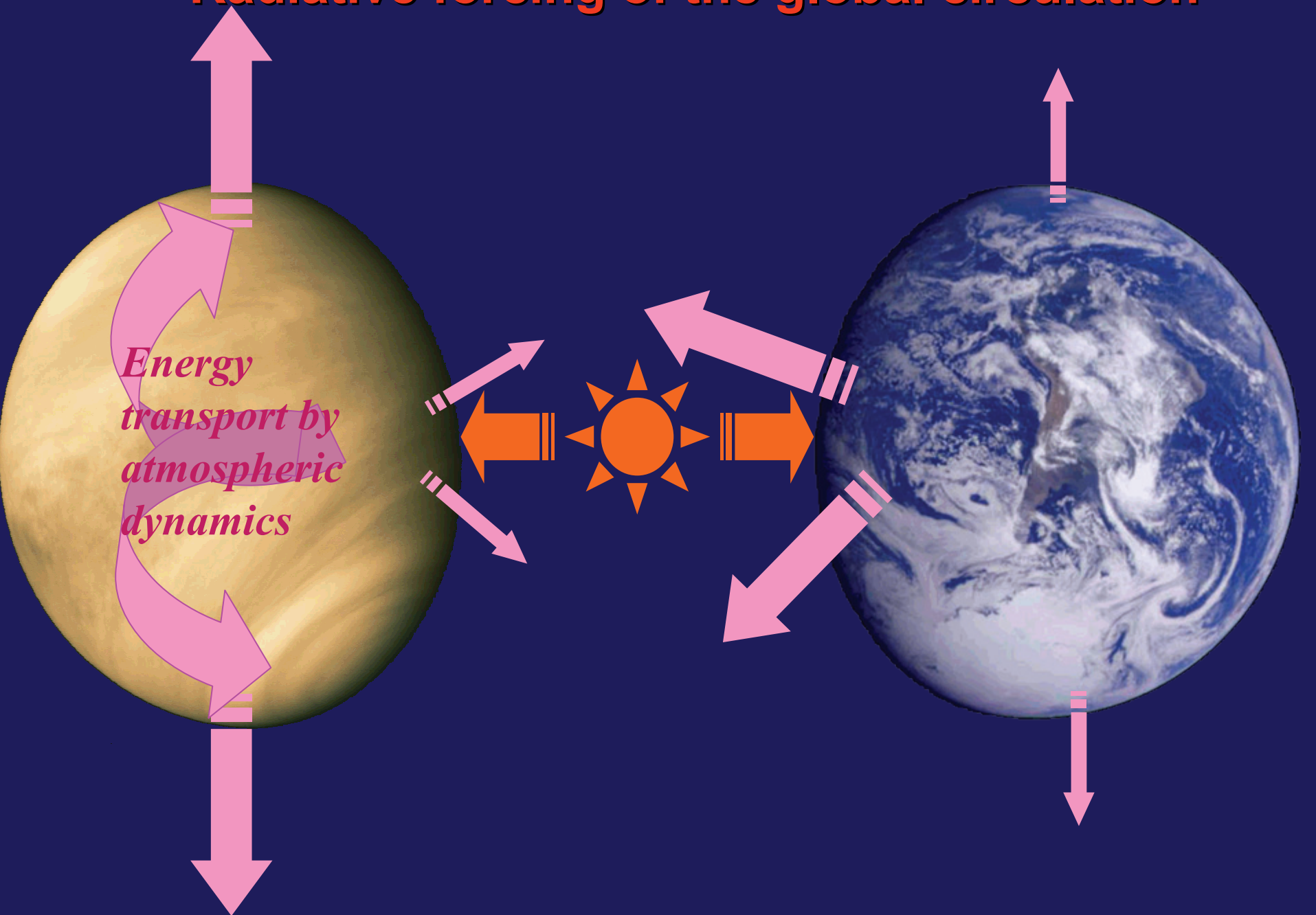
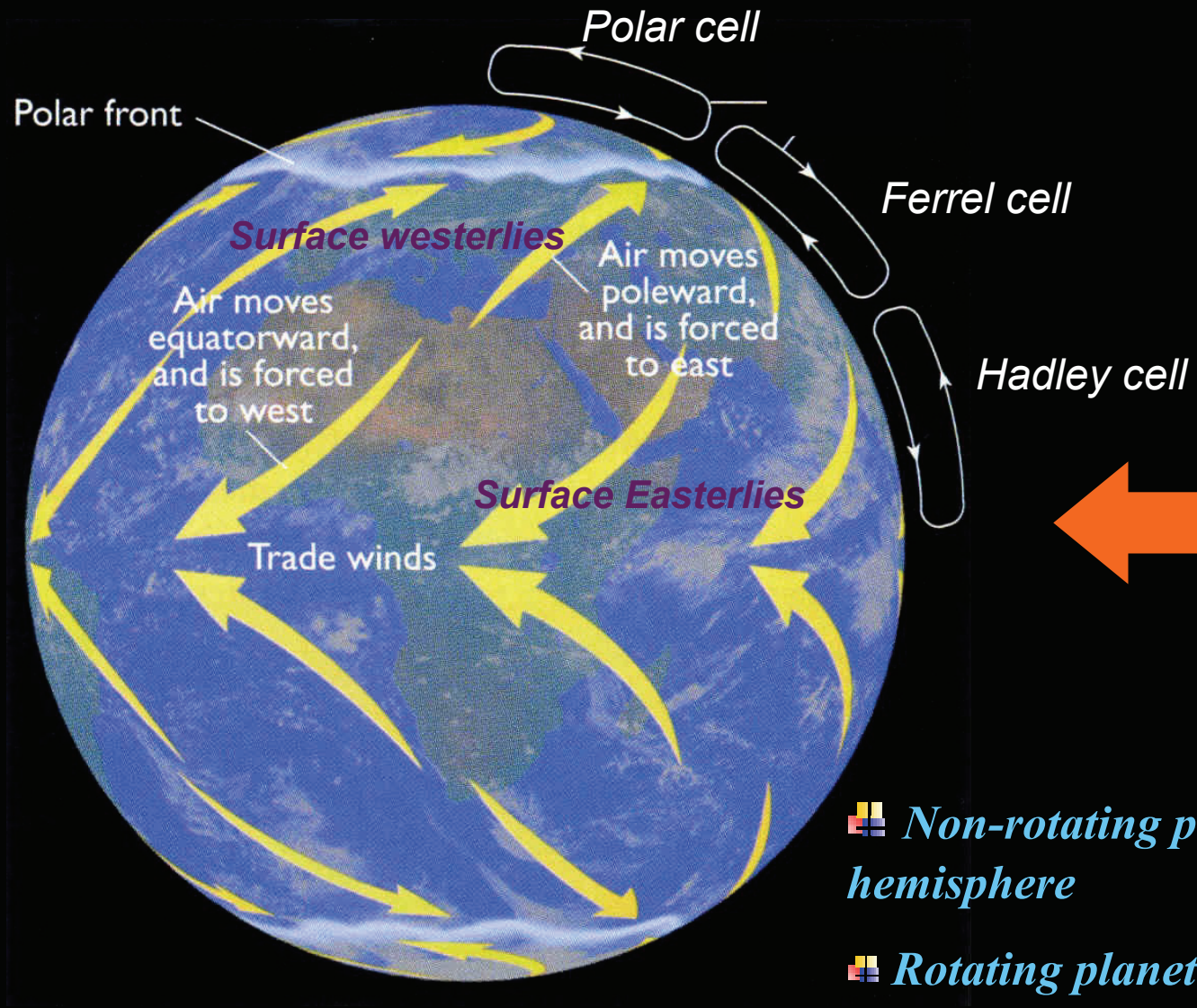
Dynamics of planetary atmospheres

