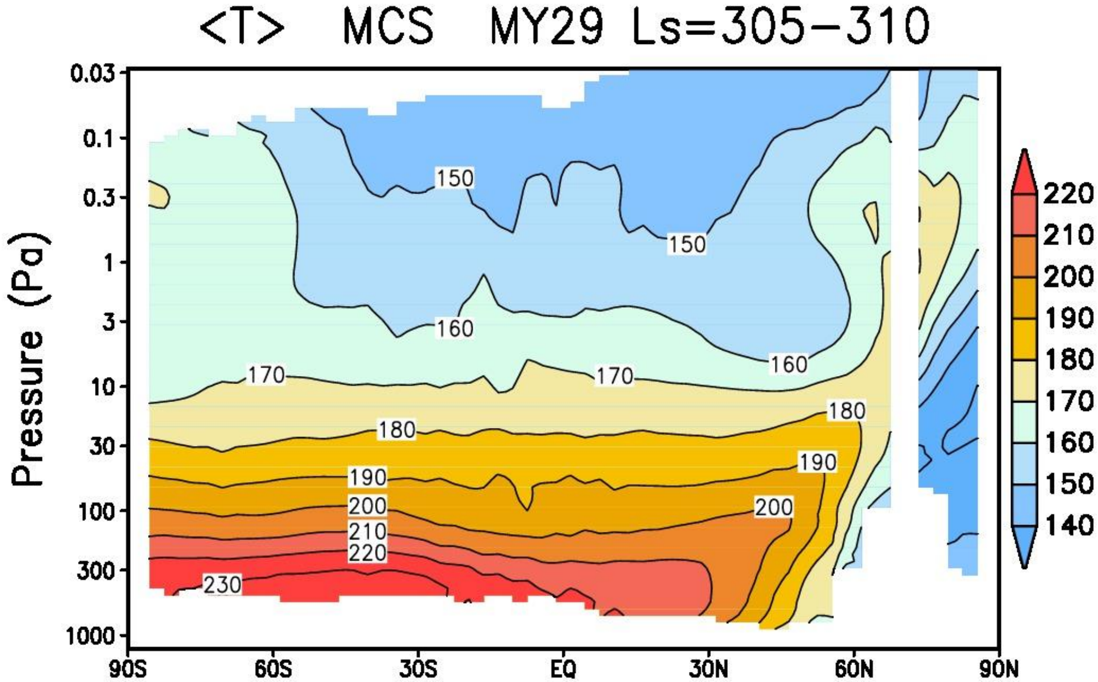

<T> MCS MY29 Ls=295-300
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140
<T> GCM MY29 Ls=295-300

<T>  MCS  MY29 Ls=300-305

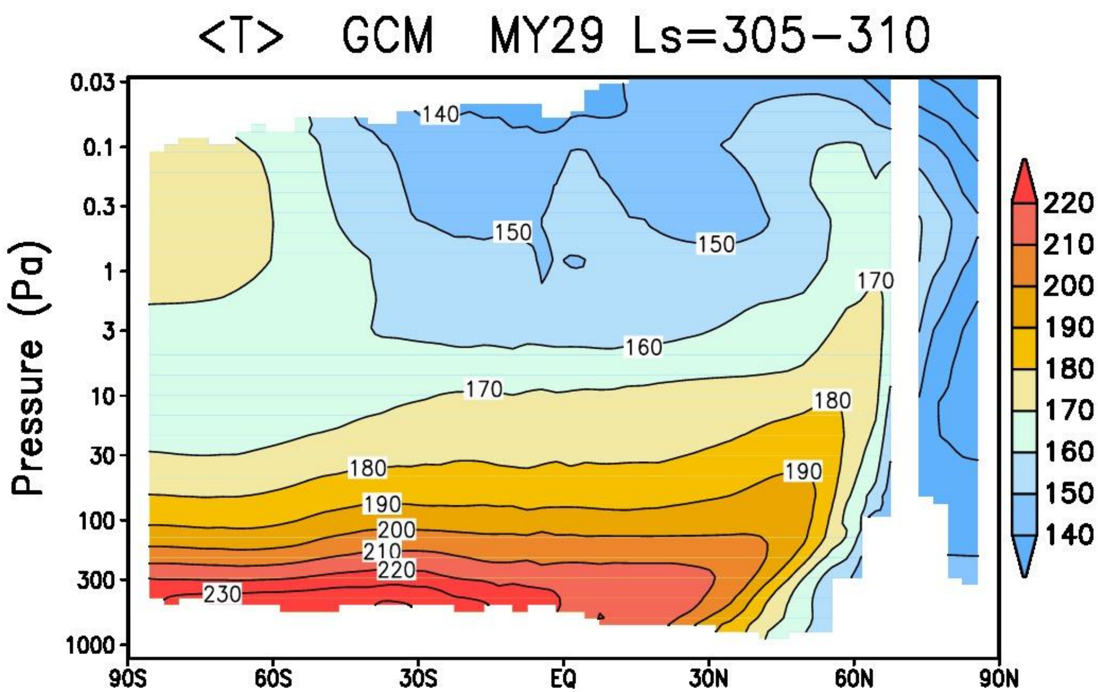



<T>  GCM  MY29 Ls=300-305

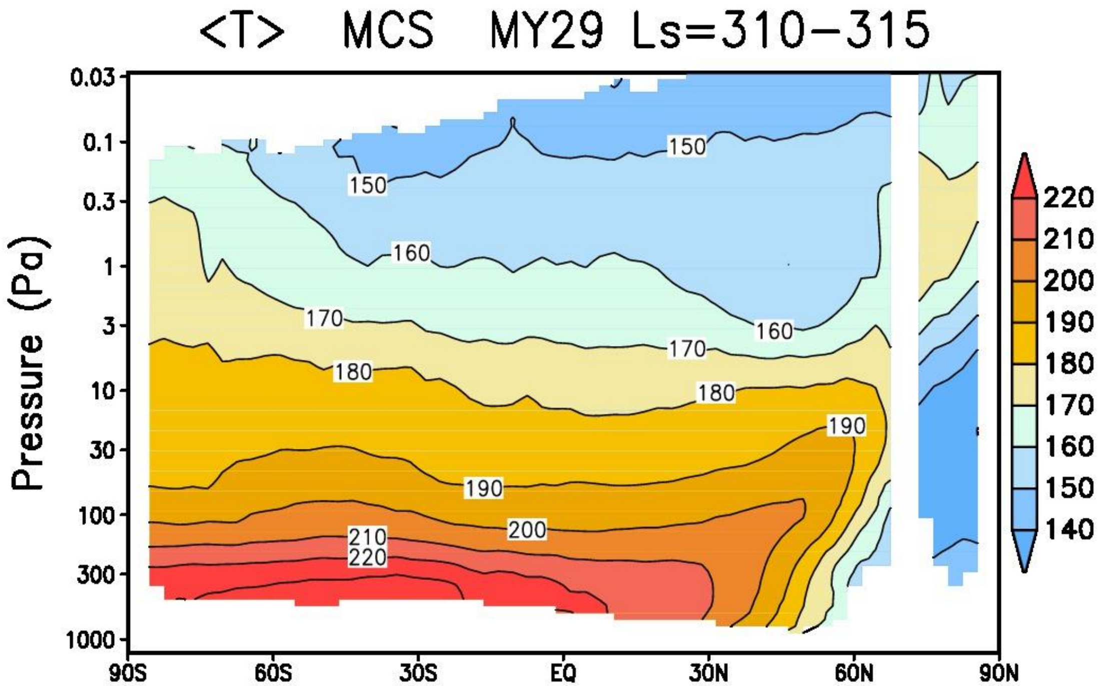




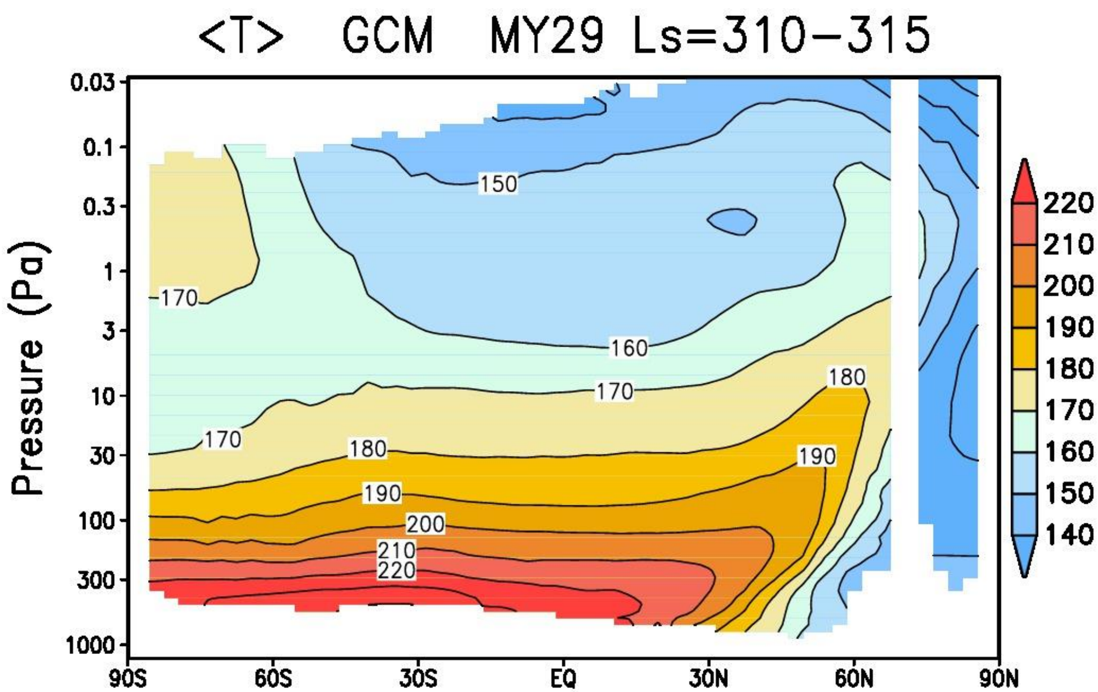
<T> MCS MY29 Ls=305-310
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
230
140

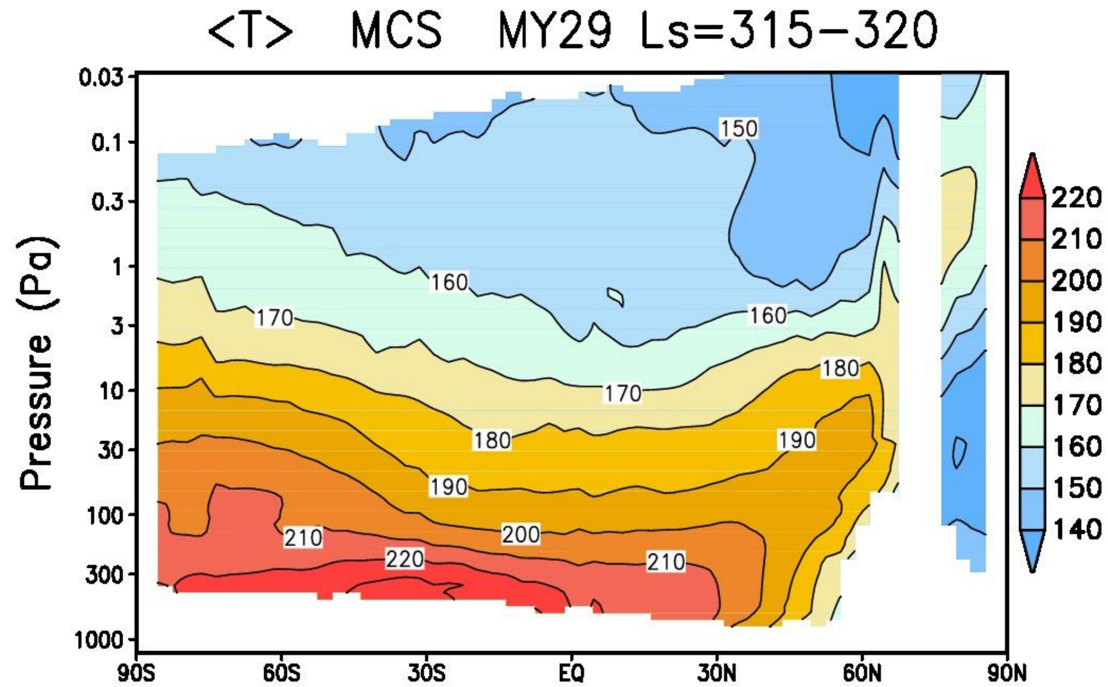
<T> GCM MY29 Ls=305-310
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220
230

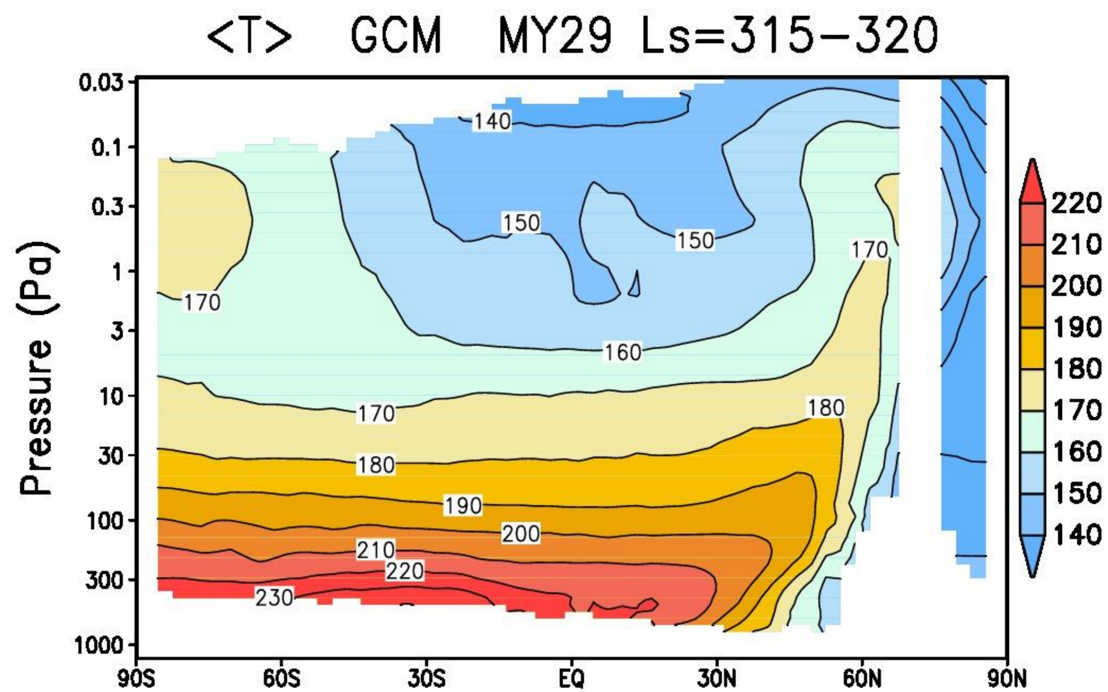


<T> MCS MY29 Ls=310-315
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140

<T> GCM MY29 Ls=310-315
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140


<T> MCS MY29 Ls=315-320
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
160
170
180
190
200
210
220
140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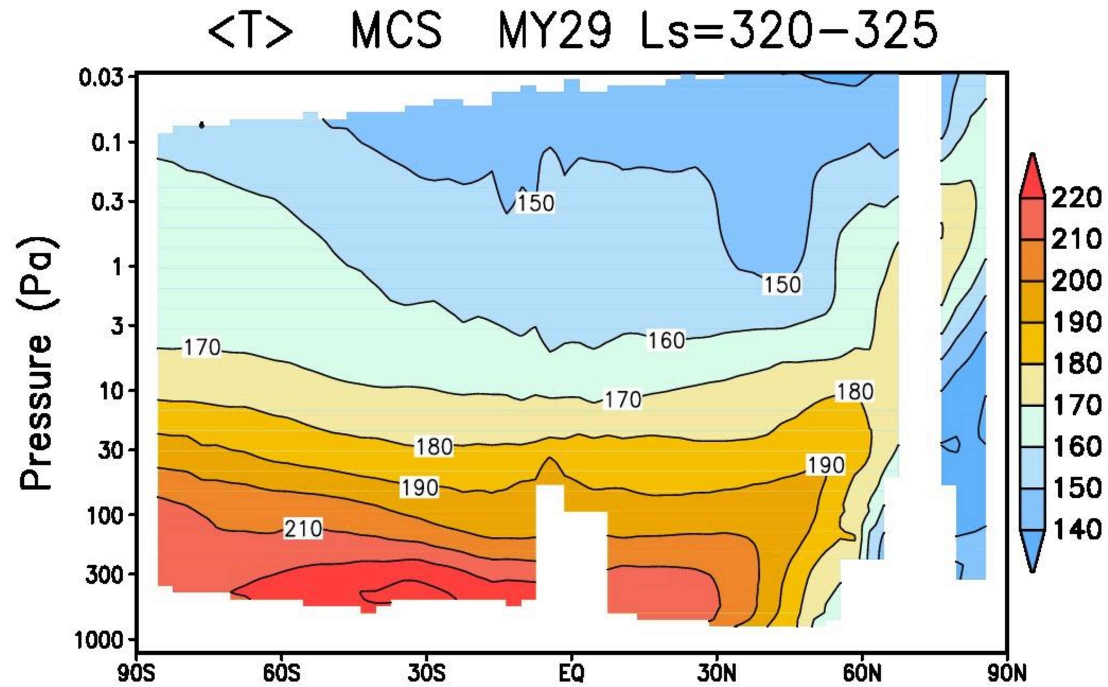
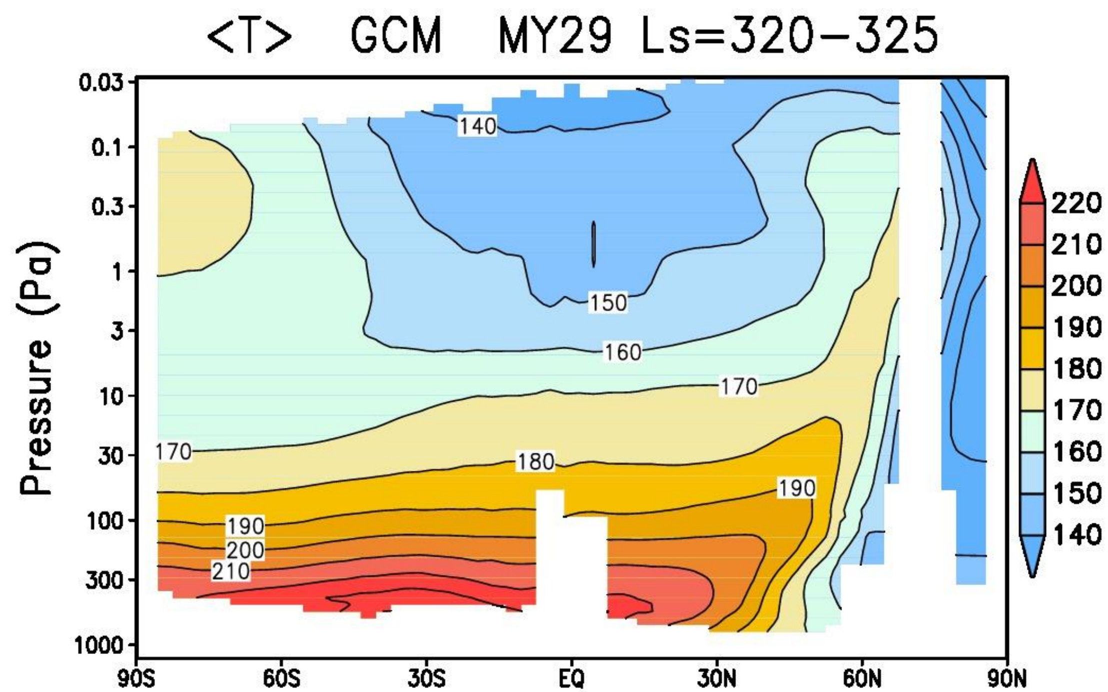
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
180
190
200
210
220
230


<T> MCS MY29 Ls=320-325
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
150
150
160
170
170
180
180
190
190
210
220
210
200
190
180
170
160
150
140


