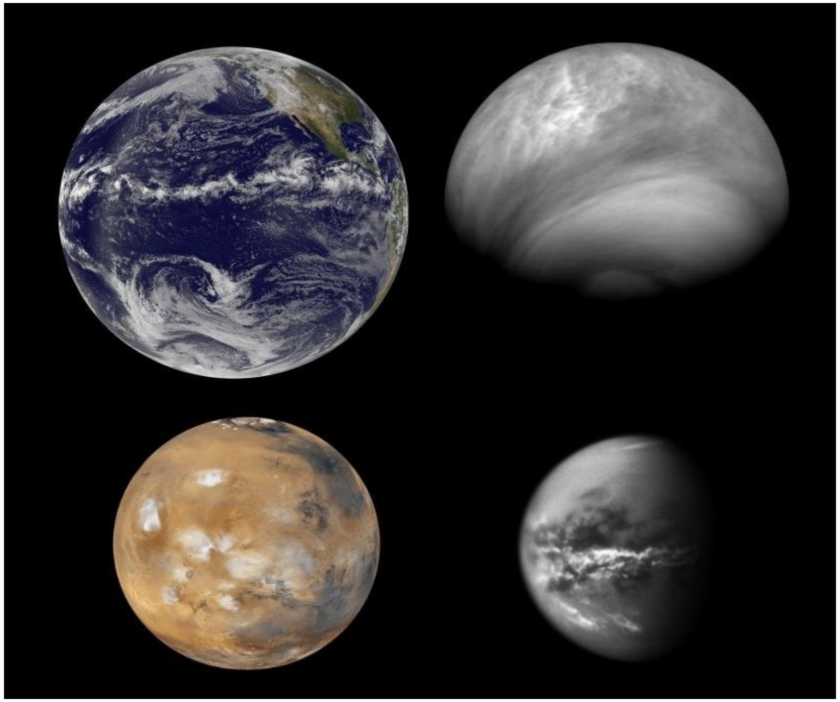
PLANETARY ATMOSPHERES

3. Atmospheric dynamics and circulation regimes



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PLANETARY ATMOSPHERES

Atmospheric dynamics and circulation regimes

- Equations of the atmospheric fluid
- Circulation patterns in terrestrial atmospheres
- Instabilities and wave activitiy
- Vortices

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Basic laws

Equation of state : ideal gas law

We consider the atmospheric gas as **ideal** :

$$\boldsymbol{p = \rho\ R\ T}$$

pressure — density — temperature

mean molecular mass

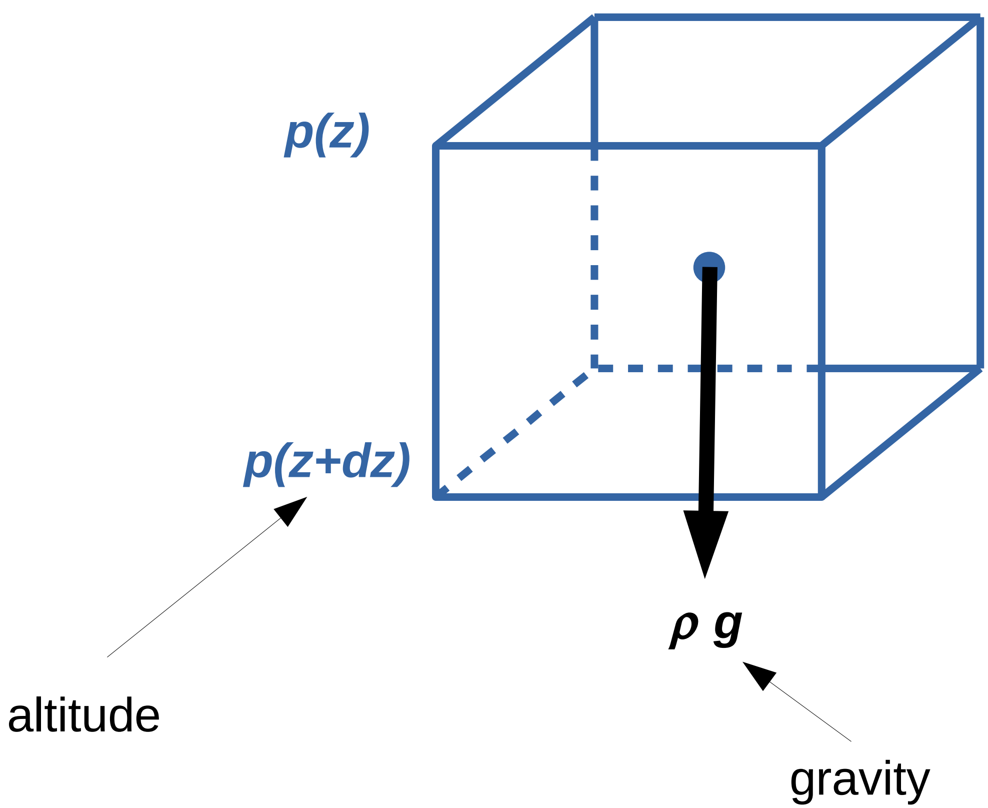
$$R = R^* / \mu$$

$R^* = 8.314\ J\ mol^{-1}\ K^{-1}$

Basic laws

Hydrostatic equilibrium

Fluid elemental particle **at rest**



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

Basic laws

Scale height

Combining ideal gas law and hydrostatic equilibrium :

$$\frac{dp}{p} = -\frac{g}{RT}dz \qquad H = \frac{RT}{g}$$

When *T* is taken as constant (**isothermal** atmosphere) :

$$p = p_0 \, e^{-z/H}$$

Basic laws

Adiabatic lapse rate

For a parcel recieving the heat quantity δq, from first principle of thermodynamics we get :

$$c_p dT = \frac{dp}{\rho} + \delta q$$

Specific heat capacity at constant pressure

When this parcel moves **adiabatically** :

$$\frac{dT}{T} = \frac{R}{c_p} \frac{dp}{p}$$

=>

$$\Gamma_d = \frac{dT}{dz} = -\frac{g}{c_p}$$

Basic laws

Potential temperature

Moving adiabatically a parcel from (p,T) to a reference pressure p_0, its temperature will be θ, defined as the potential temperature.

To get the expression for θ, we integrate this expression

$$\frac{dT}{T} = \frac{R}{c_p}\frac{dp}{p}$$

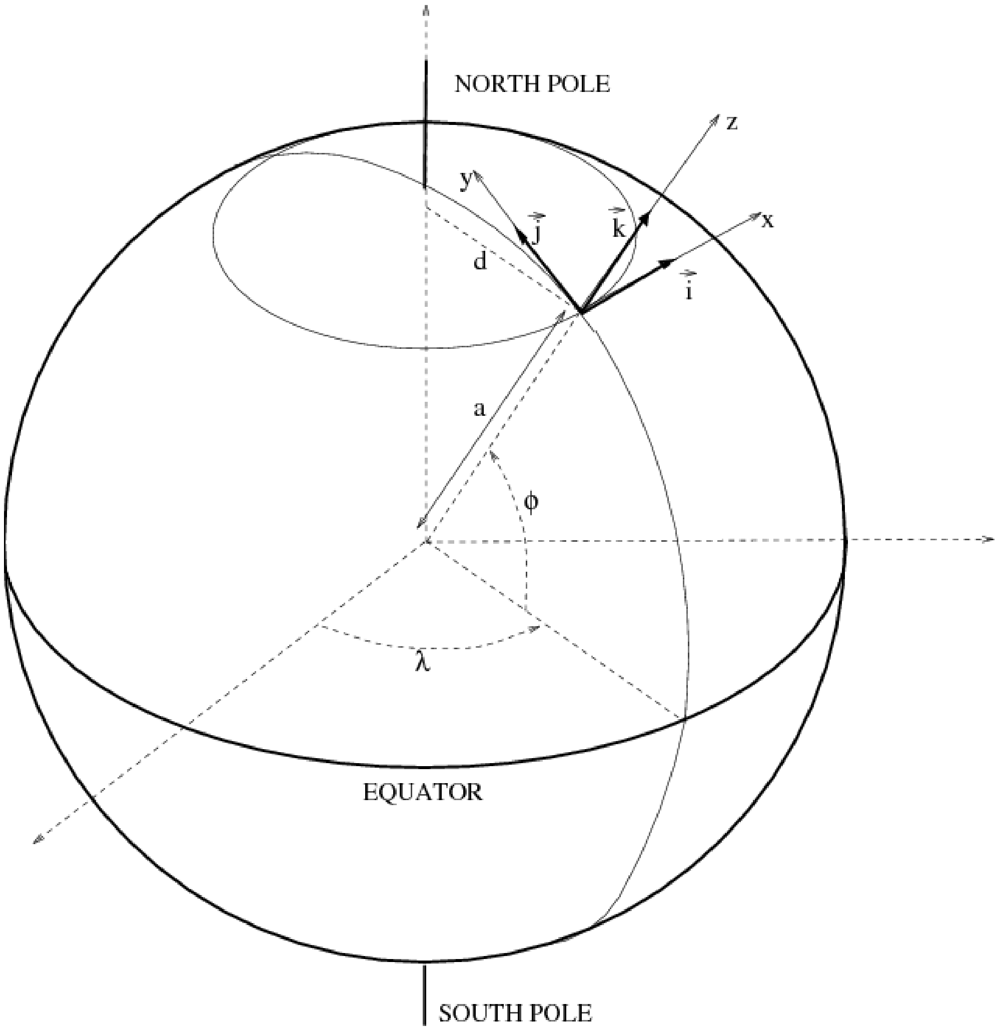
If c_p does not depend on T, we get

$$\theta = T\left(\frac{p_0}{p}\right)^{\kappa}$$

$\kappa = R / c_p$

Momentum equations

Spherical coordinates, local frame



Lagrangian view
vs
Eulerian view

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

Momentum equations

Momentum equations derived in the local frame

relative acceleration = pressure gradient + gravity + friction + Coriolis force + centrifugal force

$$\frac{du}{dt} - \frac{uv\tan\phi}{r} + \frac{uw}{r} = 2\Omega\left(v\sin\phi - w\cos\phi\right) - \frac{1}{\rho}\frac{\partial p}{\partial x} + Fr_x$$

$$\frac{dv}{dt} + \frac{u^2\tan\phi}{r} + \frac{vw}{r} = -2\Omega u\sin\phi - \frac{1}{\rho}\frac{\partial p}{\partial y} + Fr_y$$

$$\frac{dw}{dt} - \frac{u^2+v^2}{r} = 2\Omega u\cos\phi - \frac{1}{\rho}\frac{\partial p}{\partial z} - g + Fr_z$$

Momentum equations

Approximations

thin atmosphere : z << a

$$\frac{du}{dt} - \frac{uv\tan\phi}{a} + \frac{uw}{a} = 2\Omega\sin\phi v - 2\Omega\cos\phi w - \frac{1}{\rho}\frac{\partial p}{\partial x} + Fr_x$$

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

$$\frac{dw}{dt} - \frac{u^2+v^2}{a} = 2\Omega\cos\phi u - \frac{1}{\rho}\frac{\partial p}{\partial z} - g + Fr_z$$

- (green) Hydrostatic balance
- (green, red) **Geostrophic** balance
- (green, brown) **Cyclostrophic** balance
- (green, red, brown) Gradient wind balance
- (green, red, blue) Quasi-geostrophic equations
- (green, red, blue, brown) Primitive equations