Radiative forcing of the global circulation

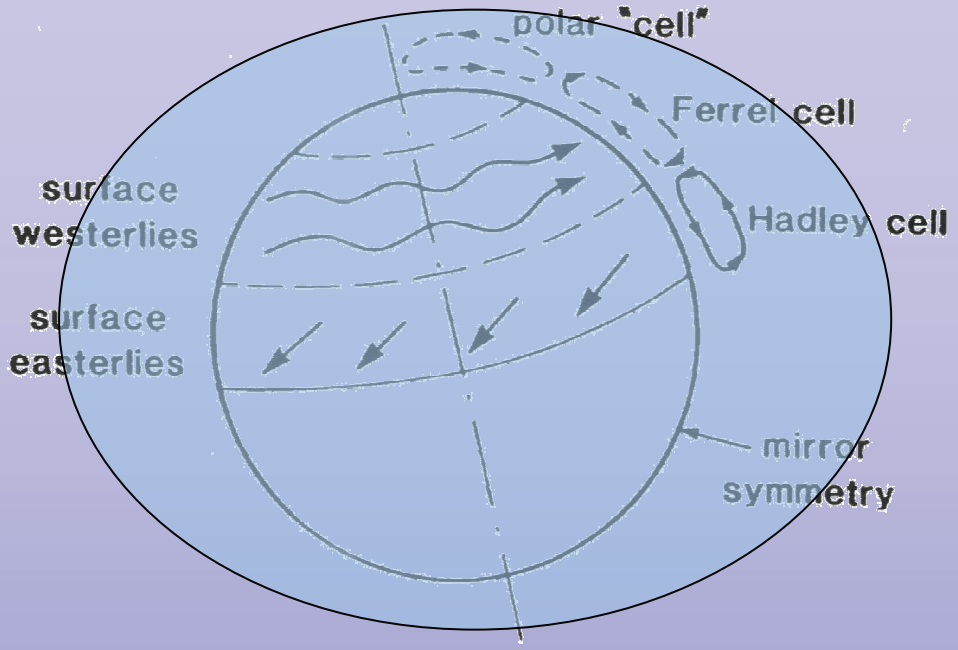


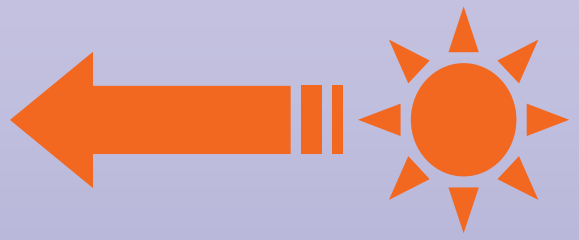
Hadley circulation



- *Non-rotating planet – one cell per hemisphere*
- *Rotating planet – deflection of meridional winds and split of Hadley circulation into several cells*
- *If planet axis is not normal to ecliptic – Hadley pattern has seasonal behaviour*

Thermal tides



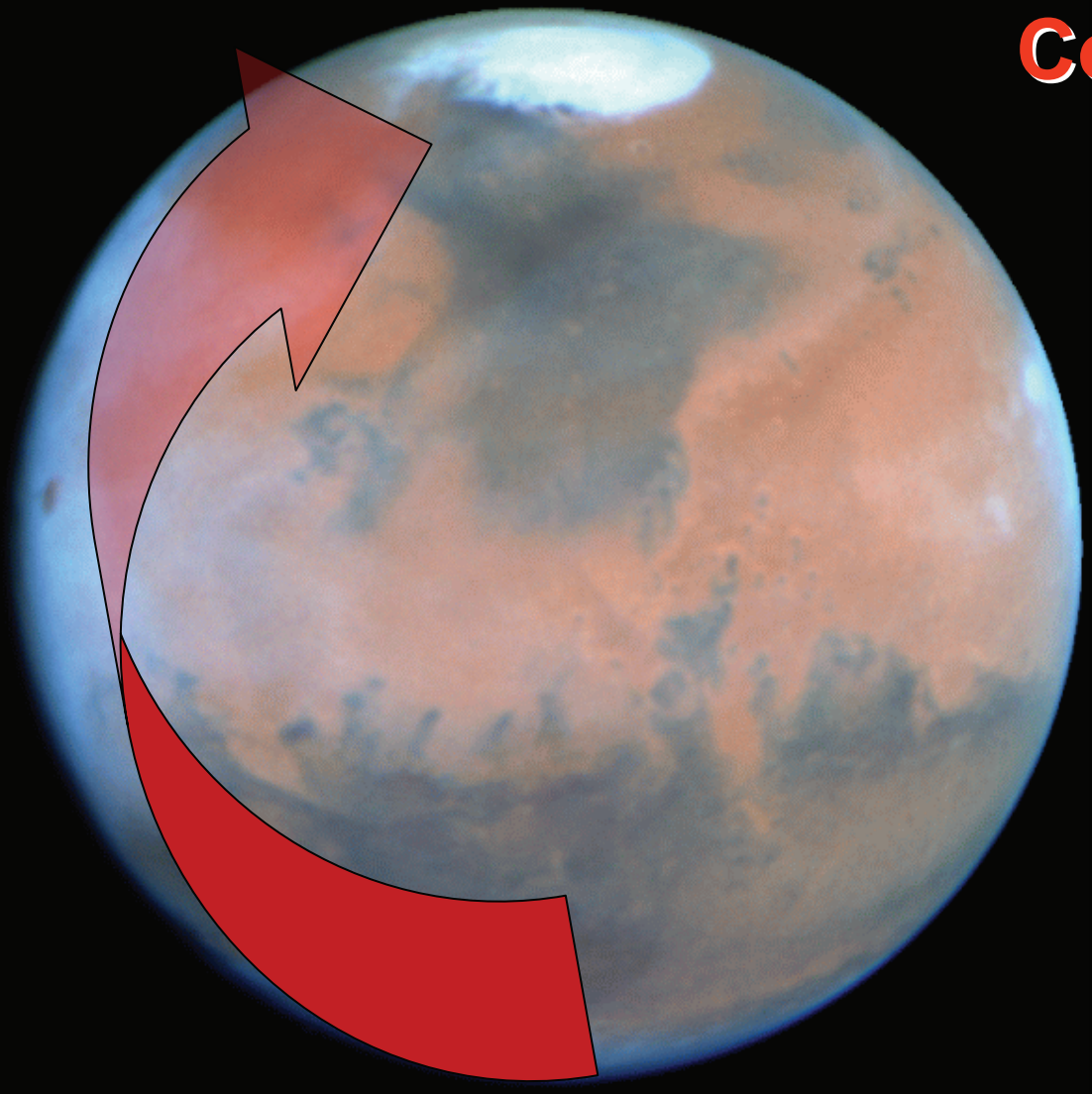


- *Global energy balance*

$$(1-A)Ft = C_p M \delta T$$

- *$\delta T / T \sim 0.4\%$ for Venus (tides in the thermosphere)*
- *$\delta T / T \sim 20\%$ for Mars (tides in the entire atmosphere)*
- *Maintenance of the Venus super-rotation*

Condensation flows



- *Mars: ~20% of the atmosphere is involved (CO_2)*
- *Pluto and Triton : condensation of N_2 and CH_4*

Atmospheric dynamics equations

- ***Navier-Stokes equation (inertial frame)***

$$\frac{D\mathrm{v}}{Dt} = -\frac{1}{\rho}\nabla P + g + \nu\nabla^2\mathrm{v}$$

- ***Navier-Stokes equation (rotating frame)***

$$\frac{D\mathrm{v}'}{Dt} = -2\omega_{rot} \times \mathrm{v}' - \frac{1}{\rho}\nabla P + (g + \omega_{rot}^2 r) + \nu\nabla^2\mathrm{v}'$$

Simplified wind equations

- *Simplifications*
  - *incompressible and inviscid fluid*
  - *centrifugal force << gravity*

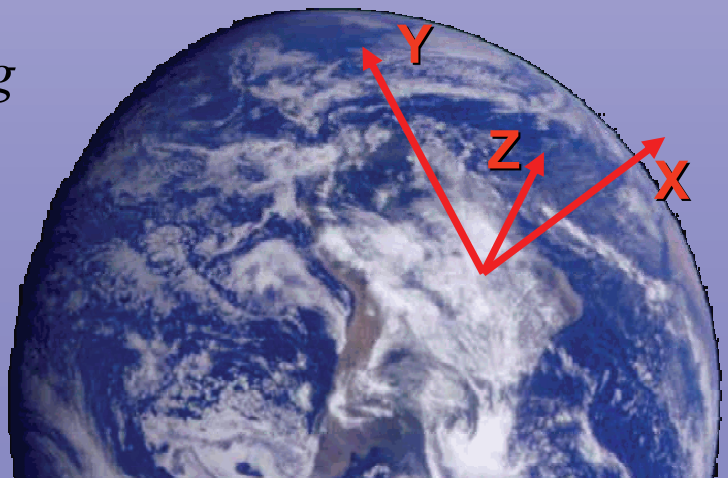
$$\frac{D\mathrm{v}'}{Dt} = -2\omega_{rot} \times \mathrm{v}' - \frac{1}{\rho}\nabla P + (g + \cancel{\omega_{rot}^2 r}) + \cancel{\nu \nabla^2 \mathrm{v}'}$$