<T> GCM MY29 Ls=320-325
Pressure (Pa)
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0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
150
160
170
170
180
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190
200
210
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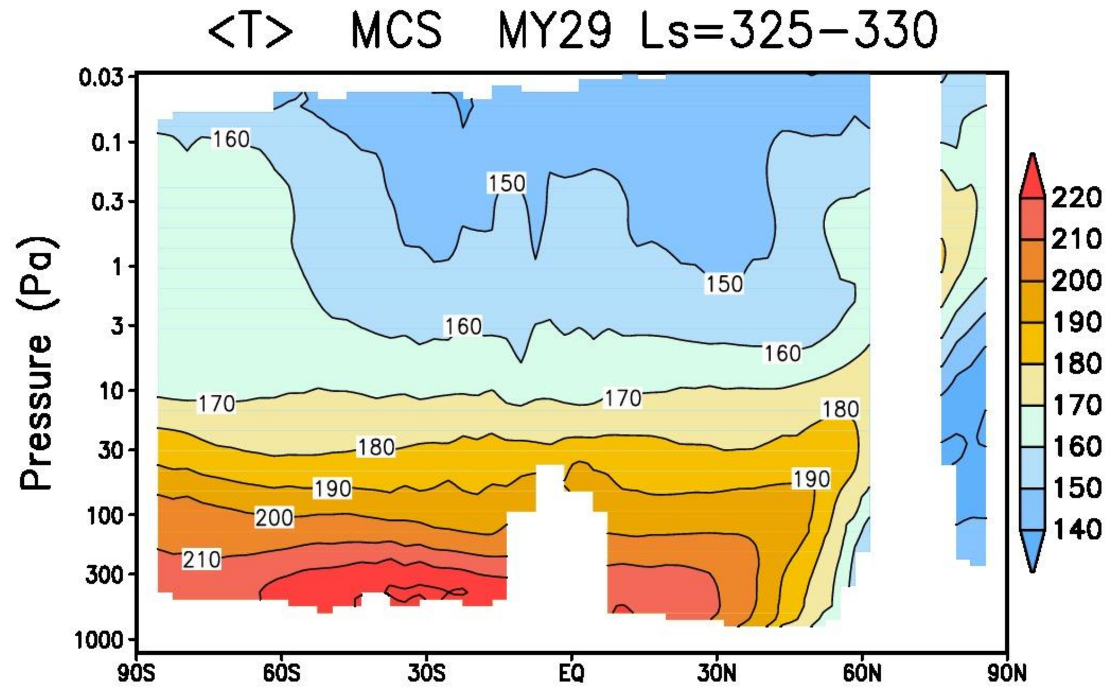
210
200
190
180
170
160
150
140



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Pressure (Pa)
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0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
160
150
150
160
160
170
170
180
180
190
190
200
210
220
210
200
190
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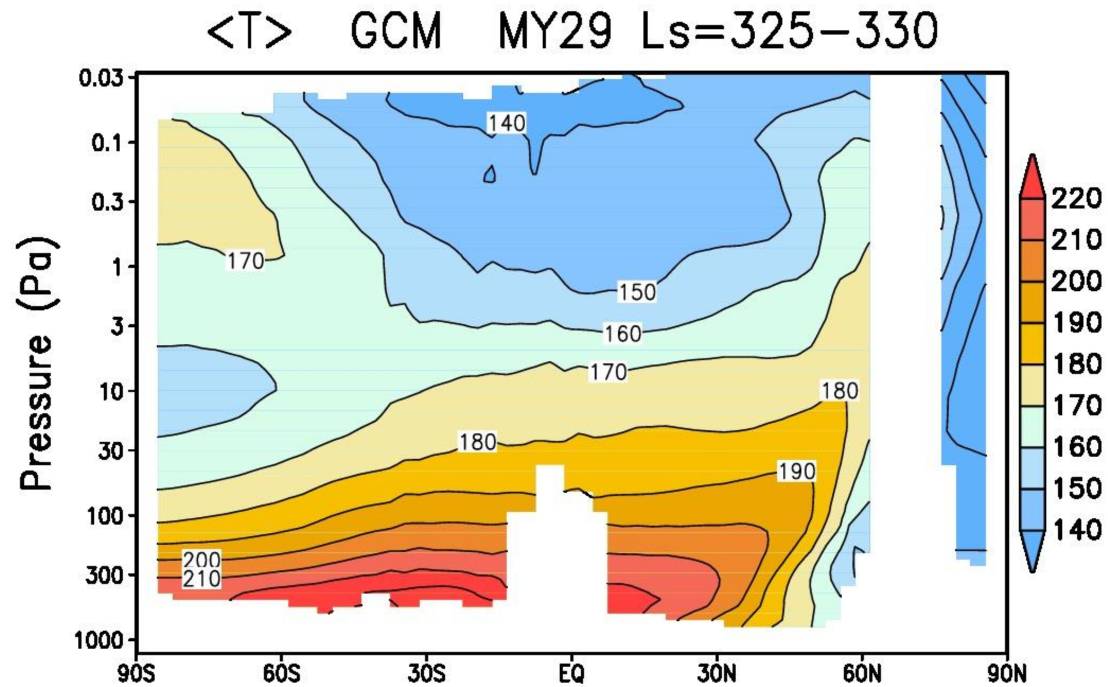
170
160
150
140

<T> GCM MY29 Ls=325-330
Pressure (Pa)
0.03
0.1
0.3
1
3
10
30
100
300
1000
90S
60S
30S
EQ
30N
60N
90N
140
170
150
160
170
180
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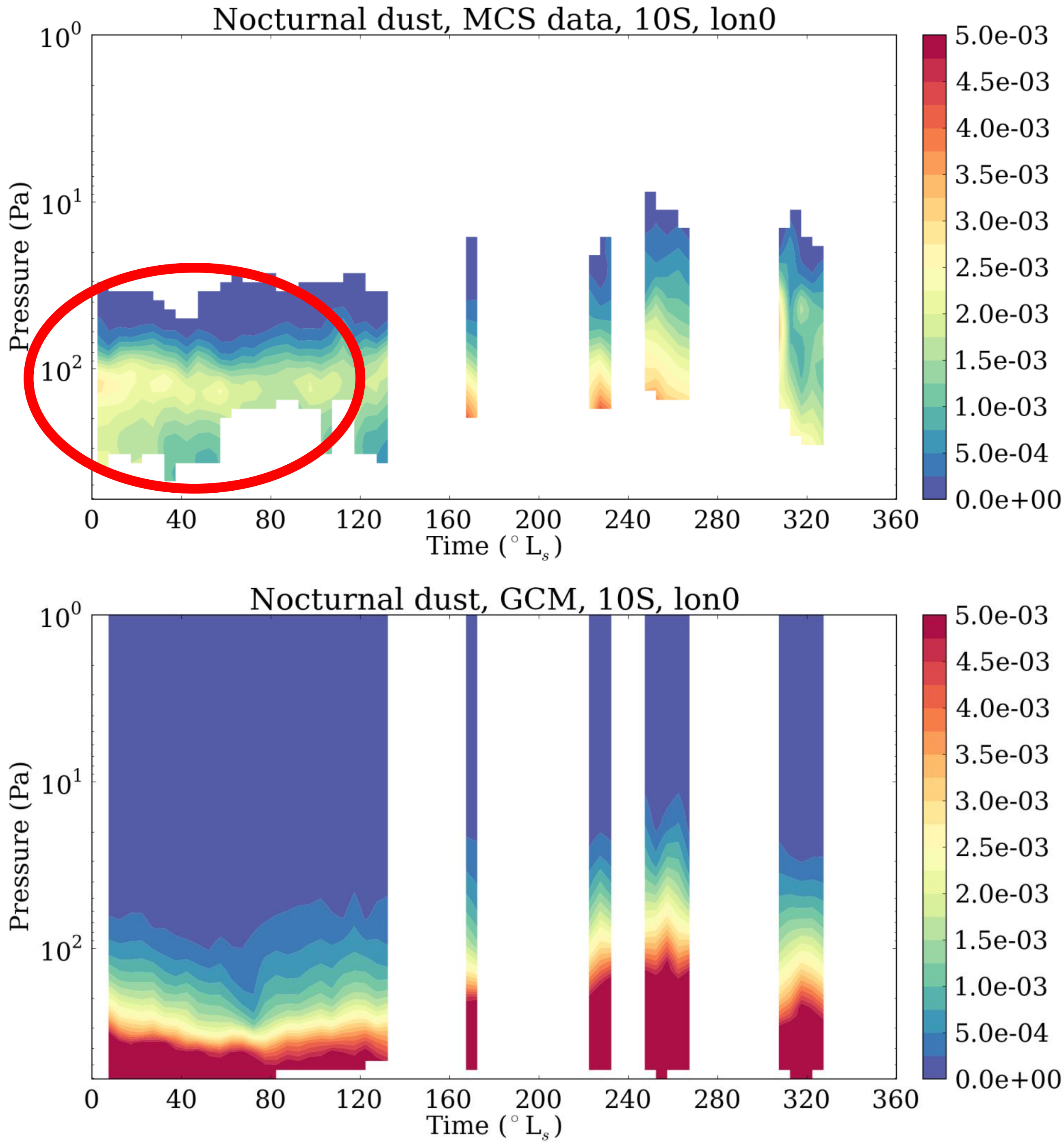
200
210
220
210
200
190
180
170
160
150
140

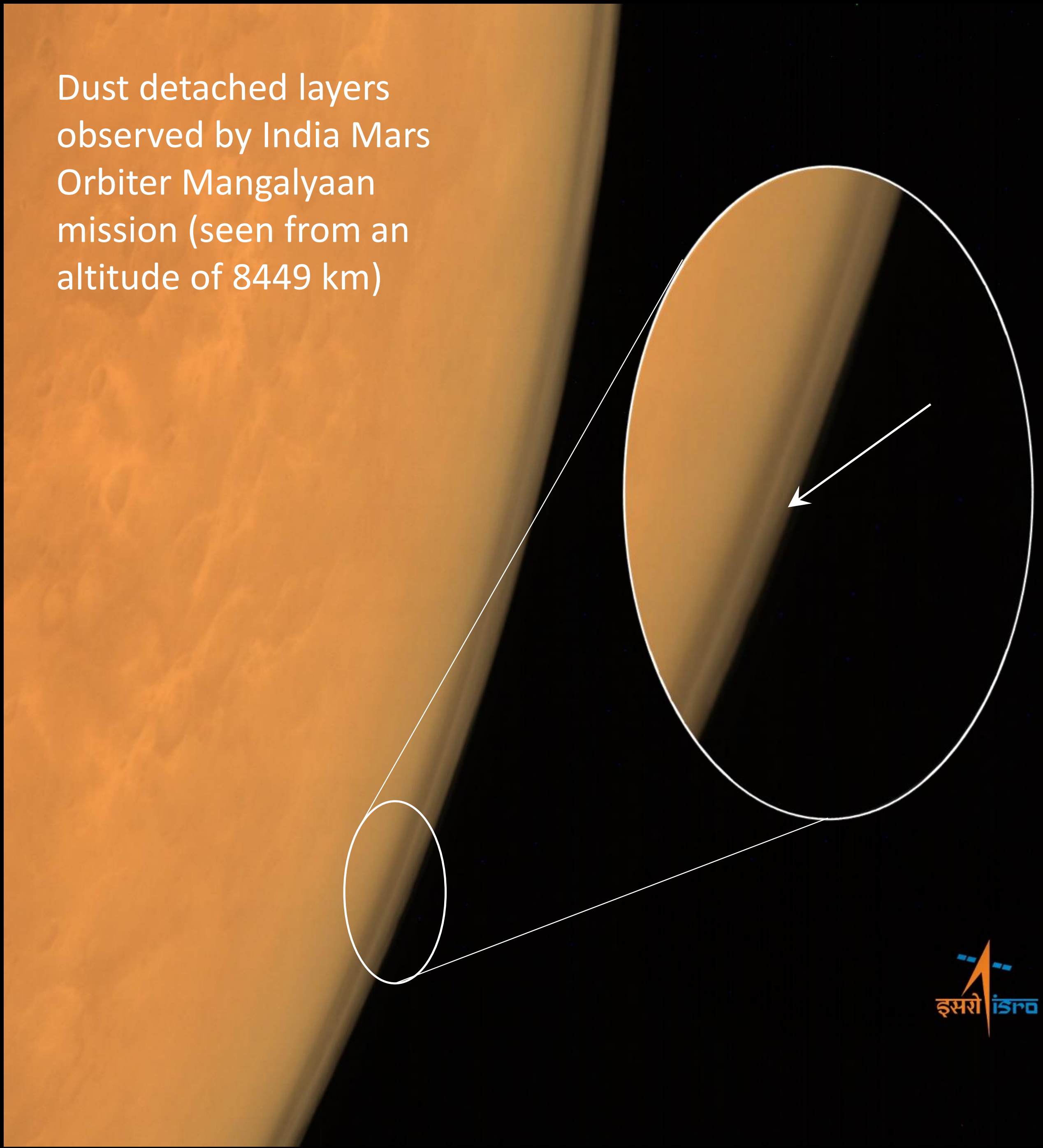
Figure from Alizee PottierC

Local Nightime dust at 10° N 0° E

MCS observations

LMD GCM Model



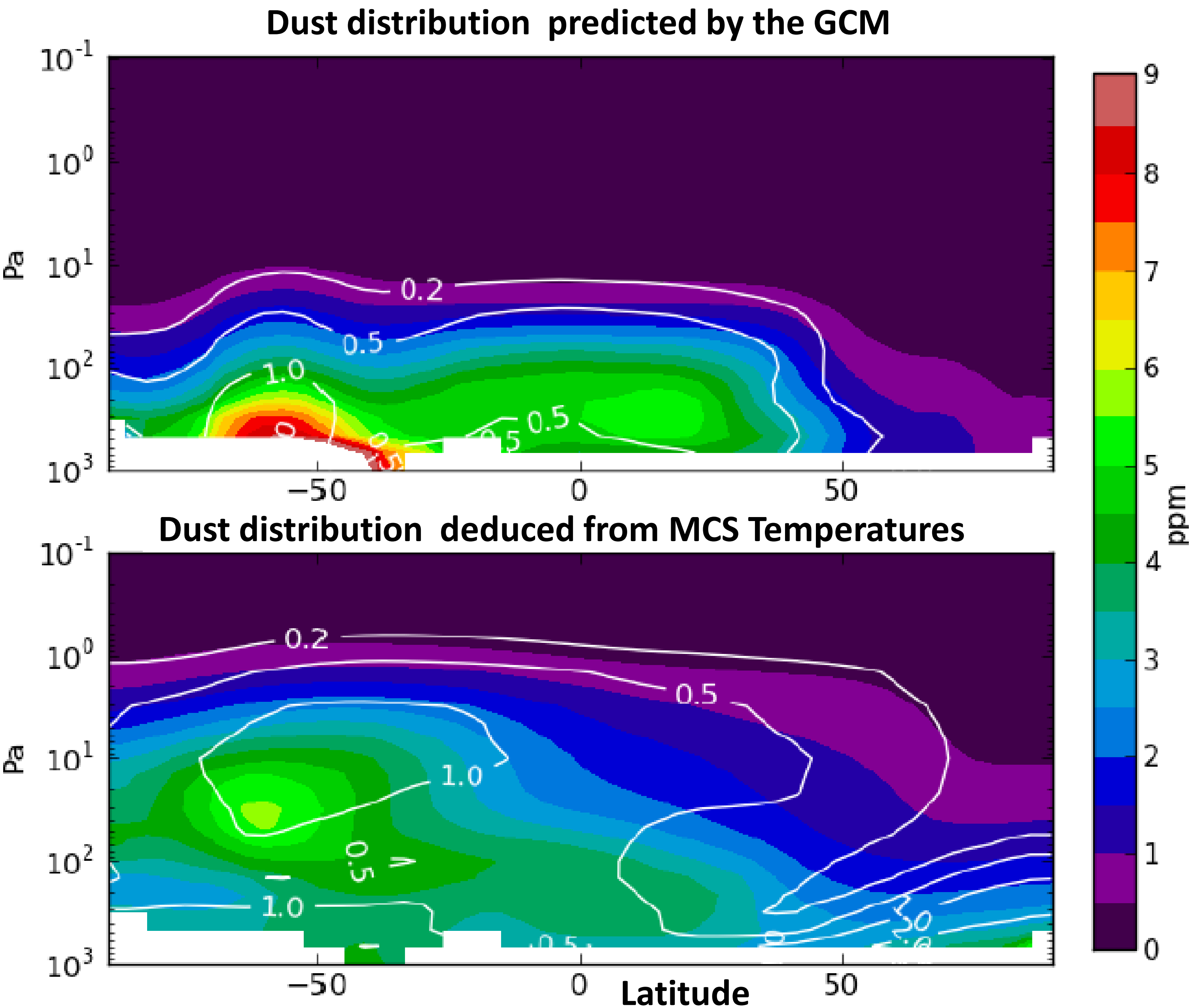

Dust detached layers
observed by India Mars
Orbiter Mangalyaan
mission (seen from an
altitude of 8449 km)
इसरो isro

# Detached dust layer necessary to explain MCS observed thermal structure

**Reconstructing the dust field from MCS temperature observations with an ensemble of GCM simulations** Ls=310 to Ls=320 MY29.

(LETKF data assimilation scheme)

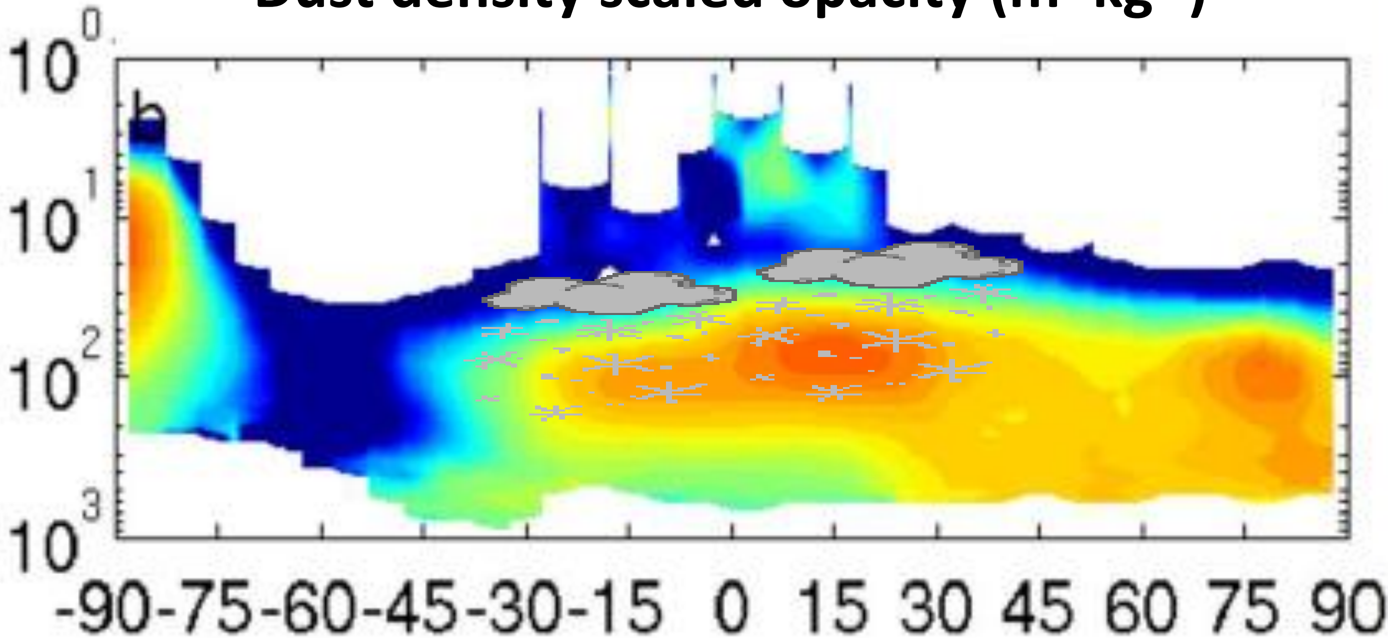
(*Navarro et al. 2014*)



# What is the process forming detached dust layers ?

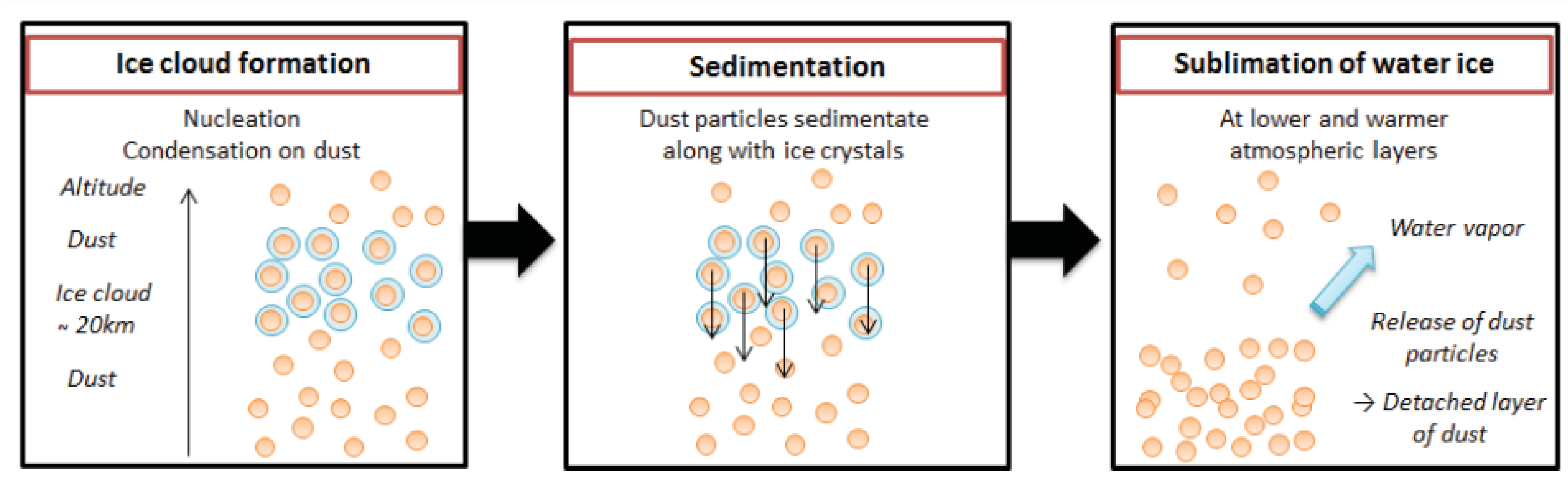
**1)** Dust enrichment below dust scavenging clouds *(Navarro et al. 2014)*