Momentum equations

Thermal wind equation

Cyclostrophic balance

$$-\frac{1}{\rho}\frac{\partial p}{\partial y} = \frac{u^2 \tan\varphi}{a}$$

φ : latitude
a :planet radius

yields

with $\zeta = -\ln \dfrac{p}{p_{ref}}$

$$2u^2 \frac{\partial u}{\partial \zeta} = -\frac{R}{\tan\varphi}\left(\frac{\partial T}{\partial \varphi}\right)_{\zeta\ cst}$$

vertical zonal wind gradient

temperature meridional gradient

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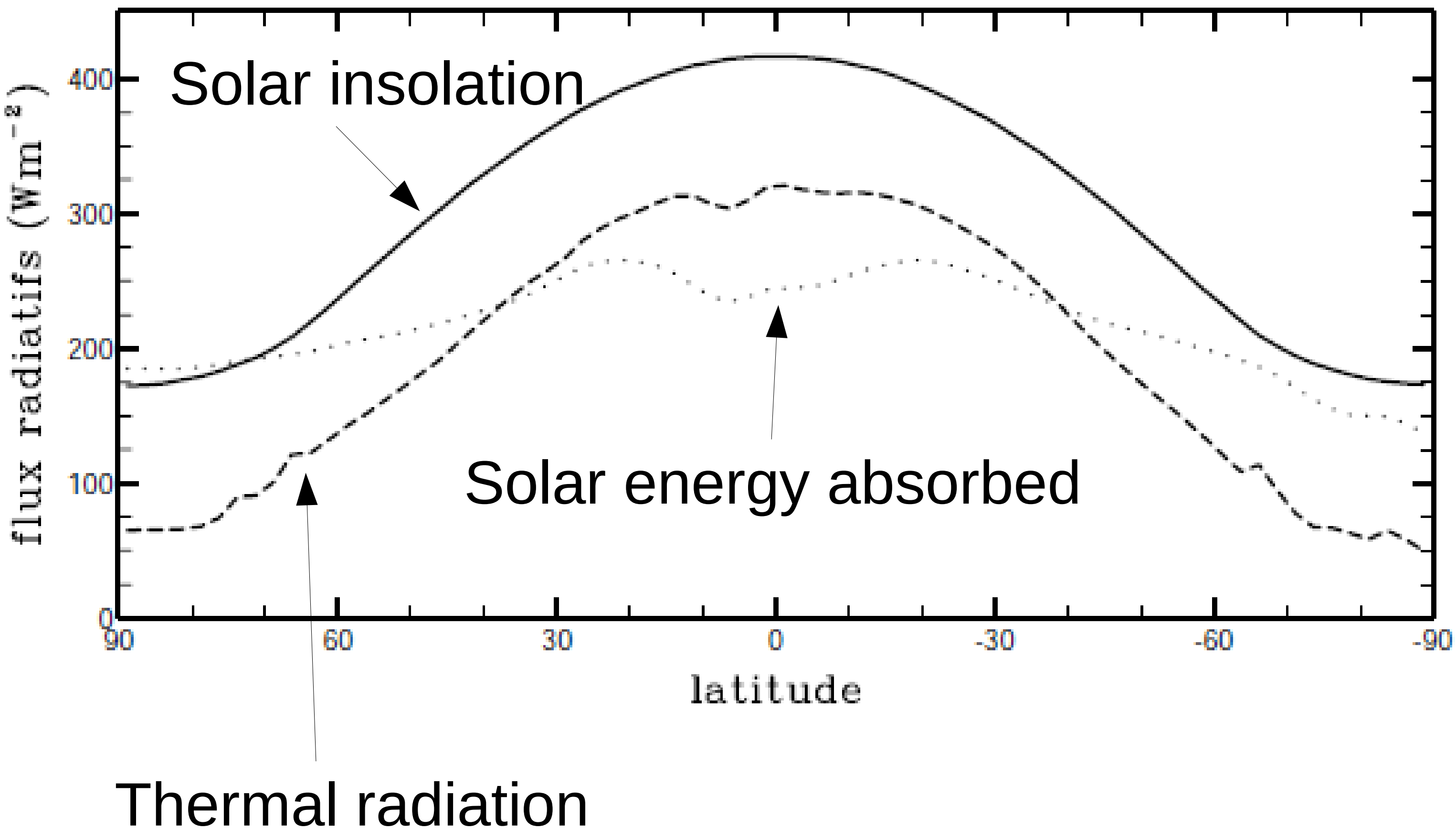
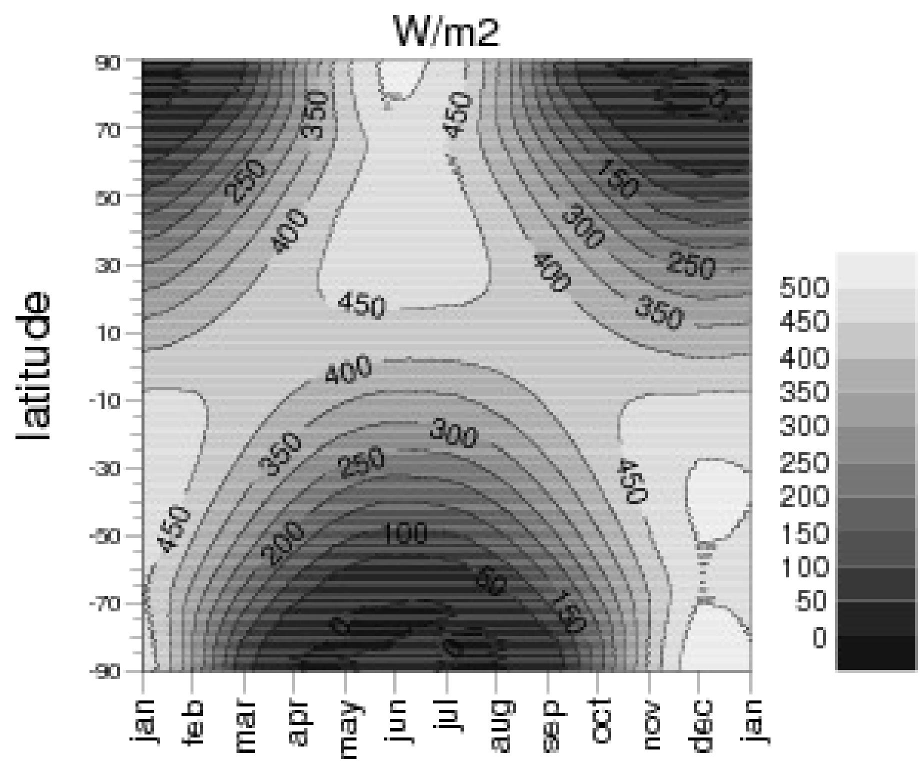
Energy redistribution