- *"shallow water" approximation*
- *hydrostatic equilibrium*

$$\begin{cases} \dfrac{du}{dt} = 2\Omega \sin\varphi \cdot v - \dfrac{1}{\rho}\dfrac{dp}{dx} \\ \dfrac{dv}{dt} = 2\Omega \sin\varphi \cdot u - \dfrac{1}{\rho}\dfrac{dp}{dy} \\ \dfrac{dp}{dz} = -\rho g \end{cases}$$

$$\frac{dV}{dt} = fV \times k - \frac{1}{\rho}\nabla p$$

f = 2Ωsinφ - Coriolis parameter



Steady horizontal flow (1)

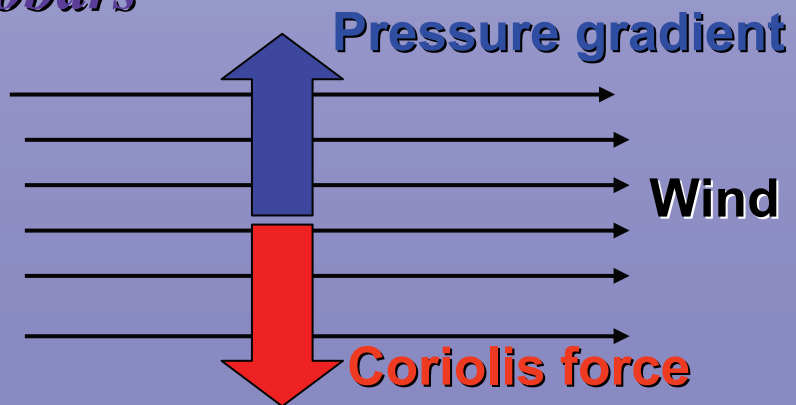
Geostrophic wind

$$\cancel{\frac{dV}{dt}} = fV \times k - \frac{1}{\rho}\nabla p \quad \Rightarrow \quad V = -\frac{1}{\rho f}\frac{\partial p}{\partial n}$$

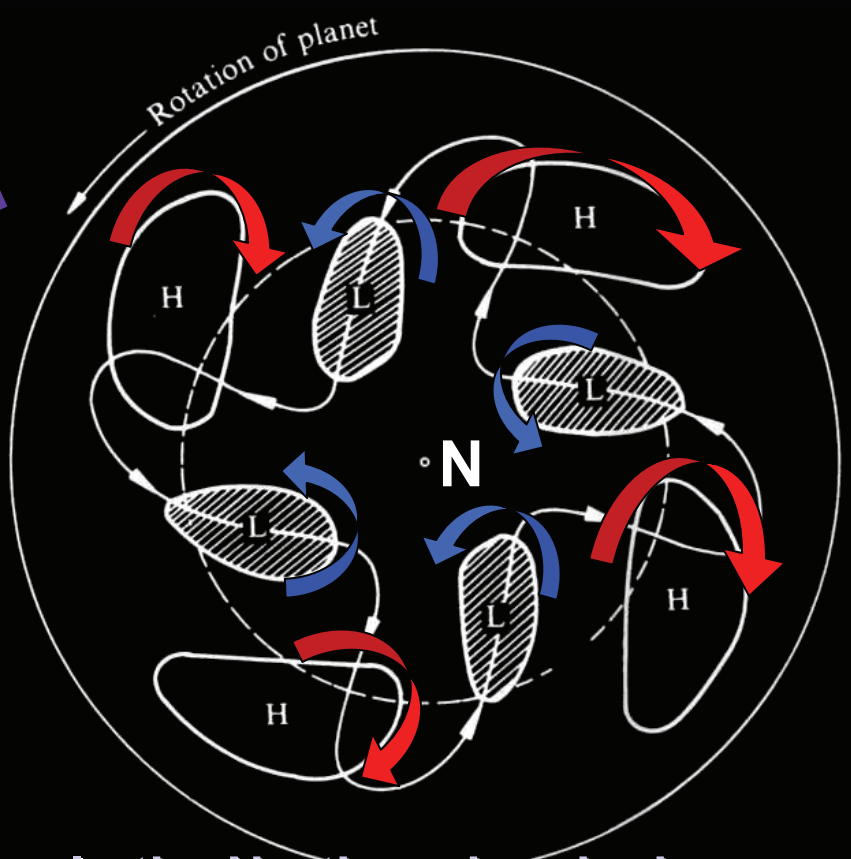
Rossby number :

$$Ro = \frac{dV/dt}{fV} = \frac{V}{L\Omega}$$

- *Ro << 1 → importance of Coriolis force*
- *Geostrophic wind blows along isobars perpendicular to* ∇p



Global circulation on Earth



In the Northern hemisphere

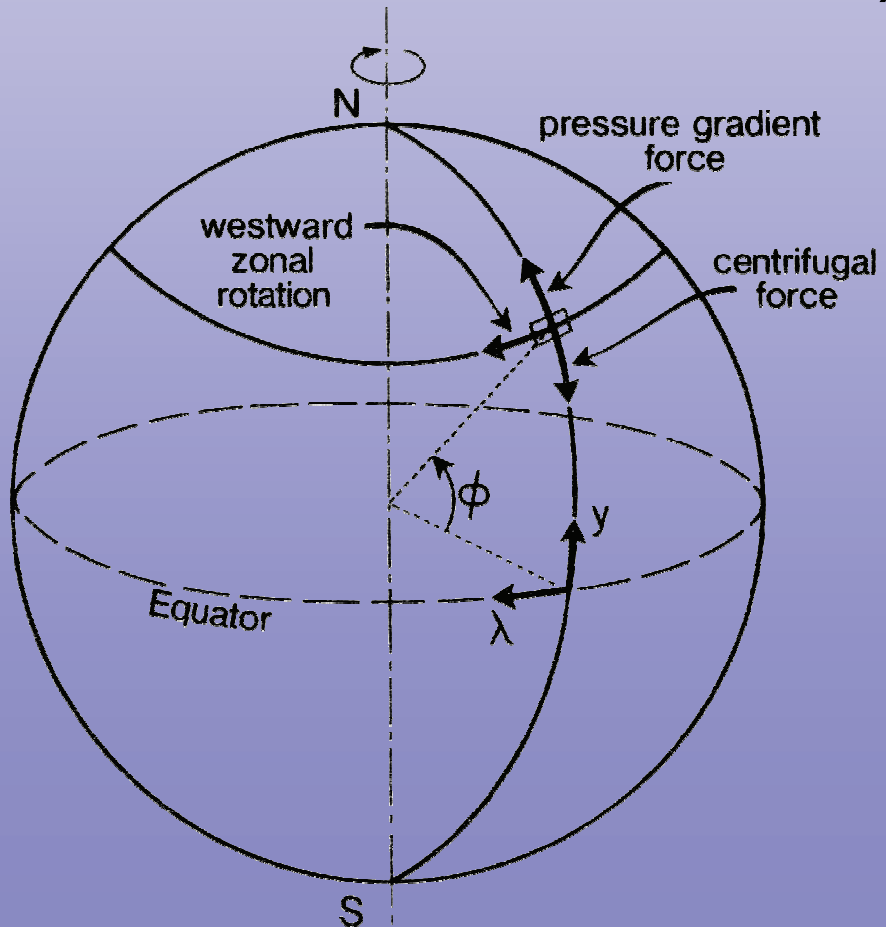
Cyclones – anticlockwise rotation

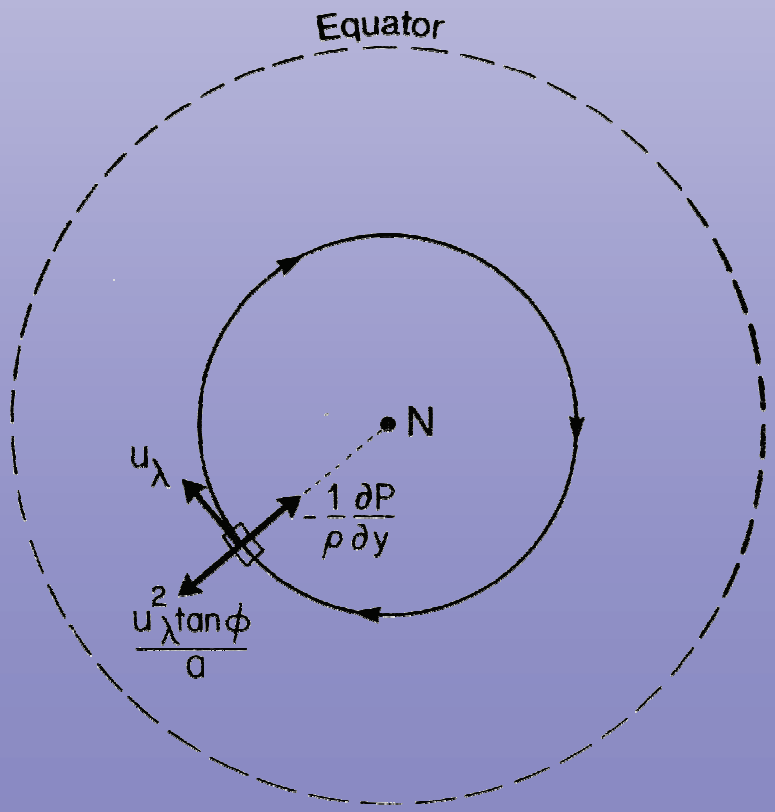
Anticyclones – clockwise rotation

Steady horizontal flow (2)

