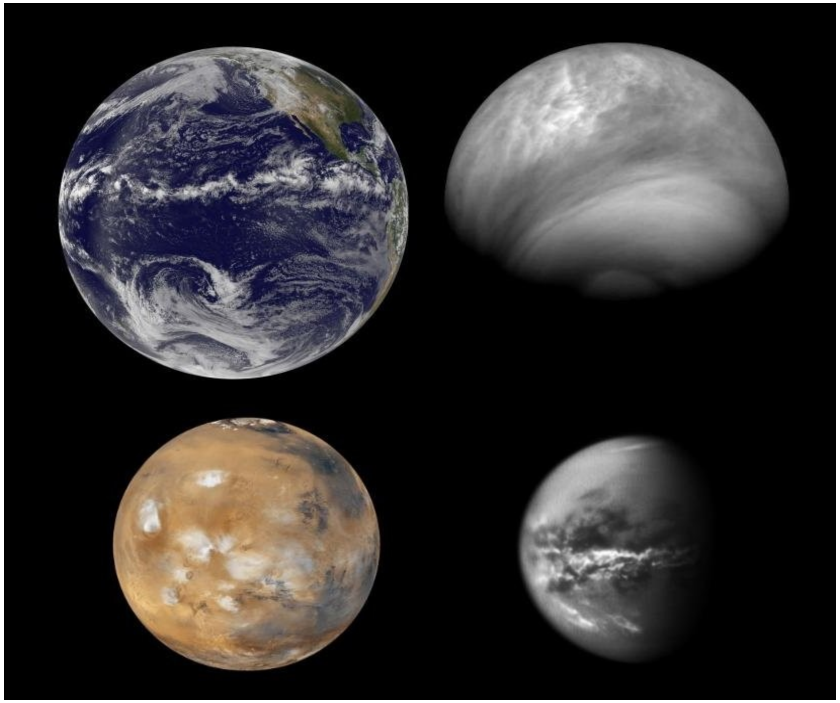
PLANETARY ATMOSPHERES

4. Global Climate Modeling



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PLANETARY ATMOSPHERES

Global Climate Modeling

- Virtual planets
- Different models for different scales
- Successes, and lessons from failure

Forget F. and Lebonnois S., « Global climate models of the terrestrial planets »
Comparative Climatology of the Terrestrial Planets, S.J. Maxwell et al. Eds.
University of Arizona, Tuscon, 2013

PLANETARY ATMOSPHERES

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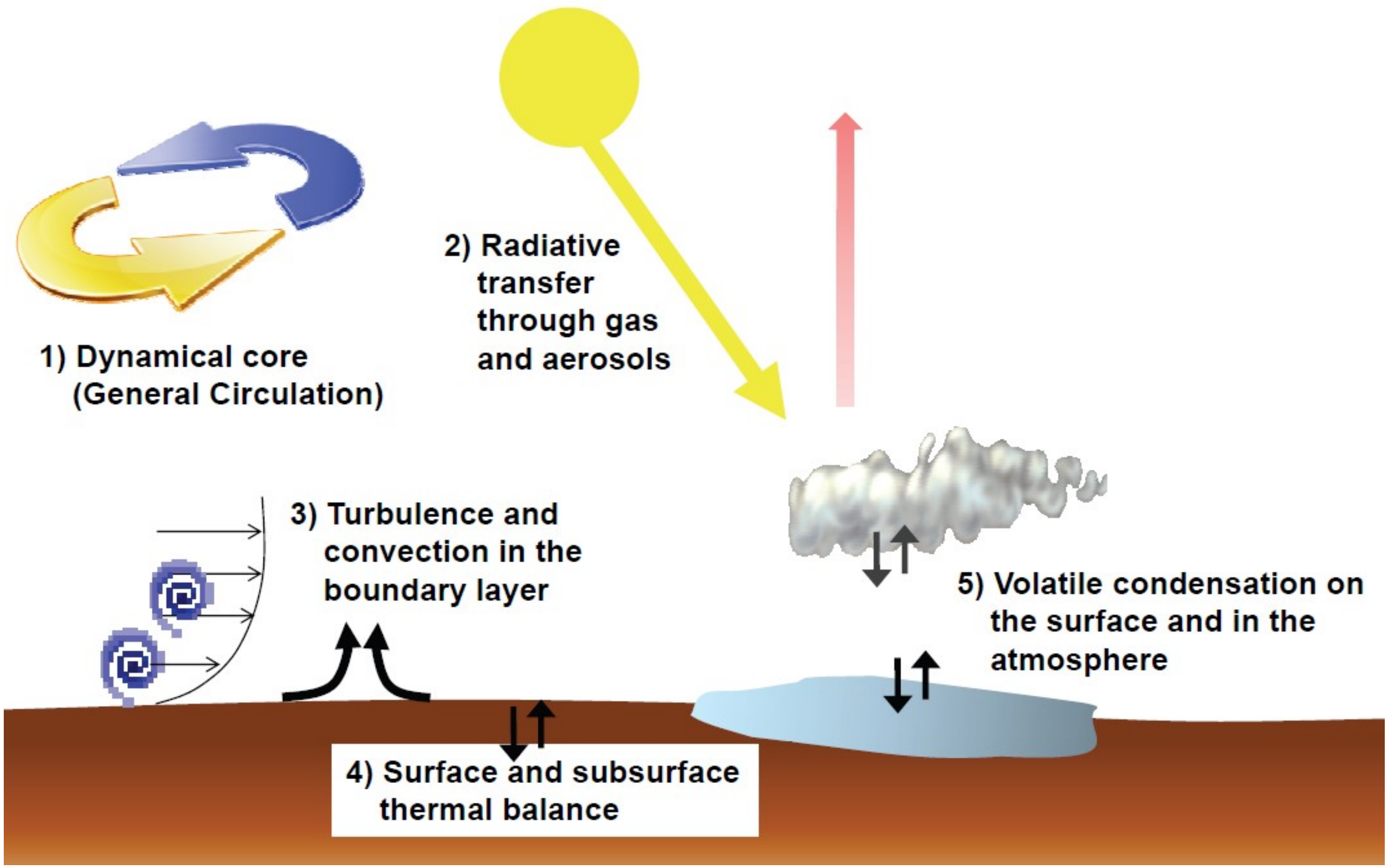
GCM : General Circulation Models