Annual average energy balance for Earth's atmosphere

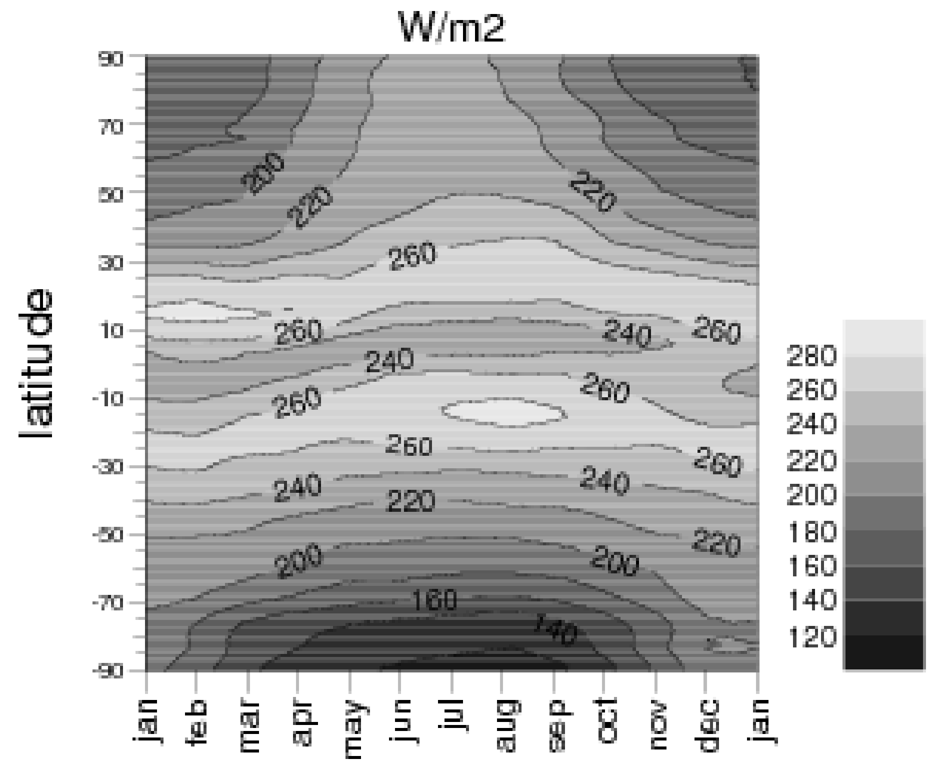


Energy redistribution

At top of atmosphere, as a function of seasons



Solar insolation

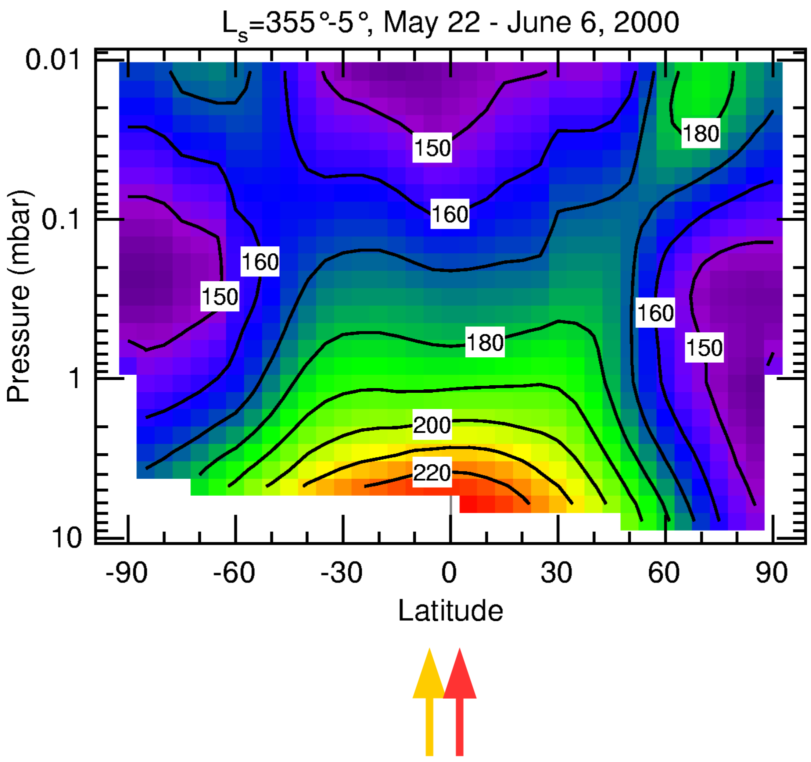


Thermal radiation

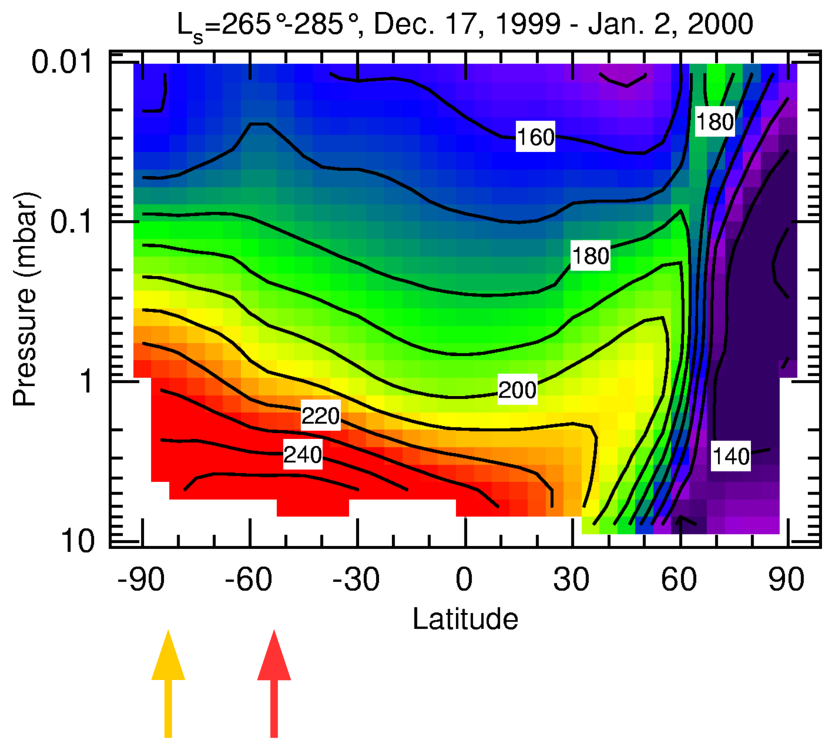
Energy redistribution

The case of Mars : role of surface thermal inertia

Equinox

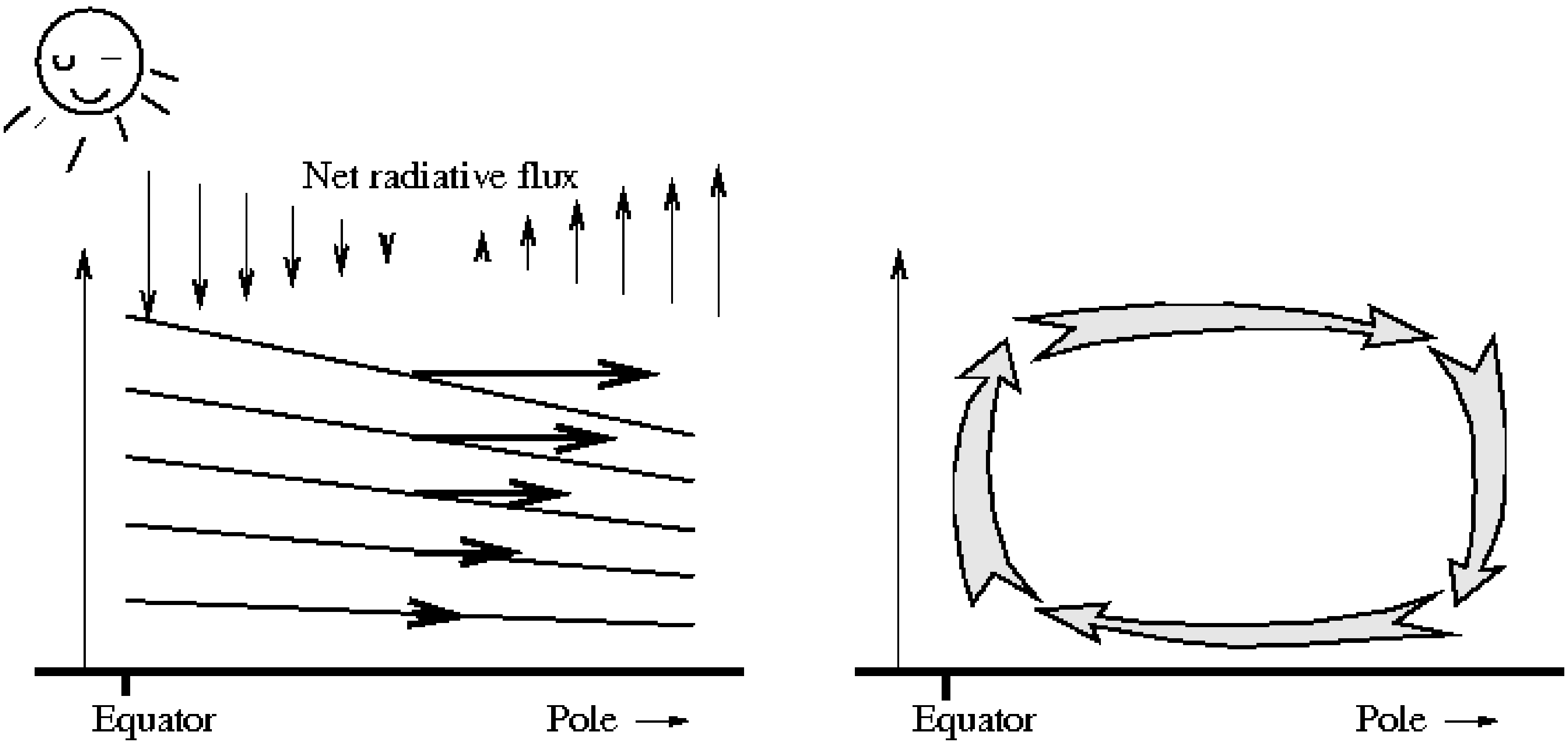


Solstice



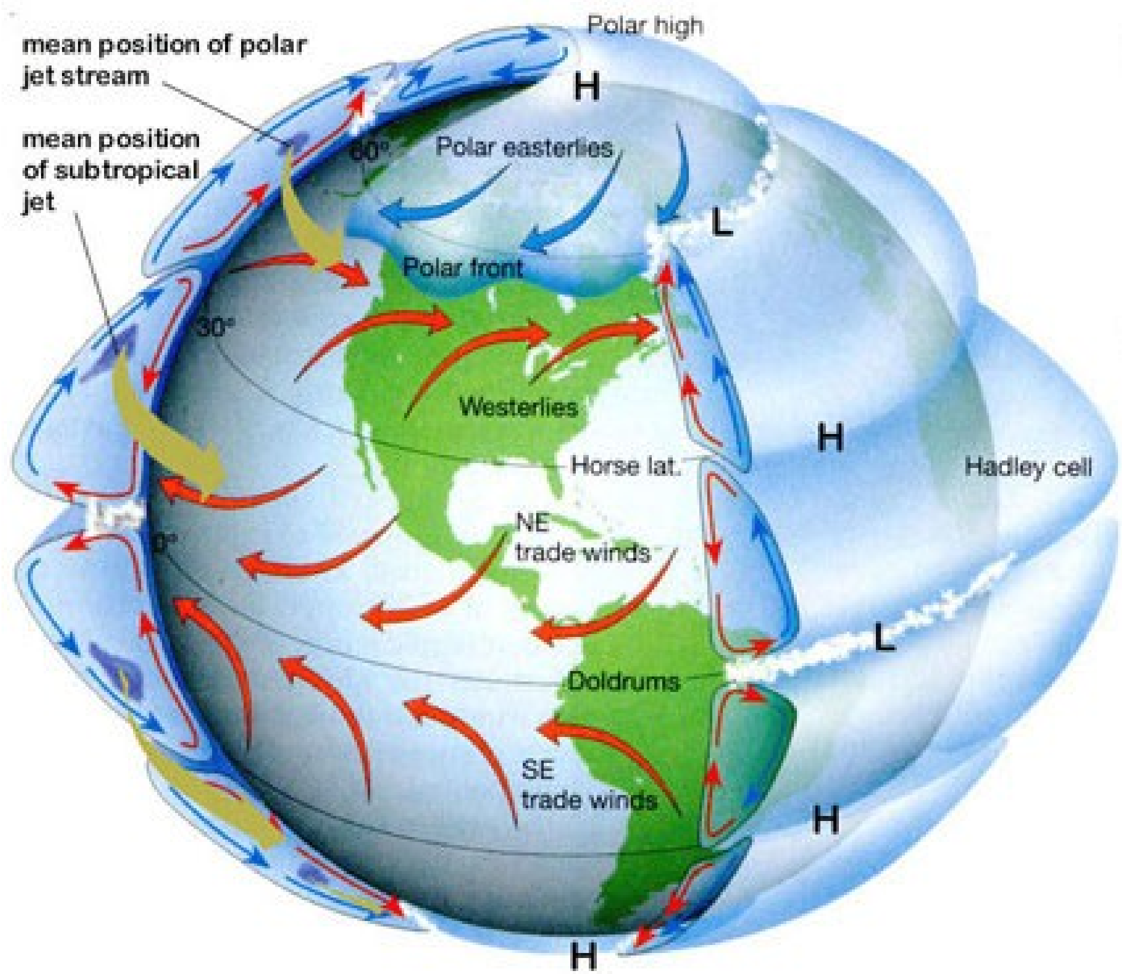
Meridional circulation

Driving mechanism



Meridional circulation

Effect on the zonal wind

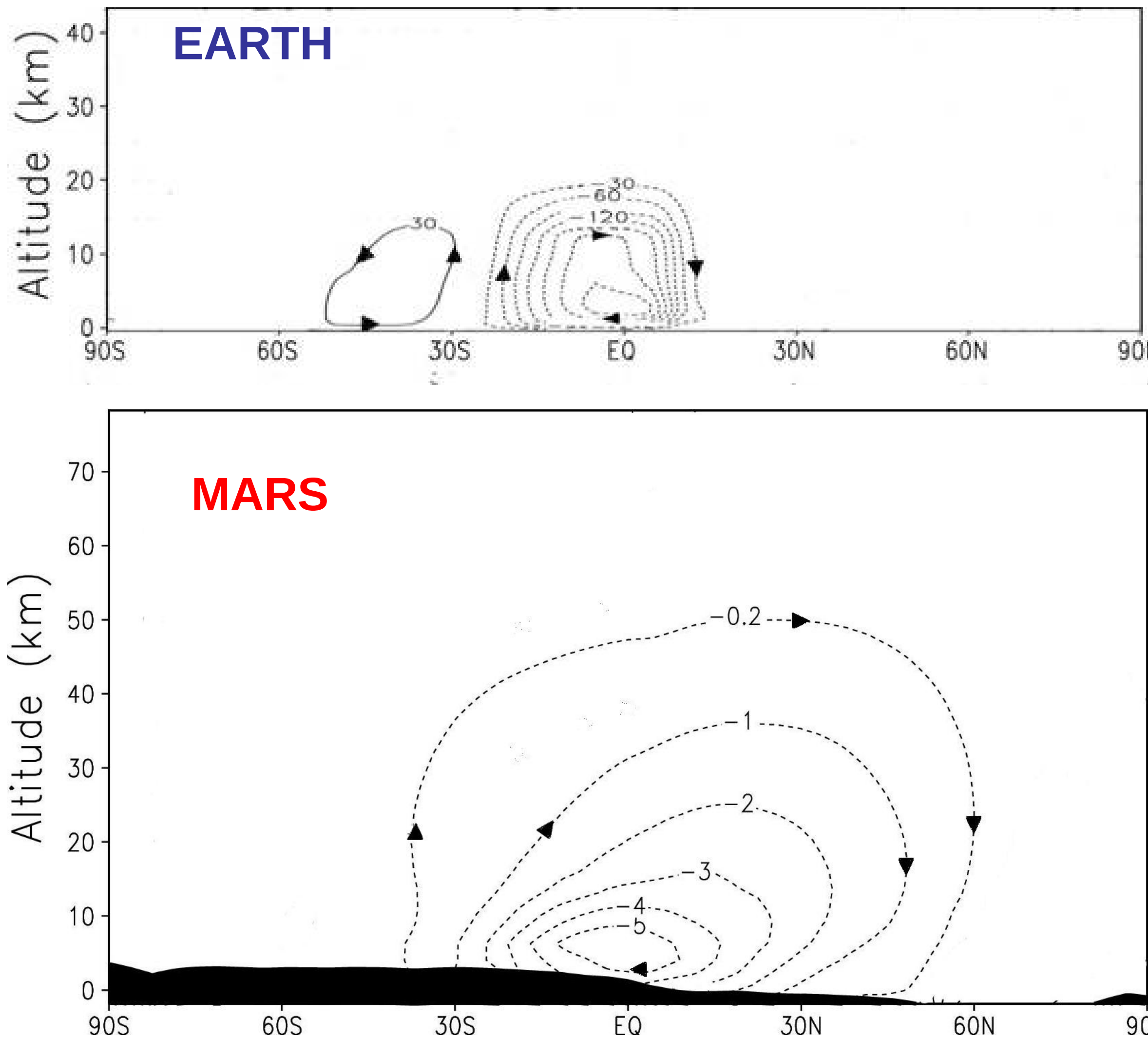


Meridional circulation

Mars Hadley cells

Mean meridional circulation (from simulations, mass flux in 10^9 kg s^{-1})

