SUPERROTATION IN THE ATMOSPHERES OF VENUS AND TITAN
Perspectives from Global Climate Models

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- Superrotation in the Solar System: Venus and Titan
  - First observations
  - Characteristics
  - Differences between Venus and Titan
- Tools to undertand: Global Climate Models
  - The IPSL Venus & Titan GCMs
  - Angular momentum budgets
- Summary
  - Mechanisms
  - Similarities and differences between Venus and Titan

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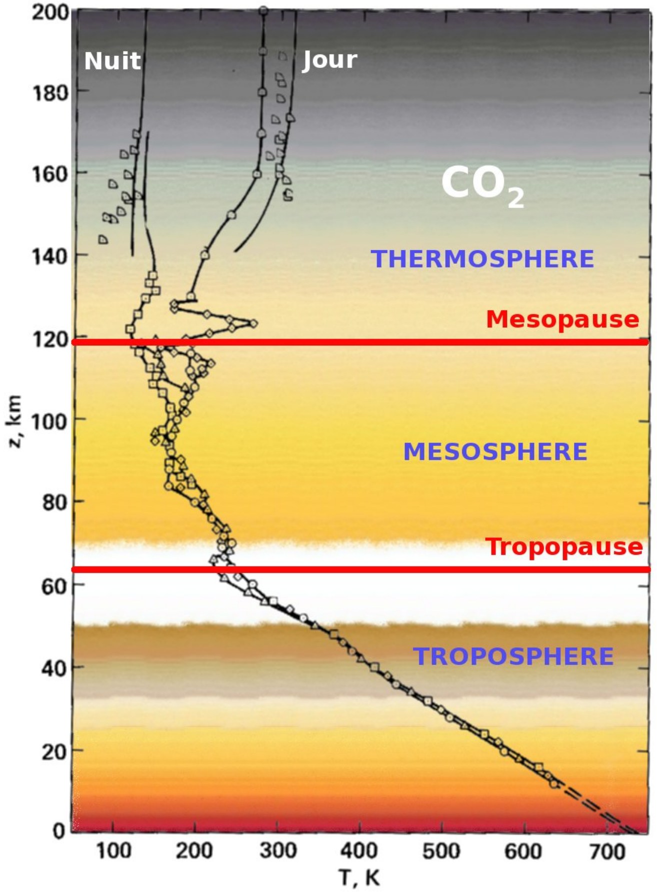
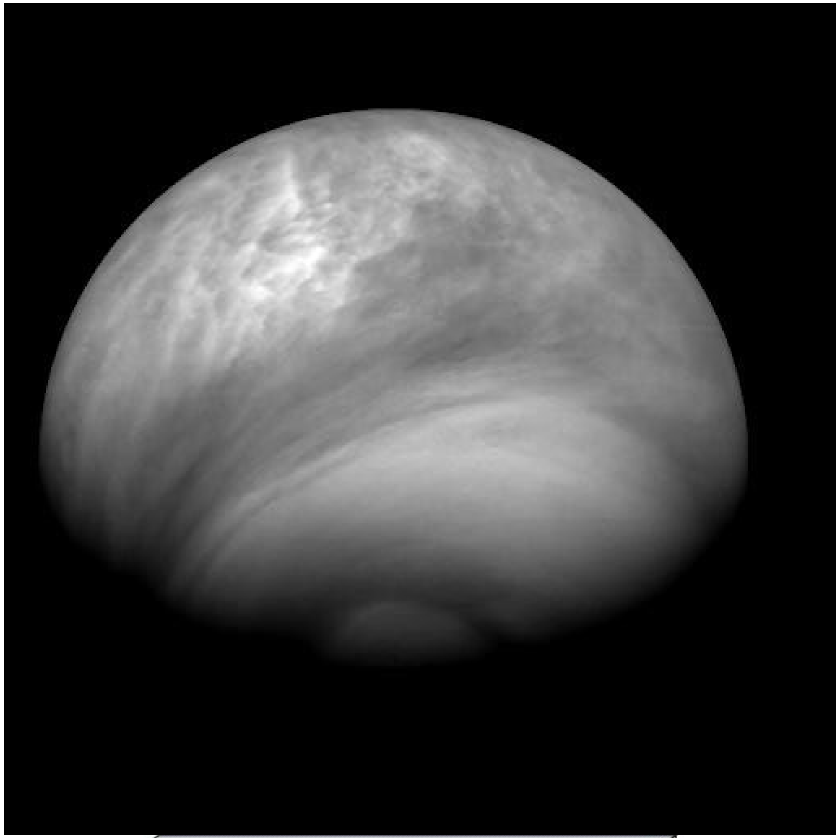
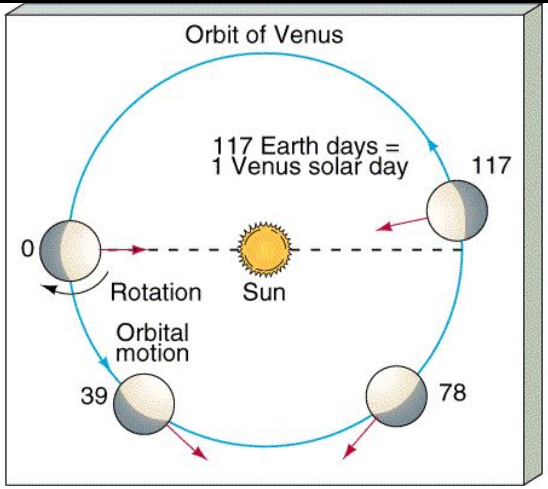
Venus : quick overview