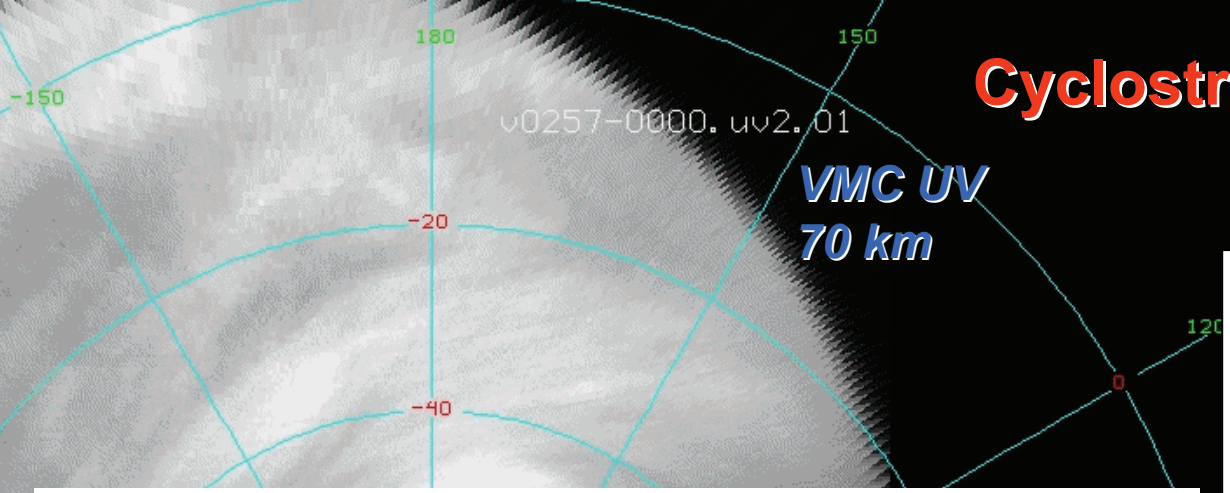
Cyclostrophic wind

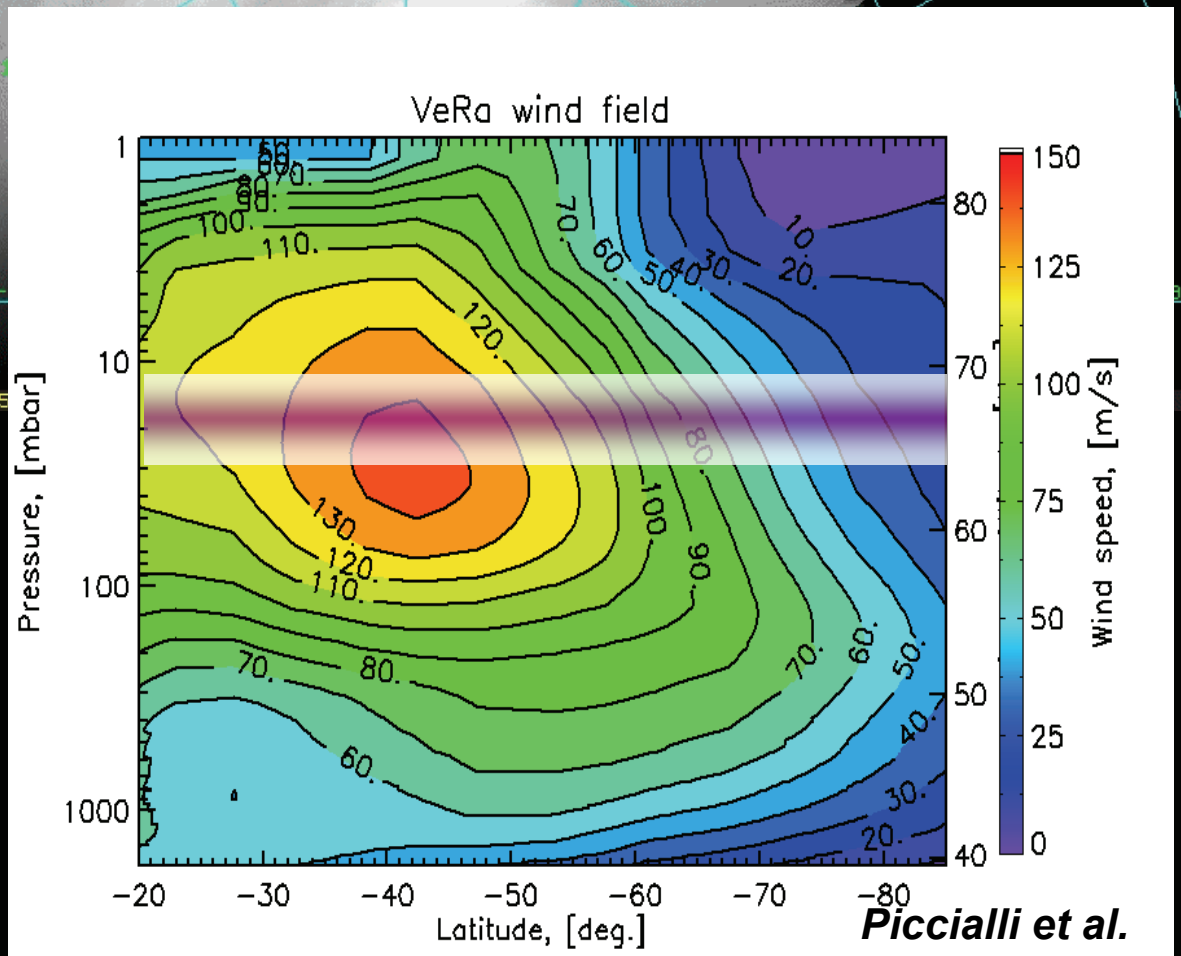
$$\frac{dV}{dt} = \cancel{fV \times k} - \frac{1}{\rho}\nabla p \quad \Rightarrow \quad \frac{V^2}{R} = -\frac{1}{\rho}\frac{\partial p}{\partial n} \quad \Rightarrow \quad \frac{\partial u^2}{\partial z} \approx -\frac{R}{\tan\varphi}\frac{\partial T}{\partial \varphi}$$