**Dust density scaled opacity ($m^2$ $kg^{-1}$)**

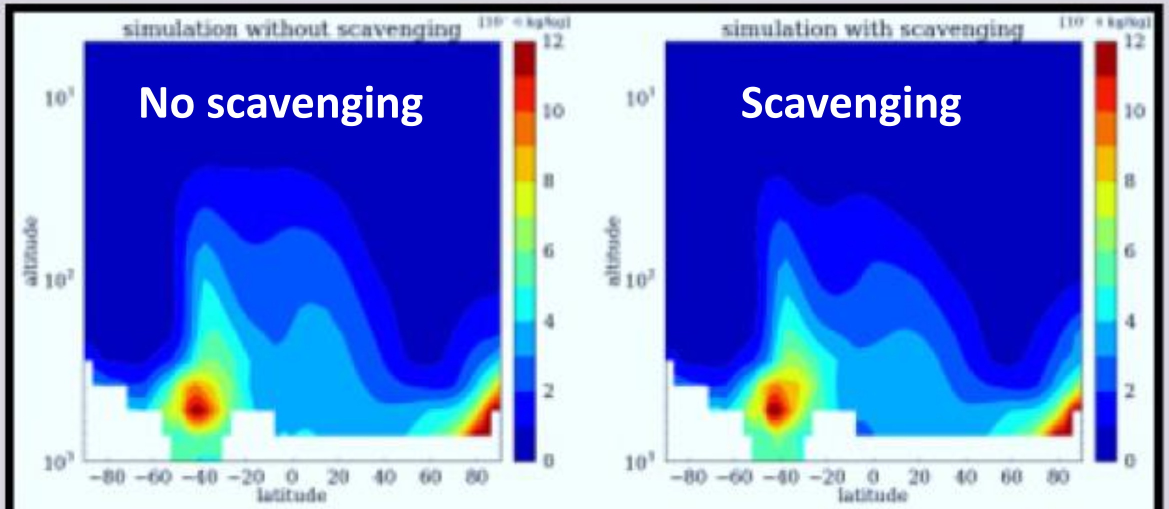


# Modelling dust scavenging by ice in LMD GCM

*(Navarro et al. 2014)*



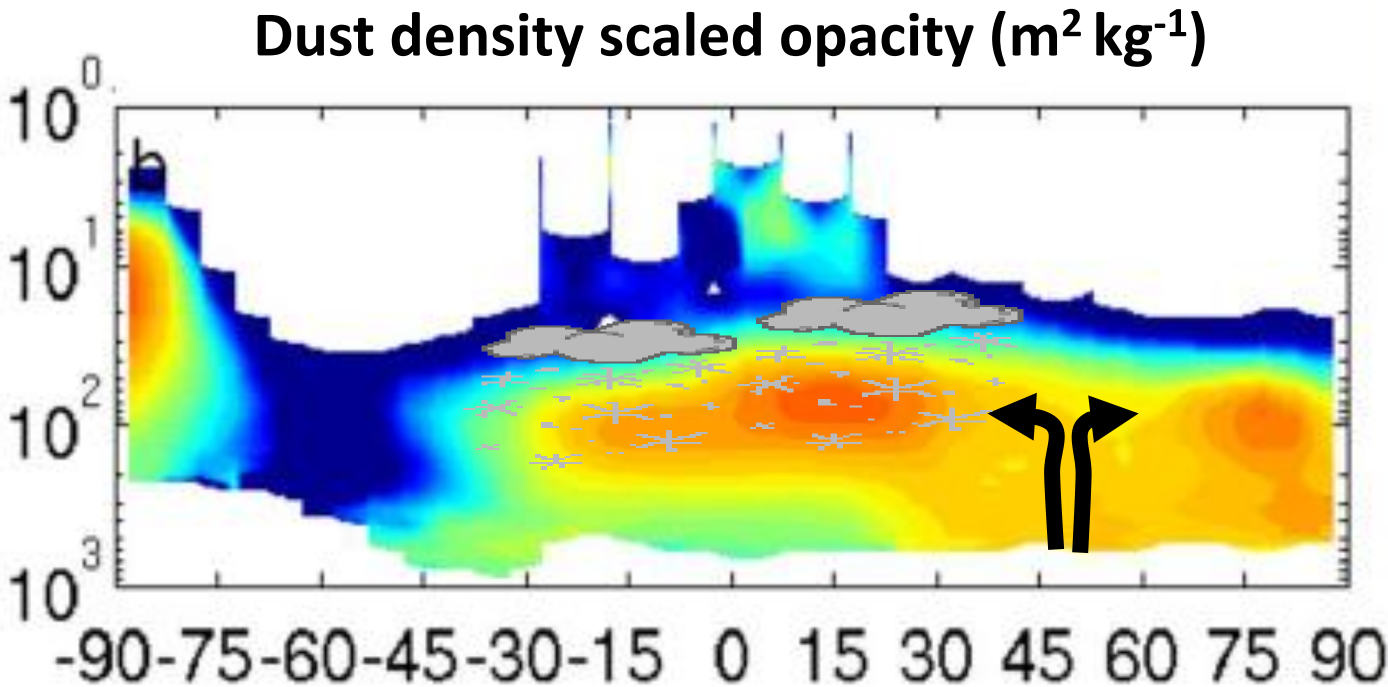

*Zonal mean dust mixing ratio for simulations with (right) and without (left) scavenging by water ice cloud, averaged between Ls=90° and Ls=120° (presence of numerous water ice clouds during this period). No significant difference was found.*




*Navarro et al. 2014; Bertrand et al. 2014*

# What is the process forming detached dust layers ?

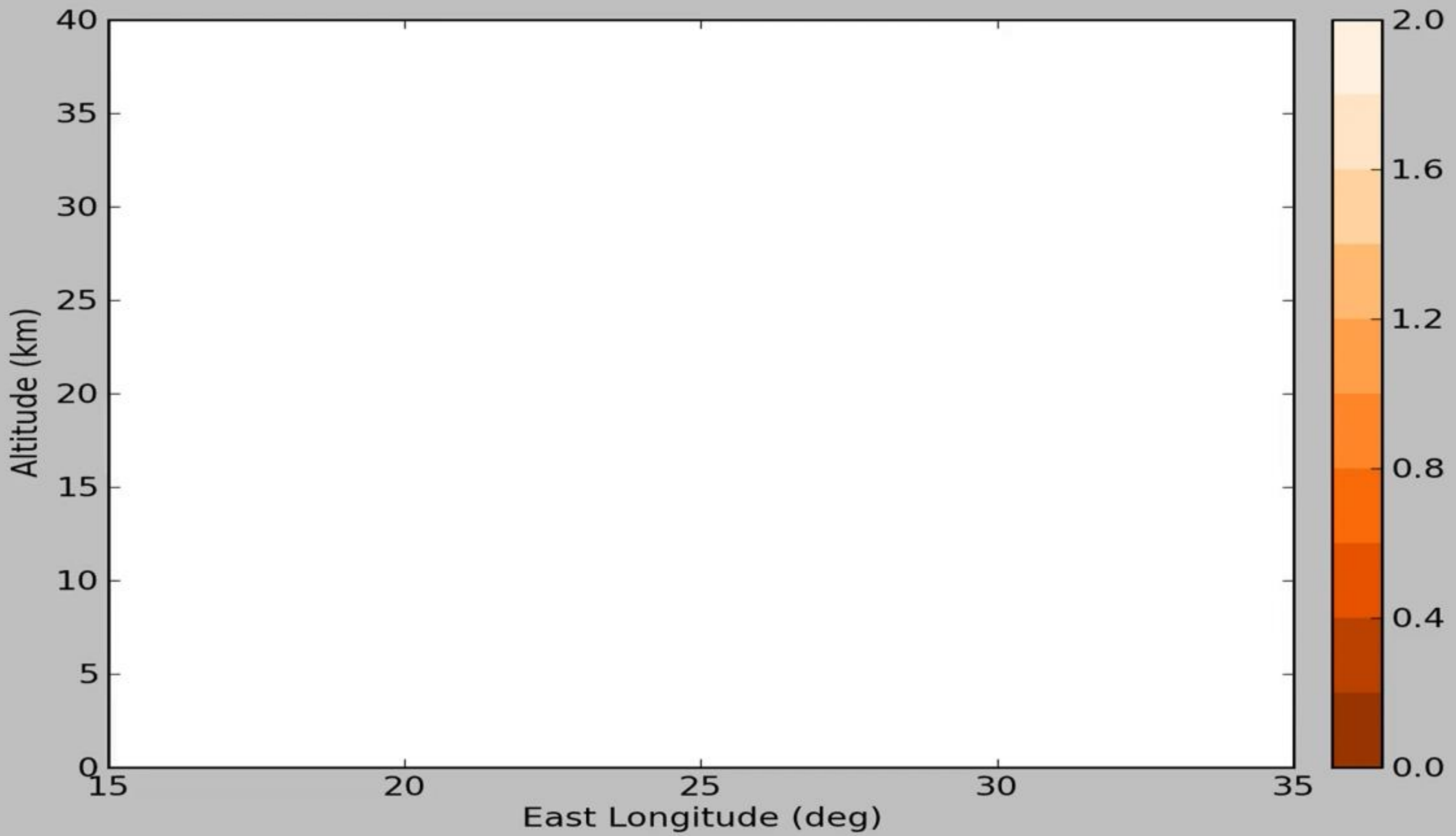
~~1) Dust enrichment below dust scavenging clouds~~ *(Navarro et al. 2014)*



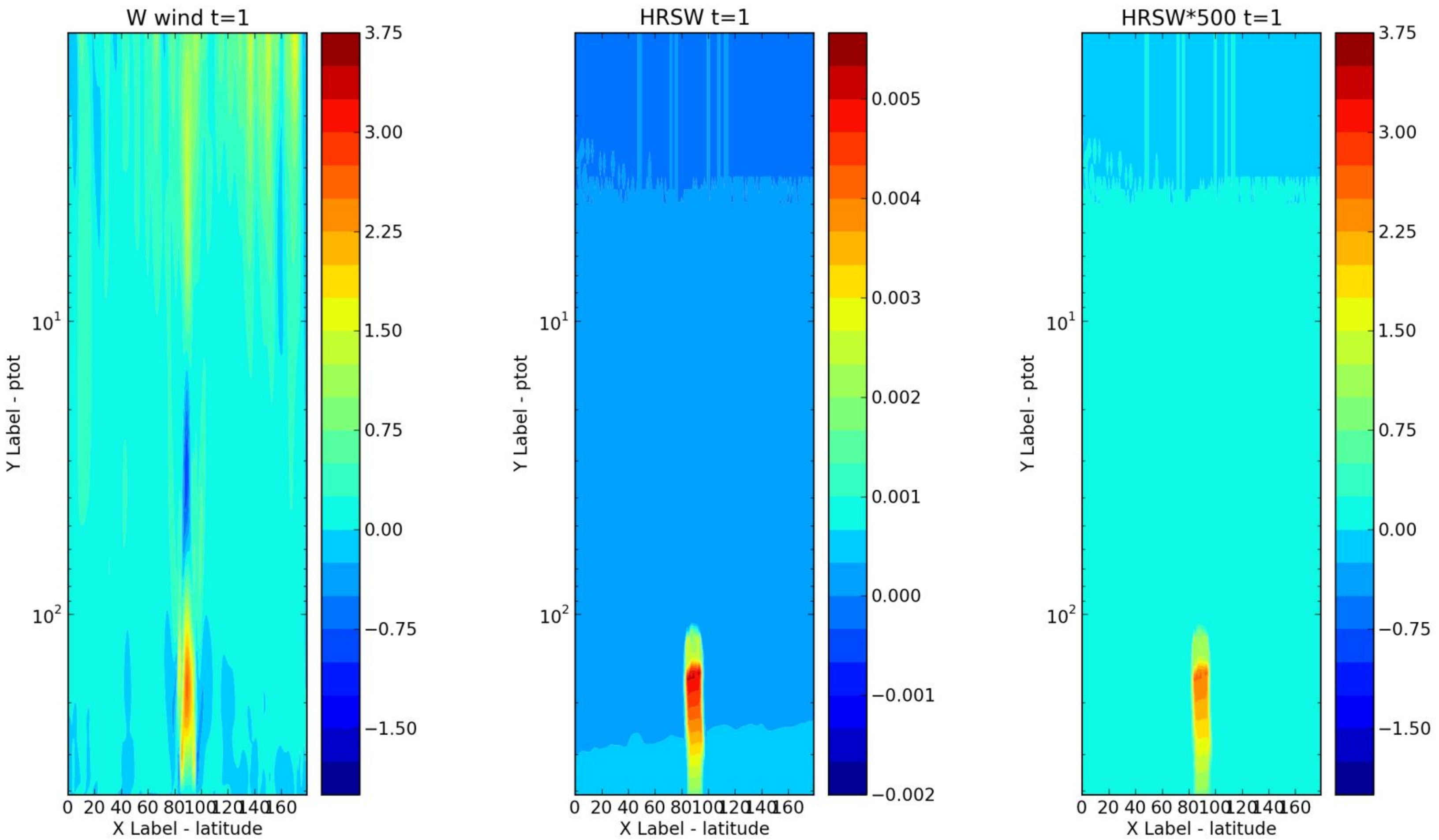

**2)** Direct transport of dust from the boundary layer to the mid atmosphere by "rocket dust storms" *(Spiga et al. 2013)* & Local topography circulation

# Rocket dust storm : evolution of a local dust storm as simulated by the LMD Mesoscale Model

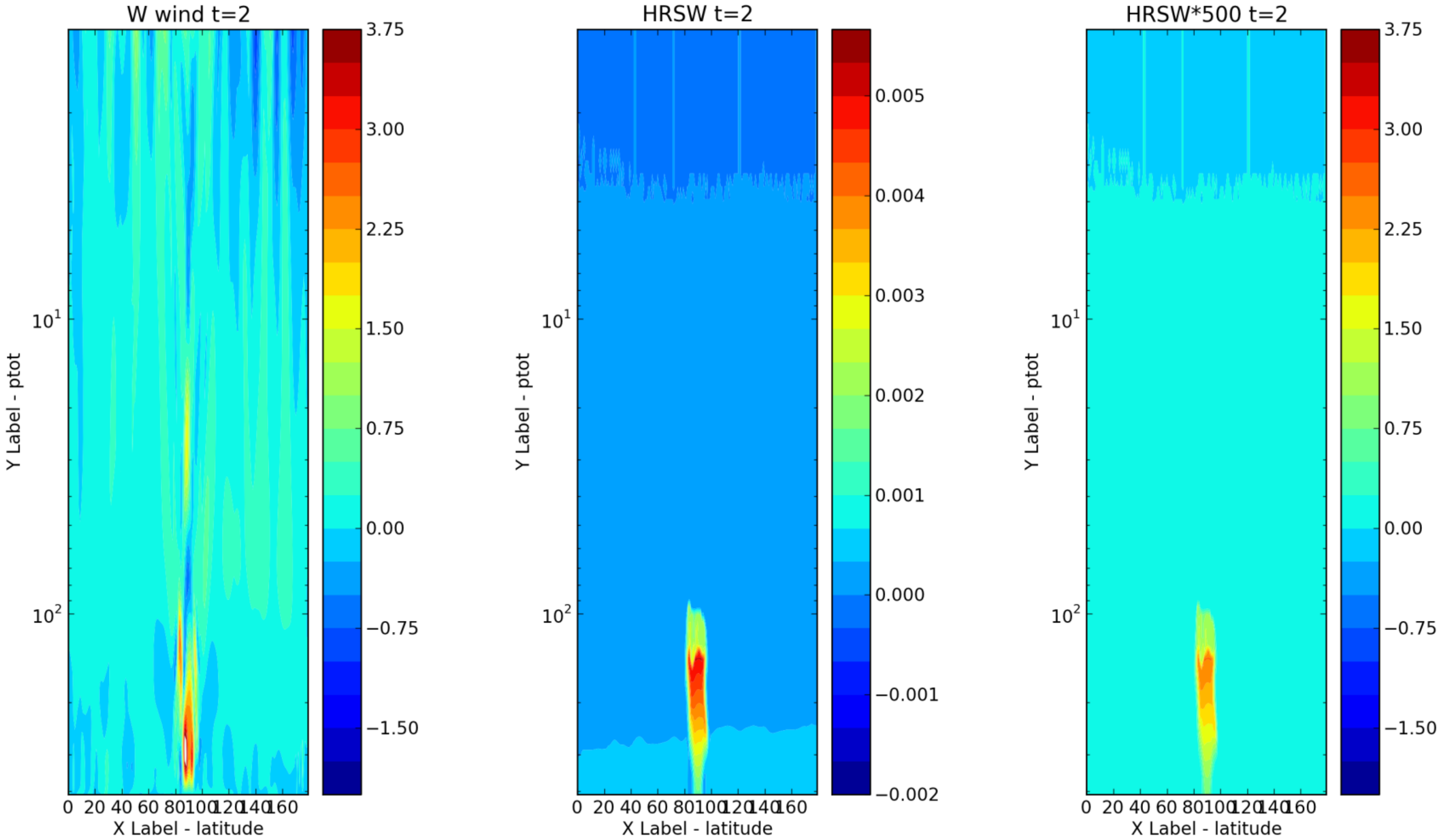
*Spiga et al. 2013. Model Resolution = 7 km*



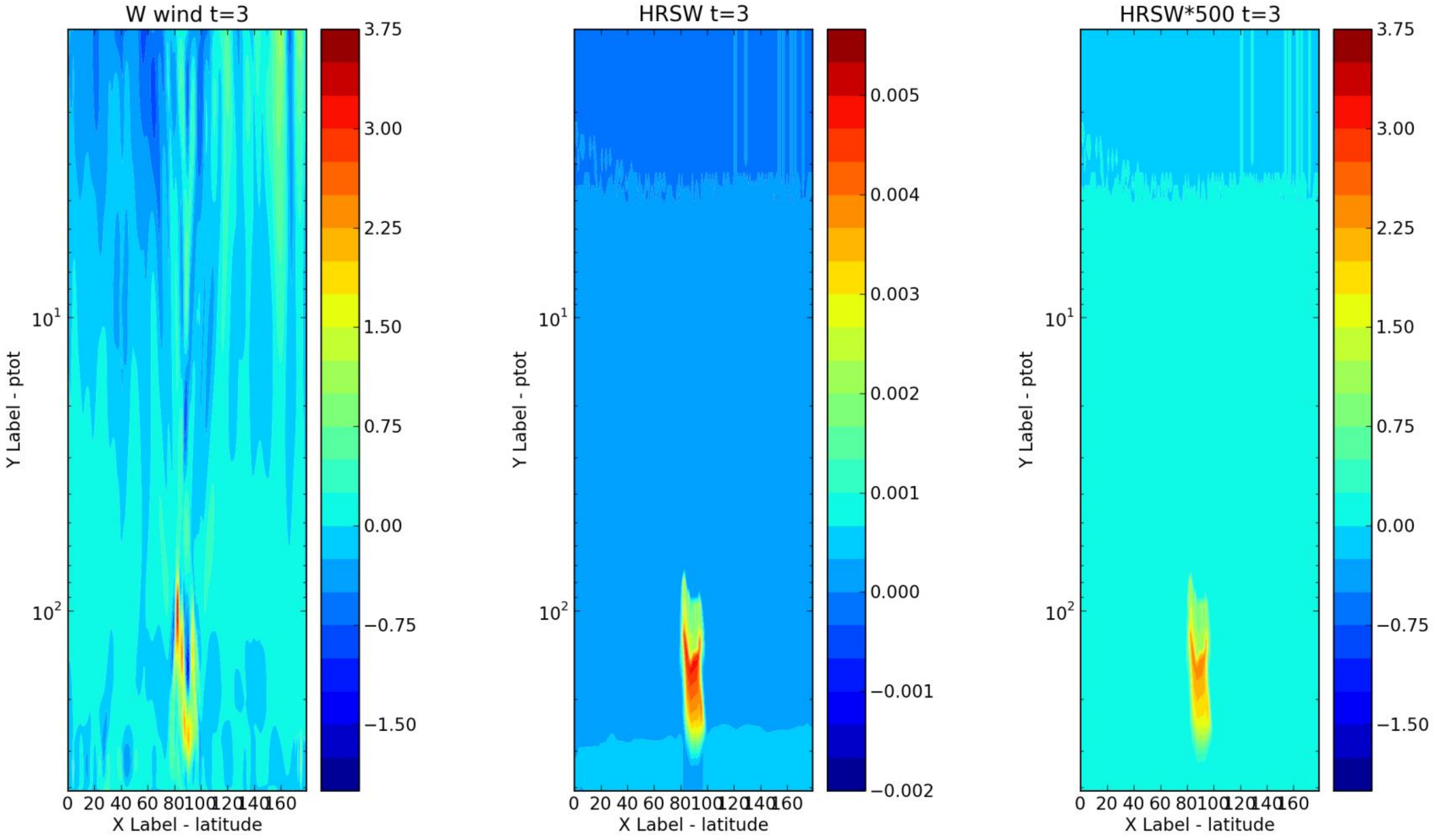
# Relation taux de chauffage – Vitesse verticale