First GCMs were designed in late 50's, early 60's

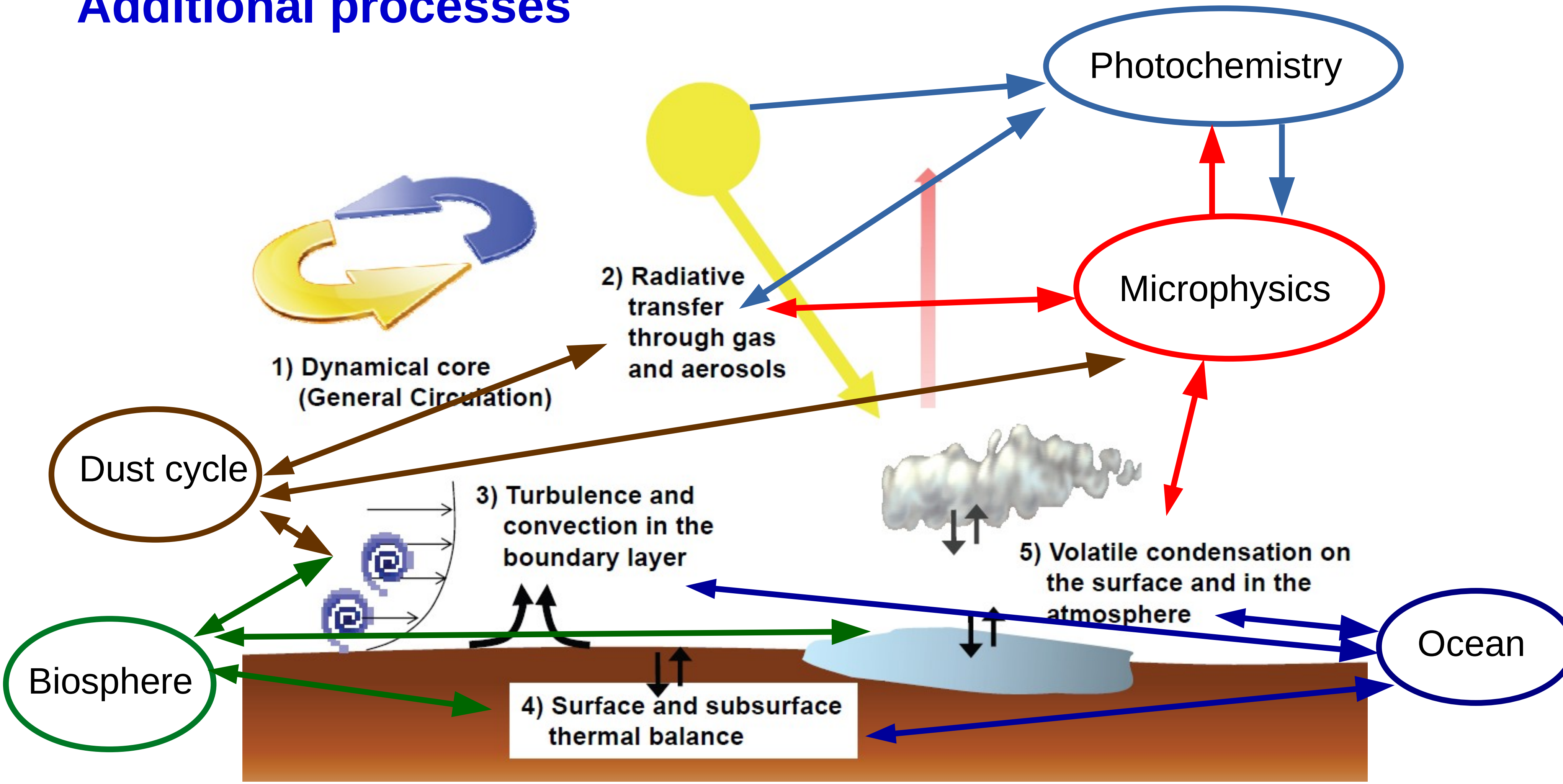
Design : mandatory bricks



GCM : Global Climate Models

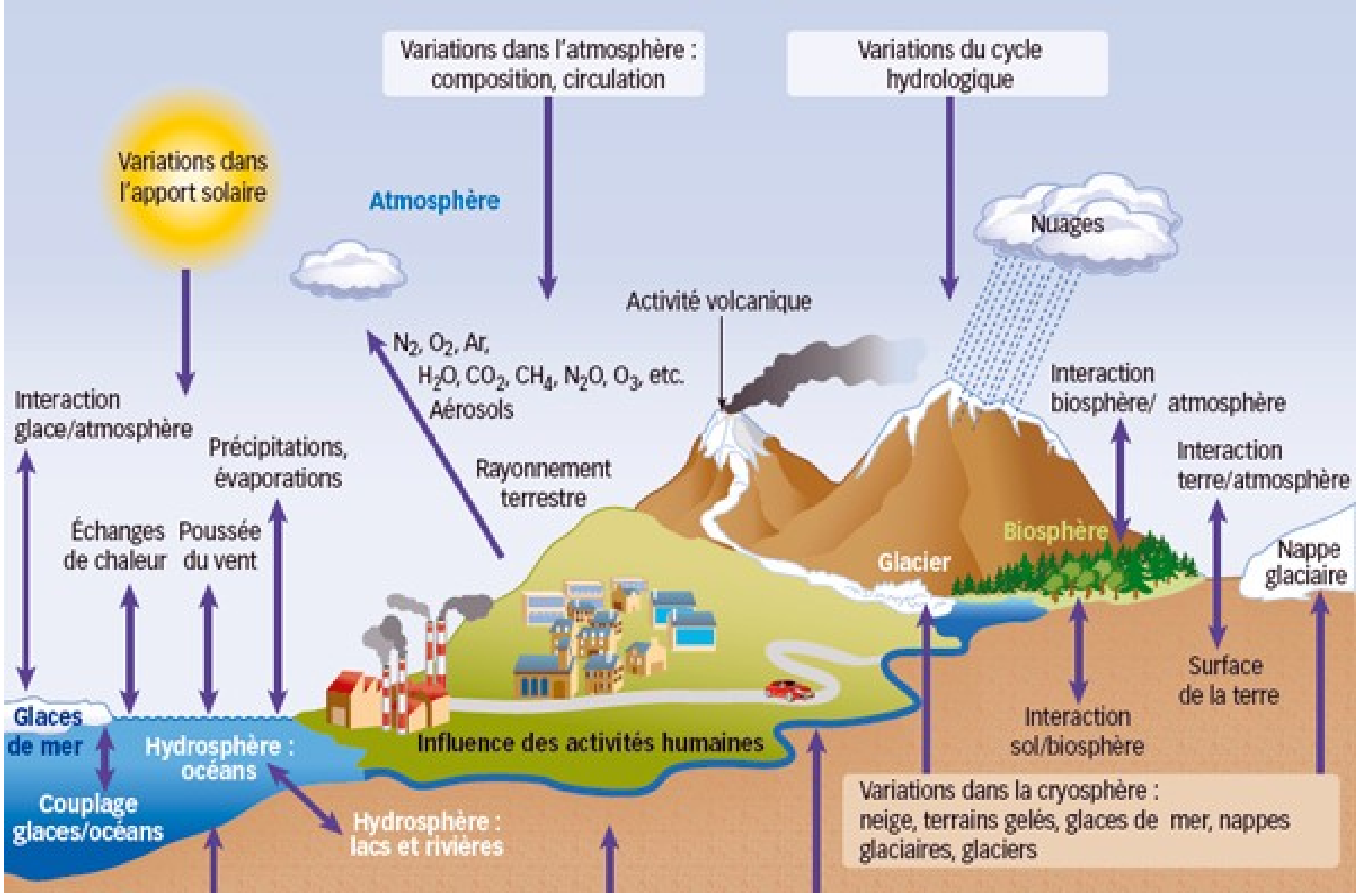
Because an atmosphere is a complex, coupled system

Additional processes



GCM : Global Climate Models

Earth



The dynamical core

6 equations

- 6 variables, dynamical and thermodynamical
- Forcings and planetary constants

Zonal momentum

$$\frac{du}{dt} - \frac{uv\tan\phi}{a} = 2\Omega\sin\phi\, v - \frac{1}{\rho}\frac{\partial p}{\partial x} + F_u$$

Meridional momentum

$$\frac{dv}{dt} + \frac{u^2\tan\phi}{a} = -2\Omega\sin\phi\, u - \frac{1}{\rho}\frac{\partial p}{\partial y} + F_v$$

Hydrostatic balance

$$-\frac{1}{\rho}\frac{\partial p}{\partial z} - g = 0$$

Mass conservation

$$\frac{\partial \rho}{\partial t} + \mathrm{div}\,(\rho\mathbf{V}) = 0$$

First principal of thermodynamics

$$\frac{c_p}{\theta}\frac{d\theta}{dt} = \frac{Q}{T} \quad \text{with} \quad \theta = T\left[\frac{p_0}{p}\right]^{\kappa}$$

Ideal gas equation of state

$$p = \rho R T$$

The dynamical core

Different types of GCM

Hydrostatic vs Quasi-hydrostatic

Shallow atmosphere vs Deep atmosphere

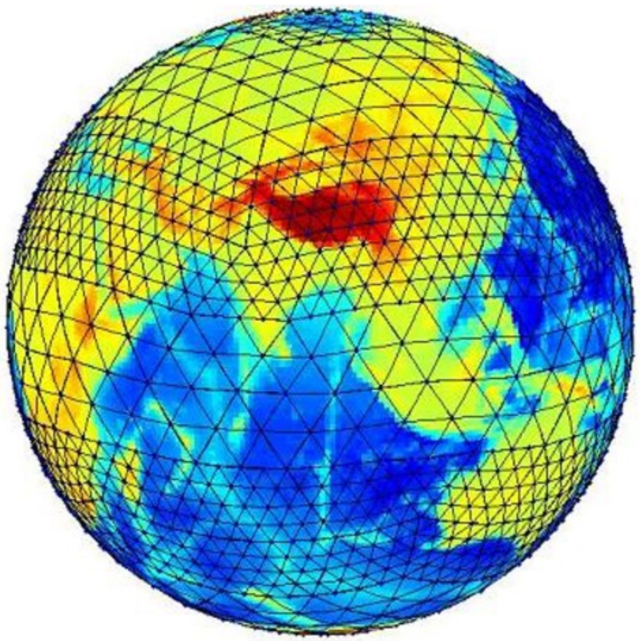
Cp(T), Cp(composition)

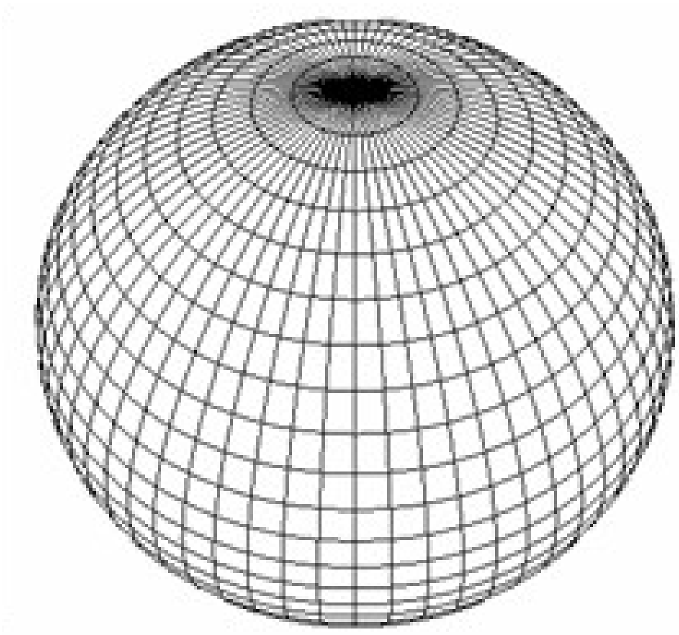
The dynamical core

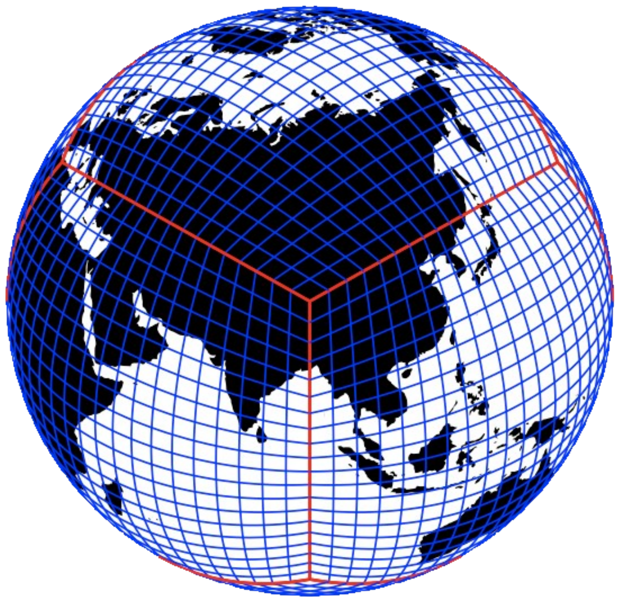
Horizontal discretization

Finite differences, finite volumes

Spectral (spherical harmonics), spectral elements







Vertical discretization : mass, altitude, pressure...

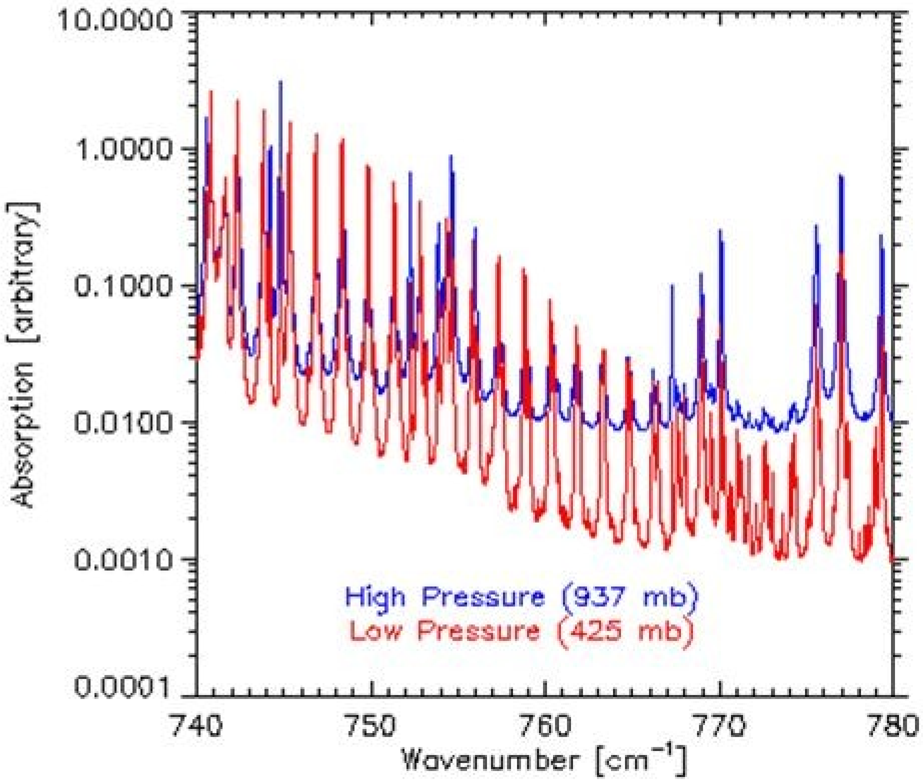
Time marching scheme

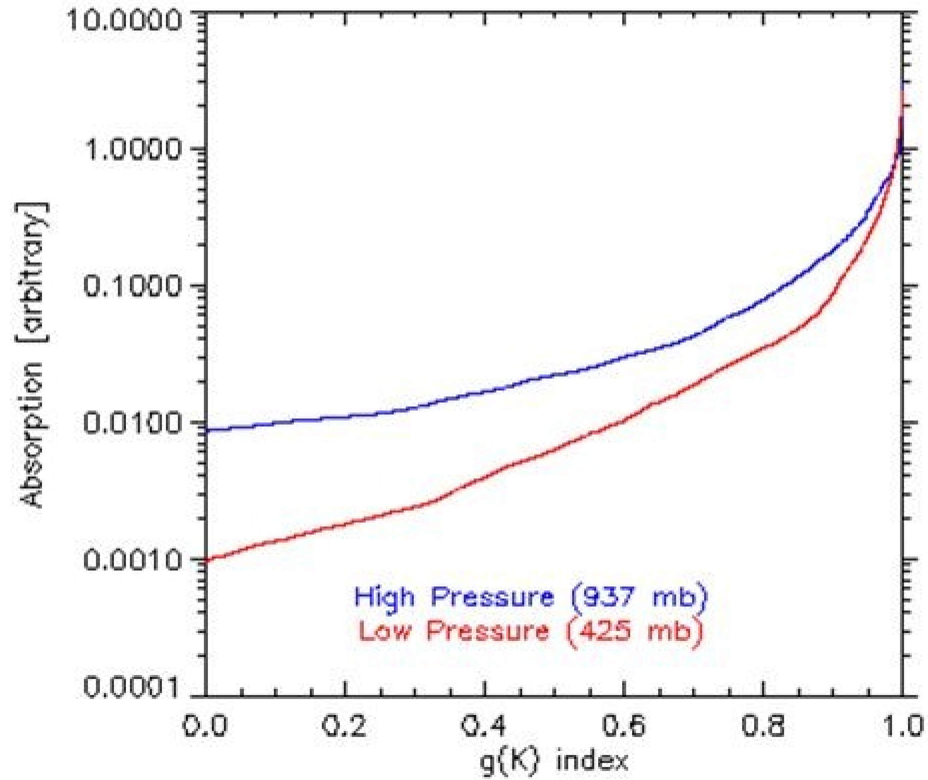
Conservation concerns : mass, energy, angular momentum

The radiative transfer

Strategy : fast computation ; versatility

Usual approach to gas opacities : correlated-k distribution





Physics processes

Table 1: Summary of key processes and related problems in low atmosphere terrestrial planet global climate models.