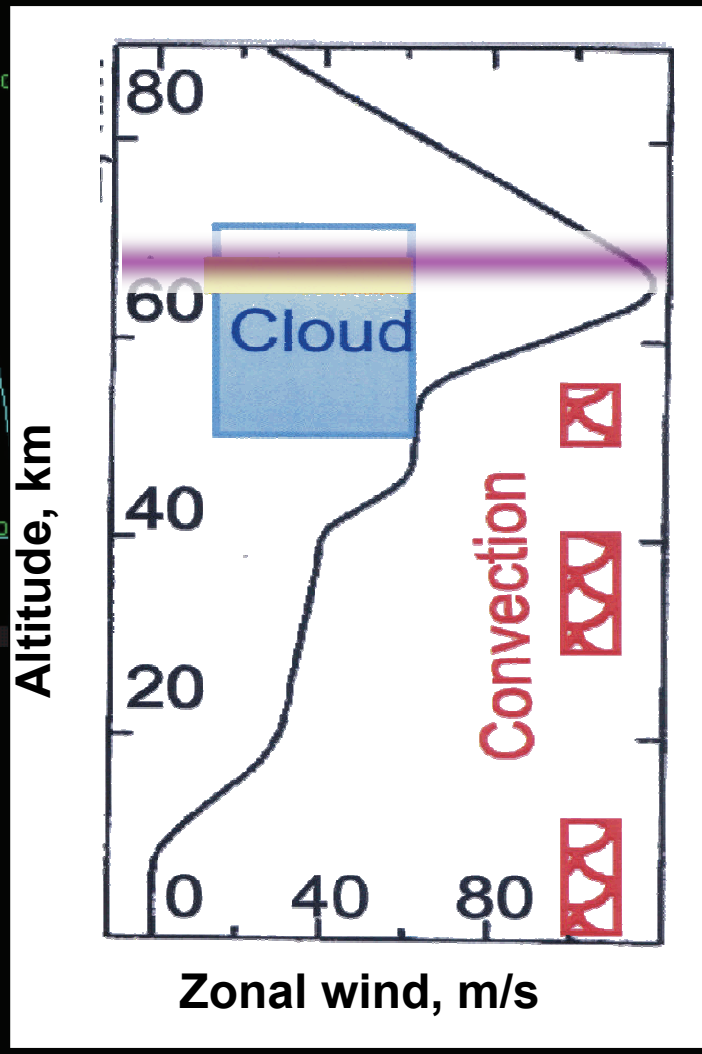


Cyclostrophic super-rotation on Venus

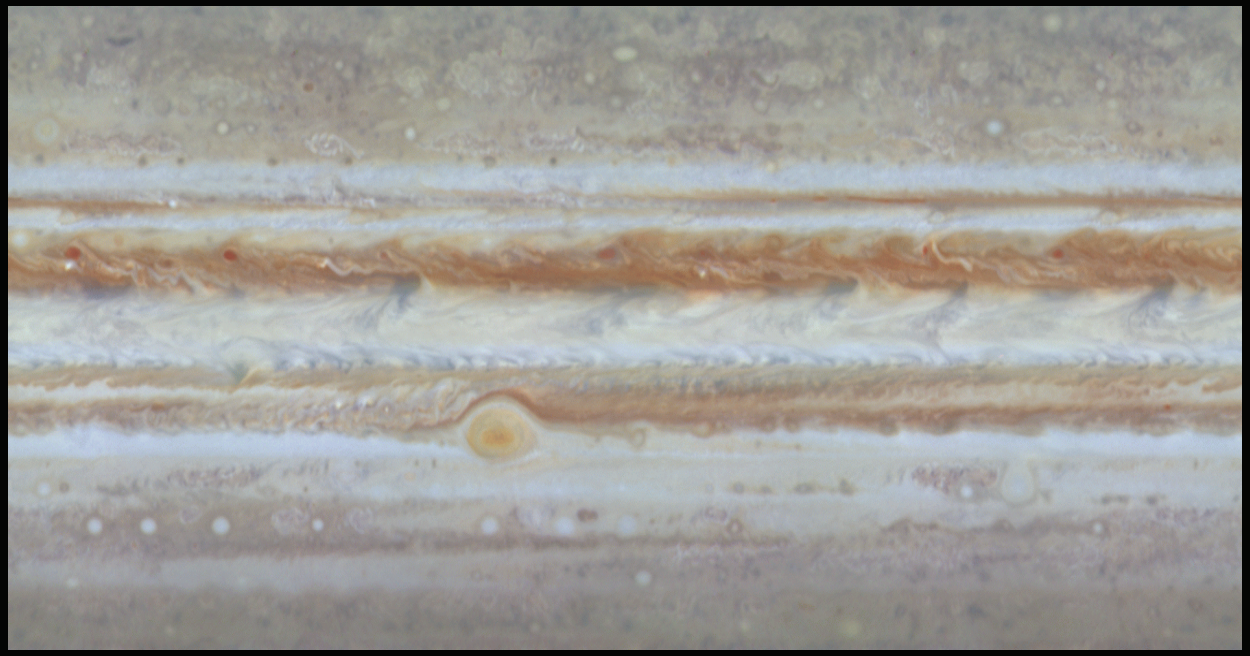




Piccialli et al.



Mean circulation on Jupiter

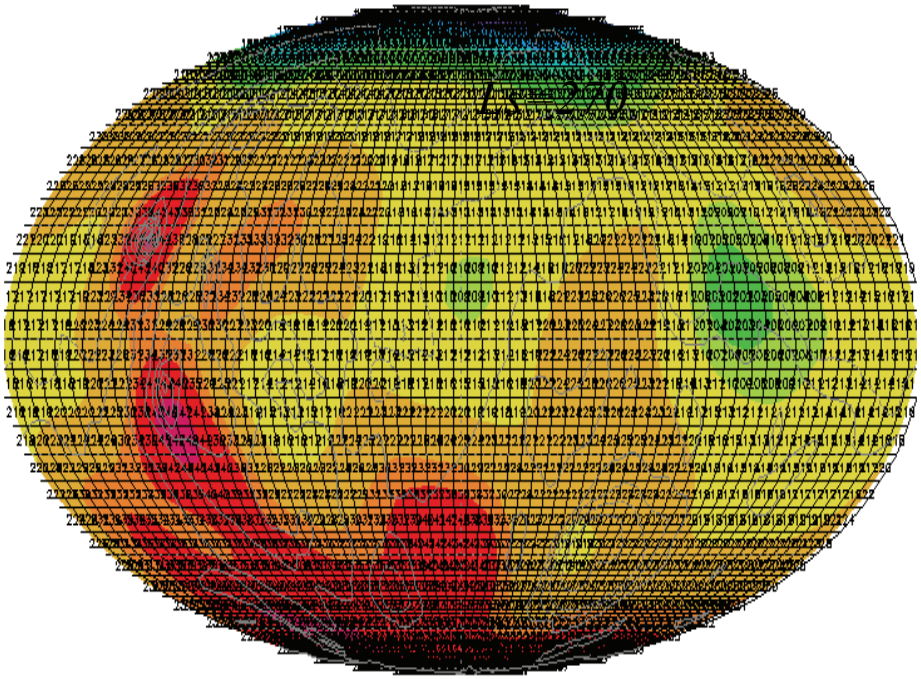


High
Low
High
Low
High

- "Zebra" of cyclonic (low P) dark belts and anticyclonic (high P) bright zones
- *Equatorial super-rotating jet*

General Circulation Model: the MAOAM example

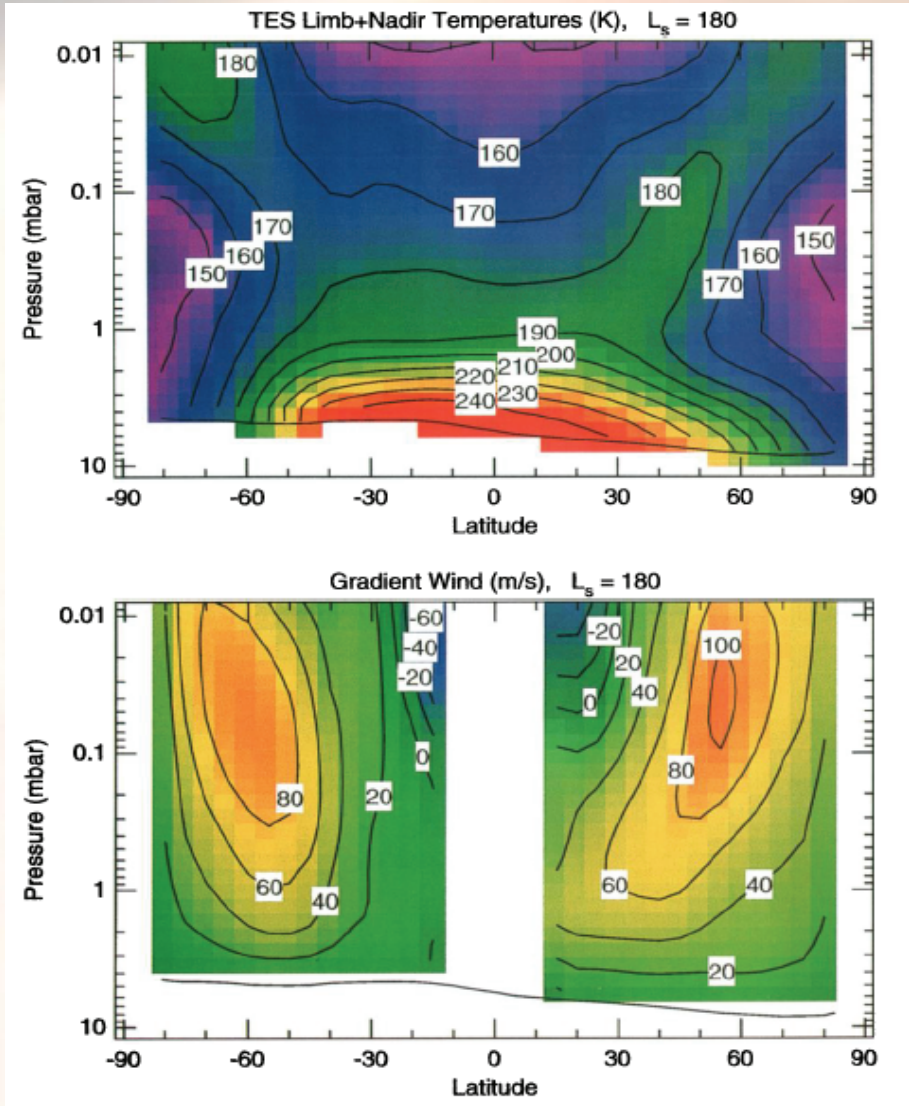
- Originate from Earth GCMs
- Grid point model from the surface to 120 km
- Variable vertical (~1 km) and horizontal (64x36) resolution
- Log-pressure coordinates (6 mb at z=0 km)
- Realistic topography and surface parameters: albedo and thermal inertia
- State-of-the-art physics package