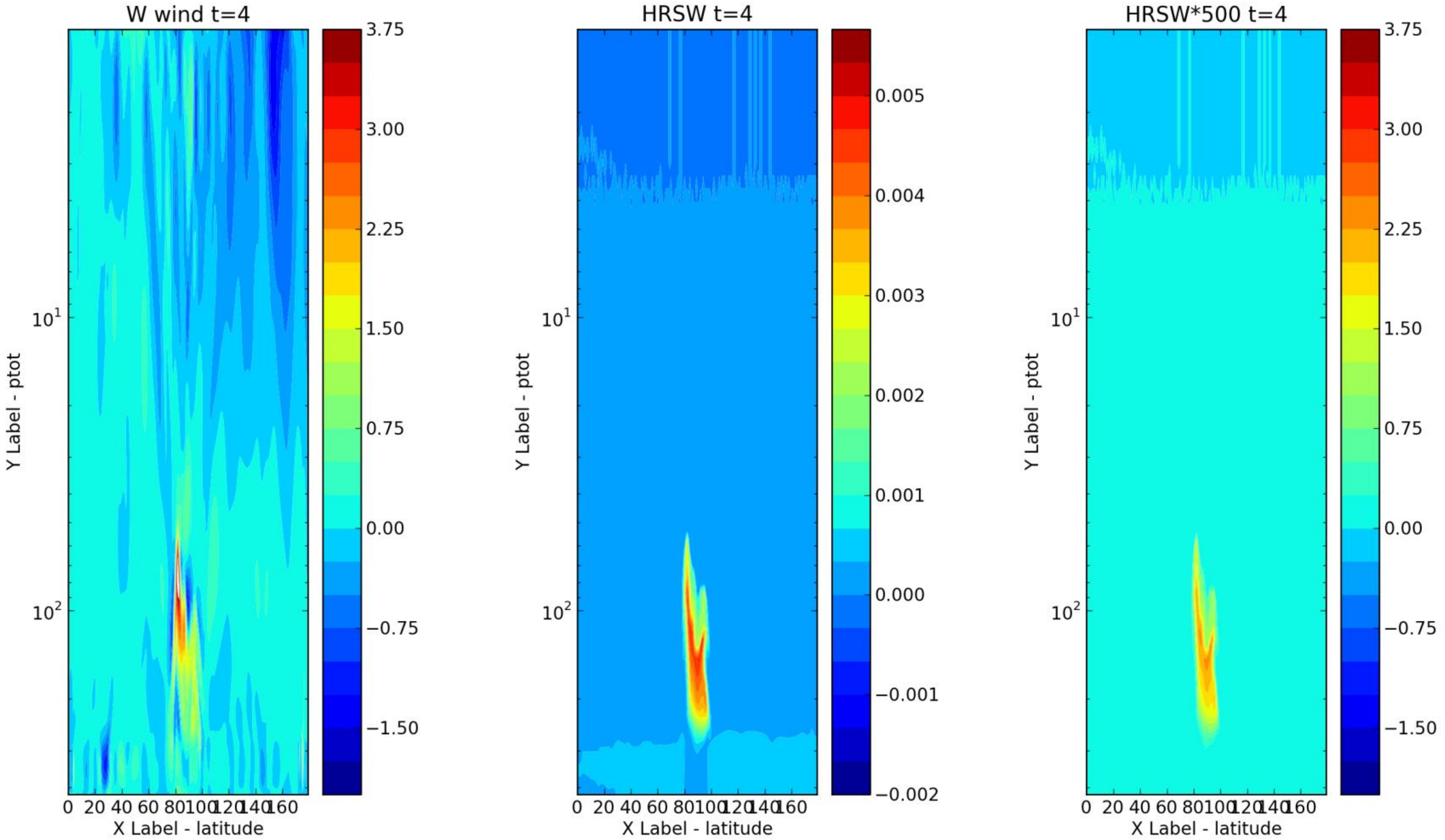
# Relation taux de chauffage – Vitesse verticale



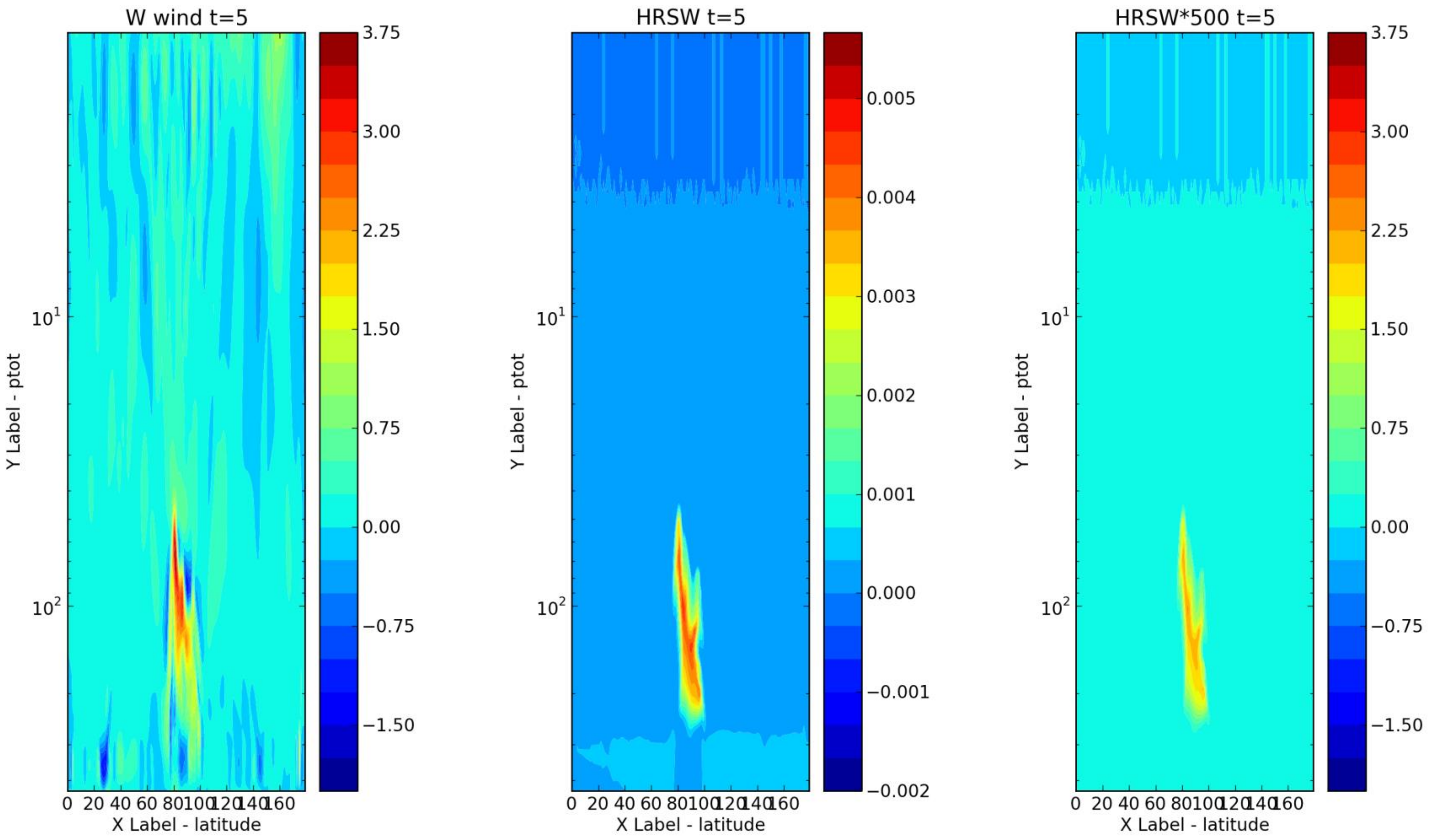
# Relation taux de chauffage – Vitesse verticale



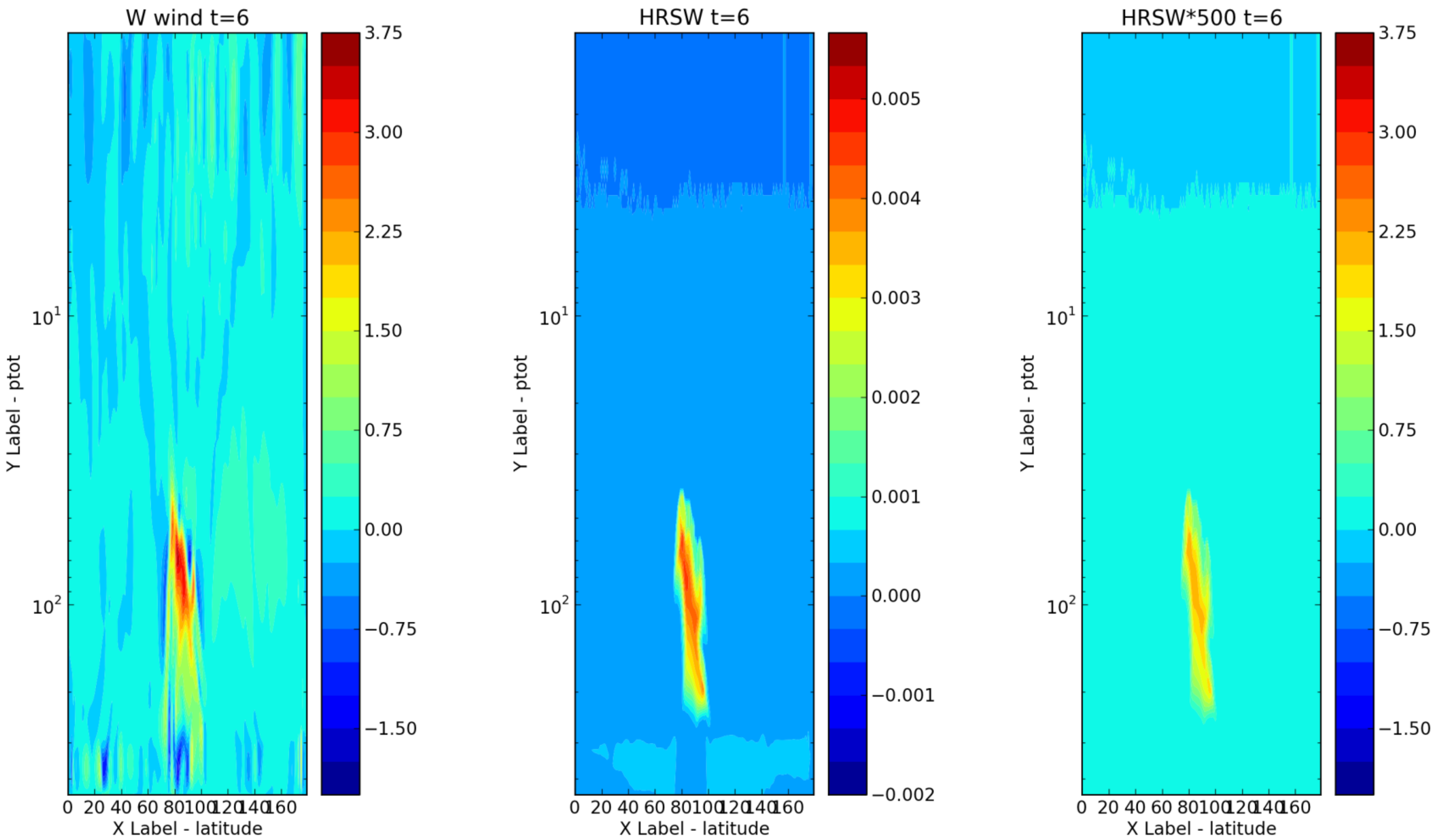
# Relation taux de chauffage – Vitesse verticale



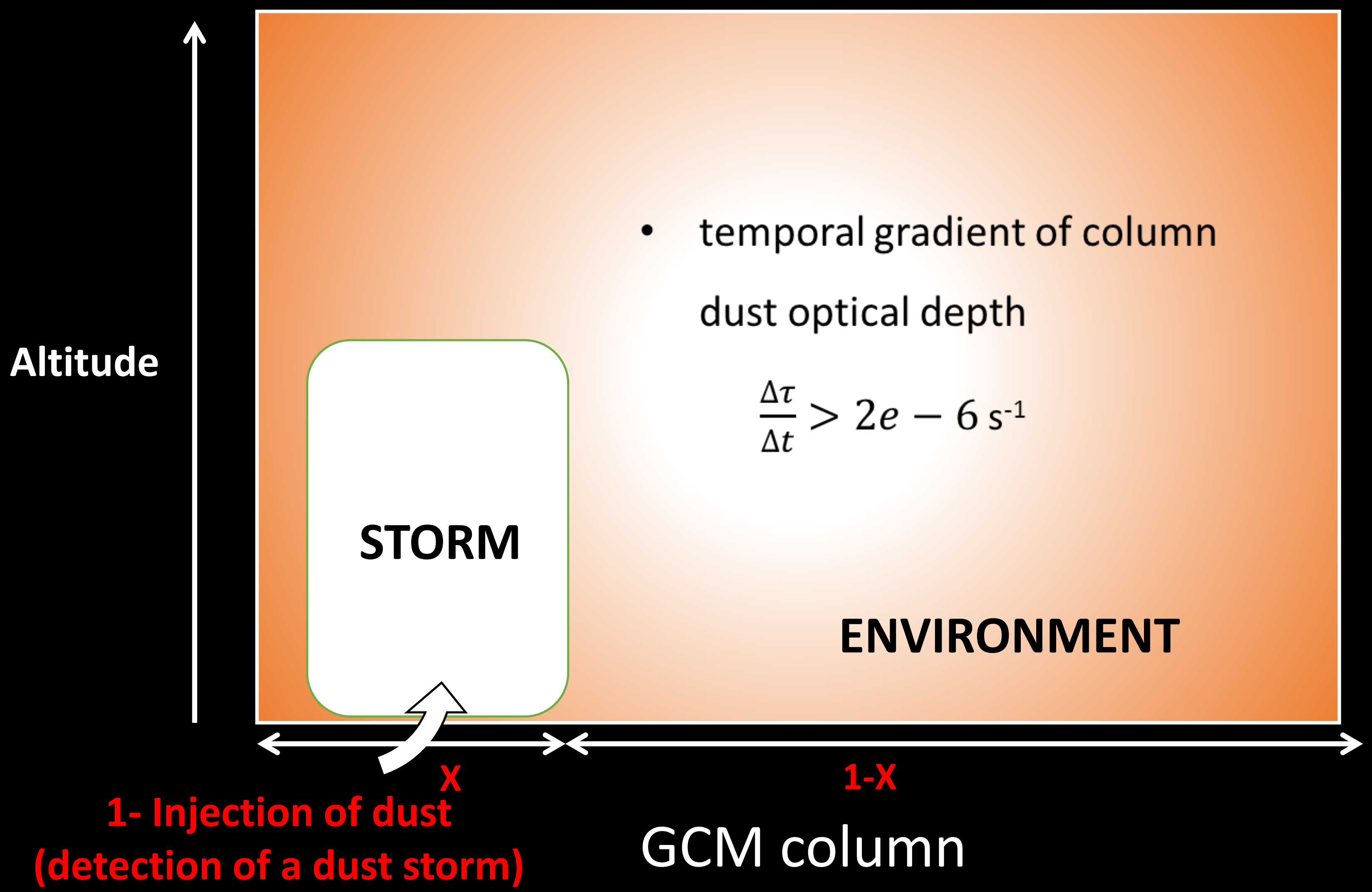
# Relation taux de chauffage – Vitesse verticale