Key physical processes	Earth	Mars	Venus	Titan	Triton/Pluto
Radiative transfer	×	×	Optical thickness[a]	×	×[b]
Clouds	H_2O	H_2O ice, CO_2 ice	H_2SO_4	CH_4, C_2H_6	N_2 ice?
Hazes	Aerosols	Mineral dust		Organic haze	Organic haze?
Turbulence and convection	Near-surface	Near-surface	Cloud layers	Near-surface	Near surface
Subsurface heat storage	With oceans	×	×	×	Long-term buffer[c]
Dominant gas condensation		CO_2			N_2
Minor species condensation	H_2O	H_2O		CH_4, C_2H_6	CH_4 ?
Dynamical core					
Deep atmosphere				×[d]	
Specific heat variations			$C_p(T)$[e]		
Composition variations		×[d]			
Momentum conservation			Critical[d]	Critical[d]	

a: Eymet et al. (2009) ; *b*: Triton's atmosphere N_2 atmosphere is so pure and teneous that gaseous absorption of radiation can be neglected; Molecular conduction then dominate heat transport. (Yelle et al. 1991; Vangvichith et al. 2013). *c*: see section 2.5 ; *d*: see section 2.2 ; *e*: Lebonnois et al. (2010a).

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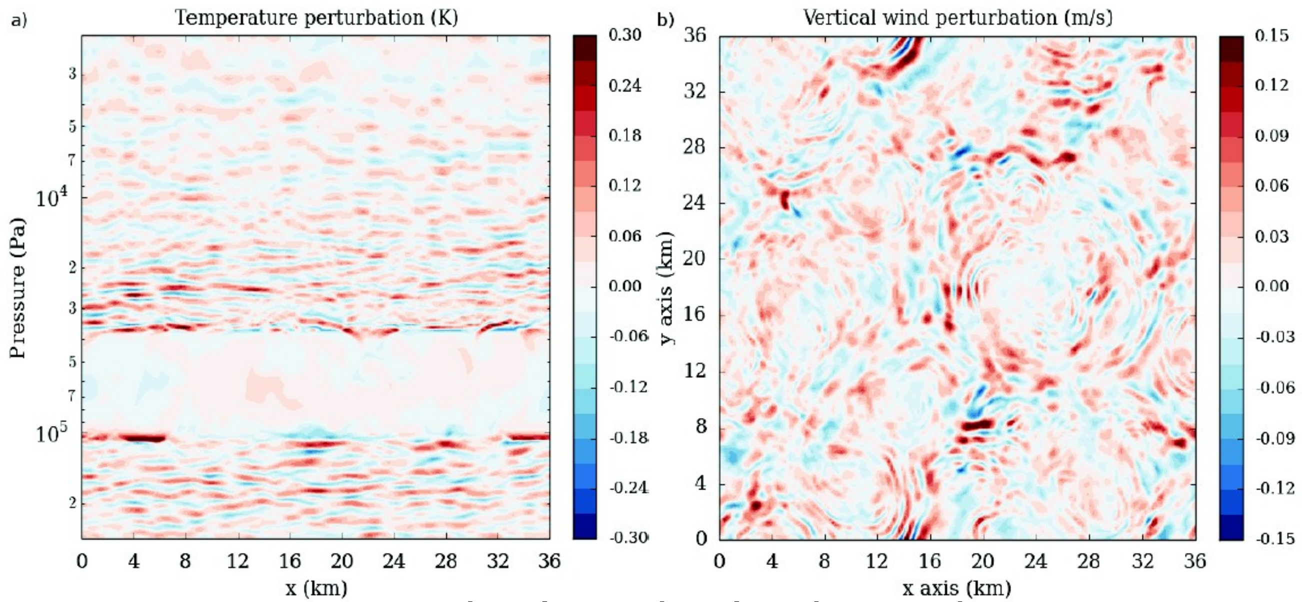
Small-scale processes

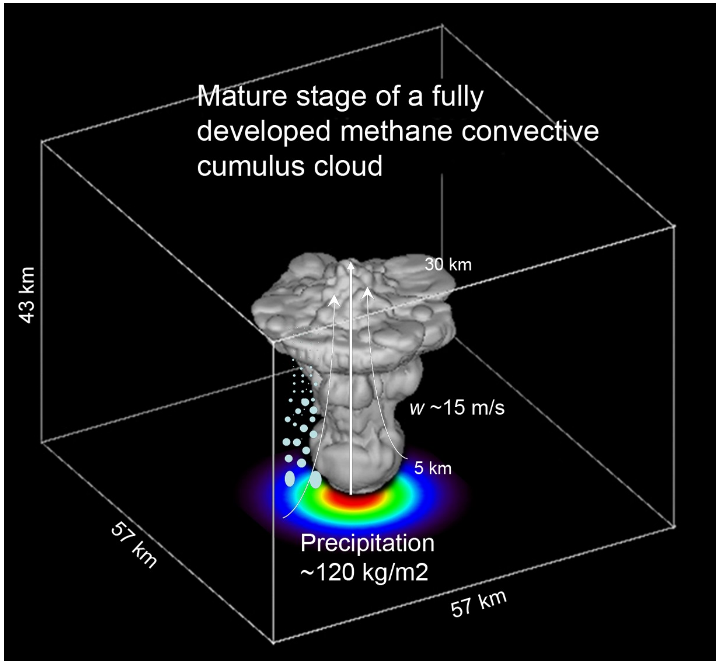
Large Eddy Similations :

small scale (1-1000m), idealized, non-hydrostatic models

=> study small-scale processes :
turbulence, convection
gravity waves



Venus convective layer in cloud : gravity waves



Titan methane convective clouds

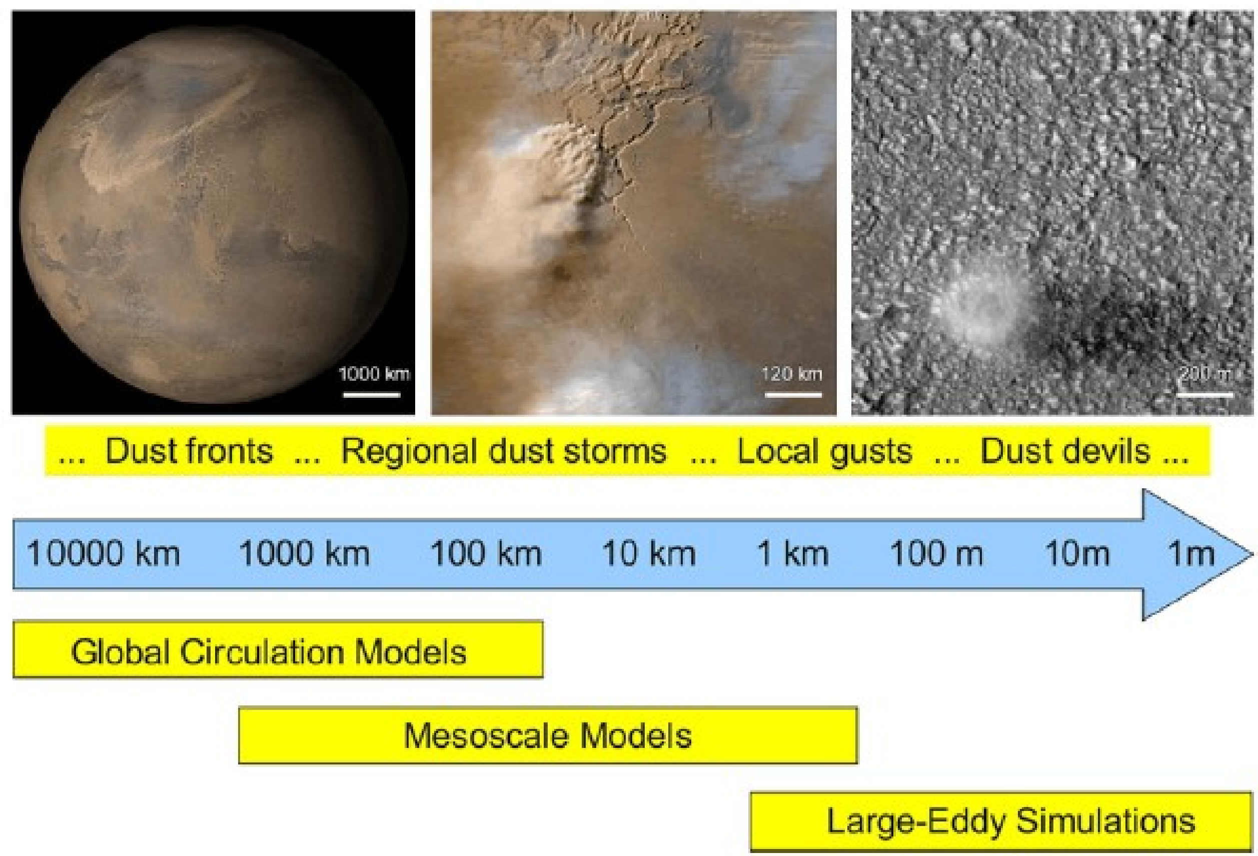
Intermediate-scale processes

Regional Climate Models :