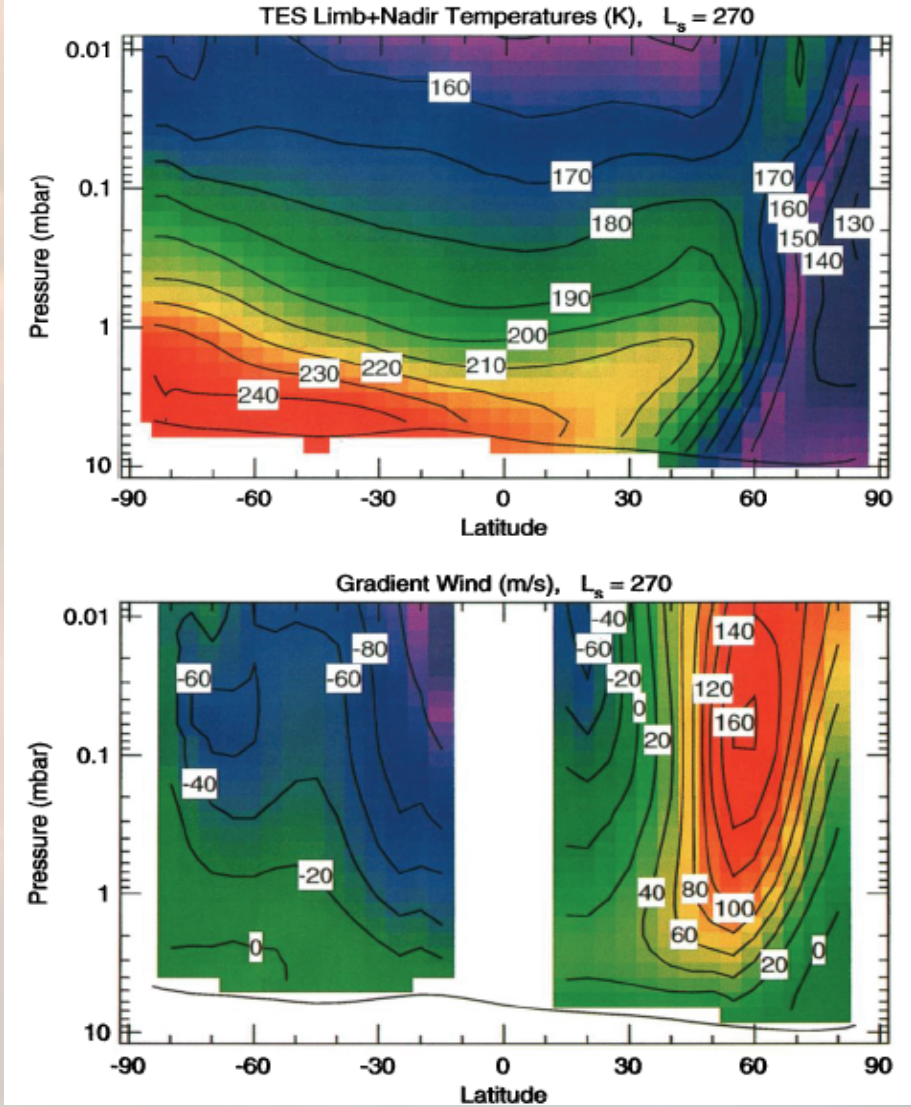


MAOAM atmospheric temperature

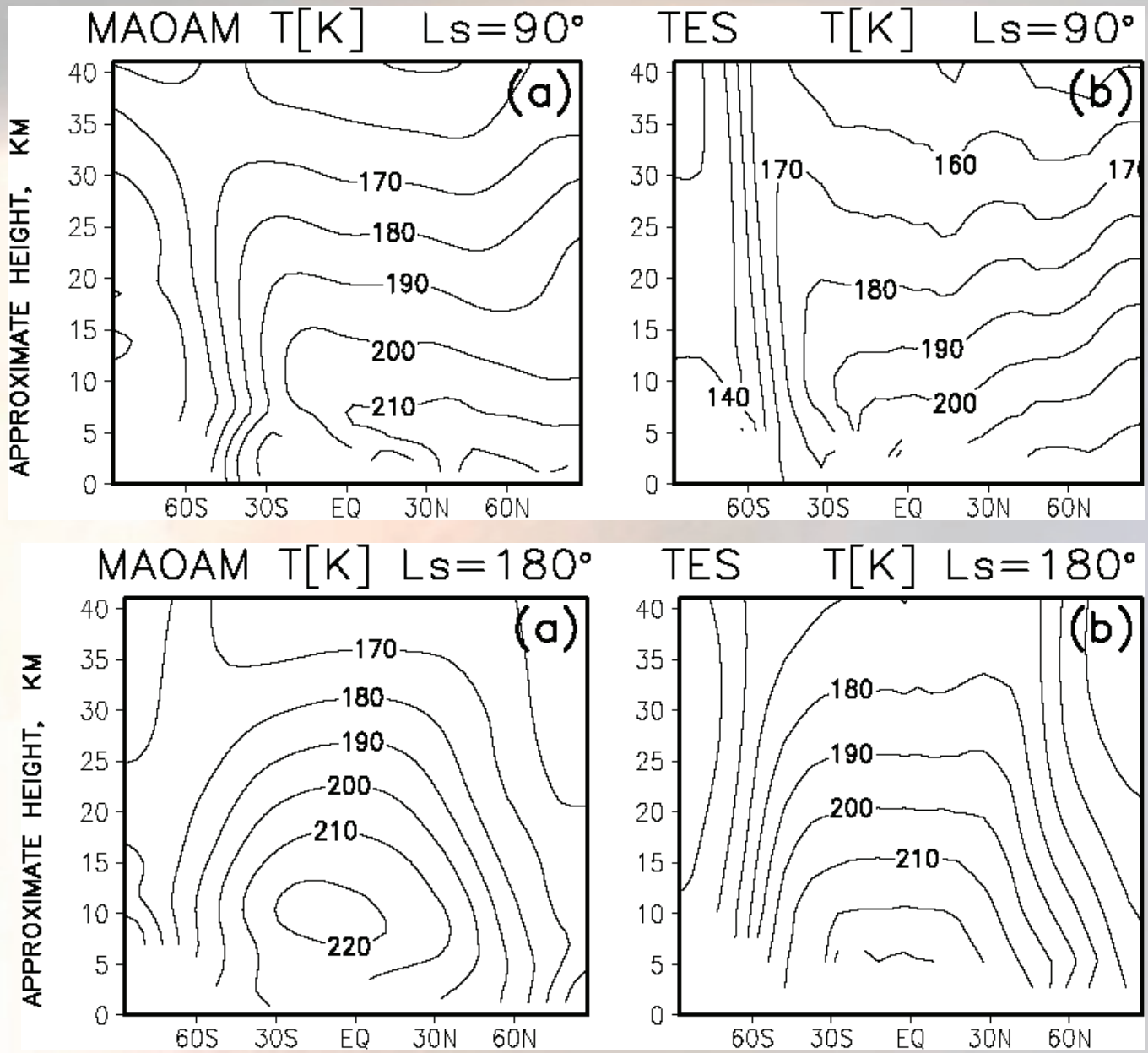
Hartogh, Medvedev, et al., JGR, 2005

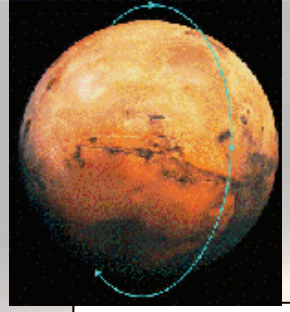
Temperature and thermal winds on Mars from TES/ MGS observations