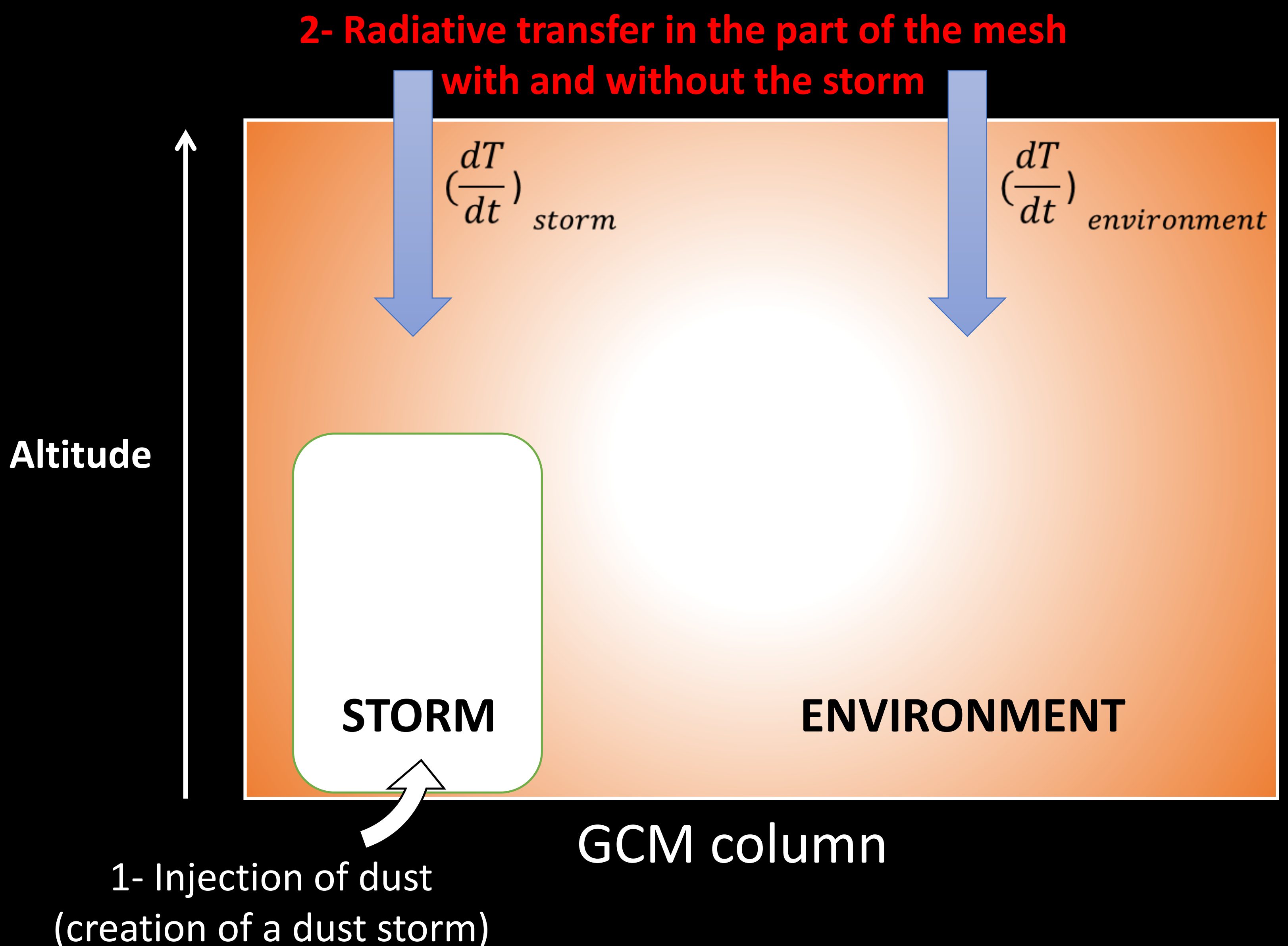


# Relation taux de chauffage – Vitesse verticale

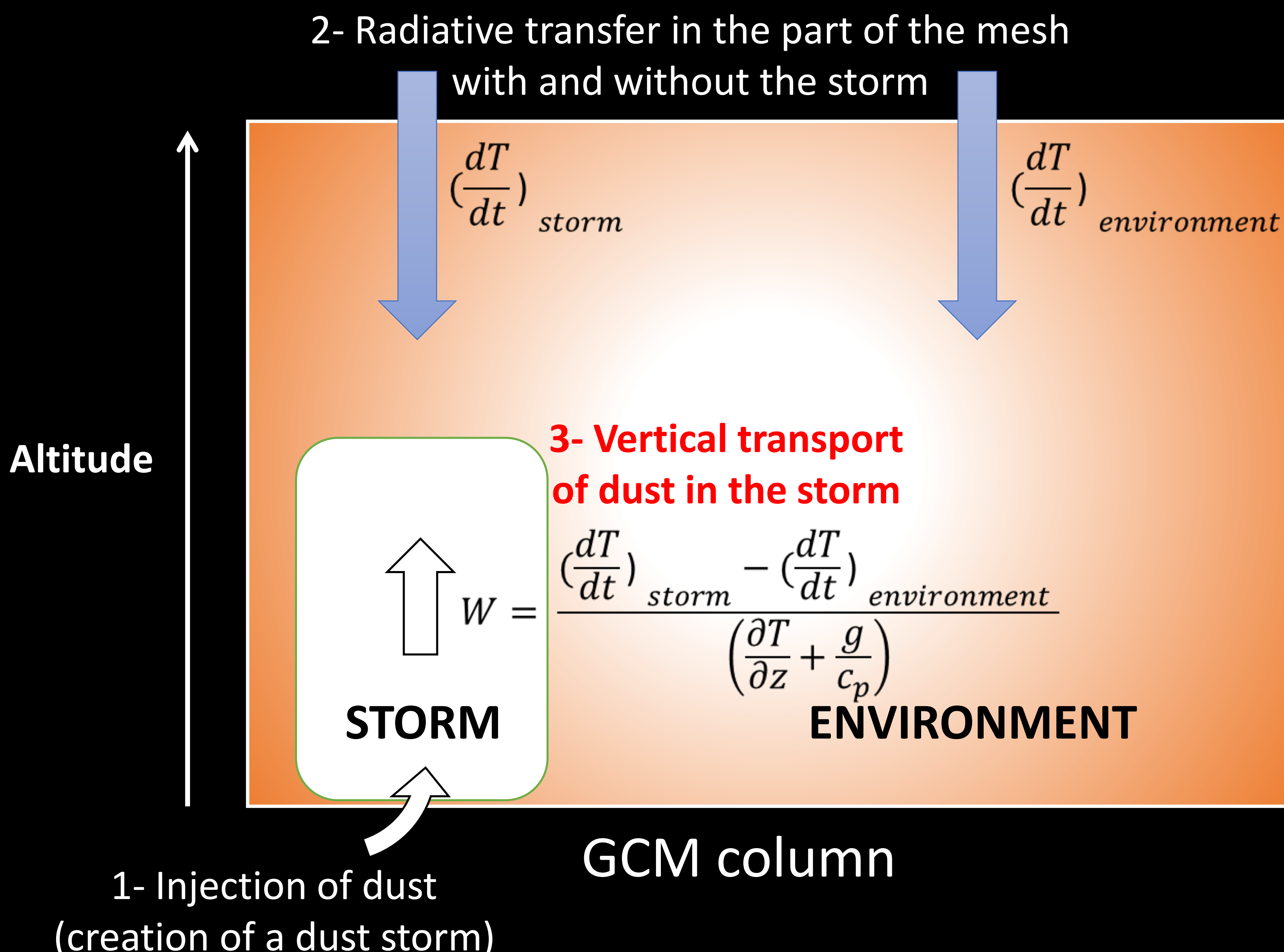


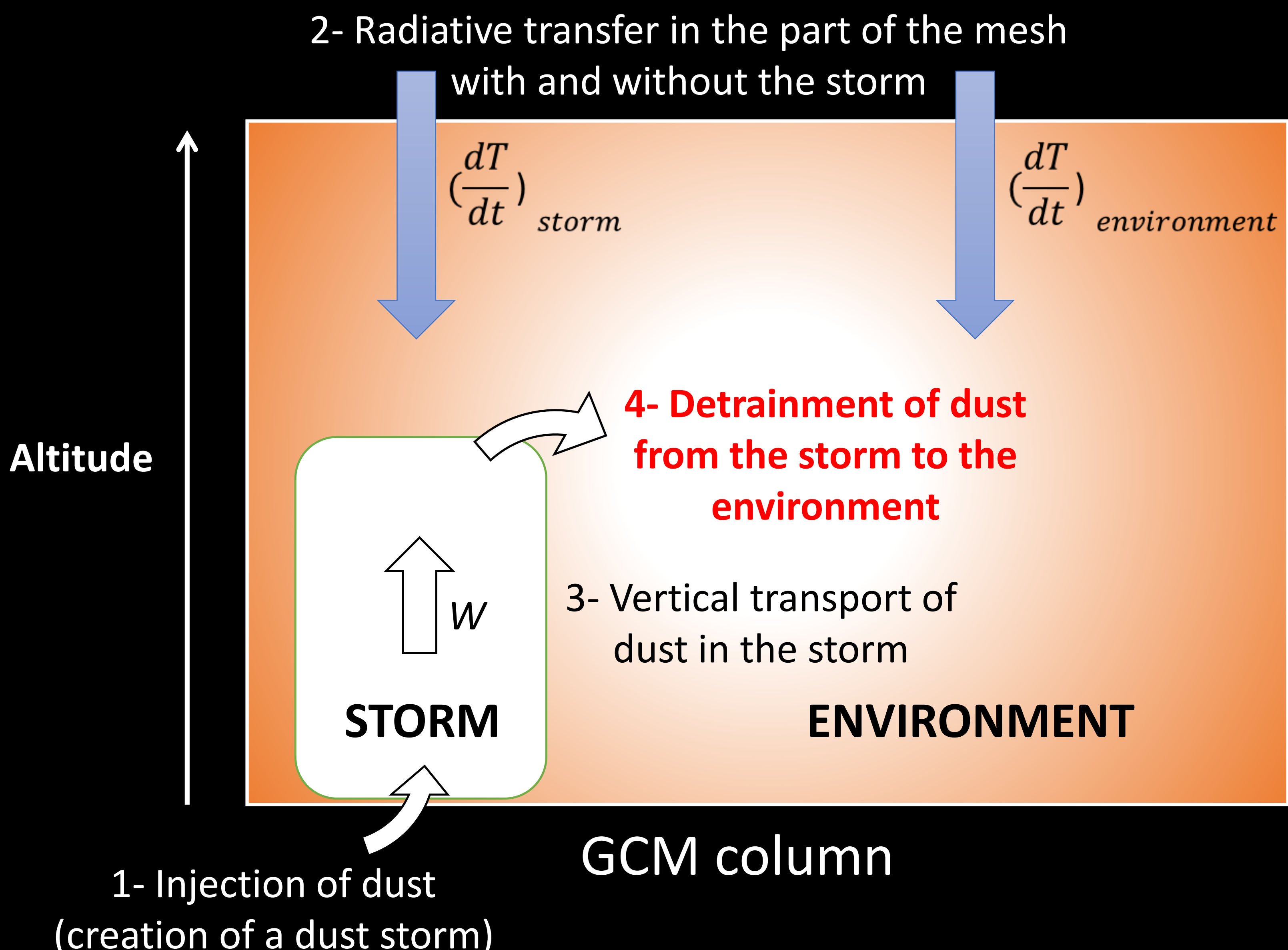
# Parameterizing rocket dust storm in LMD Global Climate Model (GCM)



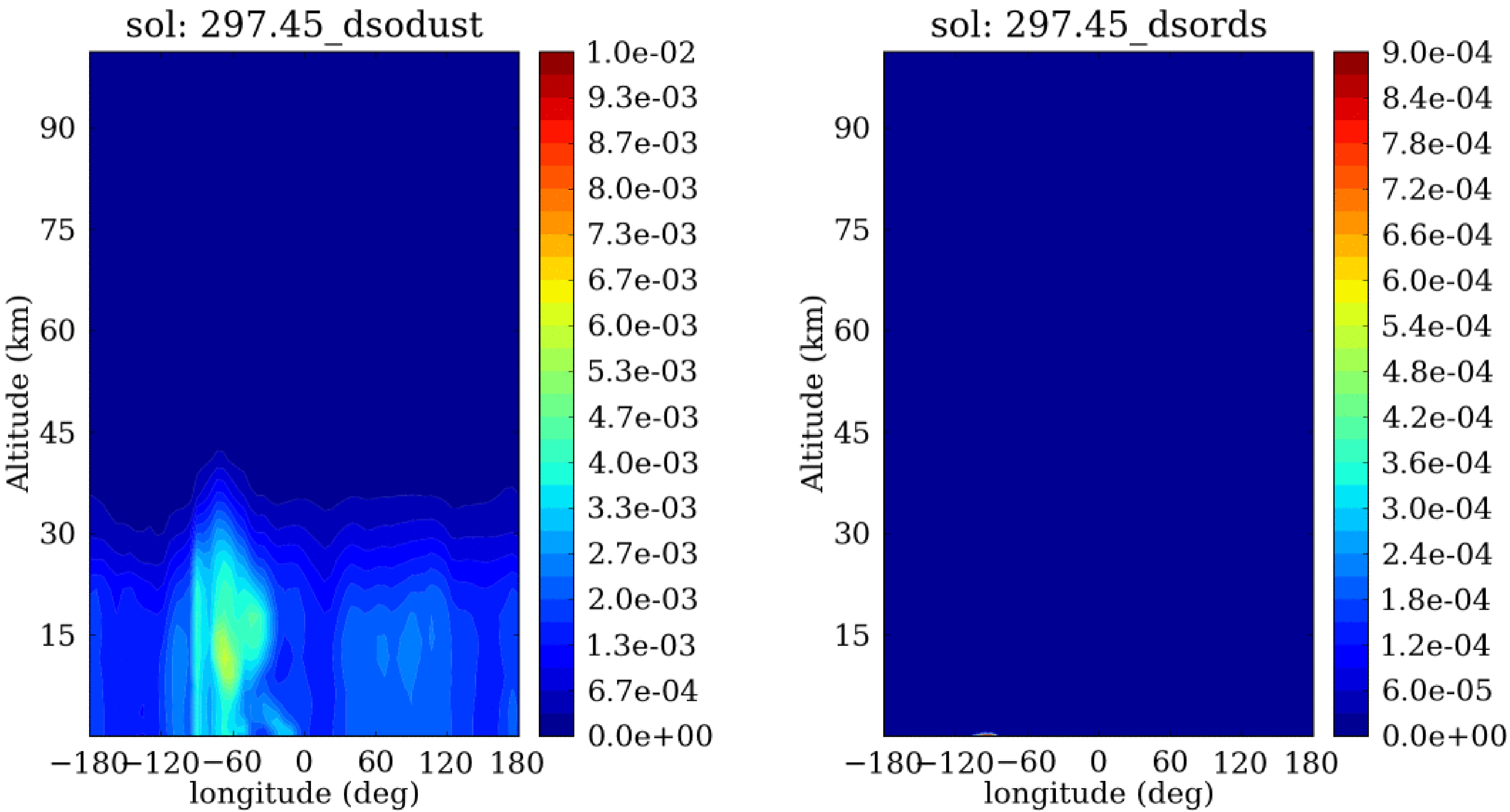


2- Radiative transfer in the part of the mesh
with and without the storm
$(\frac{dT}{dt})_{storm}$
$(\frac{dT}{dt})_{environment}$
Altitude
STORM
ENVIRONMENT
GCM column
1- Injection of dust
(creation of a dust storm)


2- Radiative transfer in the part of the mesh with and without the storm
$(\frac{dT}{dt})_{storm}$
$(\frac{dT}{dt})_{environment}$
Altitude
3- Vertical transport of dust in the storm
$W = \frac{(\frac{dT}{dt})_{storm} - (\frac{dT}{dt})_{environment}}{\left(\frac{\partial T}{\partial z} + \frac{g}{c_p}\right)}$
STORM
ENVIRONMENT
GCM column
1- Injection of dust (creation of a dust storm)

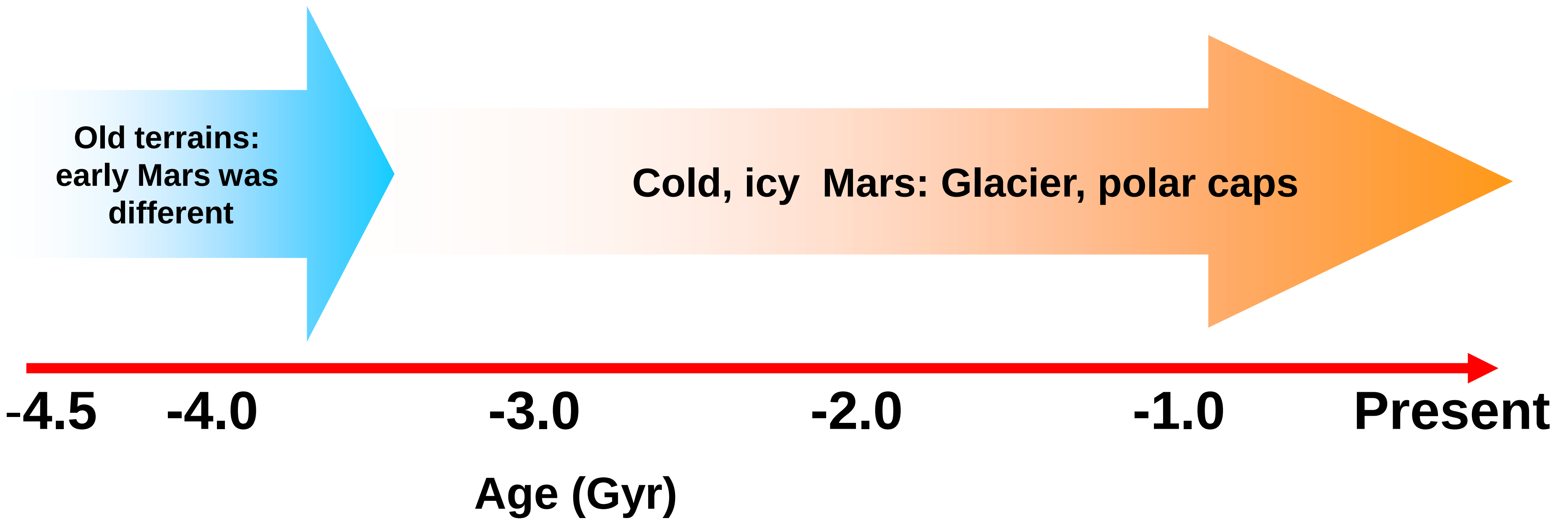


2- Radiative transfer in the part of the mesh with and without the storm
$(\frac{dT}{dt})_{storm}$
$(\frac{dT}{dt})_{environment}$
Altitude
4- Detrainment of dust from the storm to the environment
$W$
3- Vertical transport of dust in the storm
STORM
ENVIRONMENT
GCM column
1- Injection of dust (creation of a dust storm)

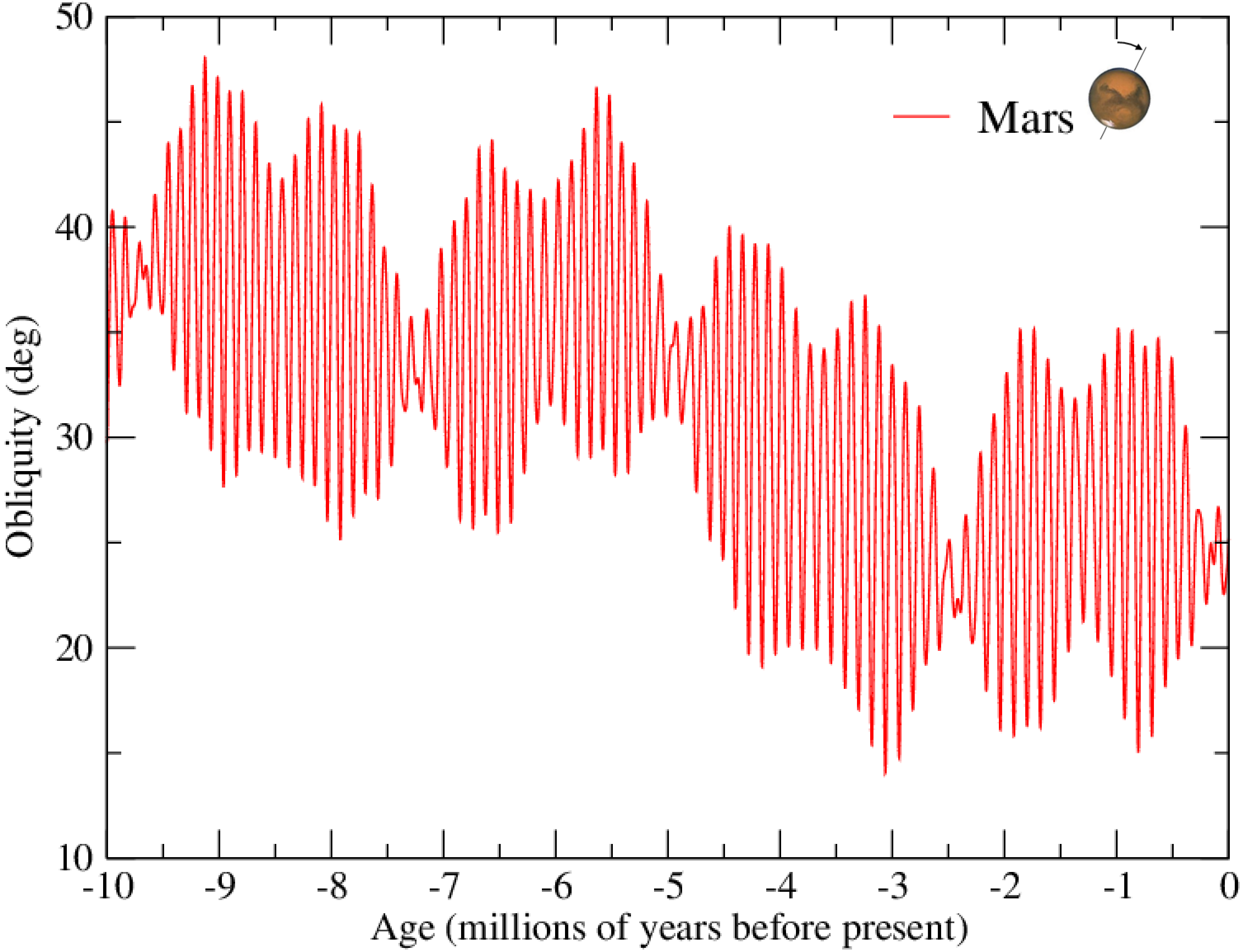


sol: 297.45_dsodust
Altitude (km)
90
75
60
45
30
15
−180
−120
−60
0
60
120
180
longitude (deg)
1.0e-02
9.3e-03
8.7e-03
8.0e-03
7.3e-03
6.7e-03
6.0e-03
5.3e-03
4.7e-03
4.0e-03
3.3e-03
2.7e-03
2.0e-03
1.3e-03
6.7e-04
0.0e+00
sol: 297.45_dsords
9.0e-04
8.4e-04
7.8e-04
7.2e-04
6.6e-04
6.0e-04
5.4e-04
4.8e-04
4.2e-04
3.6e-04
3.0e-04
2.4e-04
1.8e-04
1.2e-04
6.0e-05
0.0e+00