Northern winter solstice

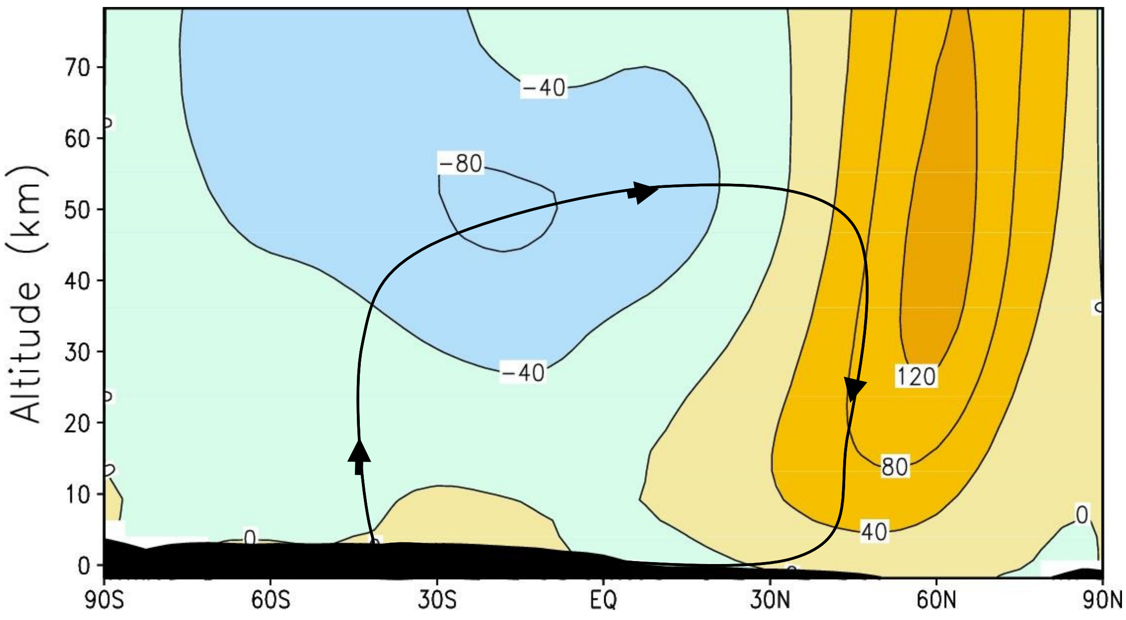


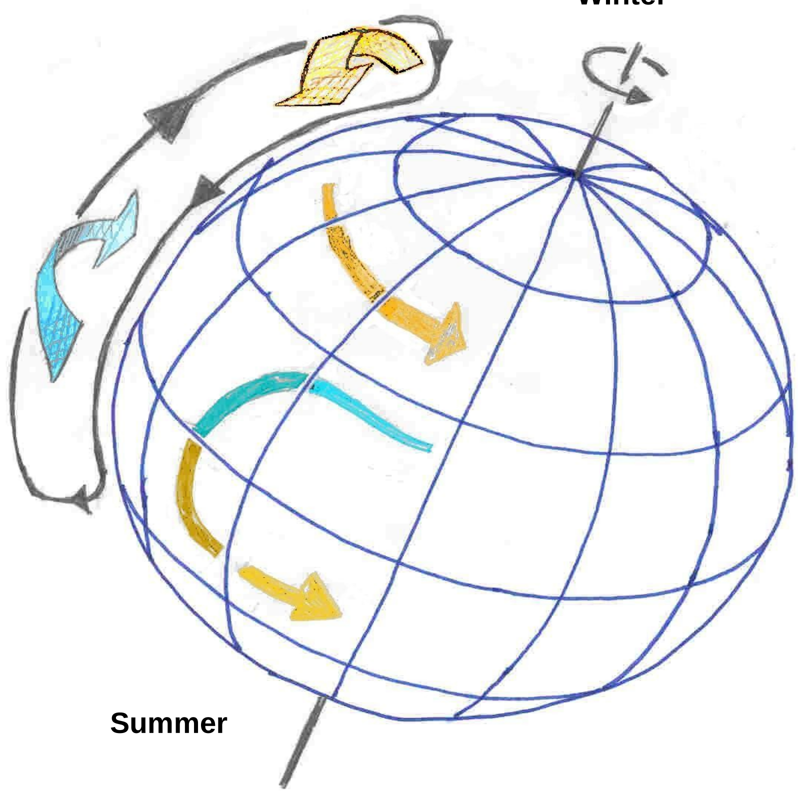
Meridional circulation

Mars Hadley cells

Mean zonal wind (m/s)

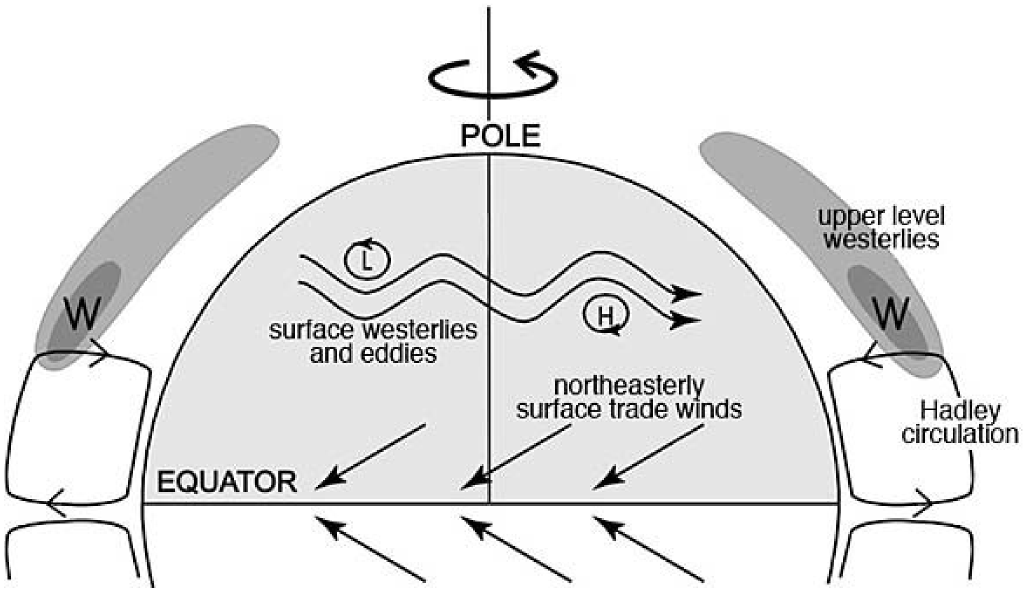
Northern winter solstice



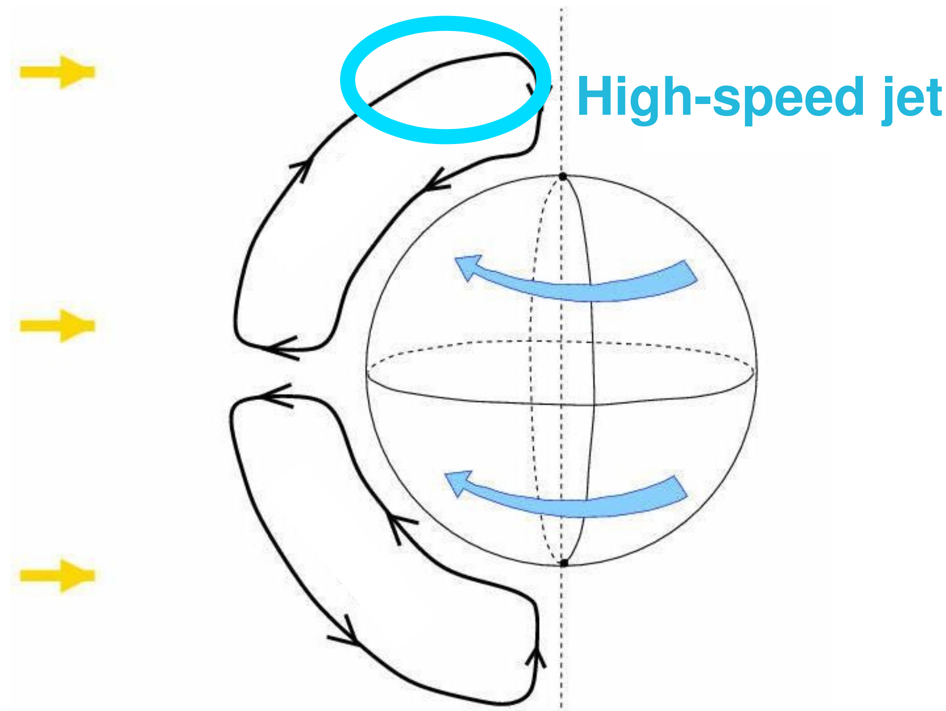


Meridional circulation

Venus and Titan : slow rotation
Extension of Hadley cells from equator to the poles