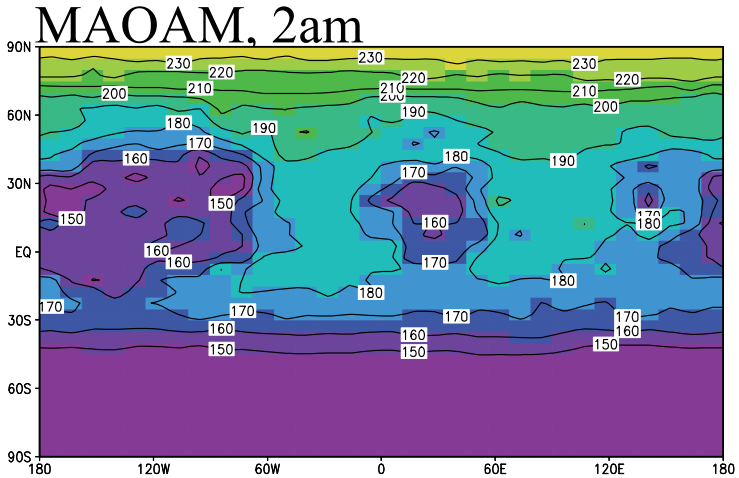


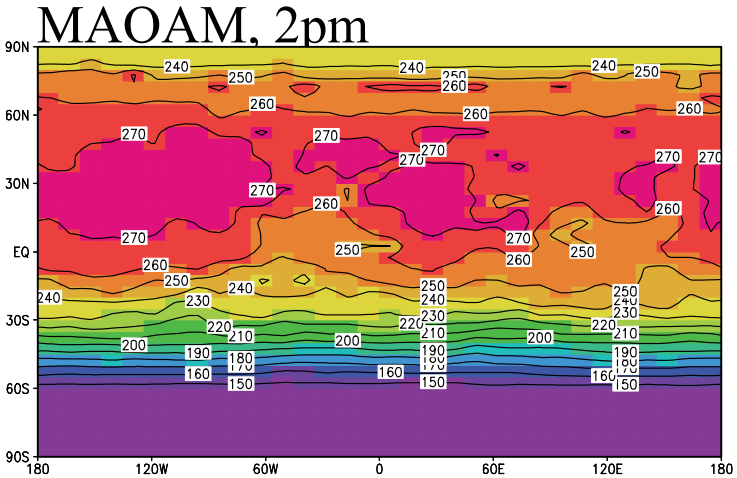
MAOAM-TES comparison

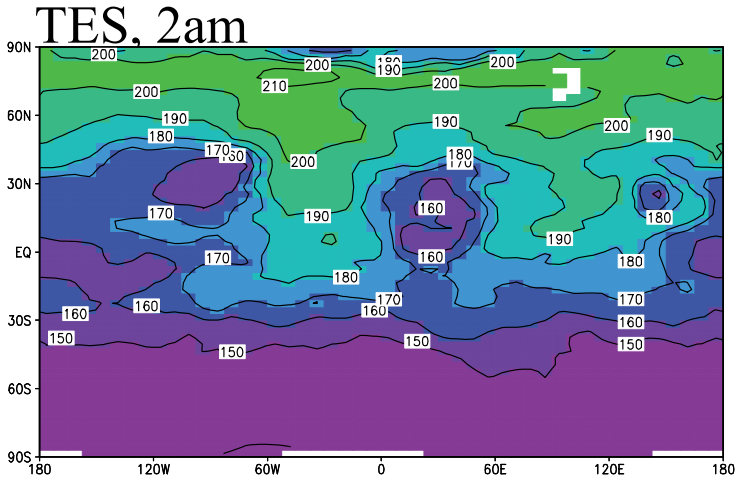


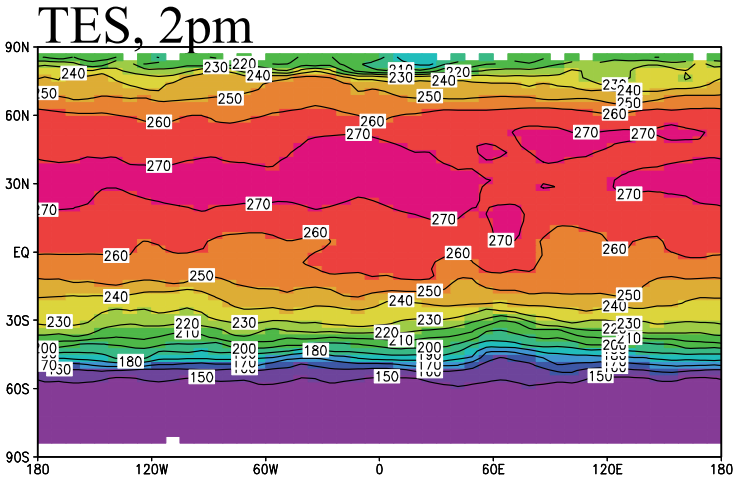


Mars surface temperature MAOAM vs. TES

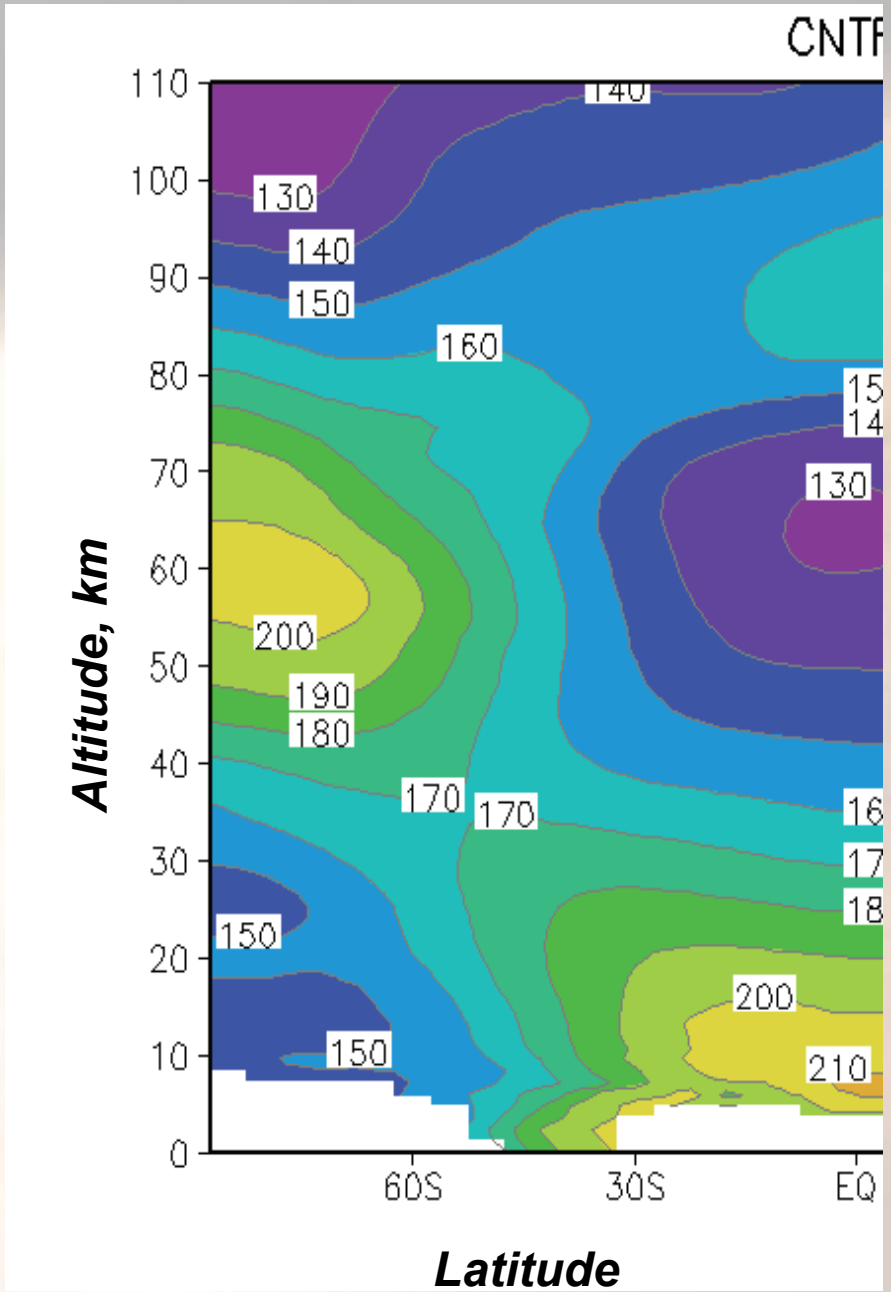




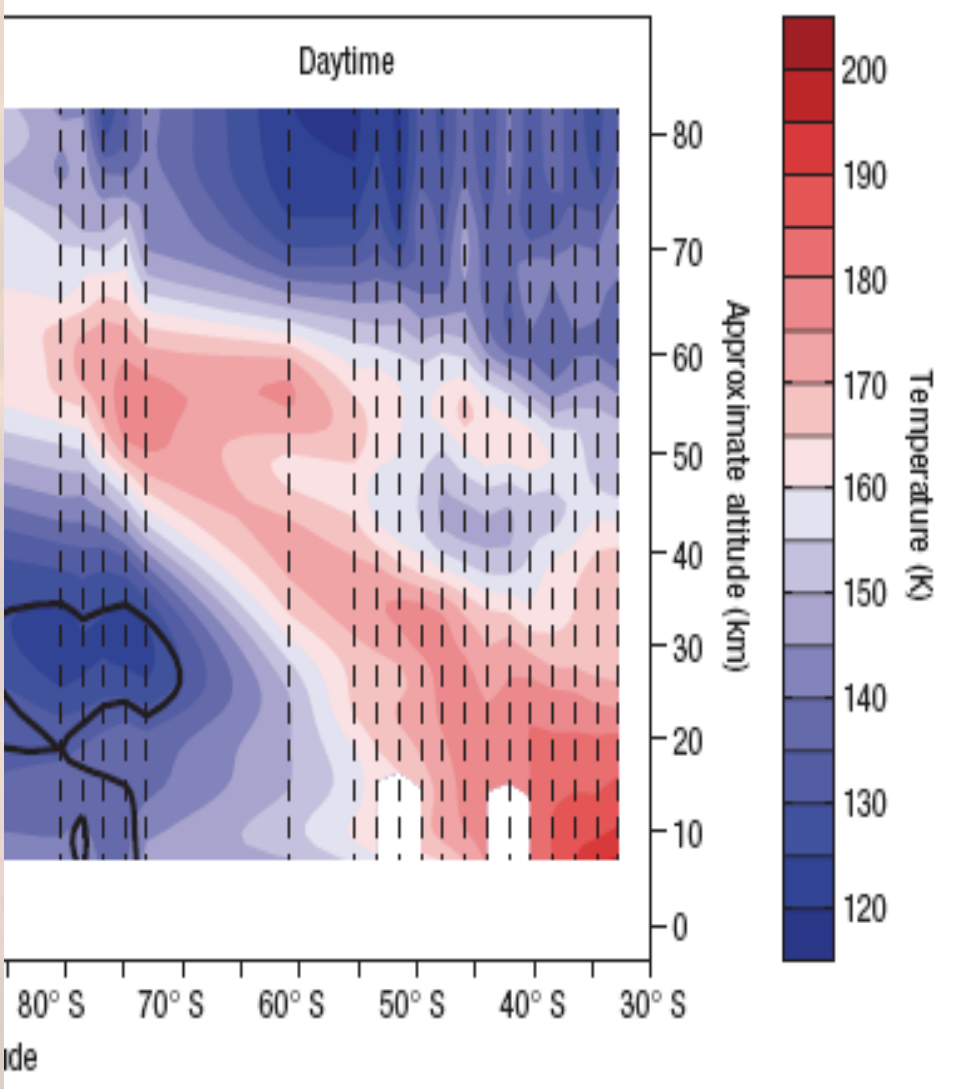




MAOAM predictions and MCS observation

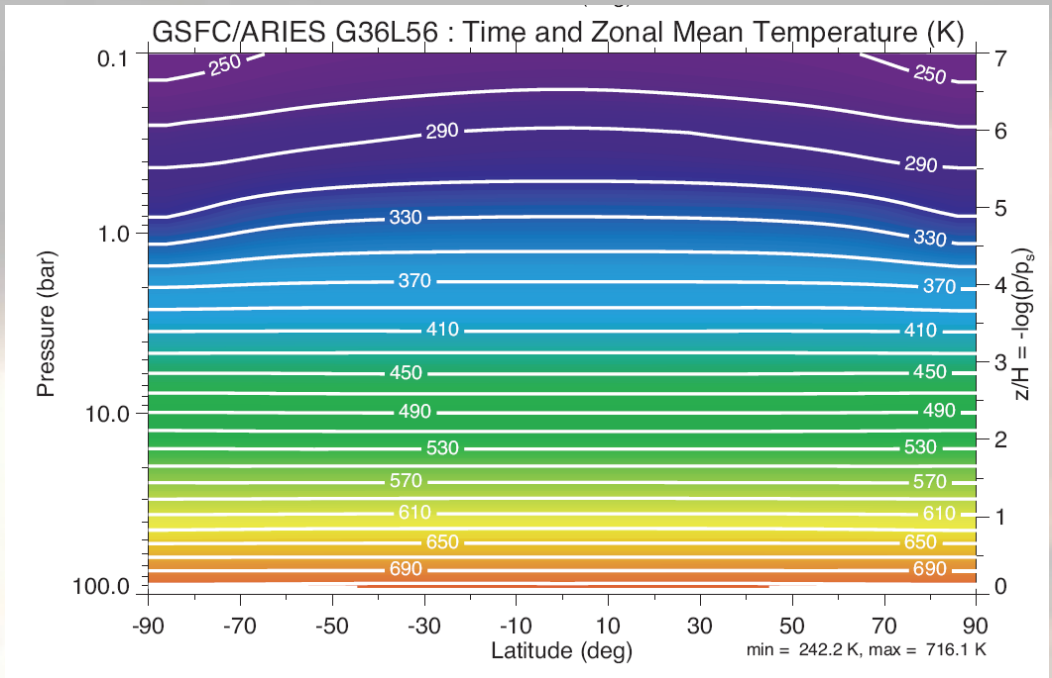