- Intermediate scales => small-scales parameterized

- non-hydrostatic

- boundary conditions from GCMs

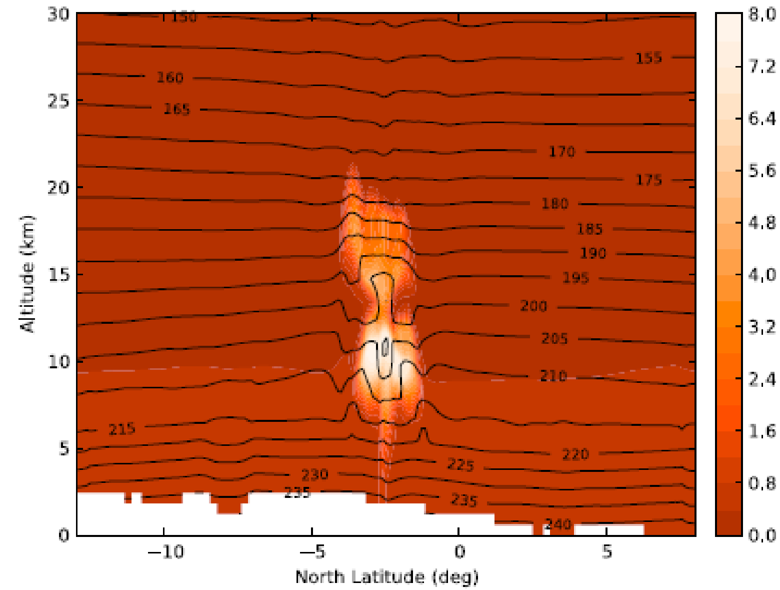


Intermediate-scale processes

Regional Climate Models

Dust optical depth

Temperature

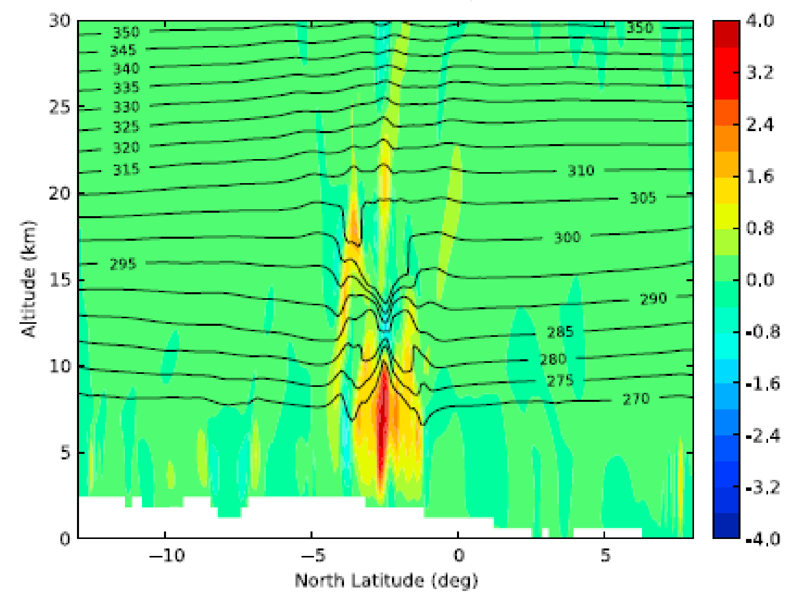


Example : rocket dust storm on Mars

(Spiga et al, 2013)

Vertical wind

Potential temperature



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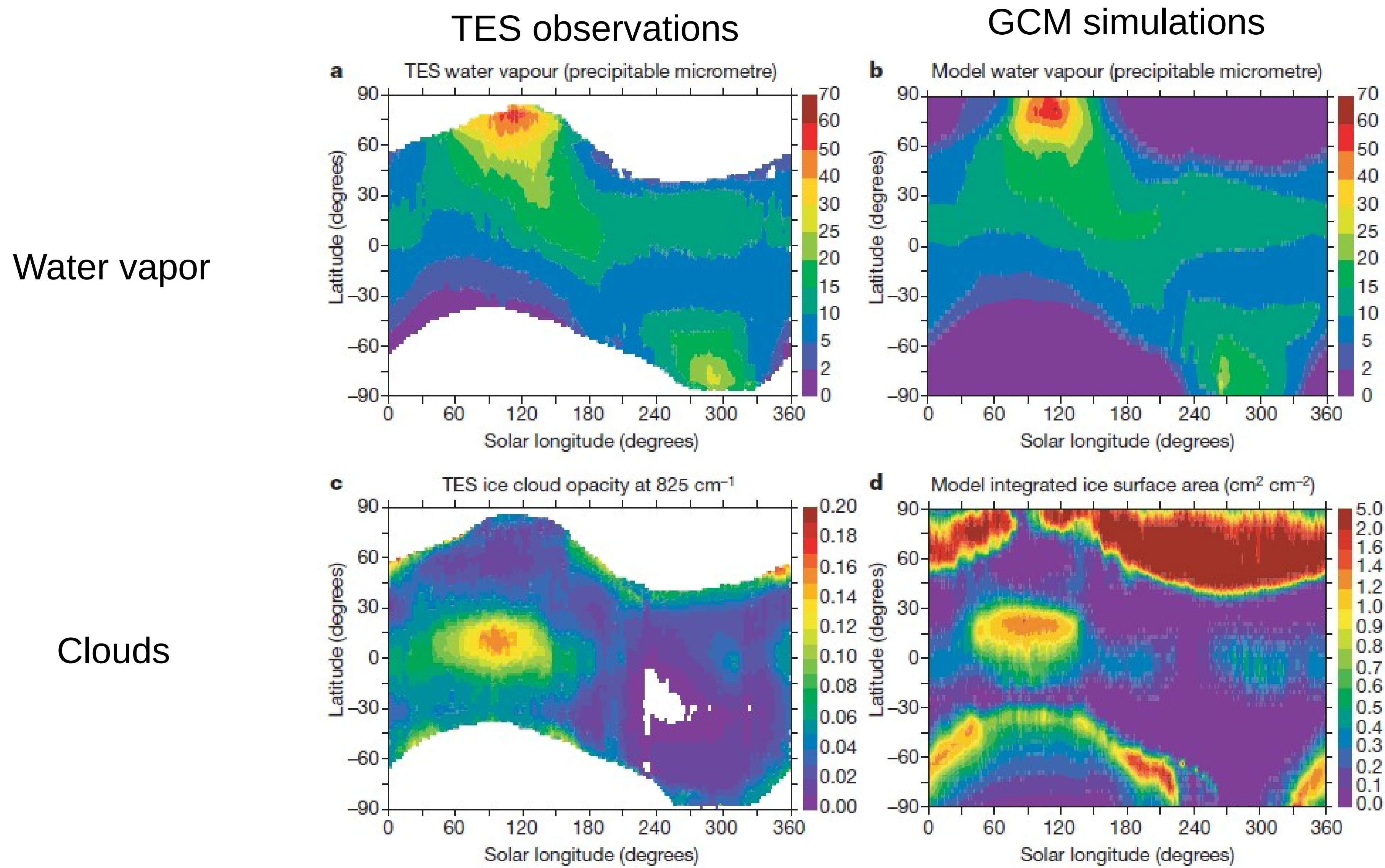
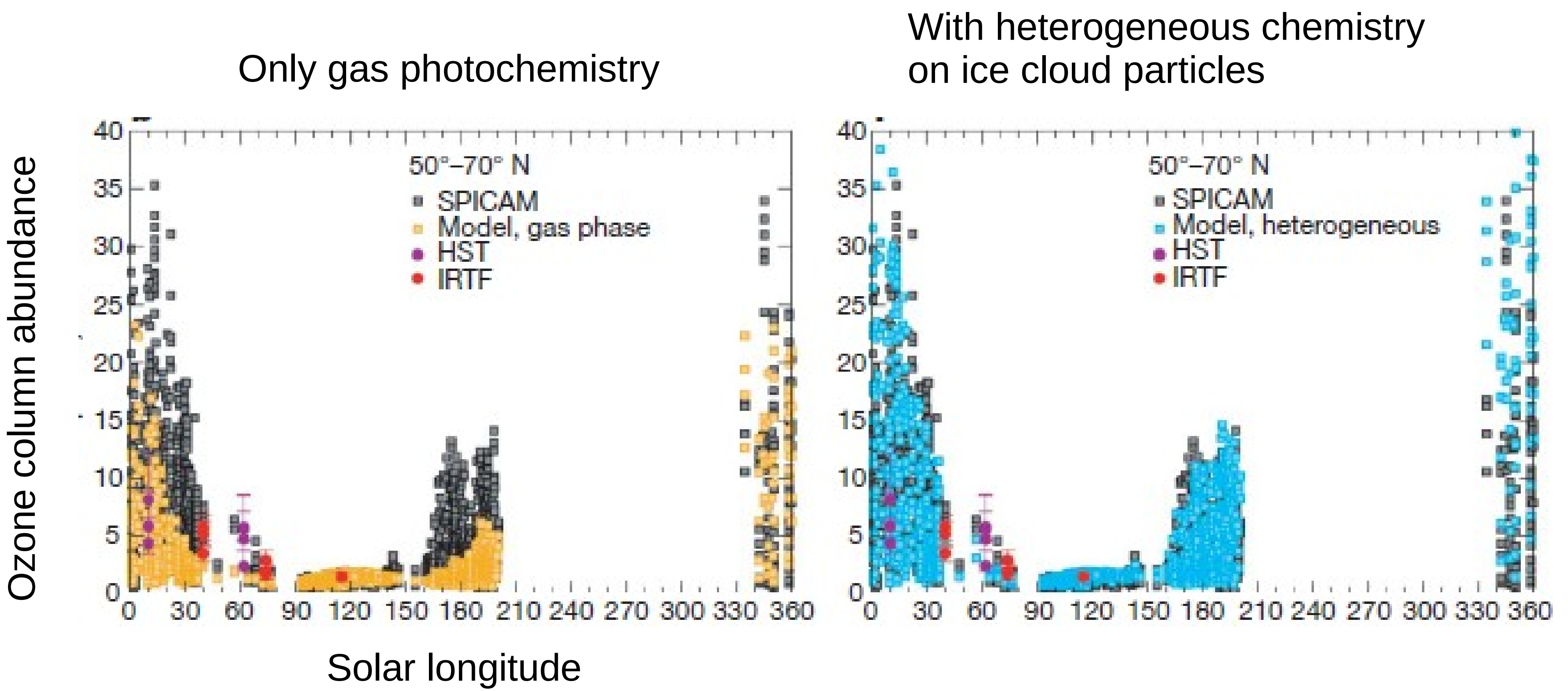
Mars climate