# Evolution of the Martian Climate

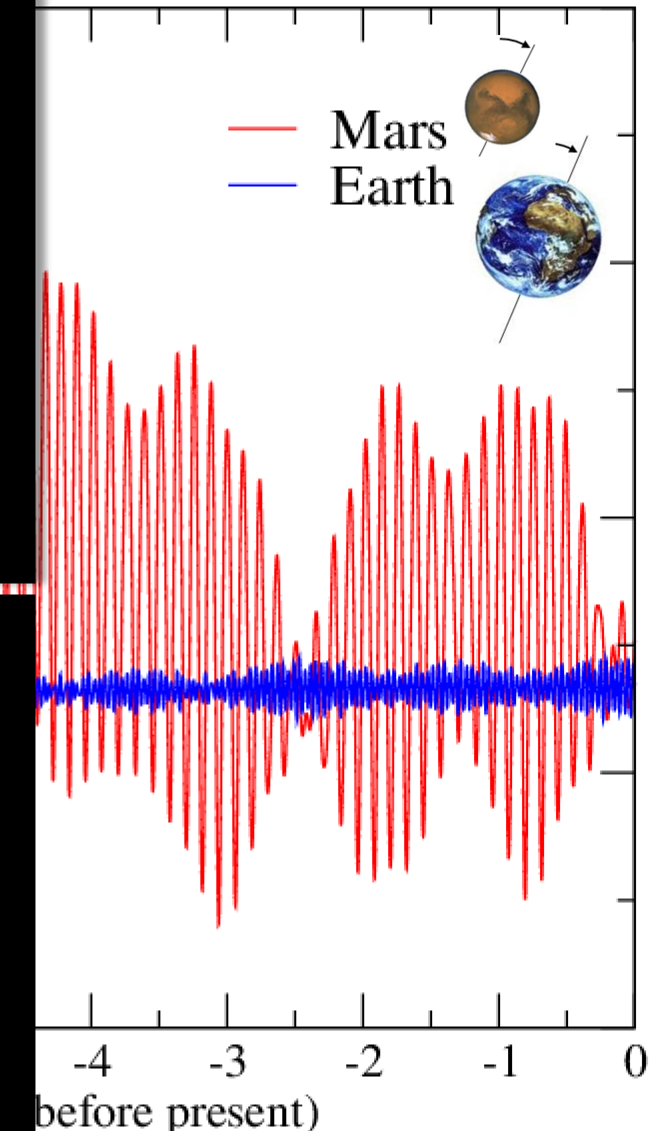


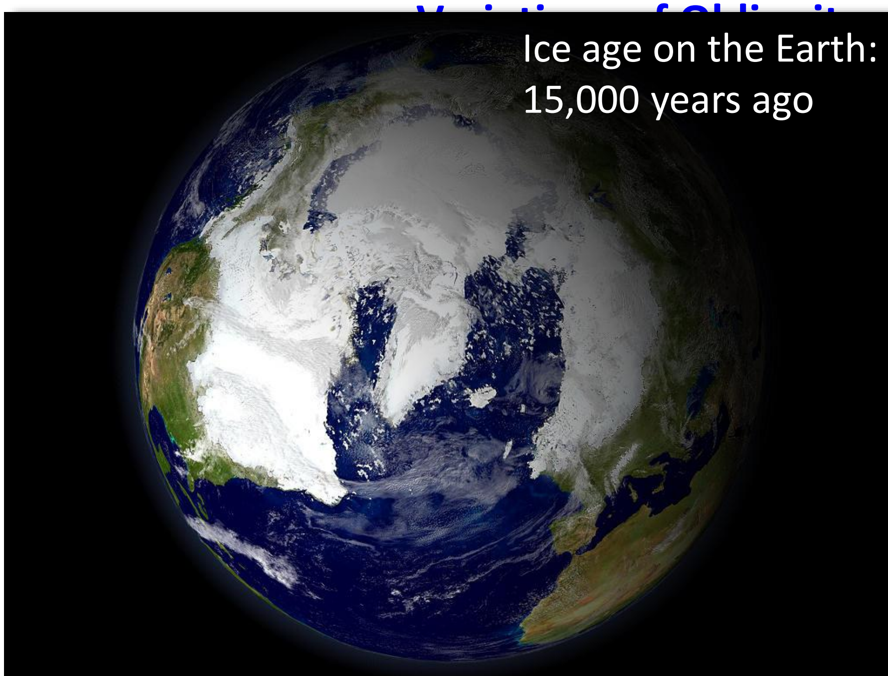
## Variations of Obliquity on Mars




***Laskar and Robutel (1993), Touma and Wisdom (1993), Laskar (2004)***

# Variations of Obliquity on Mars





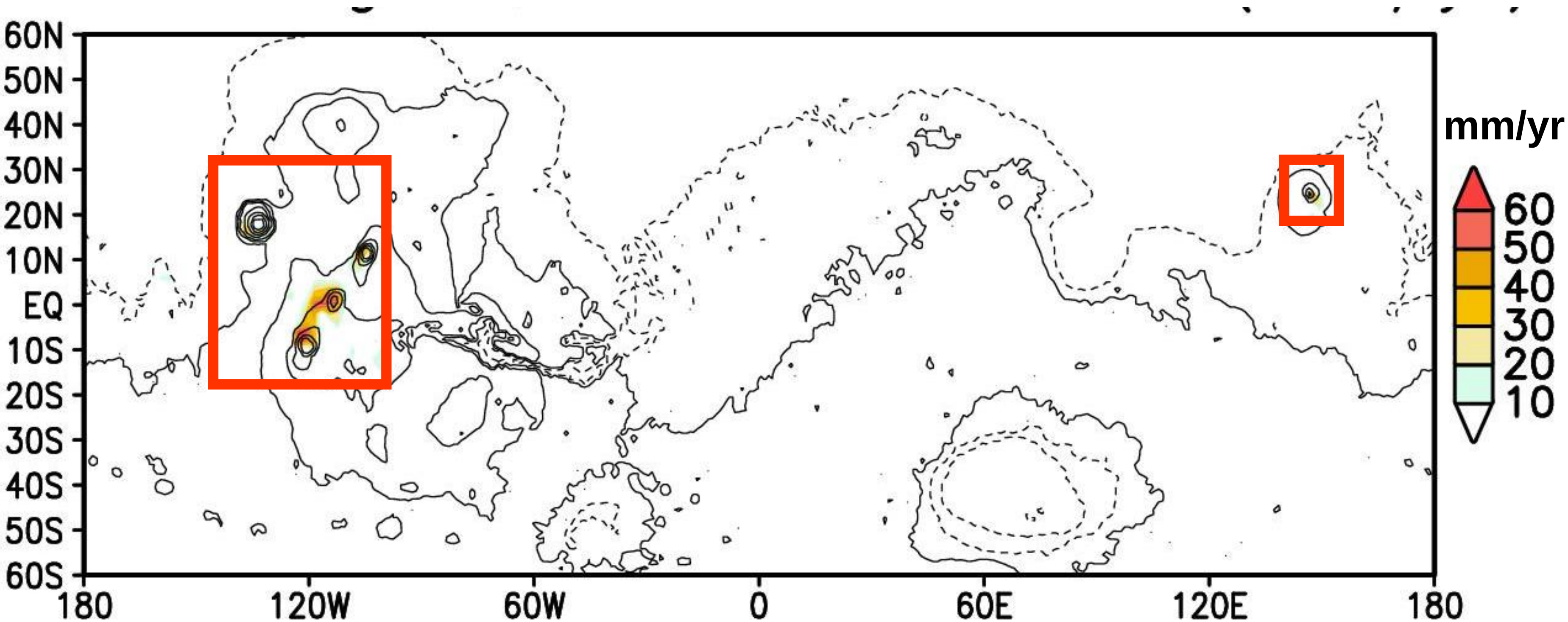
*Laskar and Robutel (1993), Touma and Wisdom (1993), Laskar (2004)*

# Ice accumulation rate (mm/yr)

**high resolution simulation (2°x2°)**

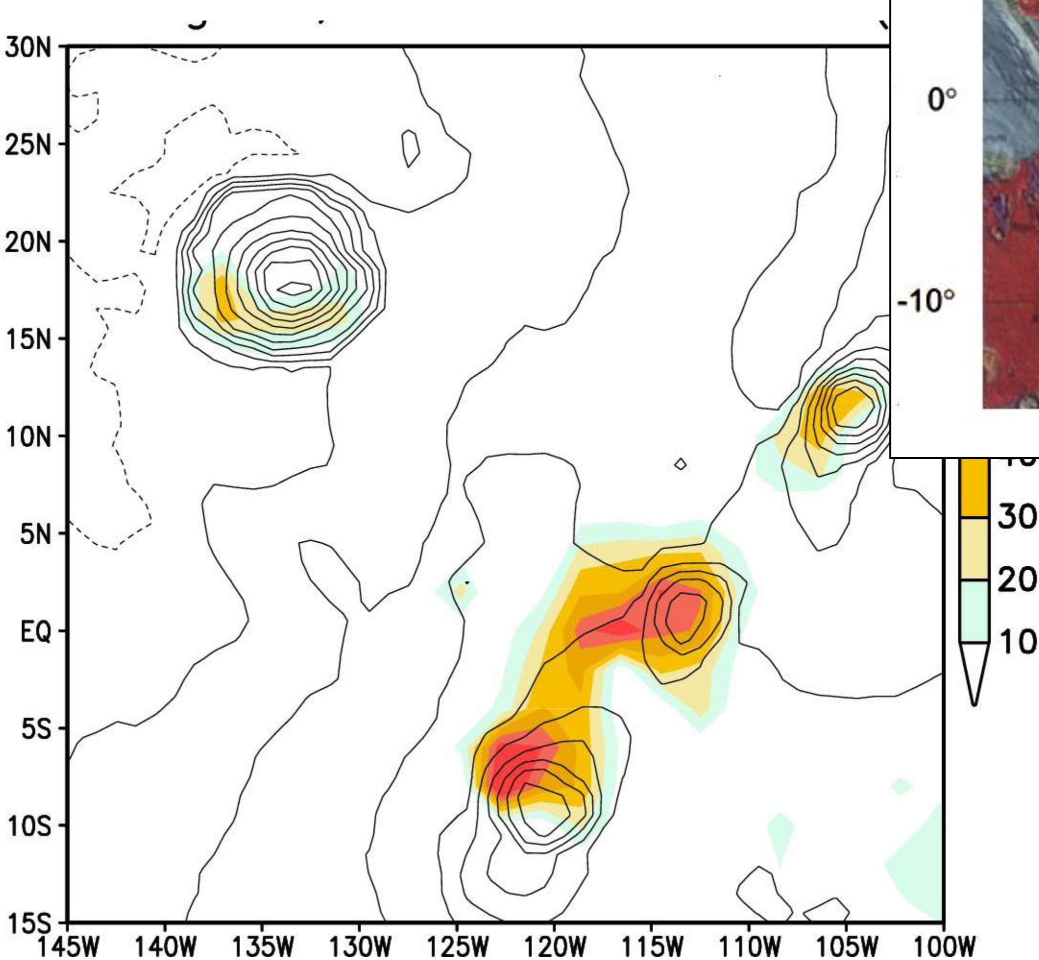
**Obliquity = 45° , Excentricity = 0, Dust Opacity =0.2**

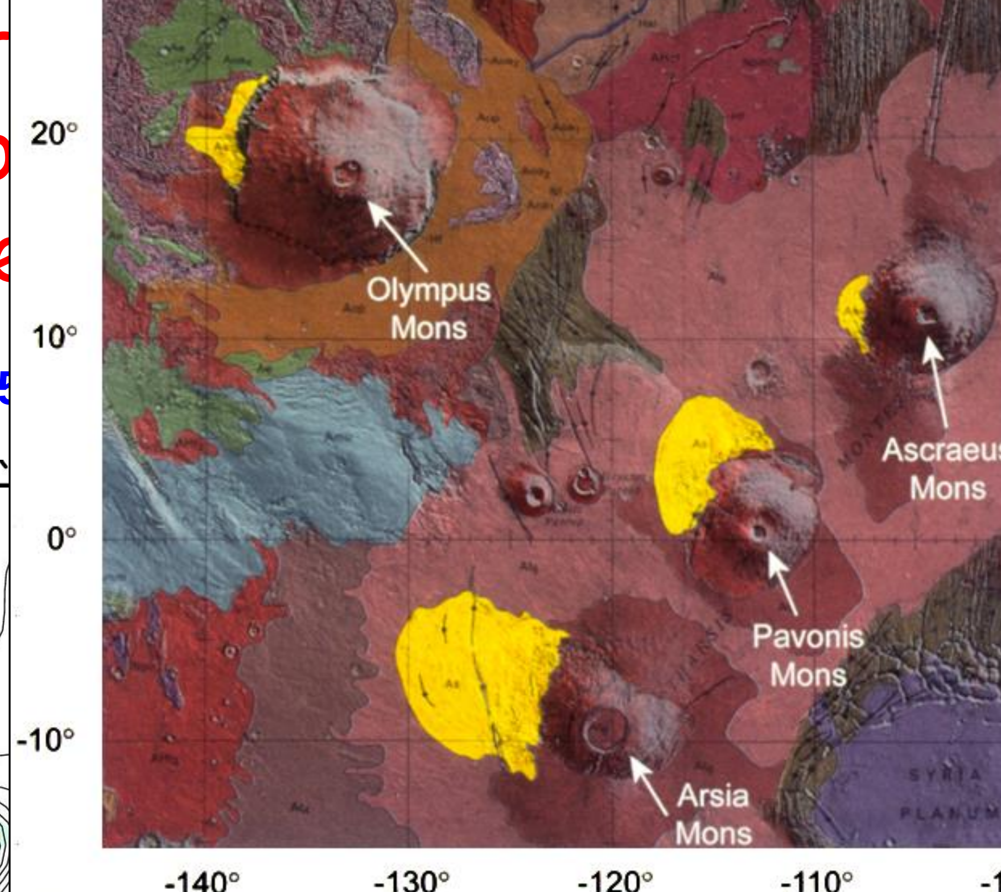
***Forget et al. Science 311, p368, 2006***



# The format
# accumulatio
# very high re

**Forget et al. 2006: Obliquity = 45**

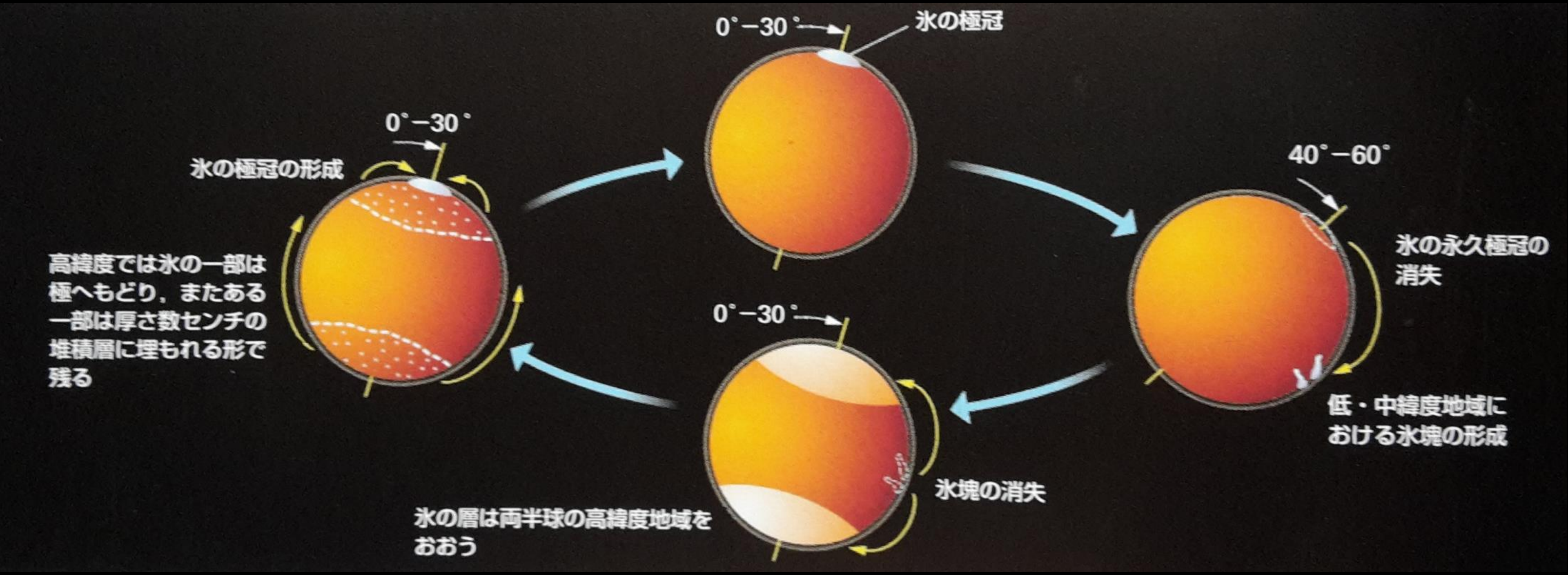


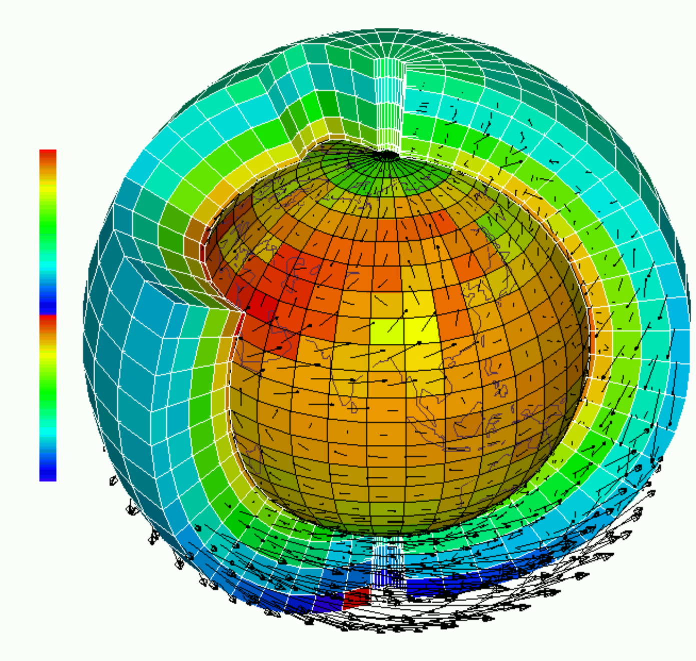

- **Fan shaped deposits, drop moraines characteristic of cold based glaciers.**
- **Rock glaciers**

***Lucchitta 1981, Head et al. 2003, Shean et al. 2005, 2007, Head et al. 2005, Kadish et al. 2008, Schon and Head 2012***

# The climates of planet Mars controlled by a chaotic obliquity

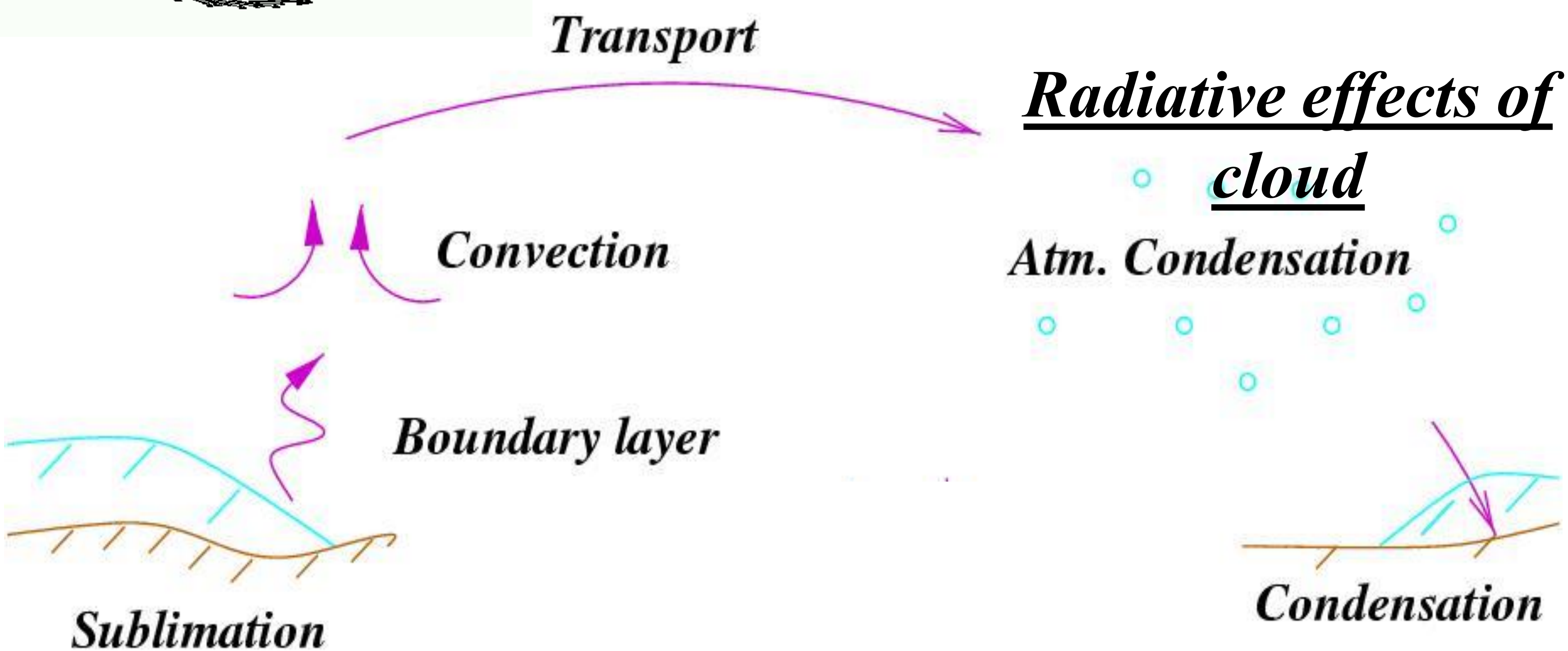



*Forget et al. 2008*



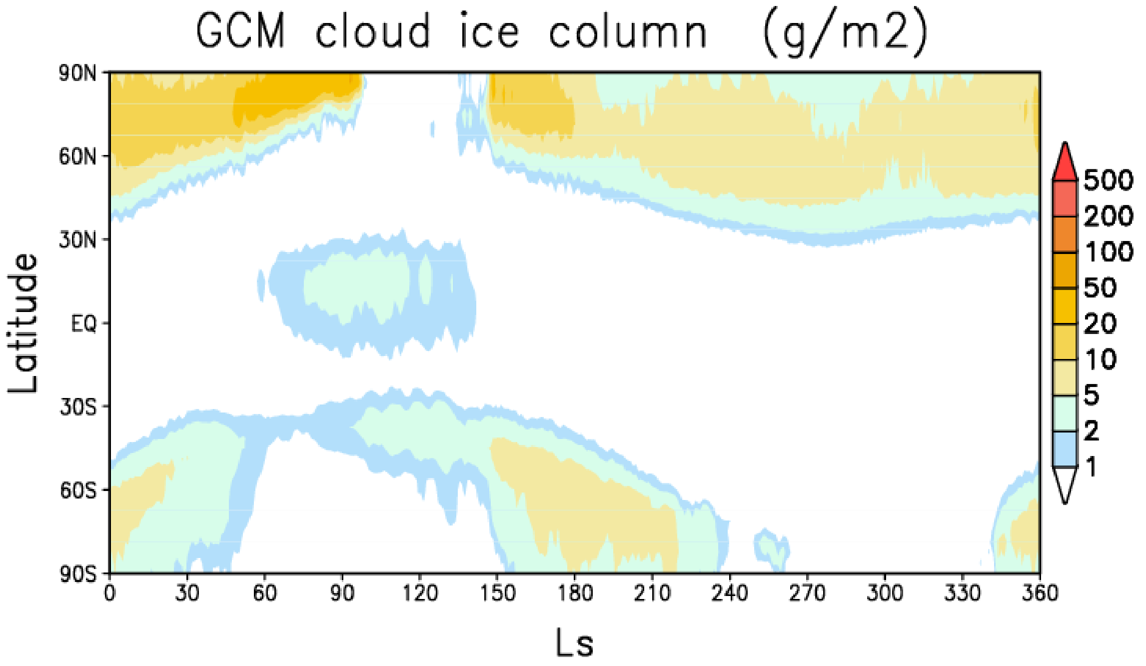
# Modelling Mars water cycle with the LMD Mars Global Climate Model