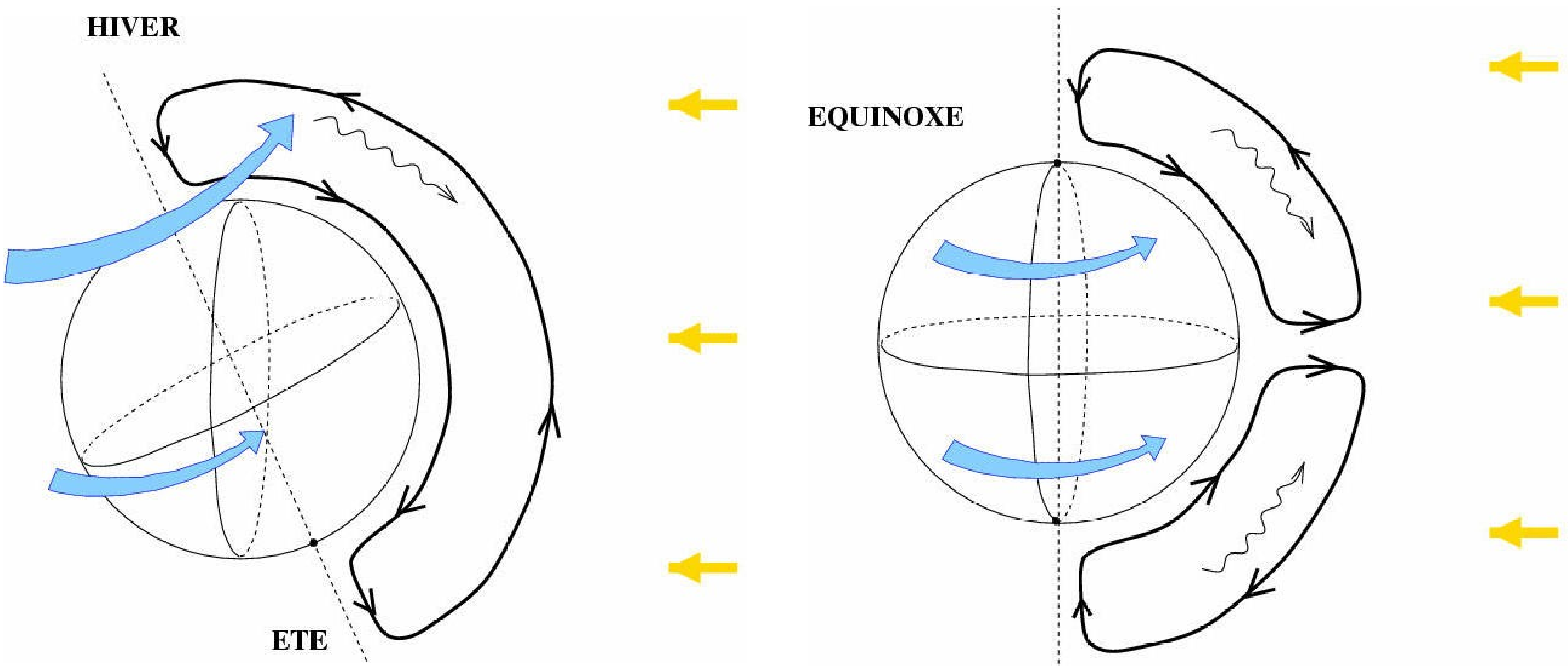
Earth



Venus

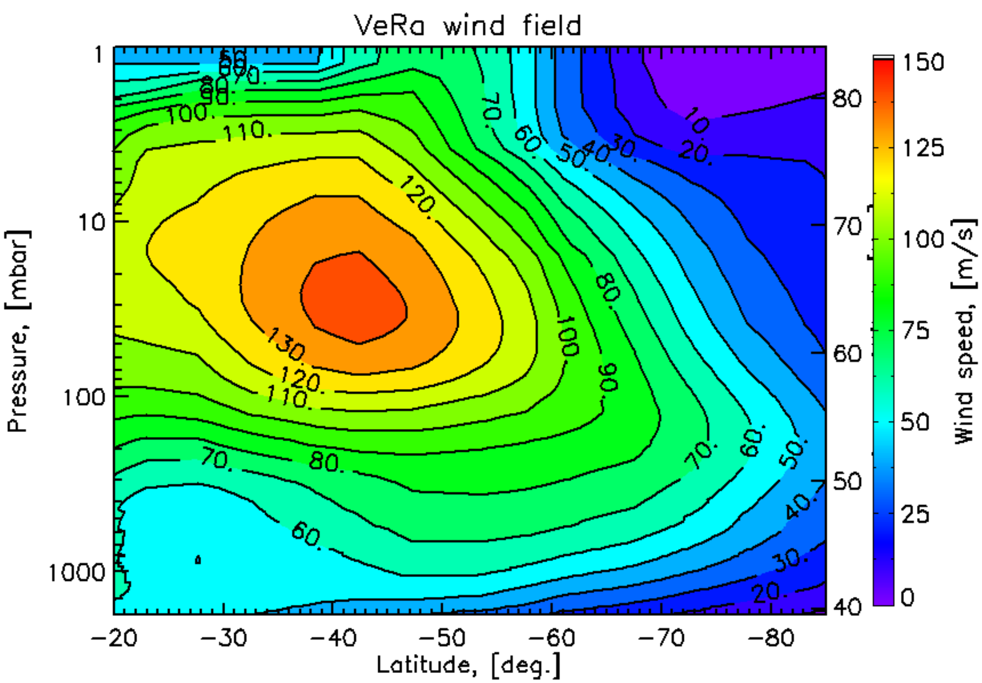
Meridional circulation

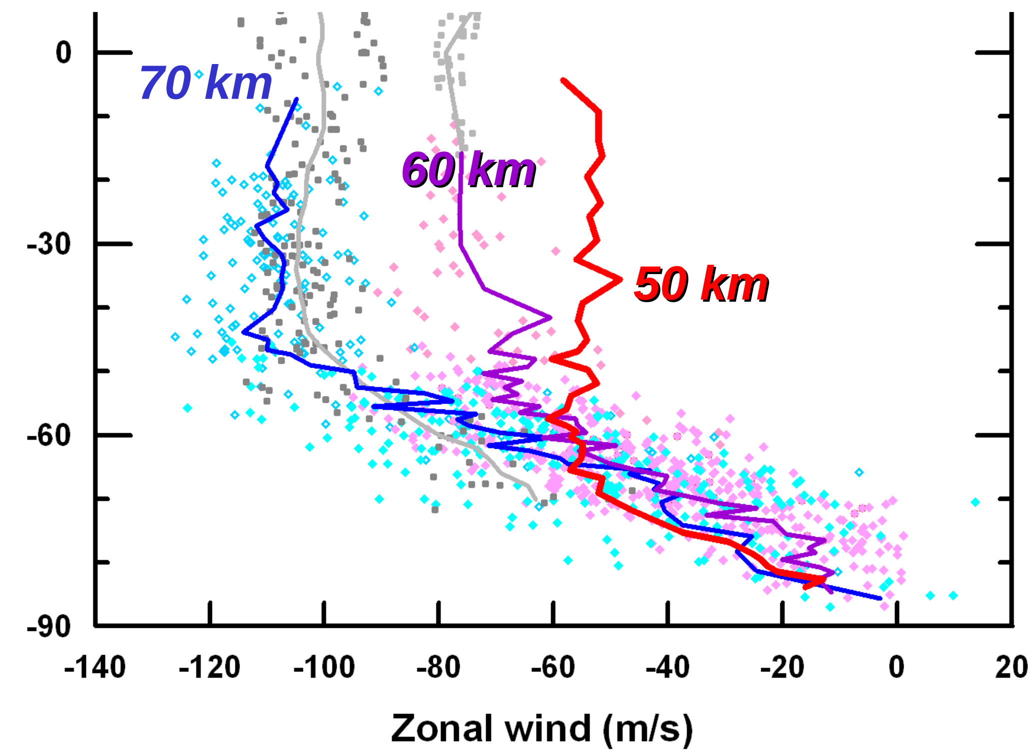
Titan : impact of seasons



Superrotation

Observations : Venus



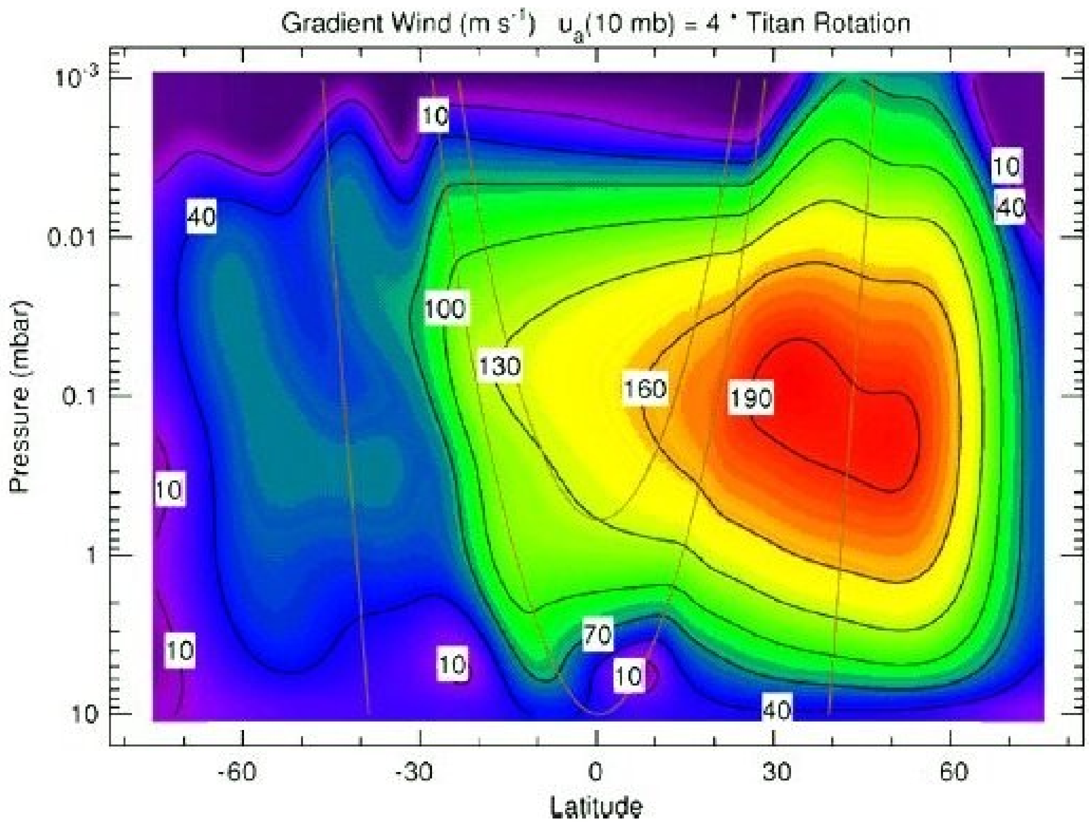


Venus Express/VeRa temperatures
=> thermal wind equation

Venus Express/VIRTIS
cloud tracking

Superrotation

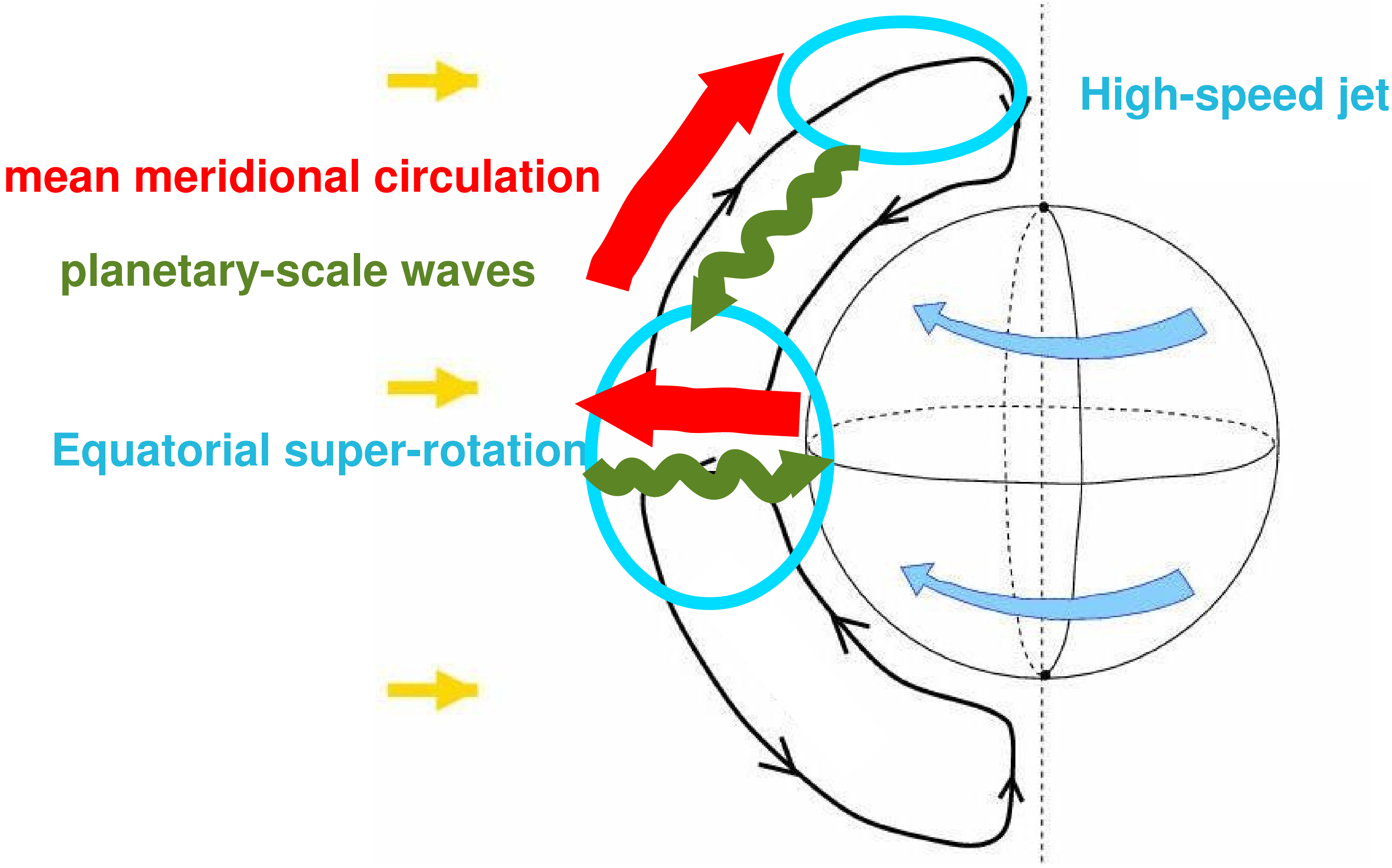
Observations : Titan



Cassini/CIRS thermal winds retrieval
(Ls ~ 300°, northern winter)

Superrotation

Mechanism : angular momentum transport



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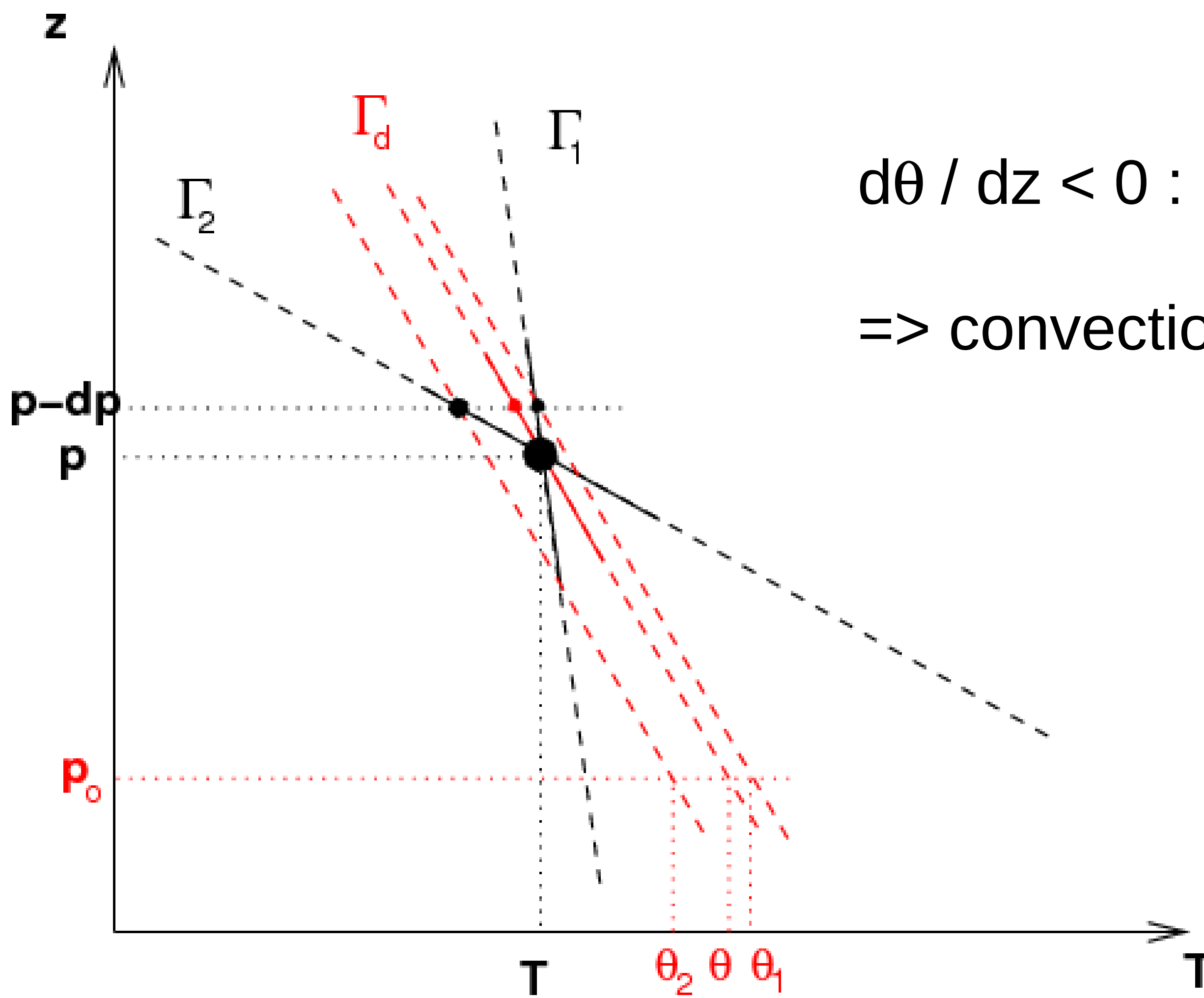
Convection