Water and cloud cycles



Mars climate

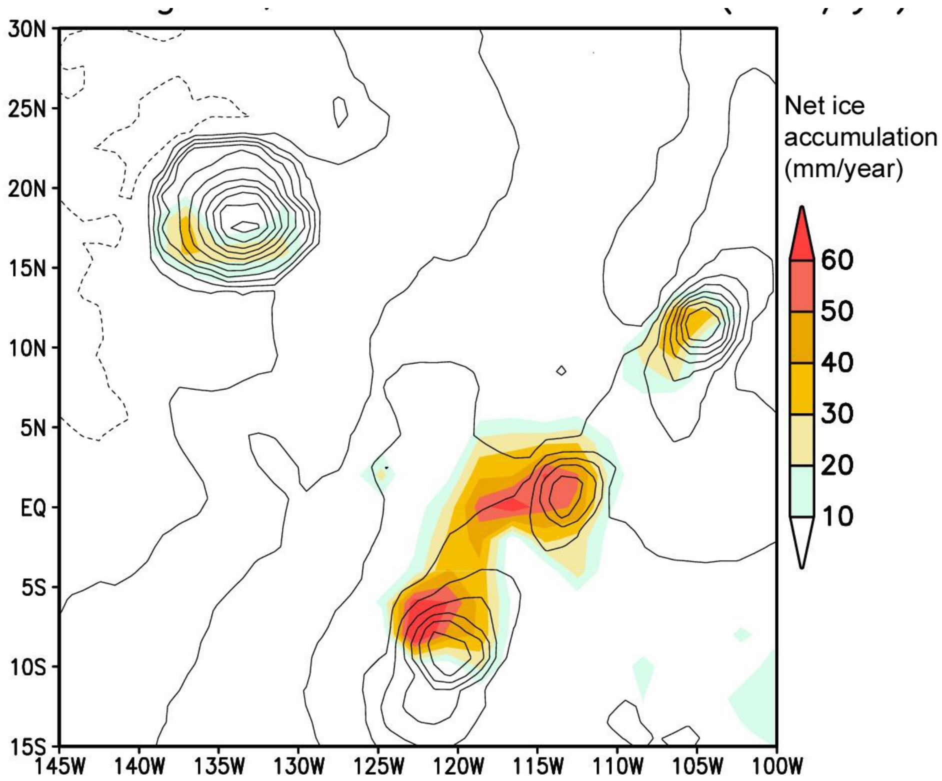
Heterogeneous chemistry

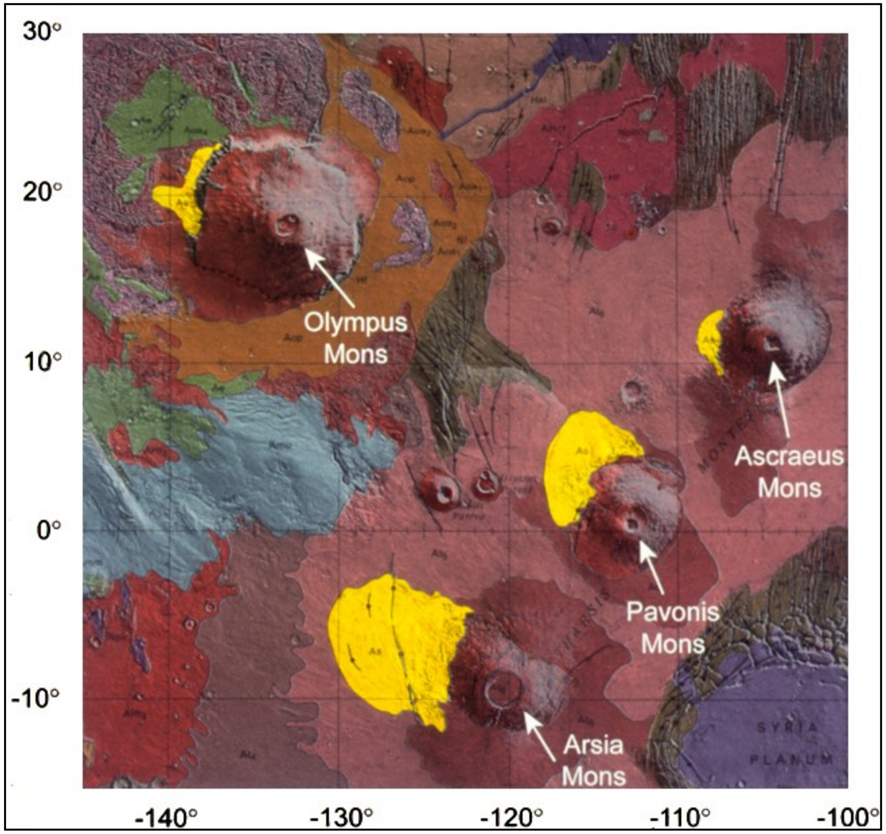


Mars paleoclimate

Non-polar glaciers, millions of years ago

Glacier formation :
Ice accumulation rate (mm/y)
with obliquity=45°

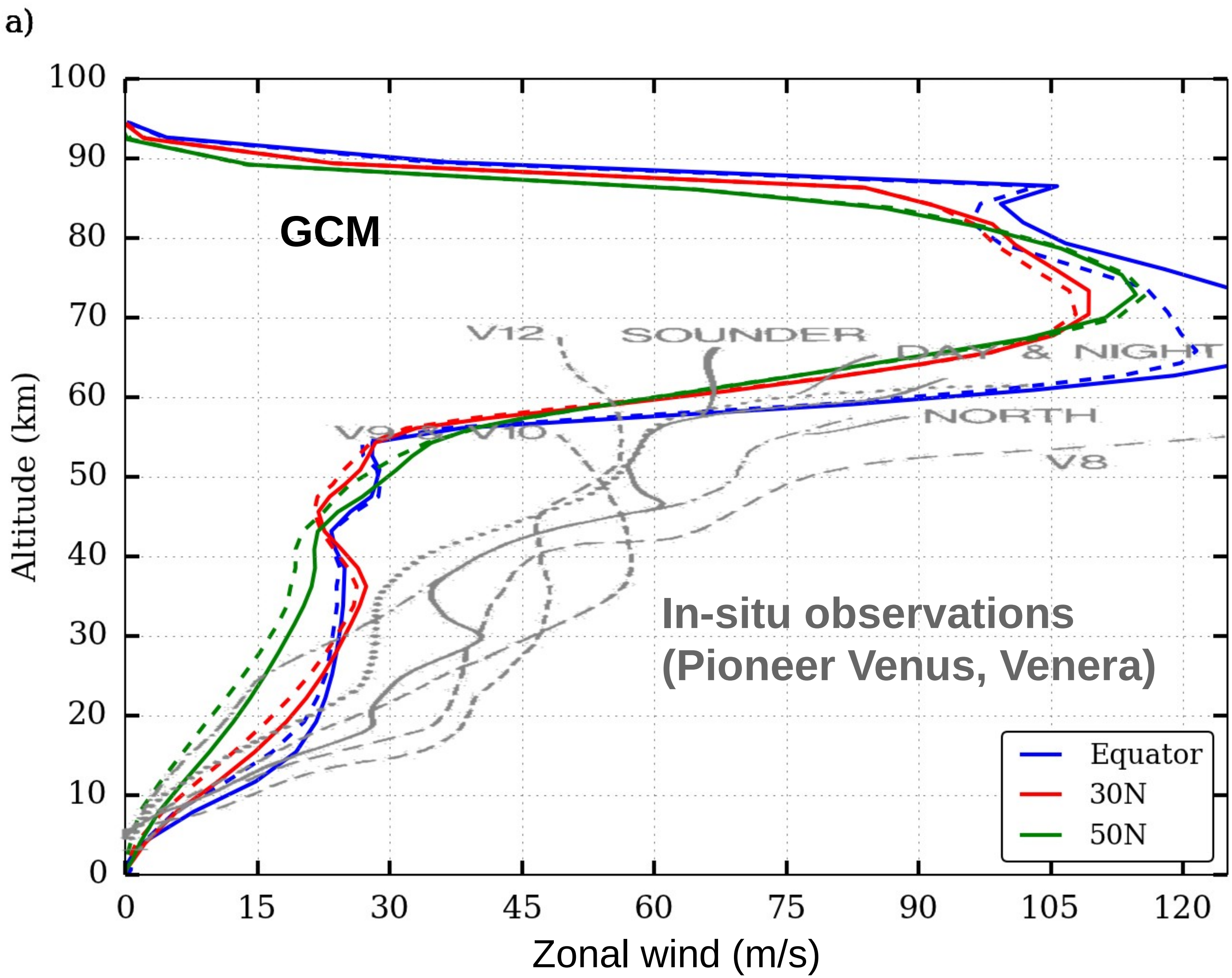




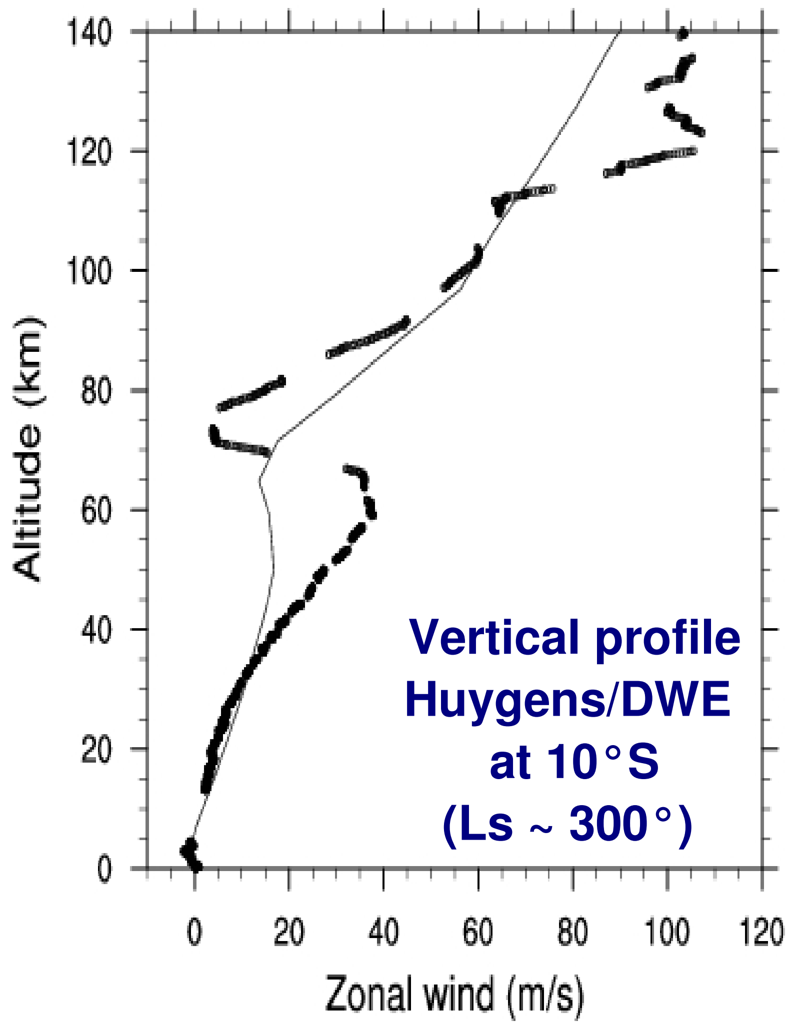
Fan shaped deposits, drop moraines characteristic of cold based glaciers.