*Forget et al. 1999, ontmessin et al. 2004, Forget et al. 2008*
*Madeleine et al. 2012, Navarro et al. 2014*

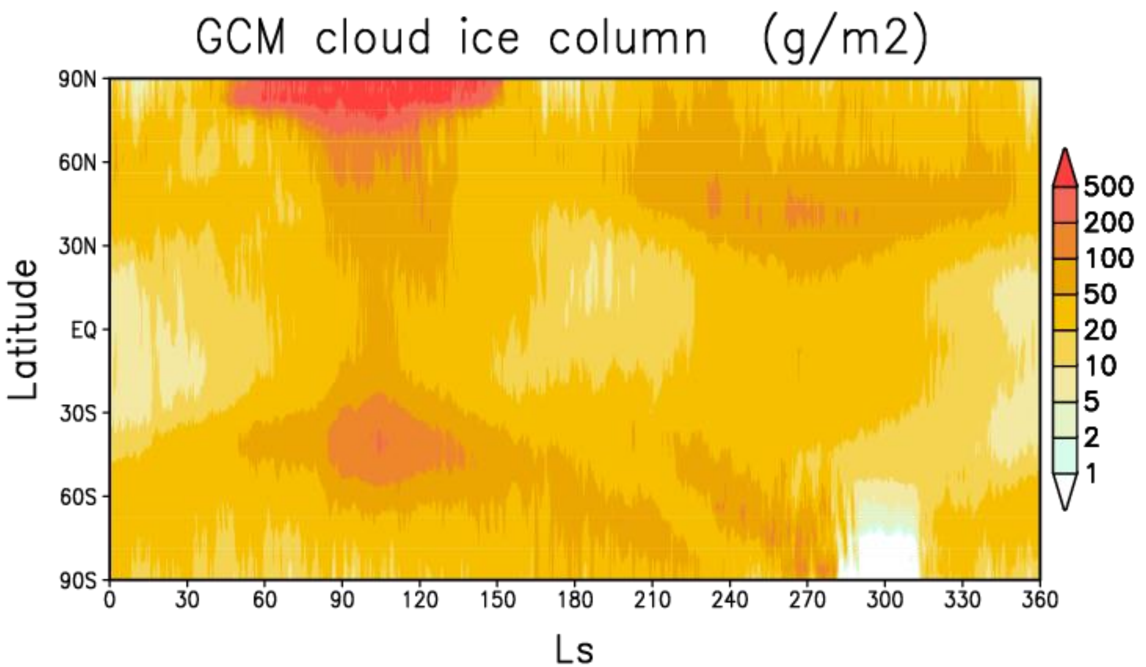


**LMD GCM**
(with radiatively active clouds)

Present day Mars
(obliquity = 25.2° )

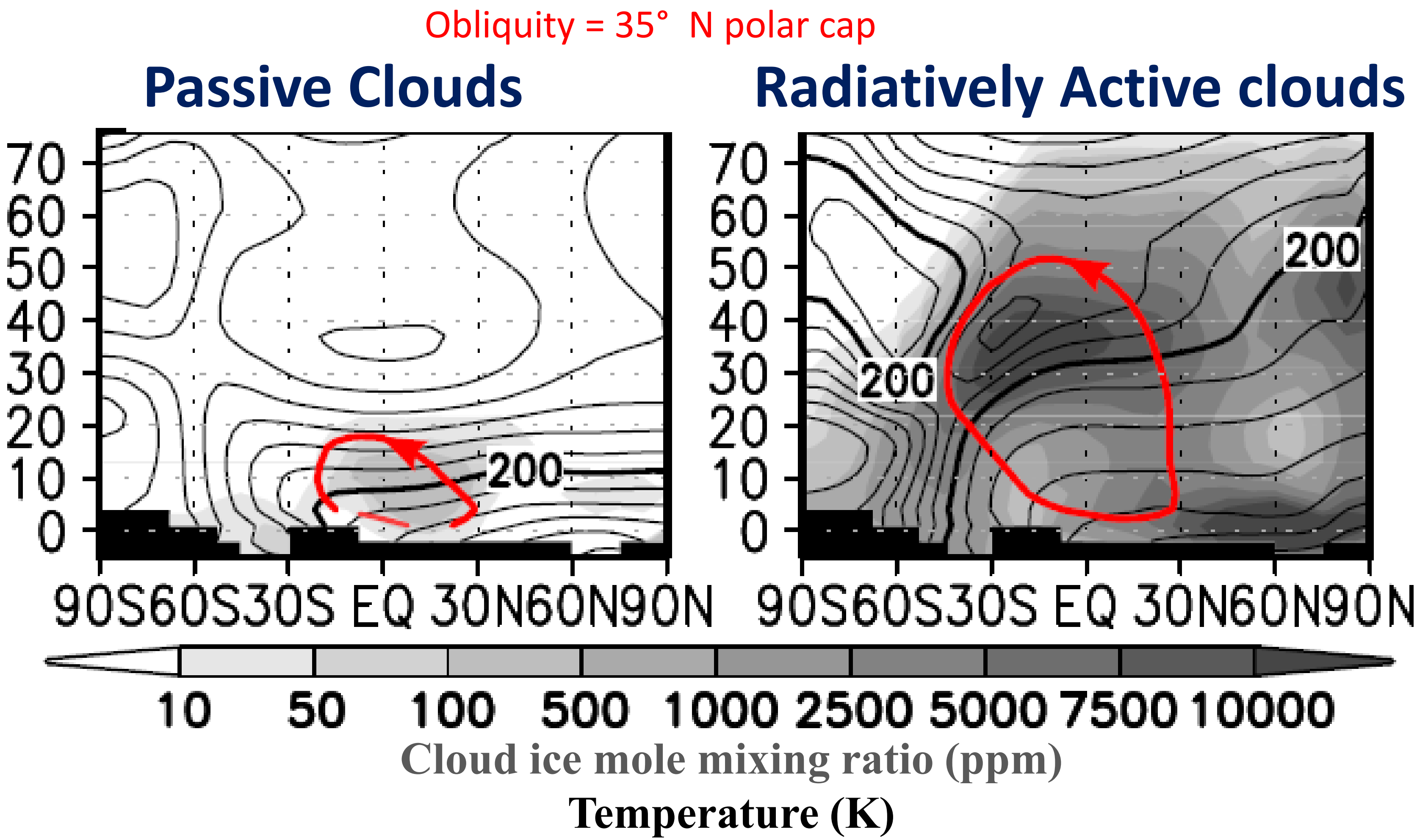



Same Mars but with
obliquity = 35°



## Radiatively active clouds warm the atmosphere

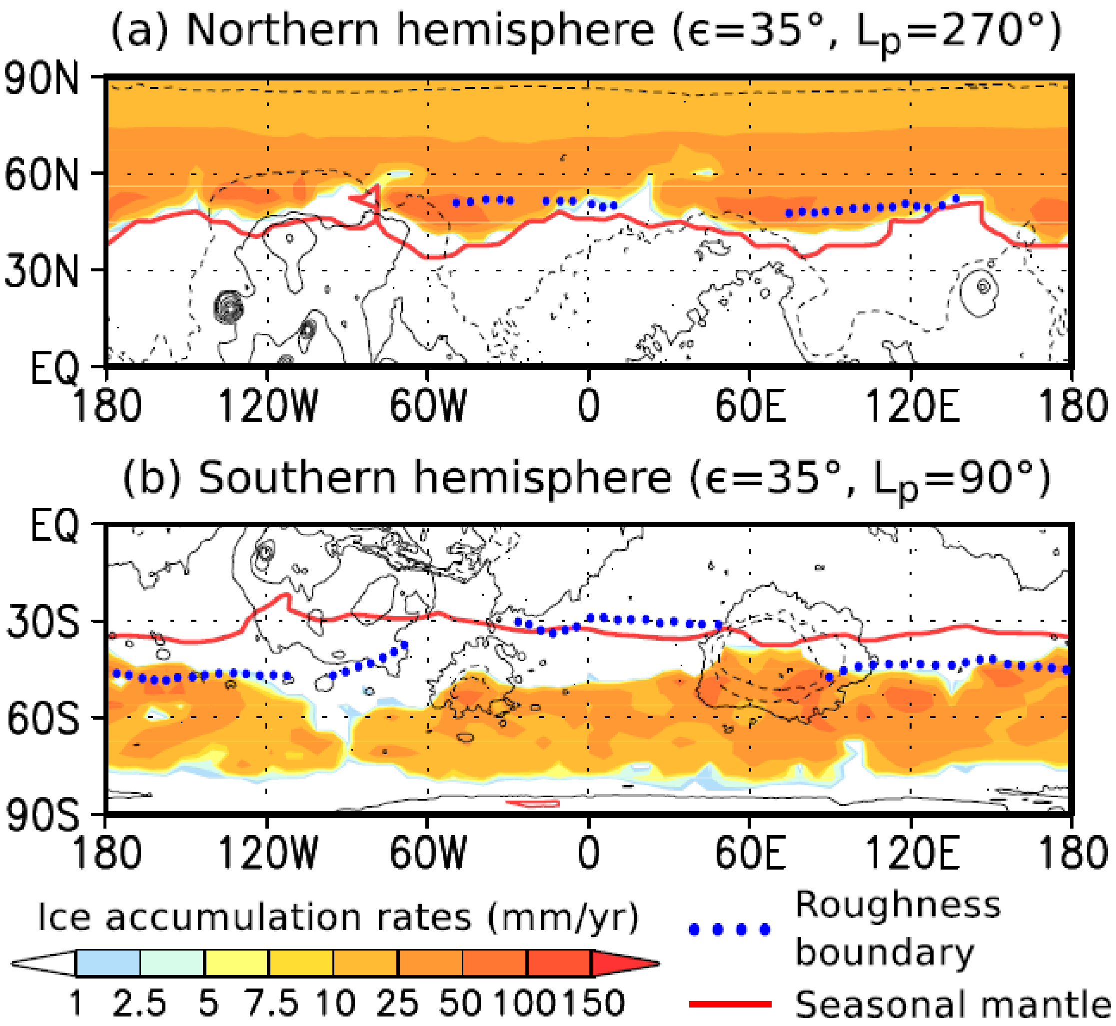
⇨ Much more intense water cycle (more water vapor)
⇨ More clouds (positive feedback)
⇨ More precipitations !