Buoyancy



$d\theta / dz < 0$: unstable

=> convection

Convection

Static stability

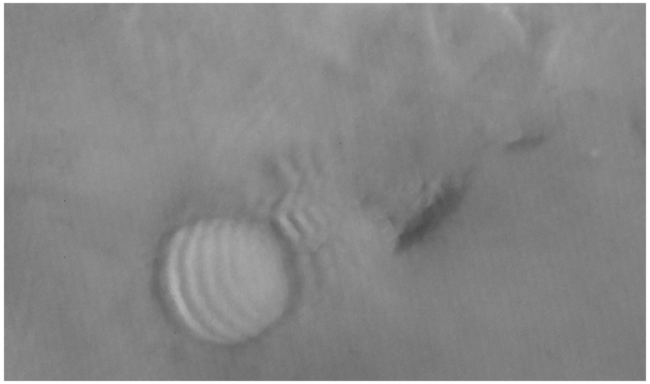
$$S = \frac{dT}{dz} + \frac{g}{c_p}$$

Brunt-Väisälä

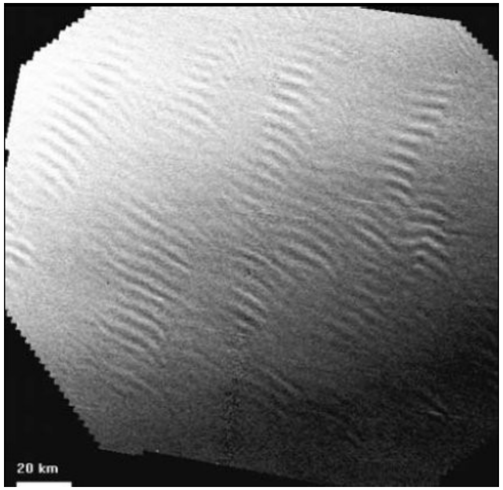
$$N_B^2 = \frac{g}{T} S = \frac{g}{\theta} \frac{d\theta}{dz}$$