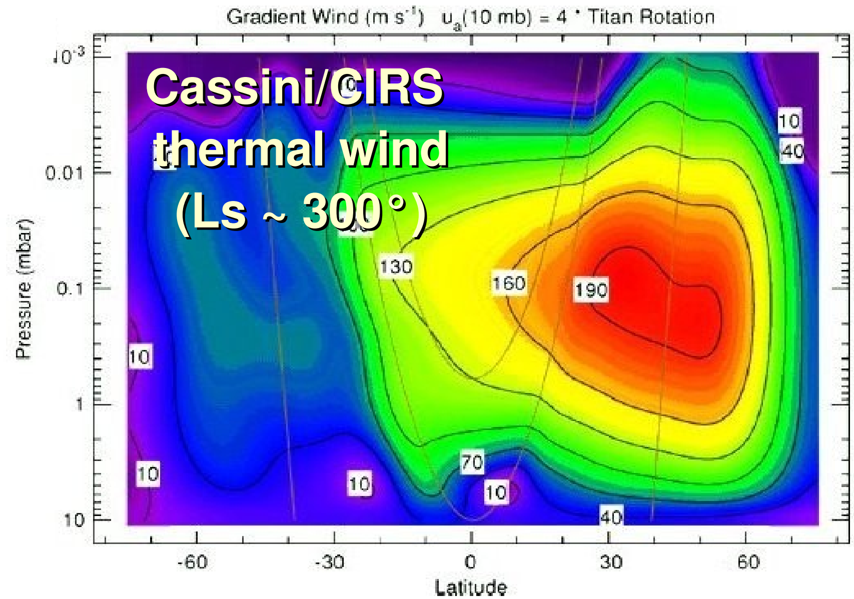
Rock glaciers

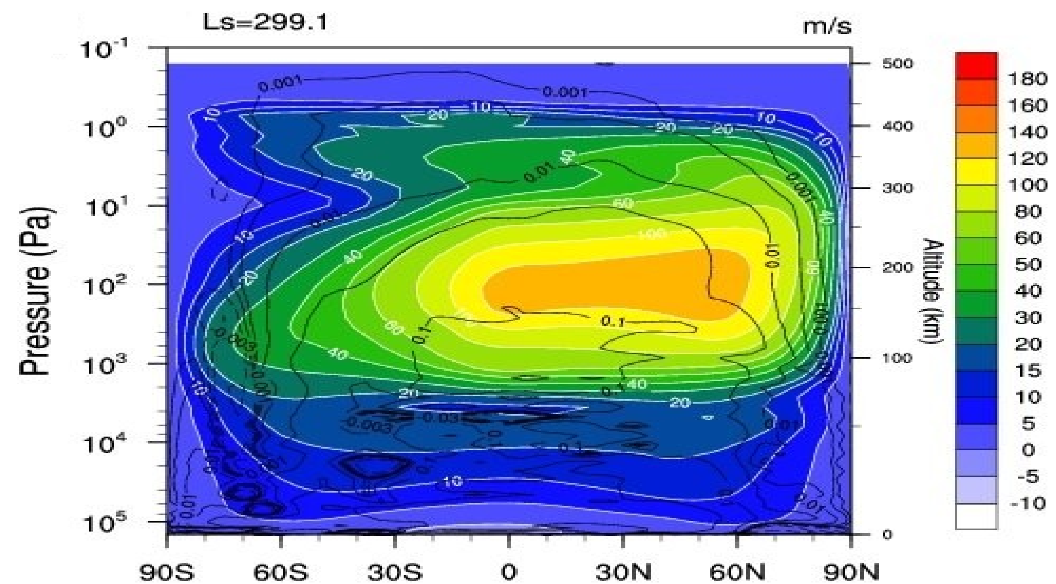
Venus superrotation



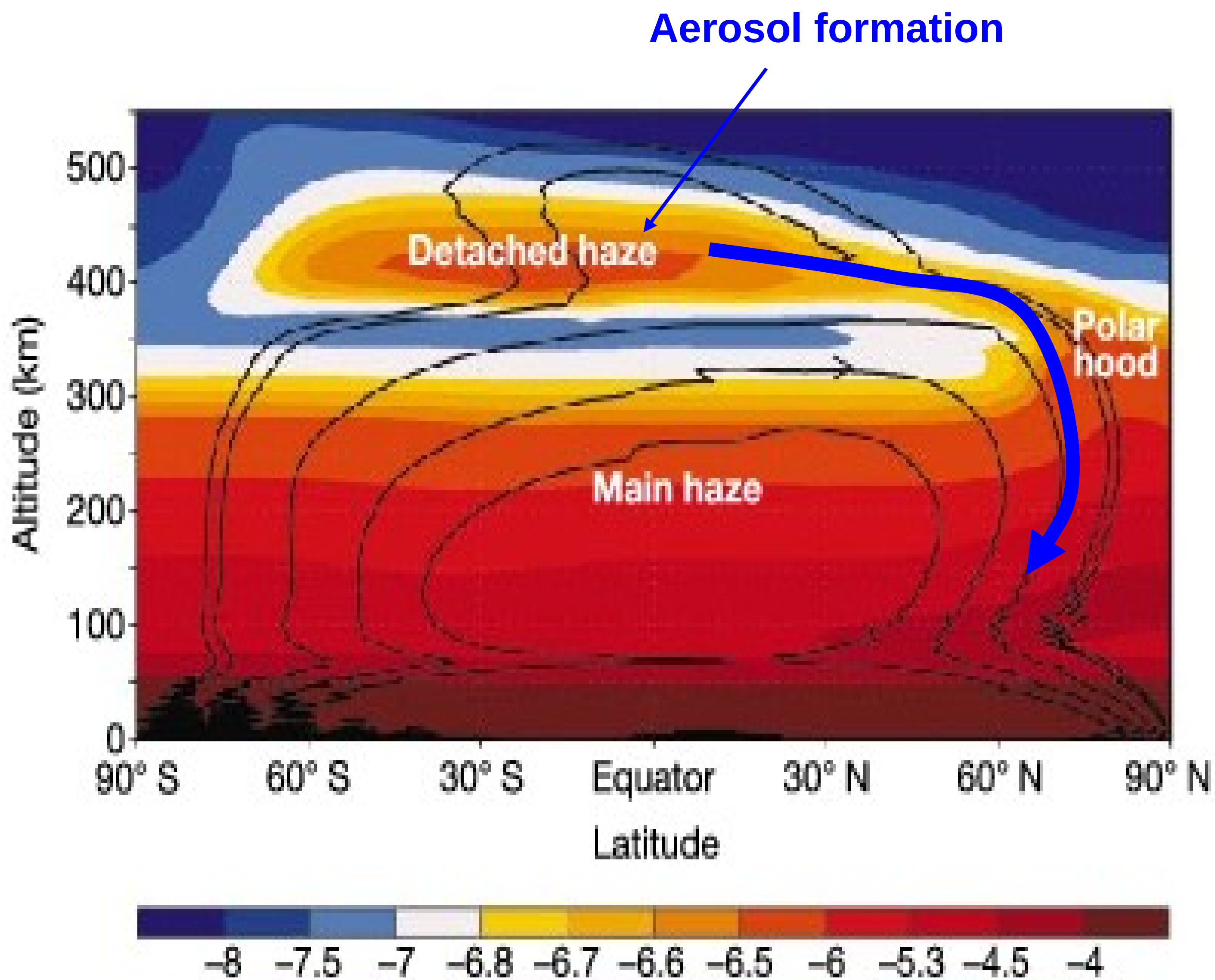
Titan superrotation



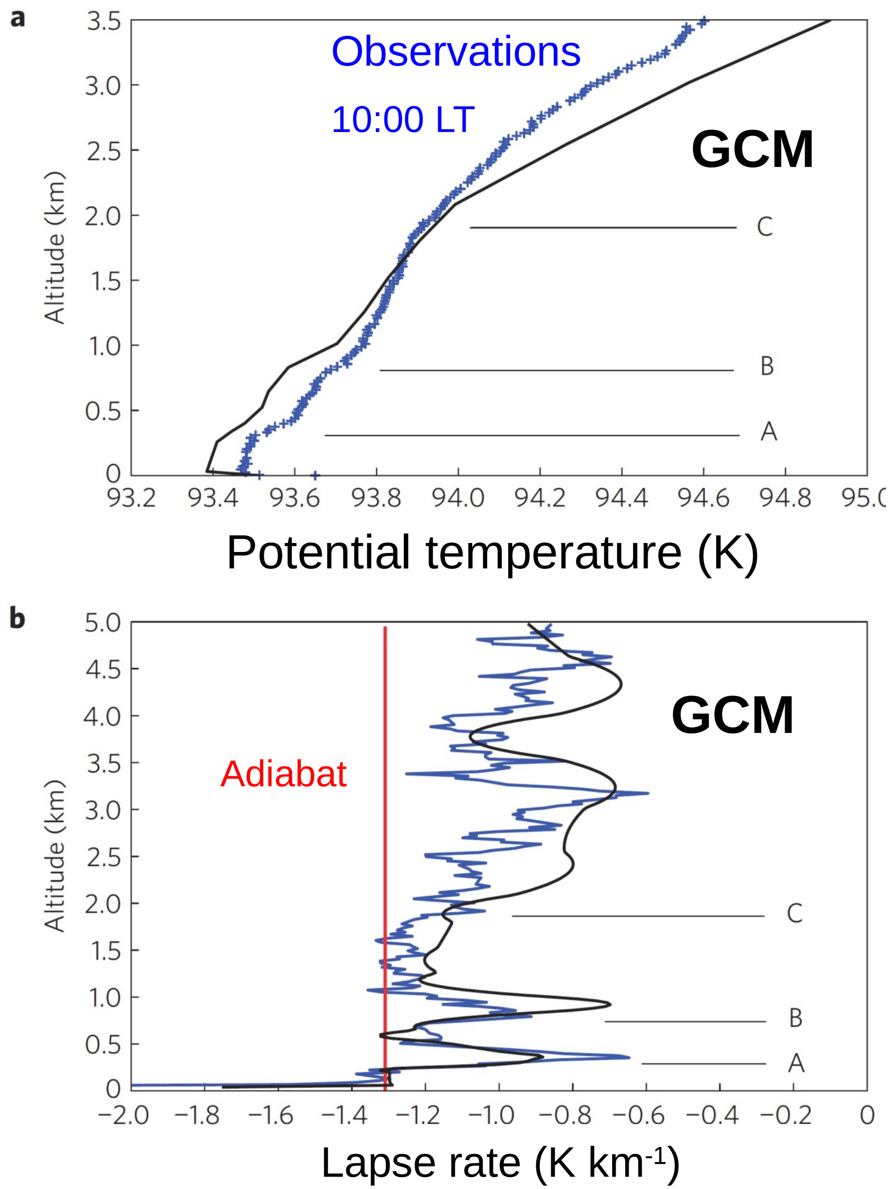




Titan detached haze layer

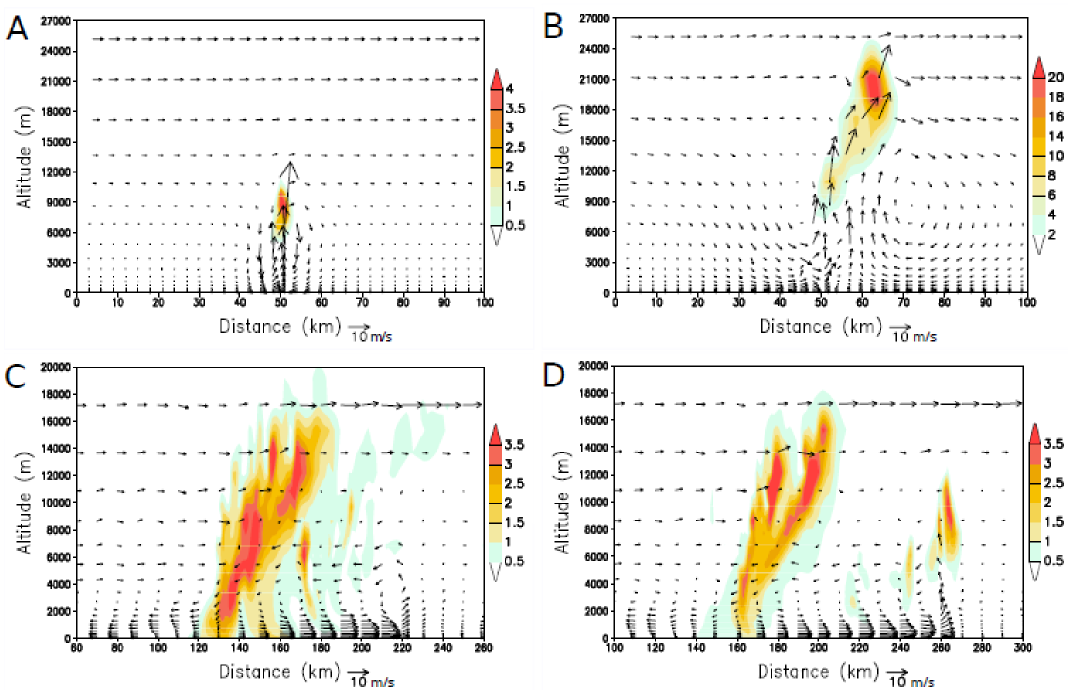


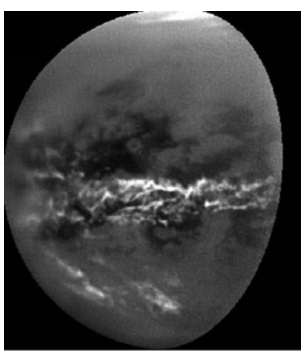
Titan boundary layer



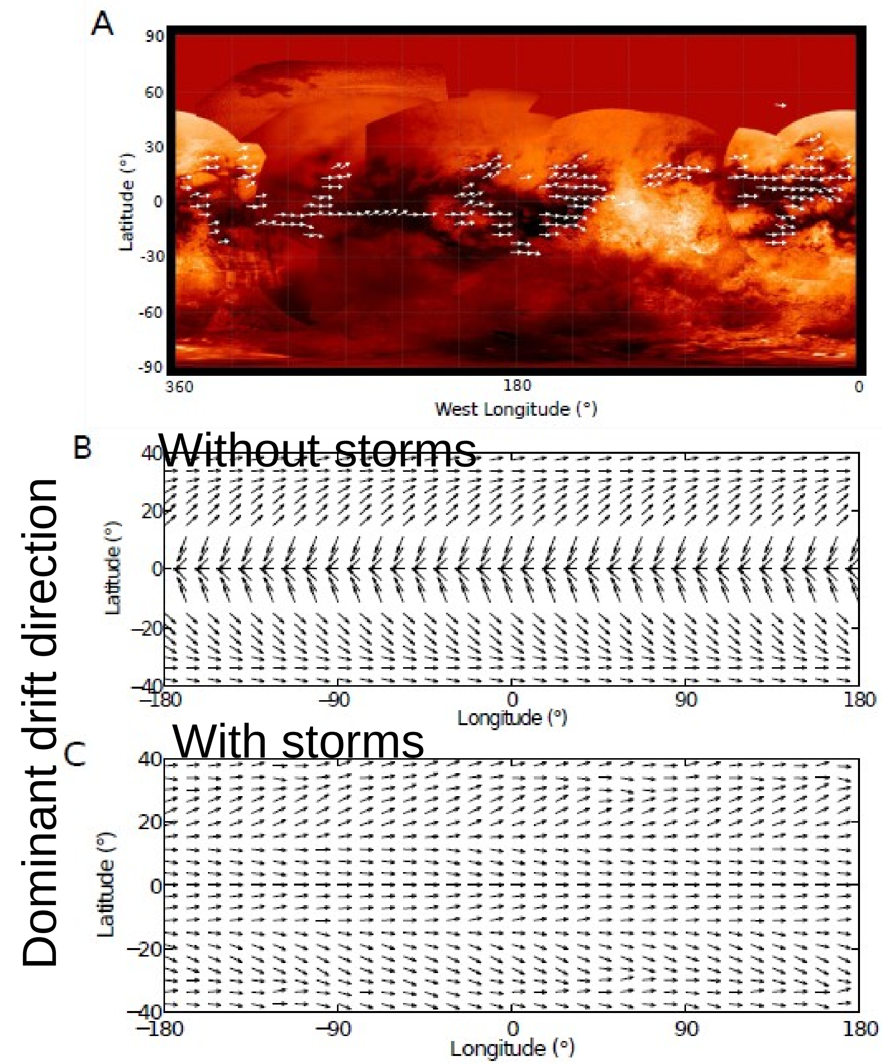
Titan equatorial dunes

Mesoscale (2D only) simulation of an equinox storm





Dunes orientation



Lessons from failure

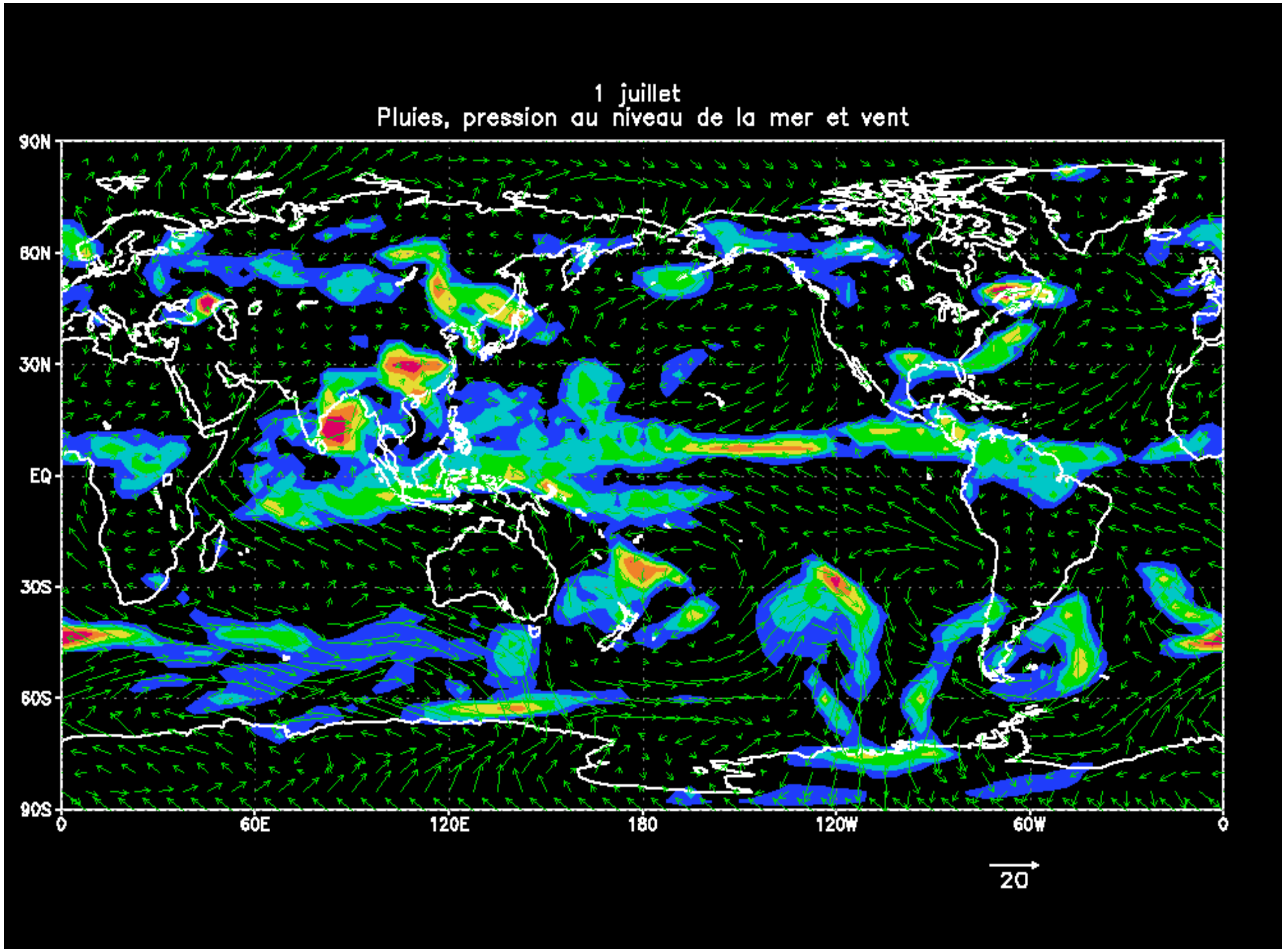
- Missing physical processes Radiative effect of Martian clouds
- Insuffisant representation of physical processes :