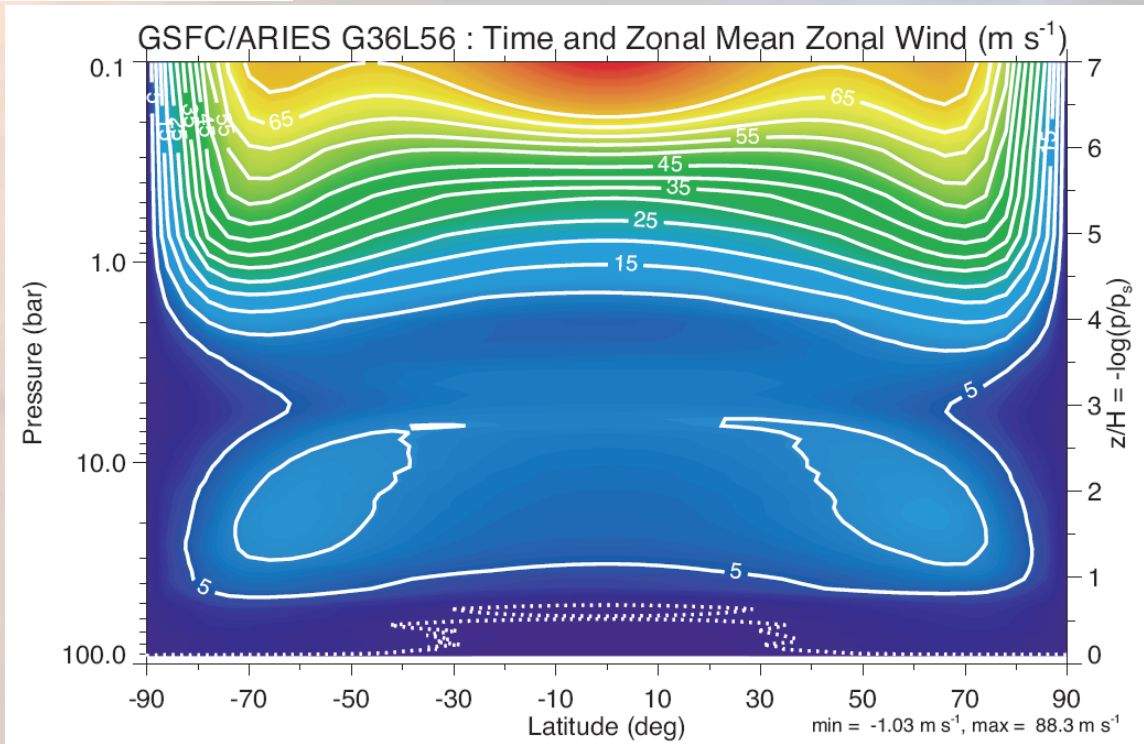
Hartogh et al, JGR, 2005



McCleese et al,
Nature Geoscience, 2008

Venus GCMs


GSFC/ARIES G36L56 : Time and Zonal Mean Temperature (K)
Pressure (bar)
z/H = -log(p/p_s)
Latitude (deg)
min = 242.2 K, max = 716.1 K


GSFC/ARIES G36L56 : Time and Zonal Mean Zonal Wind (m s-1)
Pressure (bar)
z/H = -log(p/p_s)
Latitude (deg)
min = -1.03 m s-1, max = 88.3 m s-1