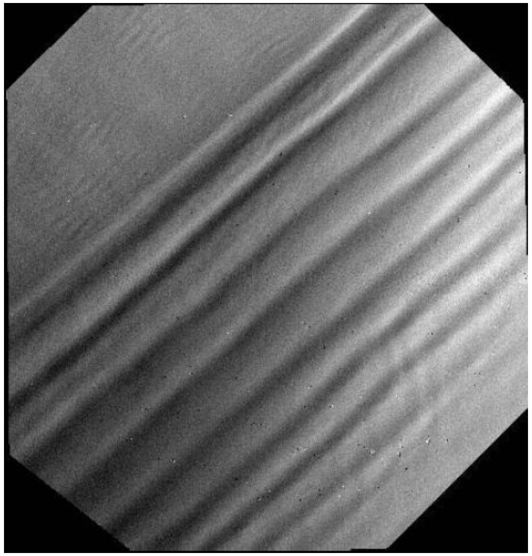
Gravity waves

Mars



Venus

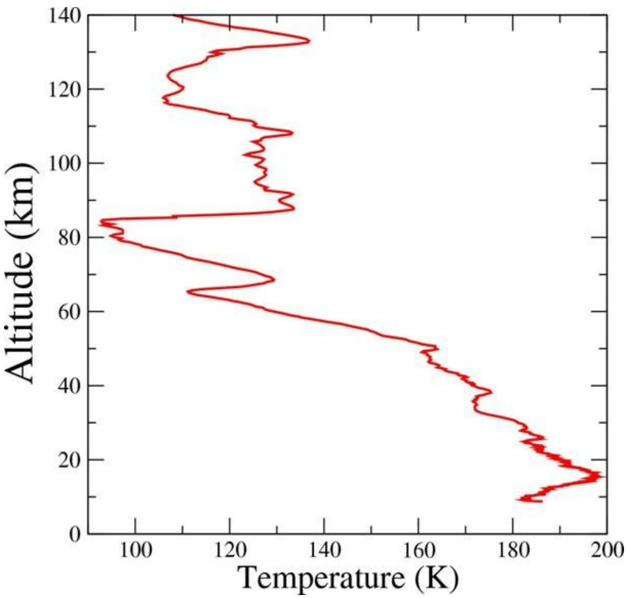




Gravity waves

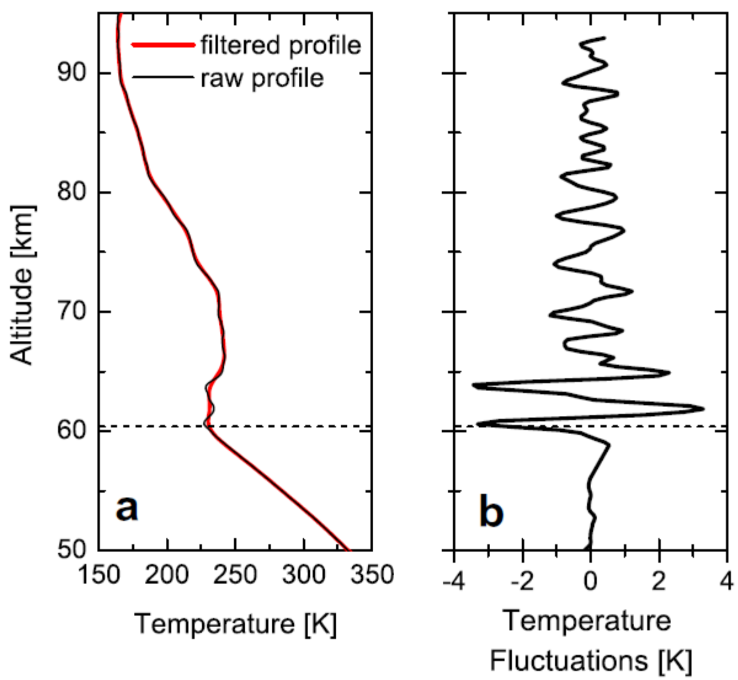
Mars

Pathfinder entry profile



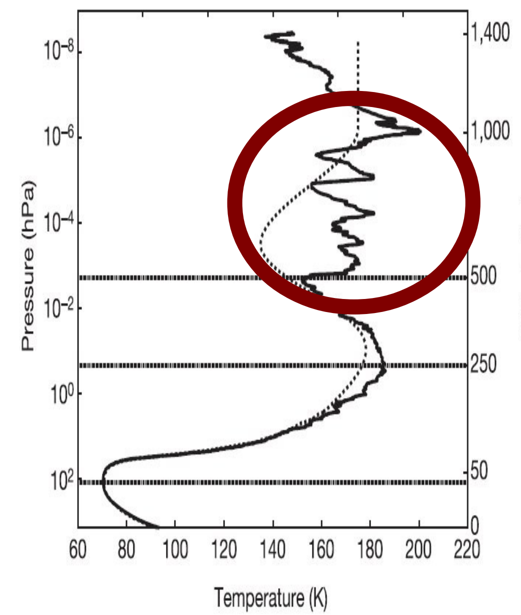
Venus

VenusExpress/VeRa



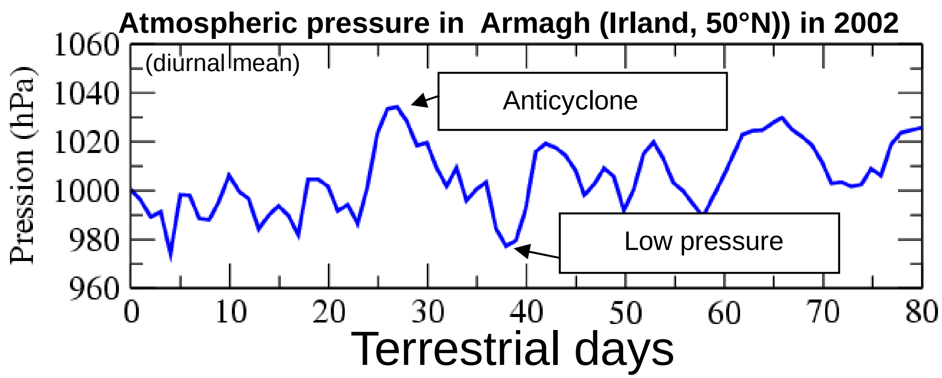
Titan

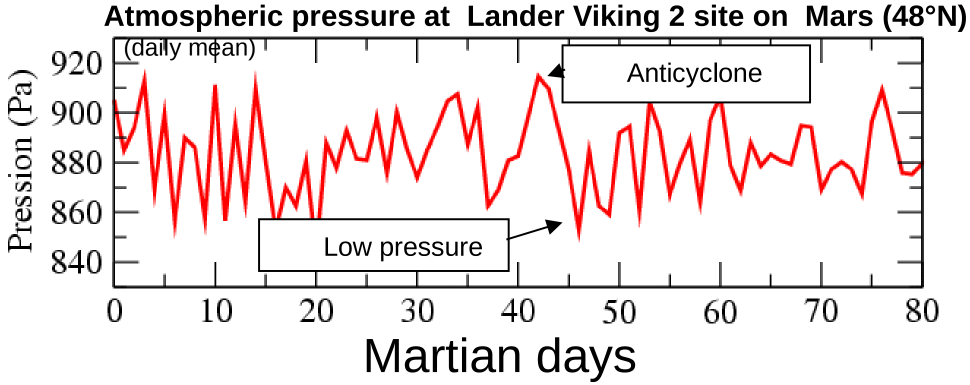
Huygens/HASI

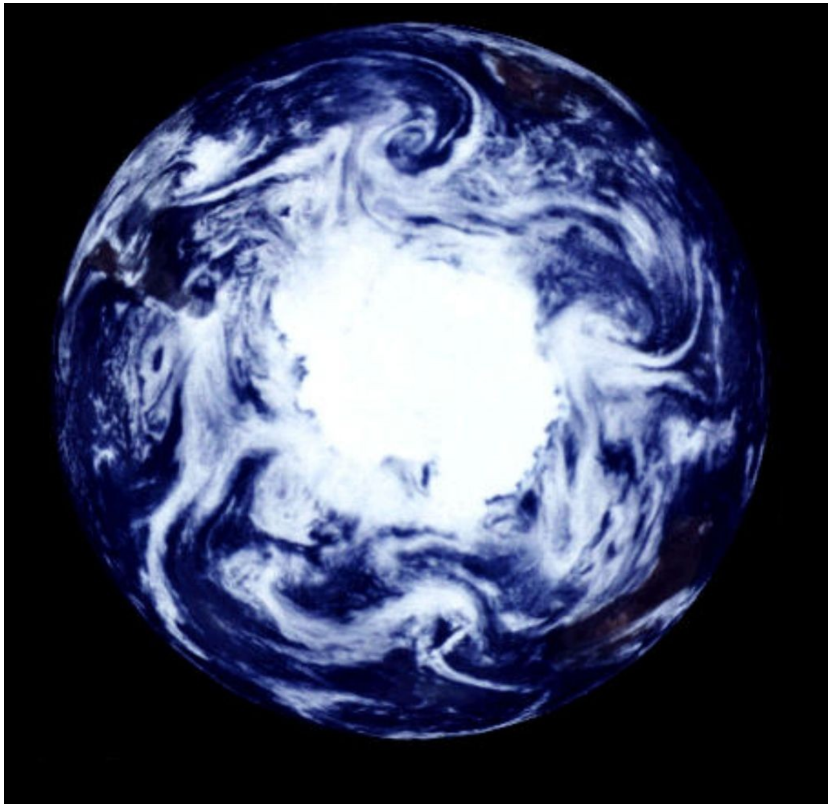


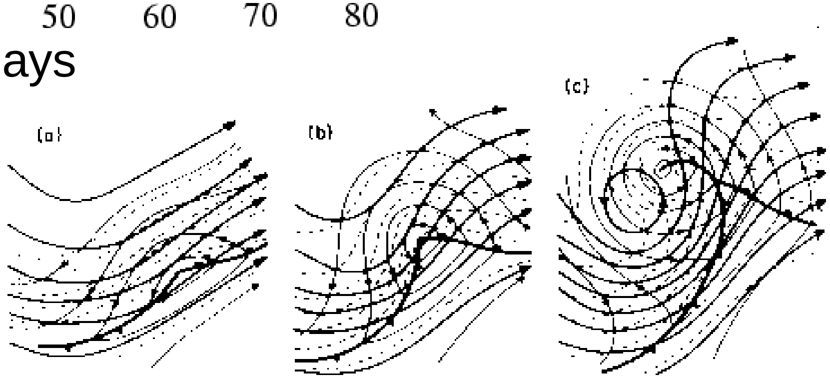
Planetary-scale waves

Baroclinic waves





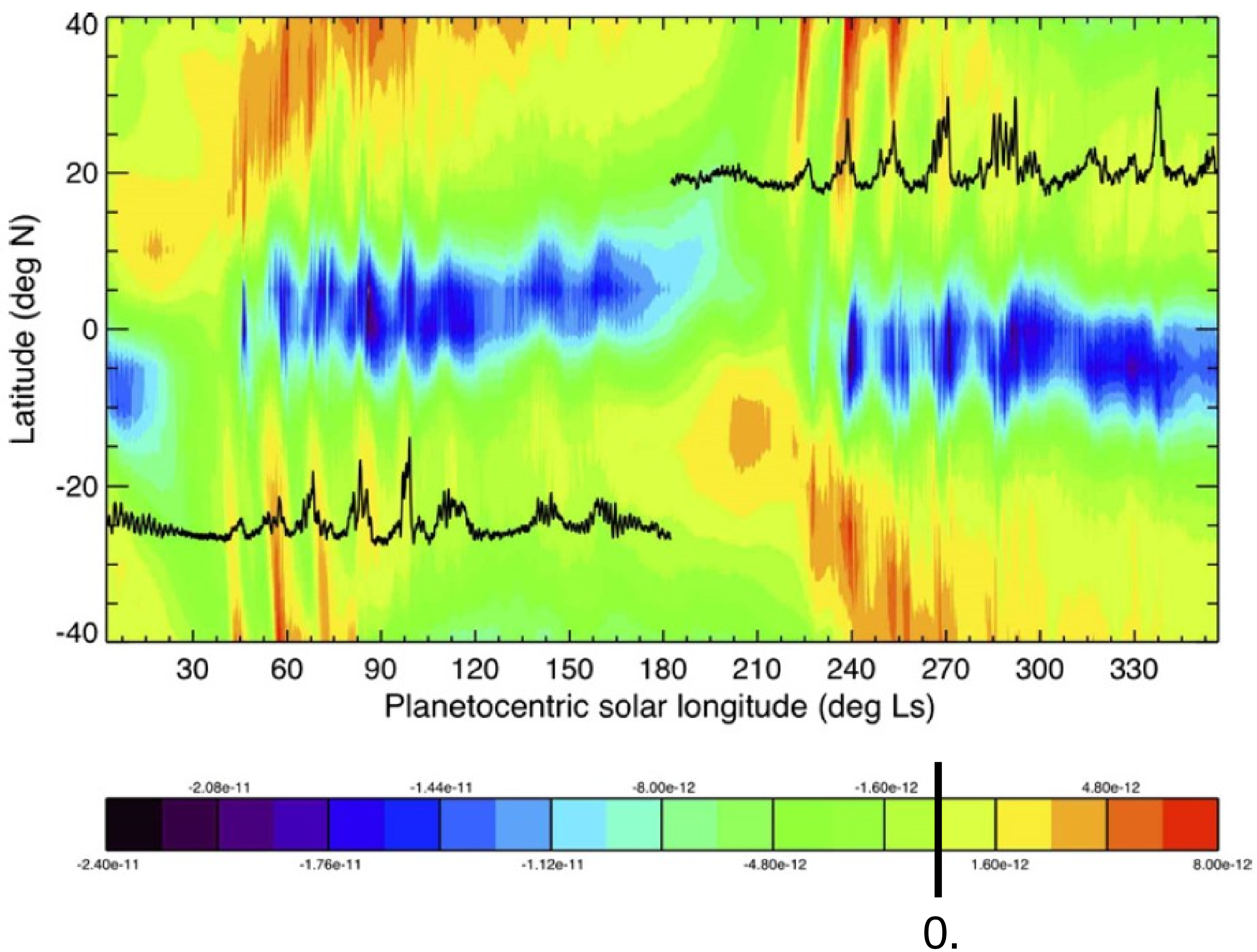




Planetary-scale waves

Barotropic waves

Barotropic instability criterion (colors)
and angular momentum transport by waves (black line)
in a climate model of Titan's stratosphere



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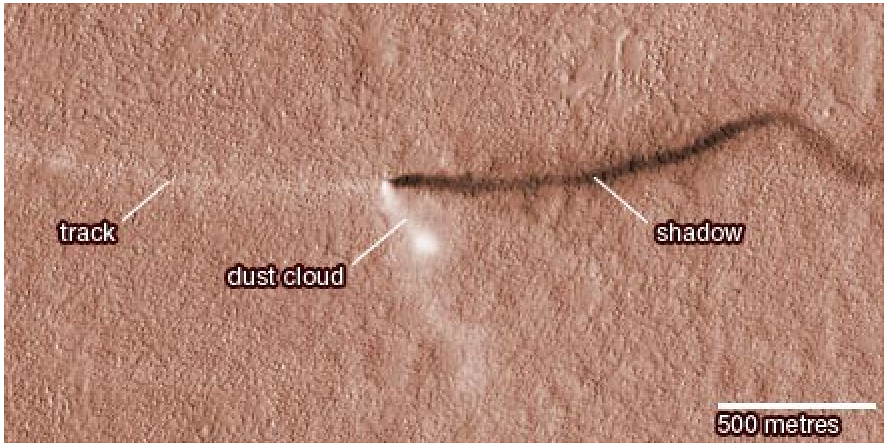
Small-scale vortices

Dust devils

EARTH

MARS



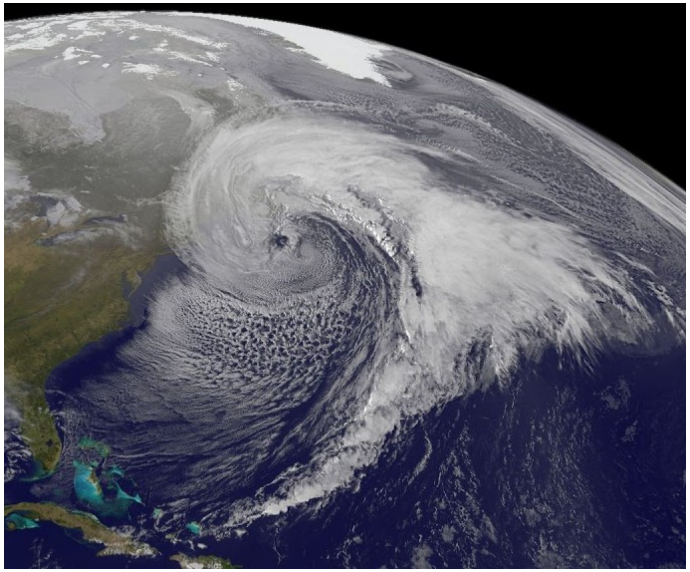
Small-scale vortices

Tornadoes

Synoptic vortices

Earth hurricanes

Earth extra-tropical cyclones

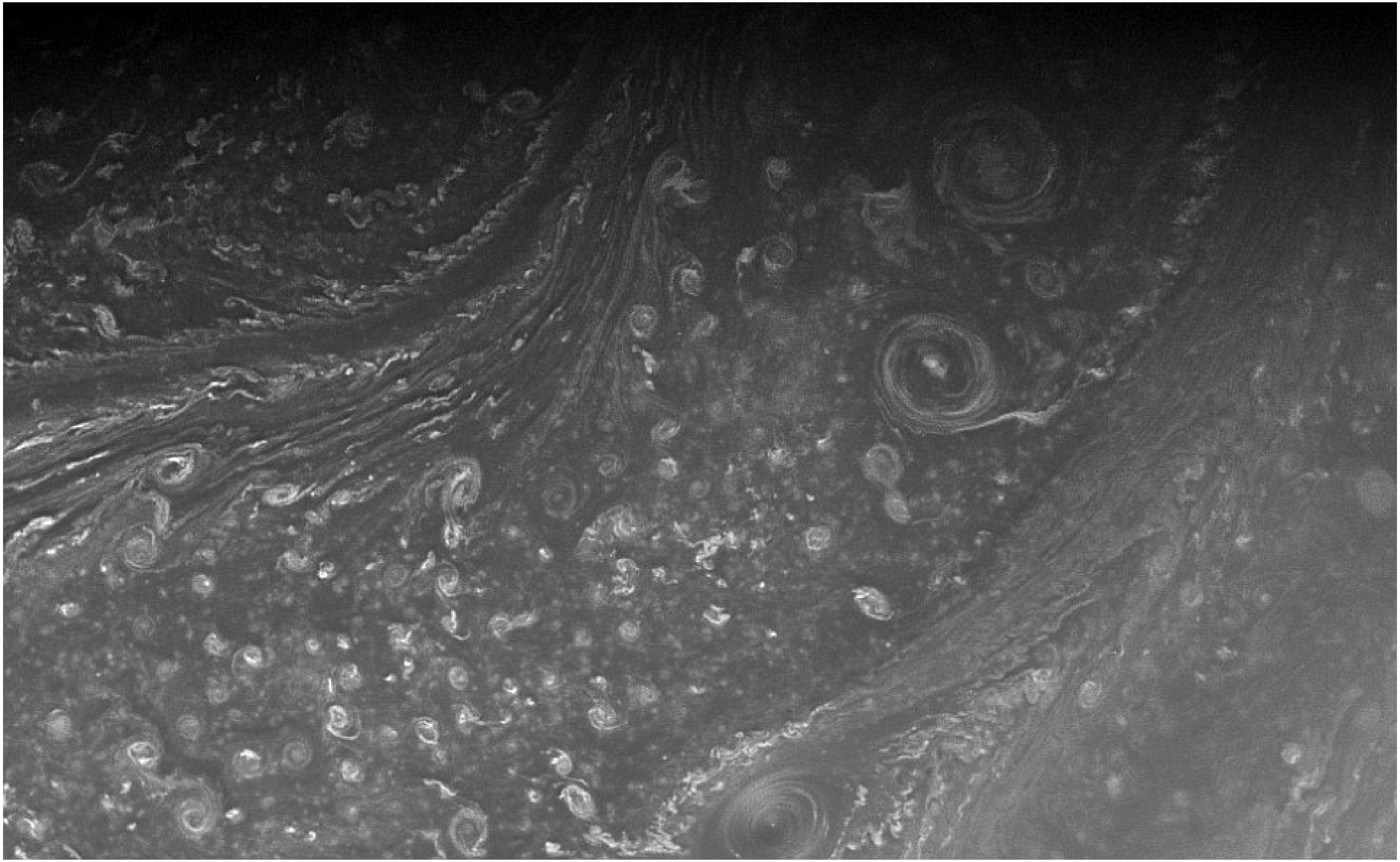


Giant planet vortices

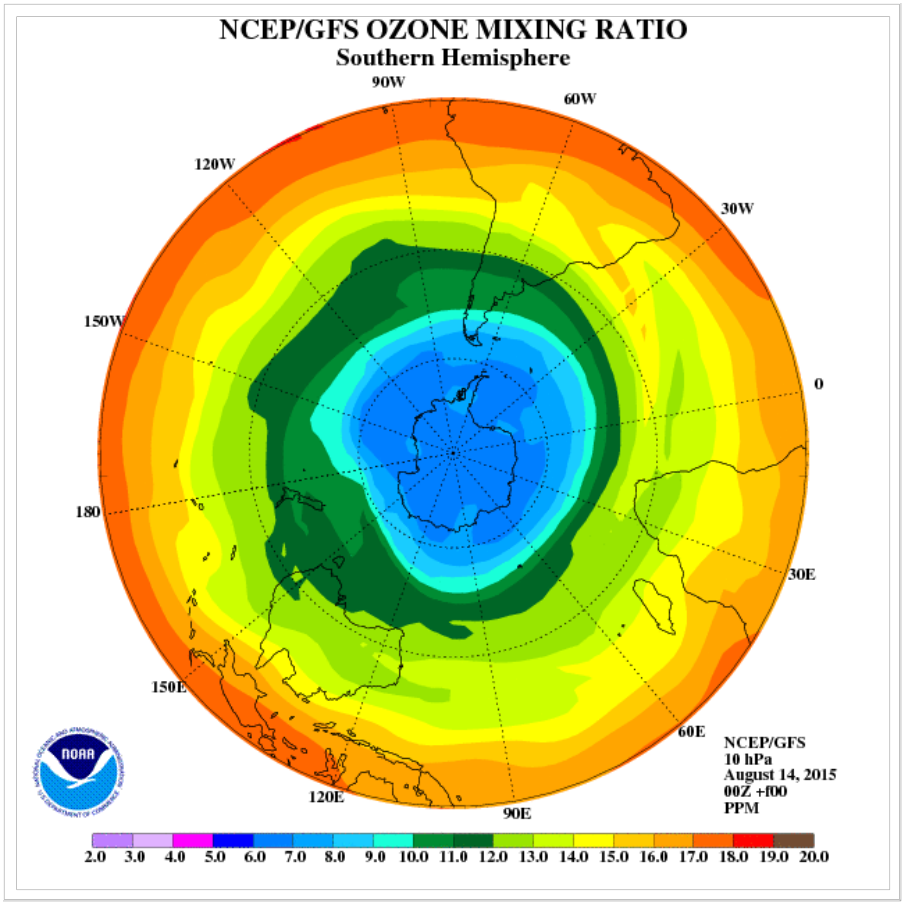
Jupiter (Voyager 1)