  - complex sub-scale processes **Terrestrial clouds** – gravity waves
  - Positives retroactions, instabilities Rétroaction due to ice albedo
  - Non-linearities, thresholds **Martian dust storms**
- Long time scales, sensitivity to initial state Pluto ices
- Weak forcings : when the system evolution is sensitive to a subtle balance between processes, and not driven by a strong forcing

  Superrotation

Terrestrial clouds

Complex microphysics
and small-scale dynamics

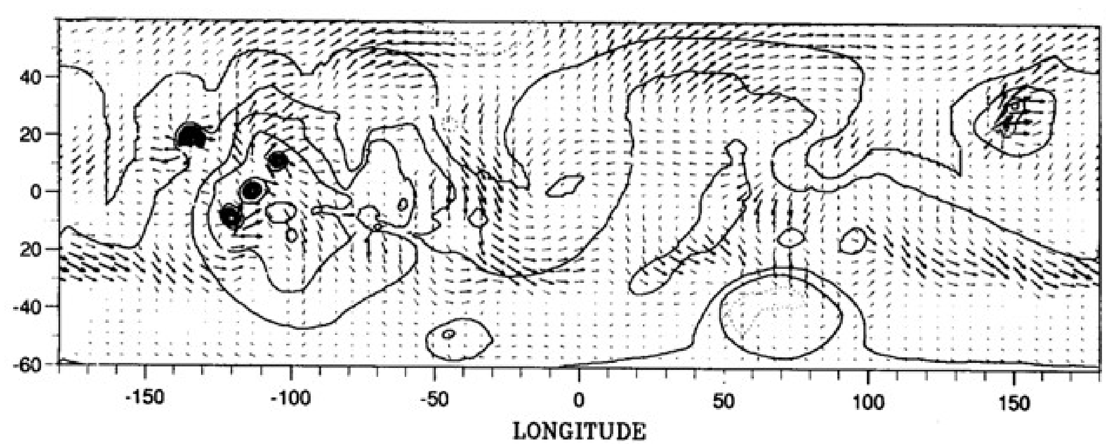
Precipitations in a GCM
Global scale, coarse resolution (~100 km)



Martian dust storms

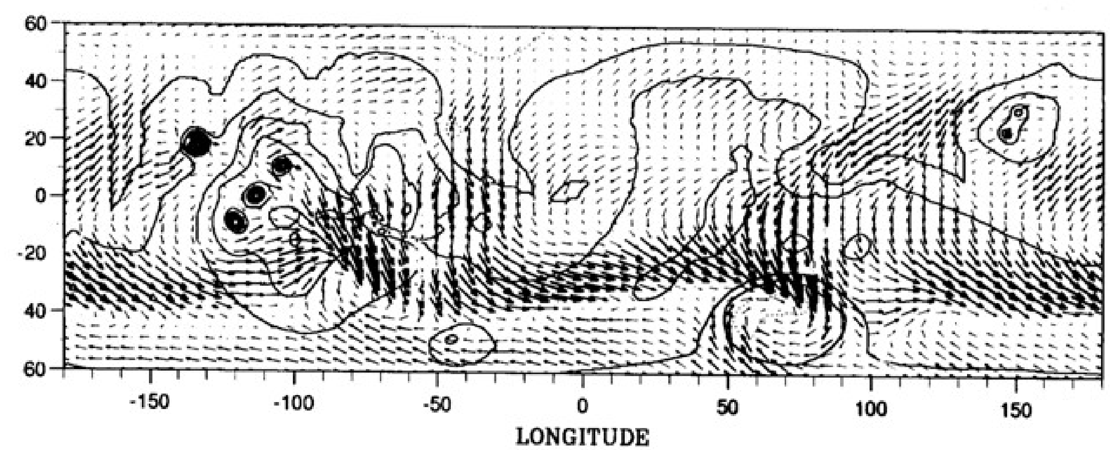
Strong positive retroaction of dust on circulation and on dust lifting