*Madeleine et al. GRL 2014*

Radiatively active clouds simulations, obliquity = 35° , excentricity = 0.1

**Low snow albedo = 0.4, but dust storm during summer**

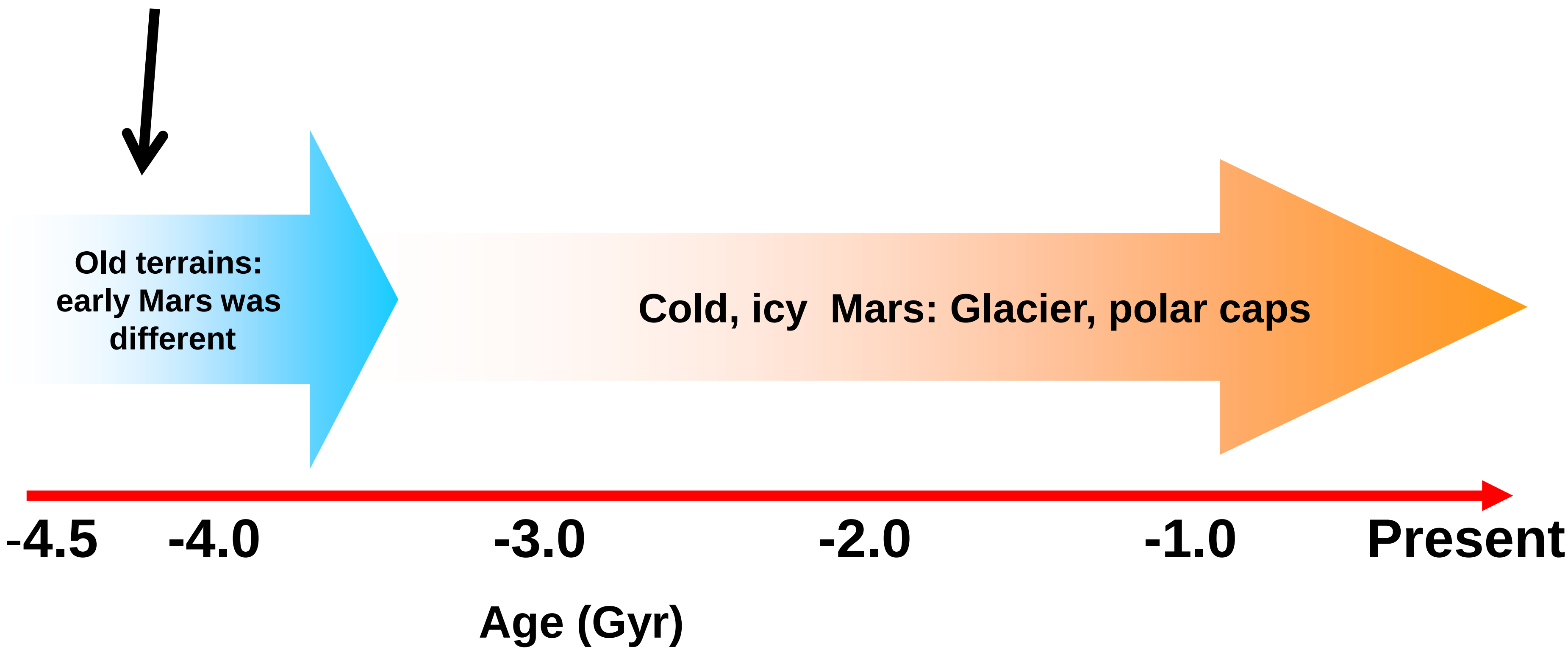


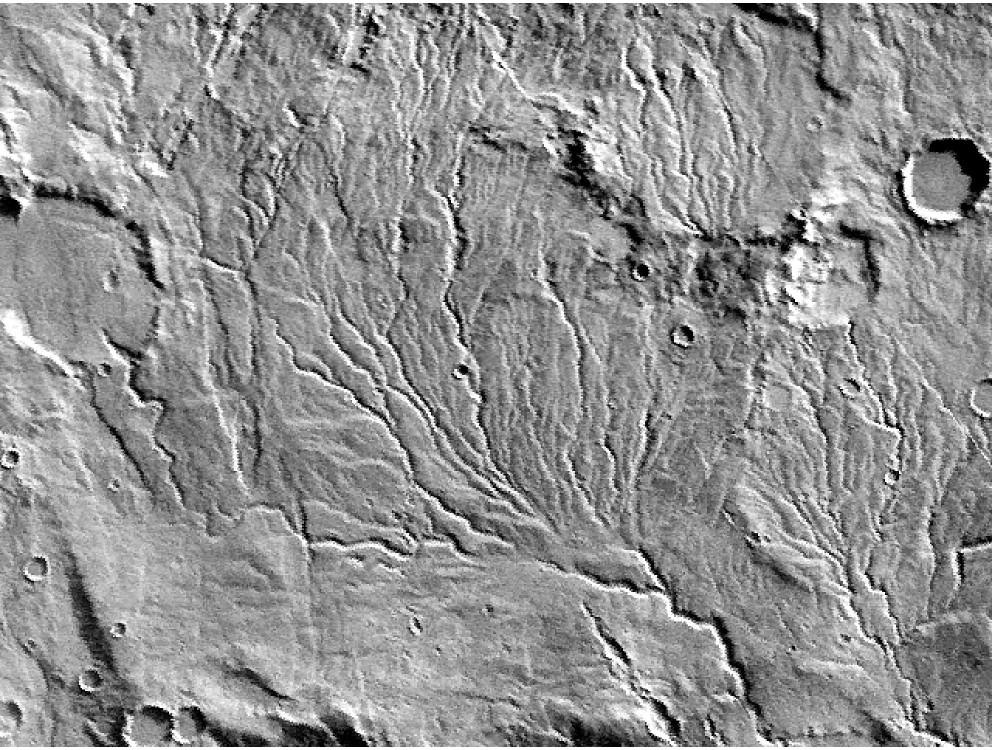

*Madeleine et al. GRL 2014*

# Evolution of the Martian Climate

過去の火星気候のなぞ

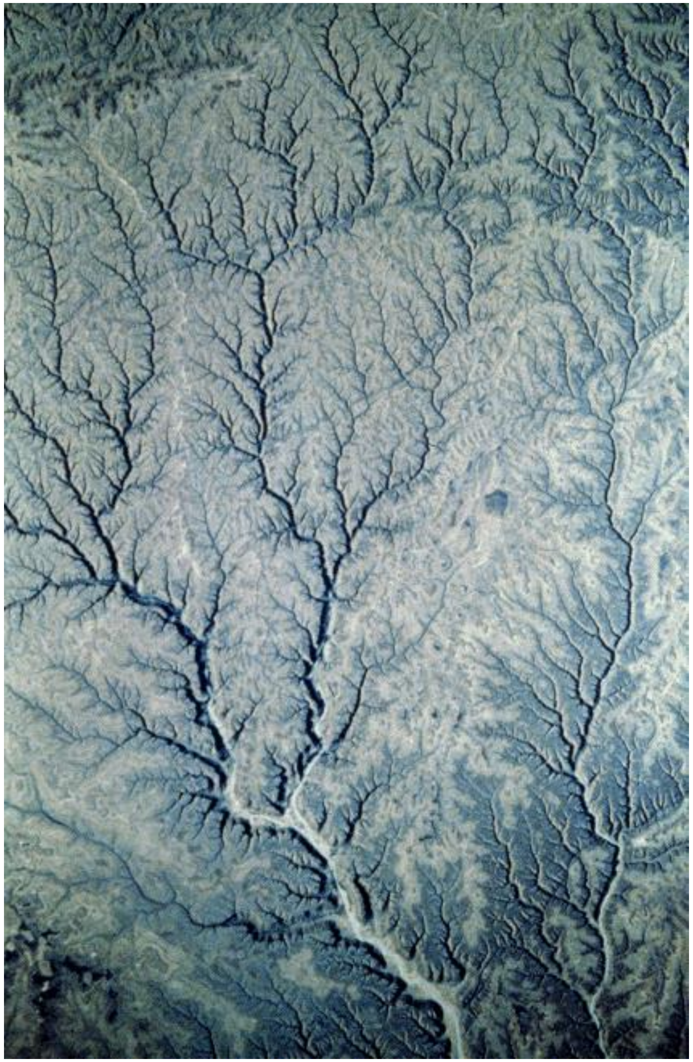
まだ若く弱々しかった太陽と火星の気候





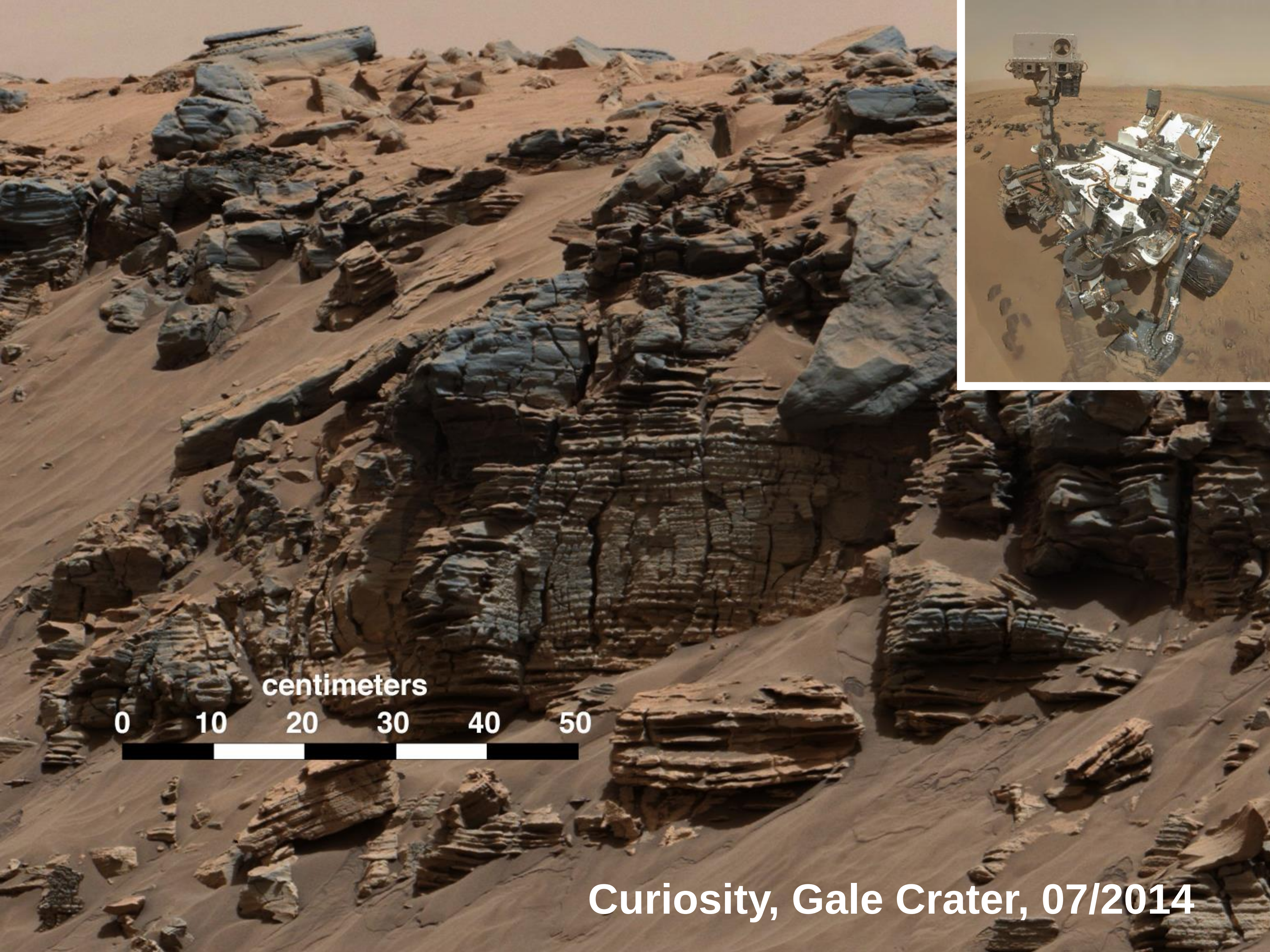
**MARS** : Warrego Vallis

150 km

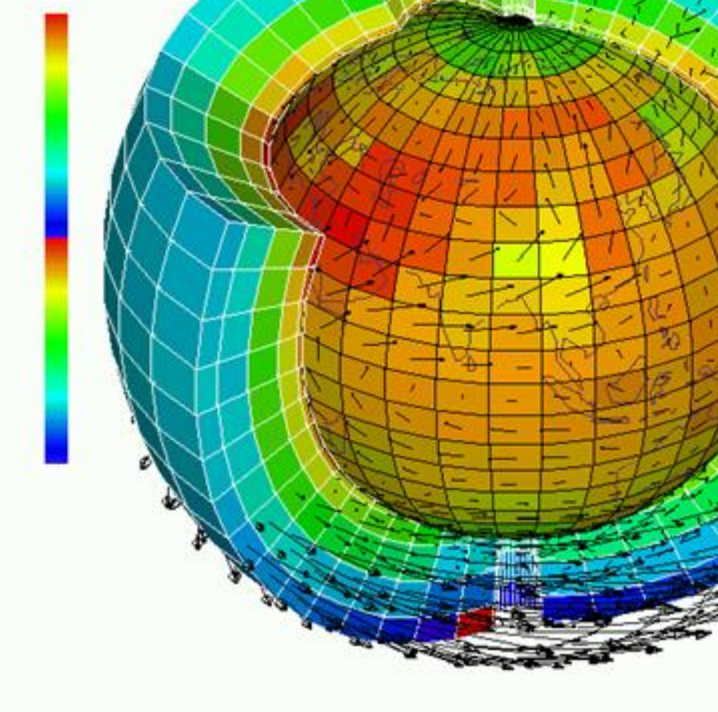


**EARTH**

(Yemen ; same scale)

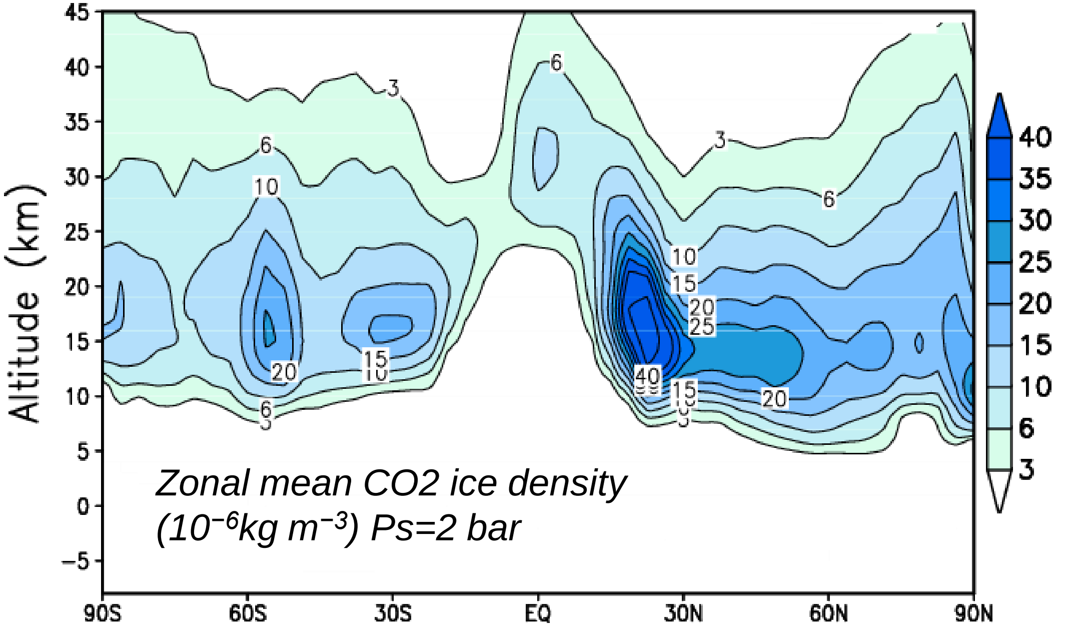

centimeters
0 10 20 30 40 50
Curiosity, Gale Crater, 07/2014

# A 3D Global Climate Model (GCM) for early Mars



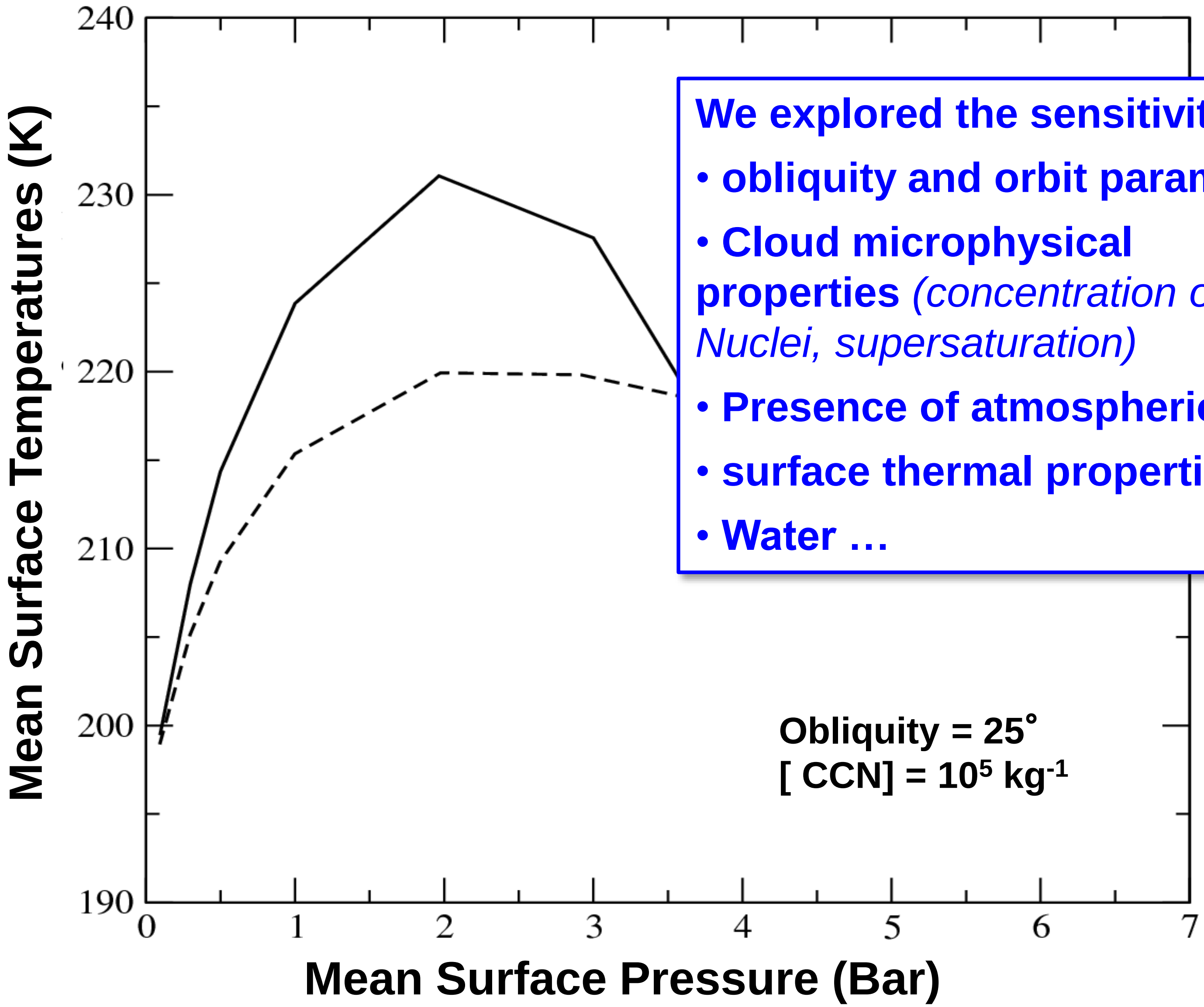
- **LMDZ grid point dynamical core,**
  - 64x48 or 32x32 grid points
  - 15 layers
- **New radiative transfer core:**
  - Correlated-k for the gaseous absorption
  - Toon et al. (1989) two-stream method for the aerosols

- **Simple parametrisation of CO2 cloud microphysics** : condensation, nucleation, transport, sedimentation
  (fixed CCN distribution, but variable mean cloud particle sizes)




*Zonal mean CO2 ice density ($10^{-6}$kg $m^{-3}$) Ps=2 bar*

# Global mean surface temperature (K)

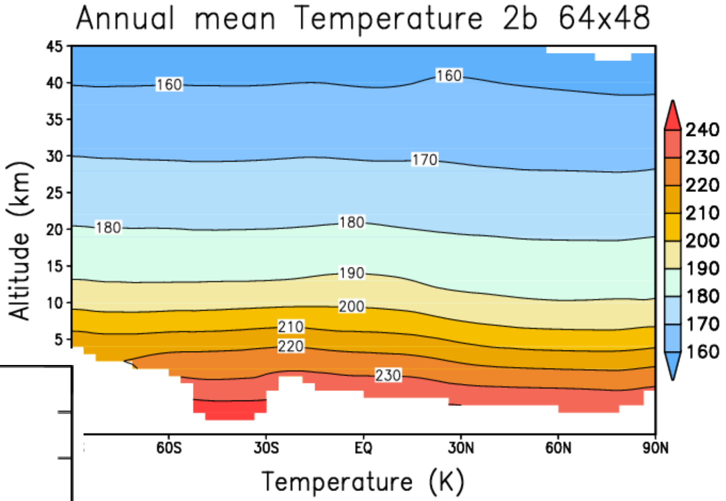


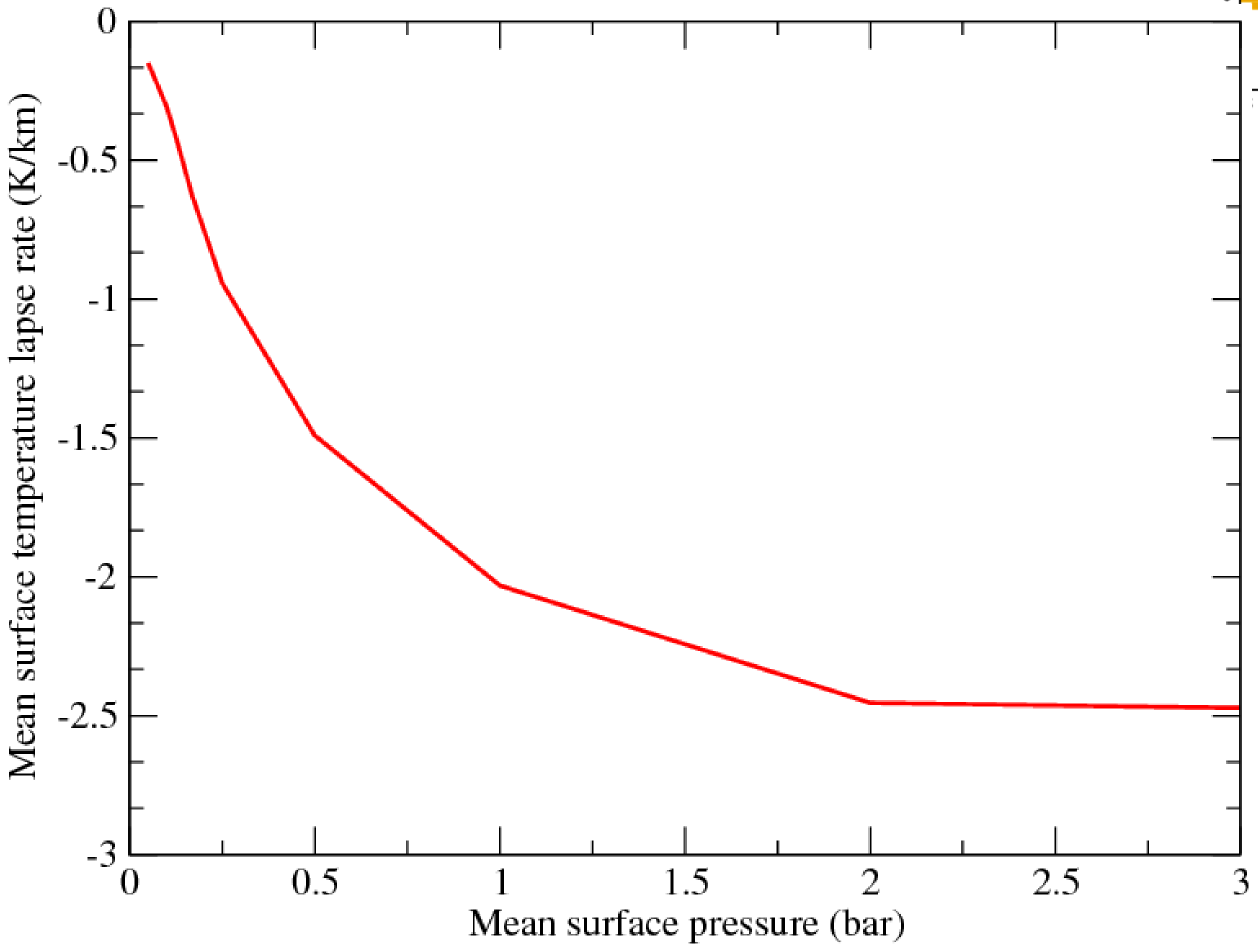

**We explored the sensitivity to**

- **obliquity and orbit parameters**
- **Cloud microphysical properties** *(concentration of Nuclei, supersaturation)*
- **Presence of atmospheric dust**
- **surface thermal properties**
- **Water …**

*Forget et al. 2012, Wordswoth et al. 2013, Kerber et al. 2015*

# Influence of pressure on surface temperature evolution with topography

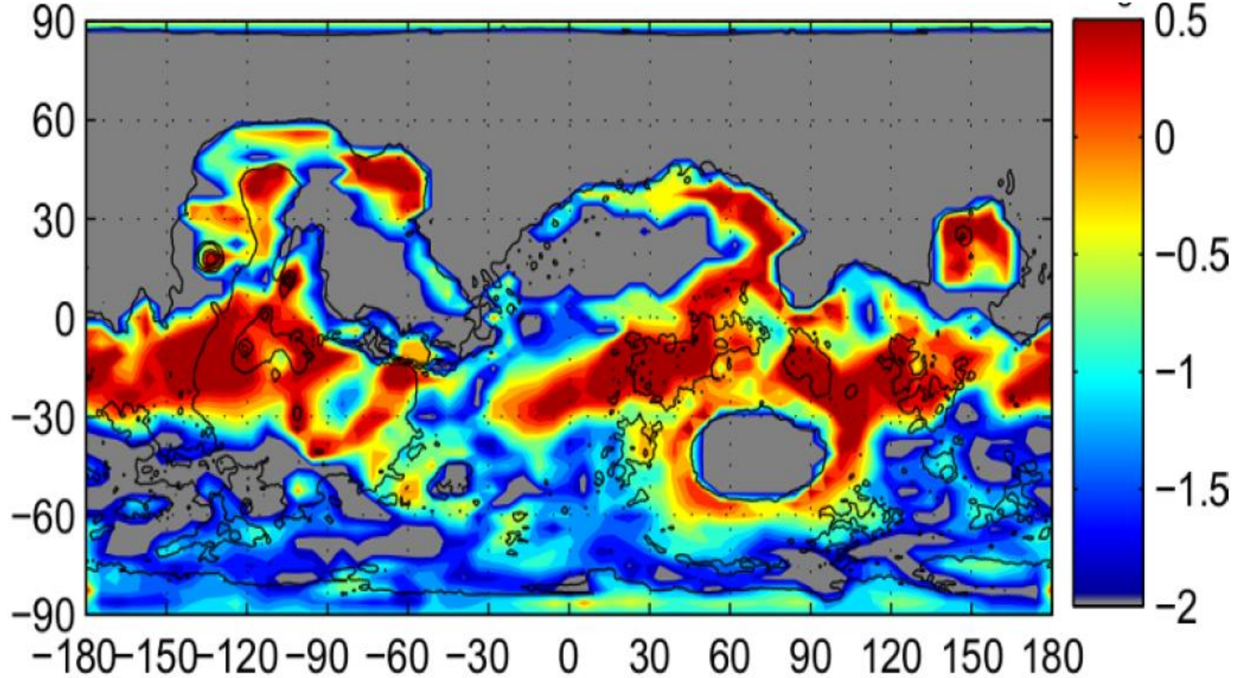



*Forget et al. 2013*

# The Icy Highland Scenario

**Map of Modeled Annual snow ice accumulation P=0.6 bar, ob=41.8°**
*(Wordsworth et al. 2015)*




**Valley Network drainage density**
*(Hynek et al.,2010)*