Giant planet vortices

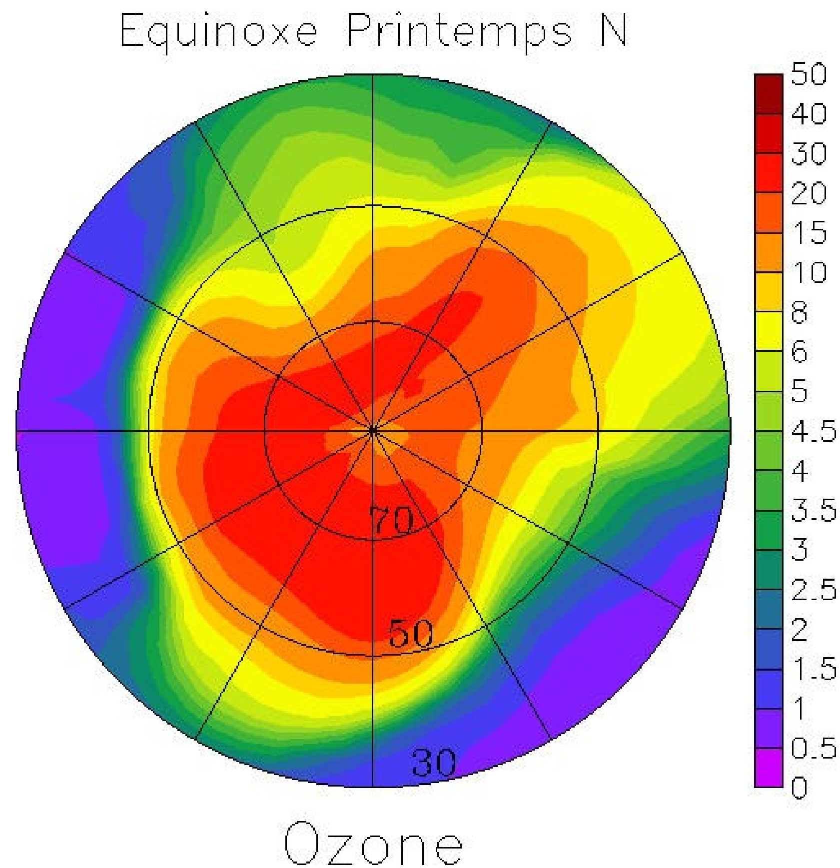
Saturn (Cassini/ISS)



Polar vortices



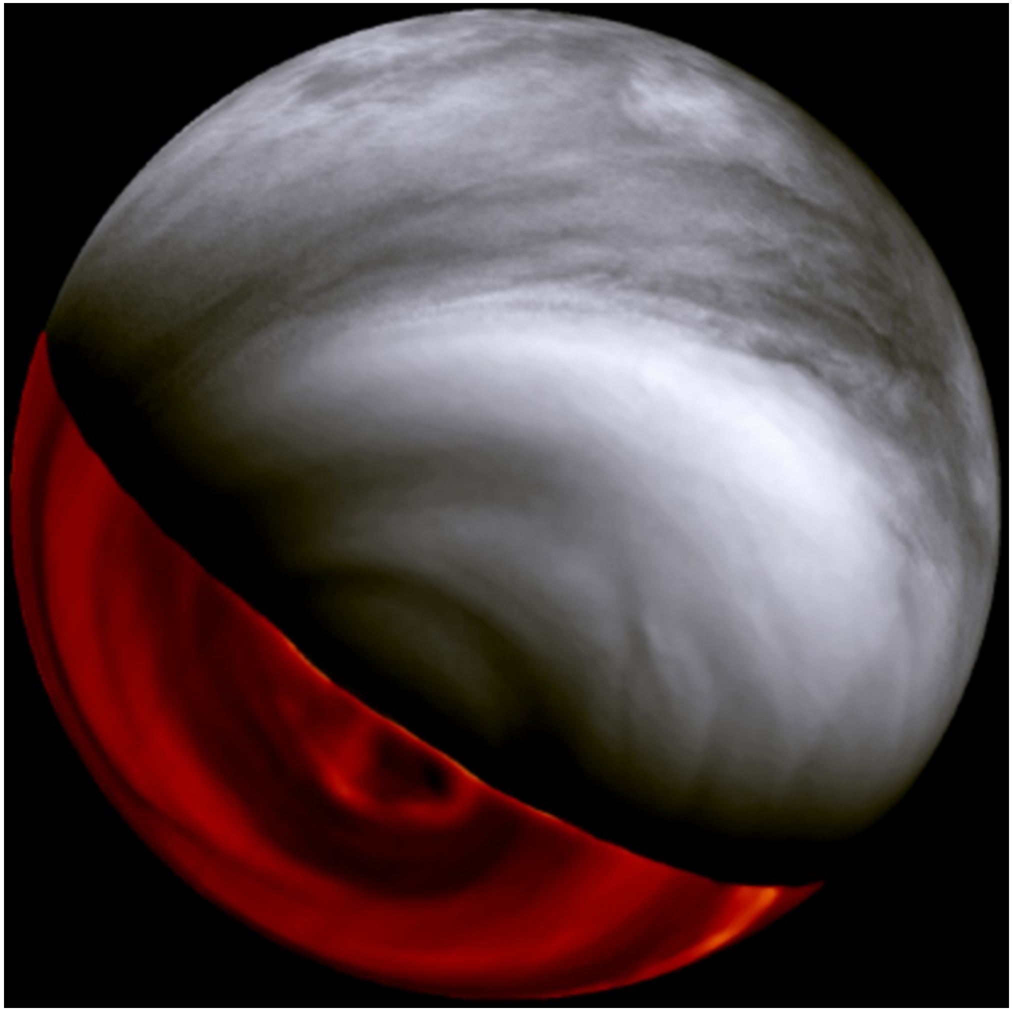
EARTH (observation)

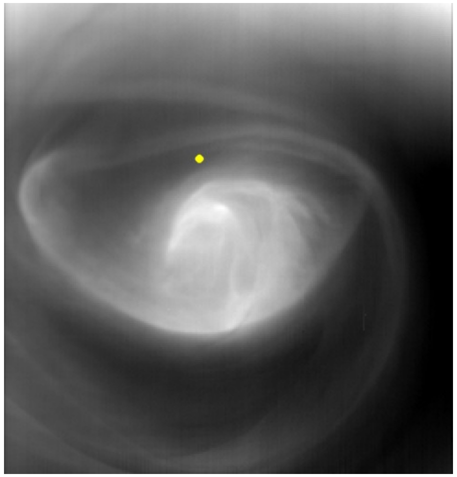


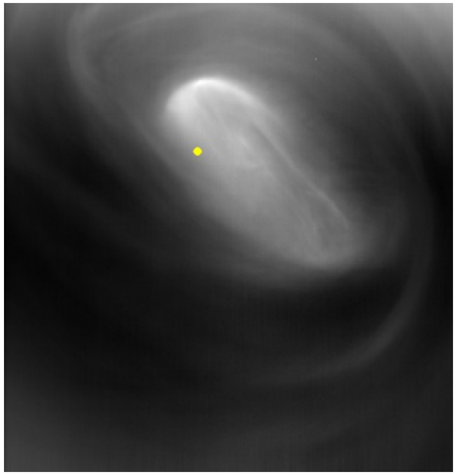
MARS (model)

Polar vortices

VENUS

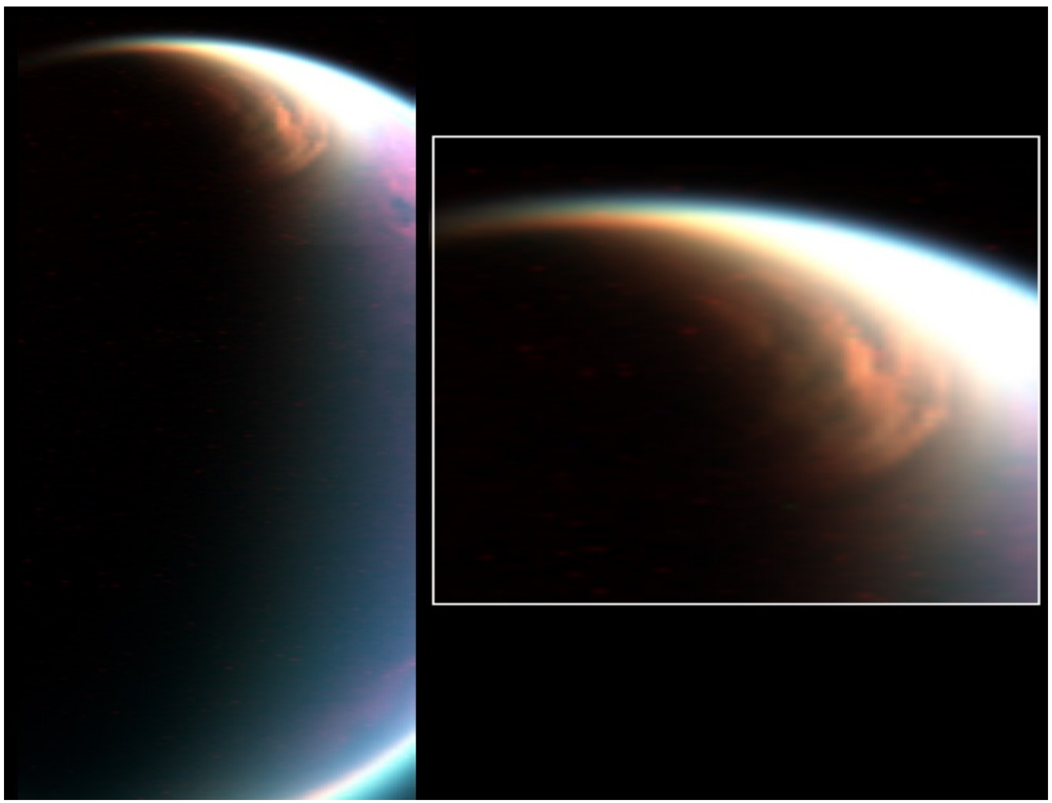


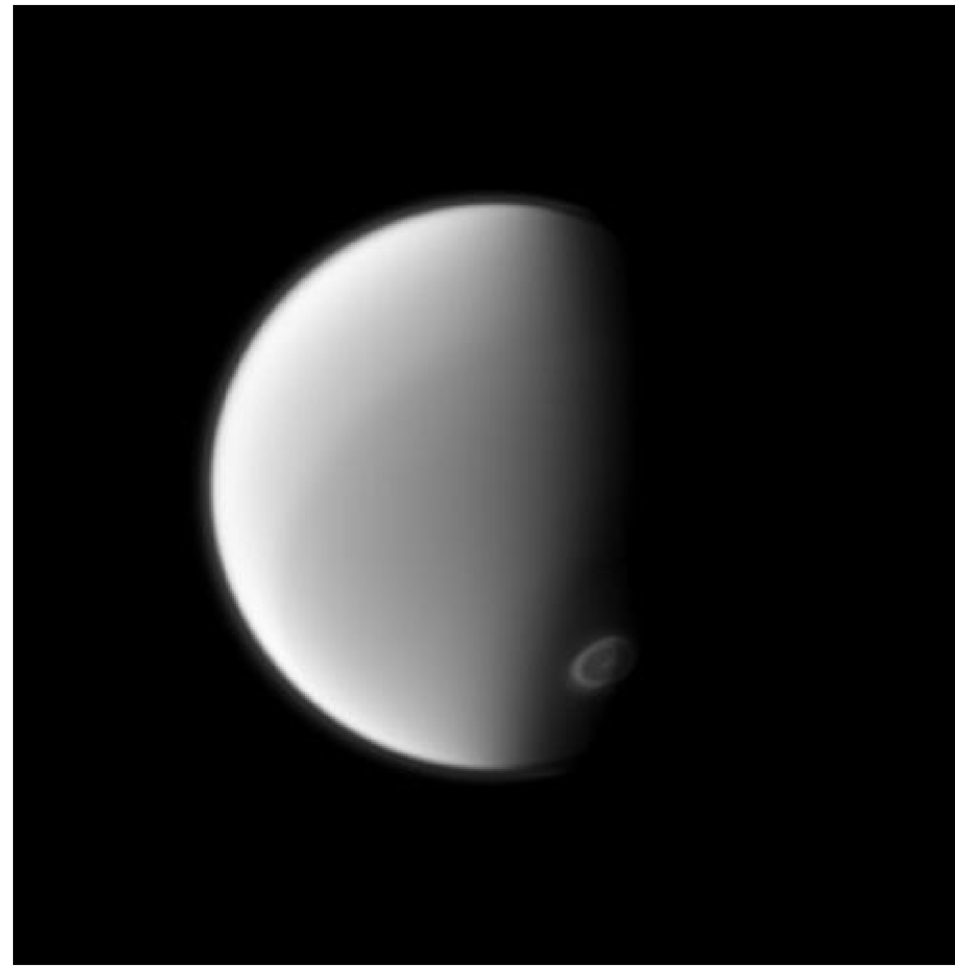




Polar vortices

TITAN





Polar vortices

Saturn (Cassini/ISS)