Clear atmosphere



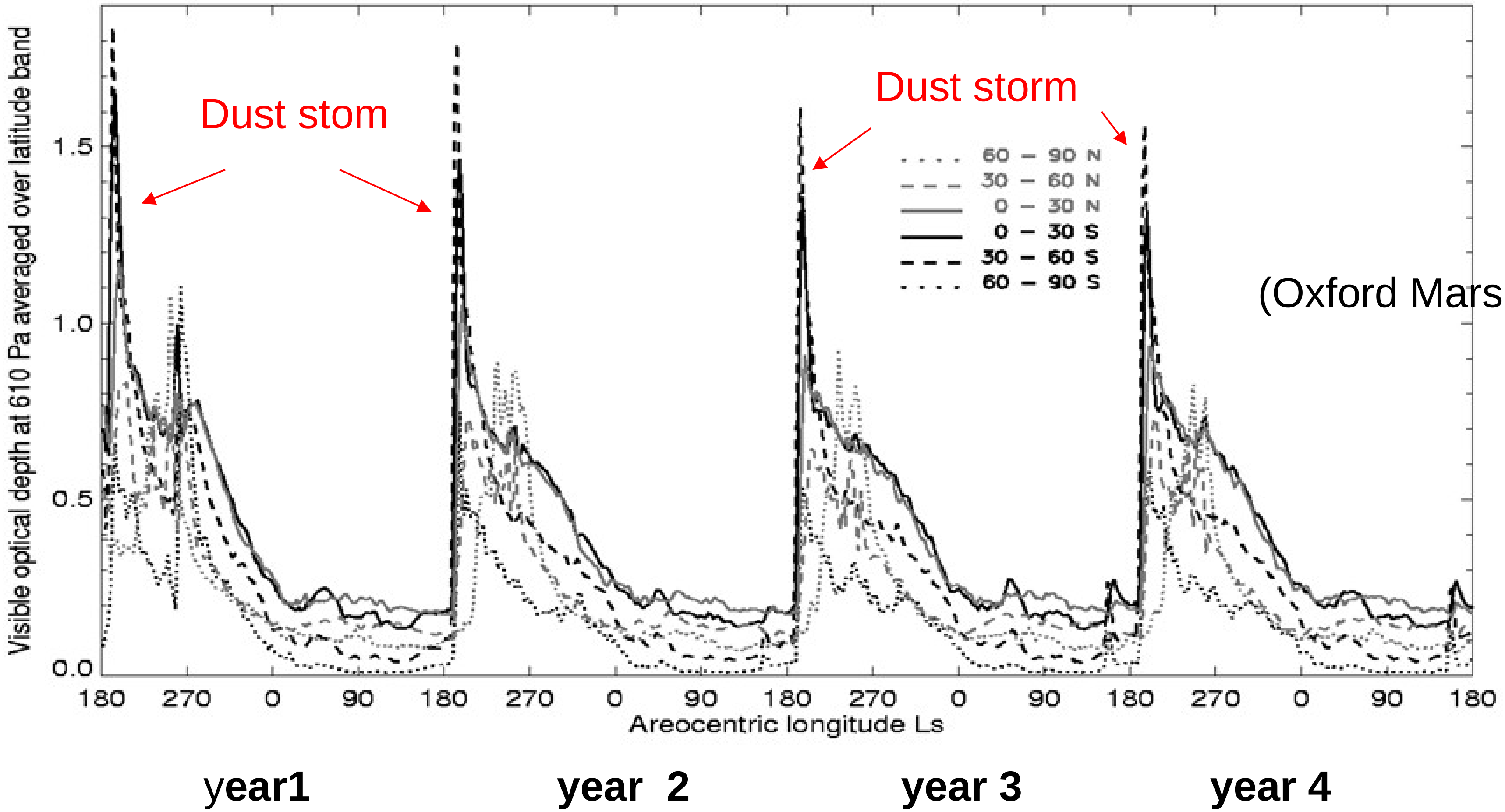
(LMD Mars GCM)

Dust storm



Martian dust storms

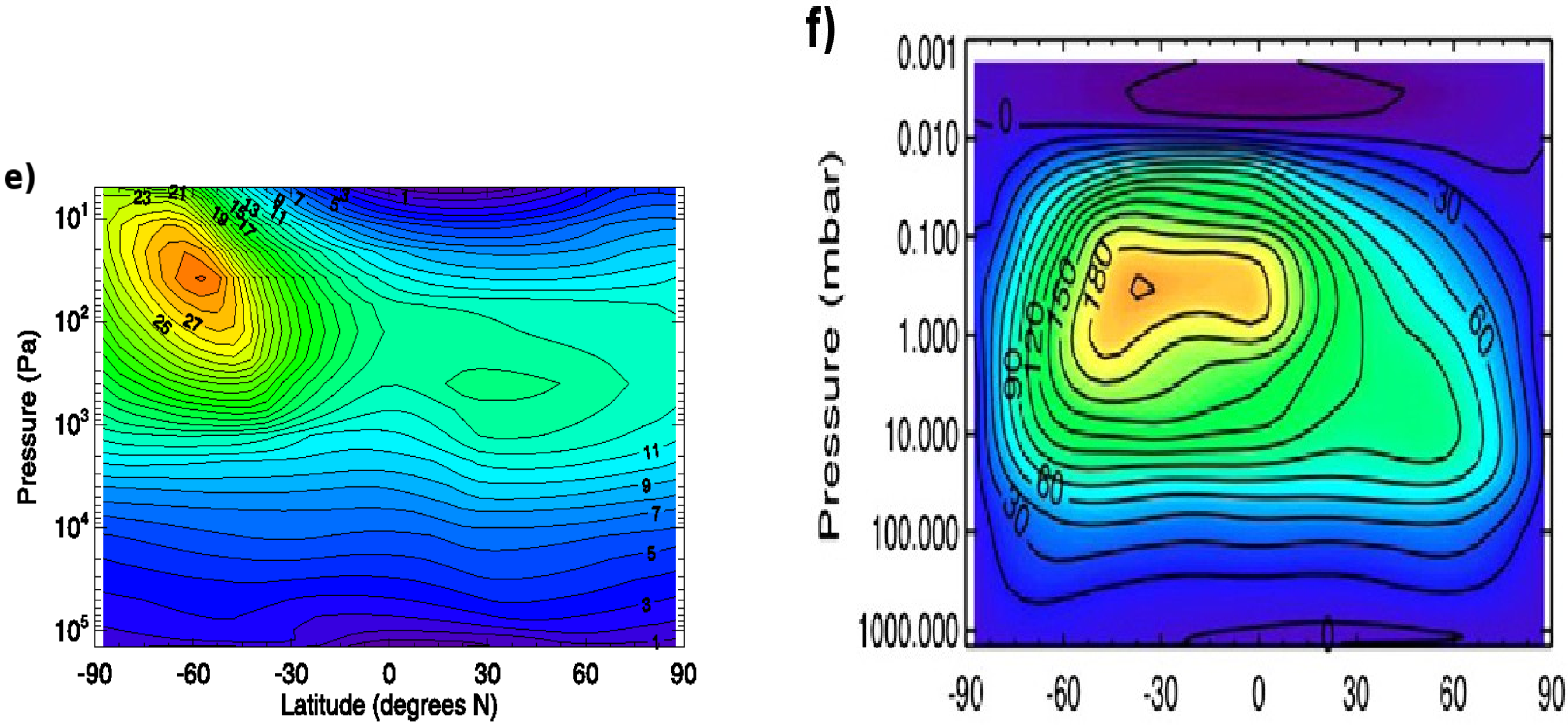
Difficult to reproduce the interannual variability...



(Oxford Mars GCM)

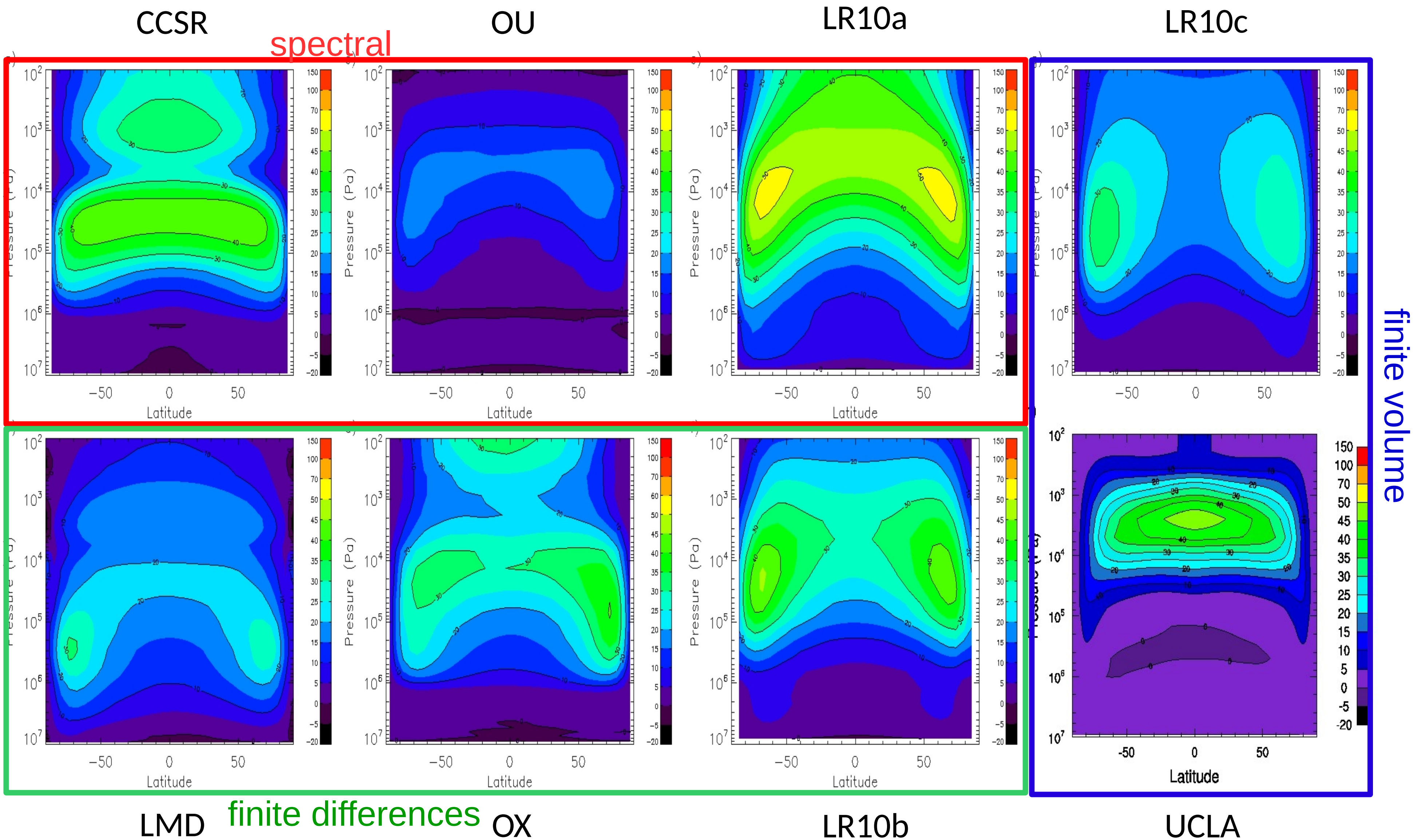
Titan superrotation

Same GCM, corrections in the dissipation formulation



Venus superrotation

Several dynamical cores, same simplified physics



To conclude

Suggested bibliography

- A. Sánchez-Lavega, *An Introduction to Planetary Atmospheres*, CRC Press, Taylor and Francis, 2011, ISBN 9781420067354.

- Forget F. and Lebonnois S., « Global climate models of the terrestrial planets »
  + Dowling T., « Earth General Circulation Models »
in *Comparative Climatology of the Terrestrial Planets*, S.J. Maxwell et al. Eds. University of Arizona, Tuscon, 2013

Acknowledgements

- thanks to the authors of all the images and plots I showed.
  I can send references upon request

- thanks to Julia and Javier for the invitation and this great Winter School.