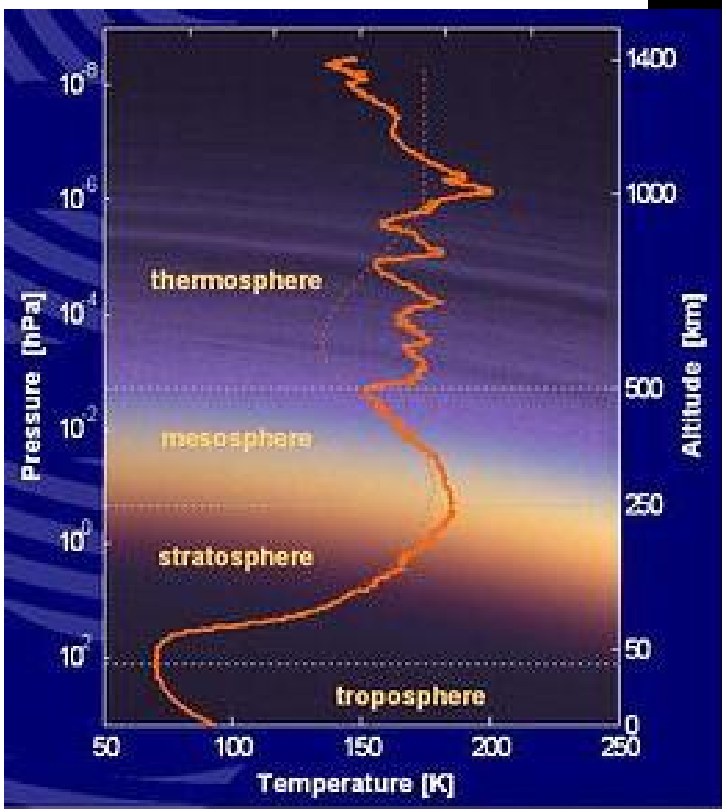


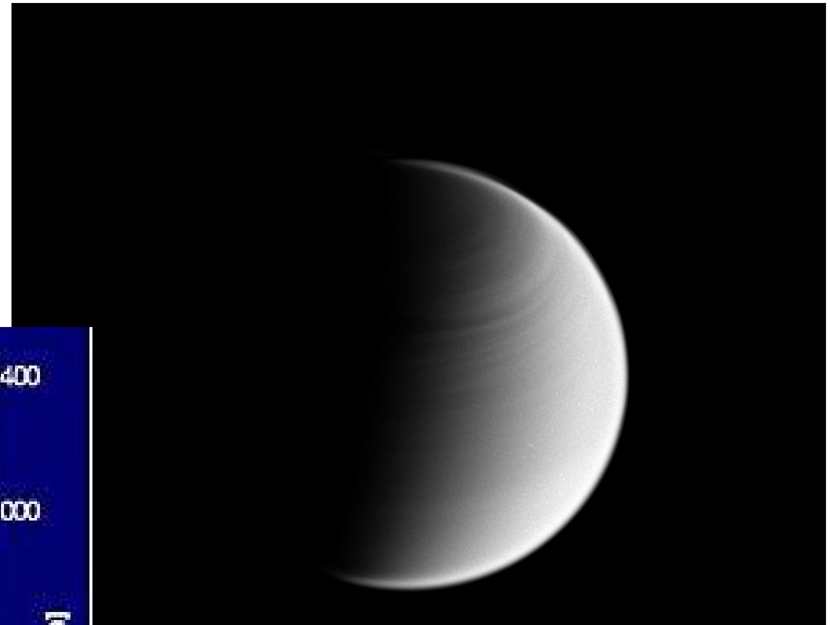


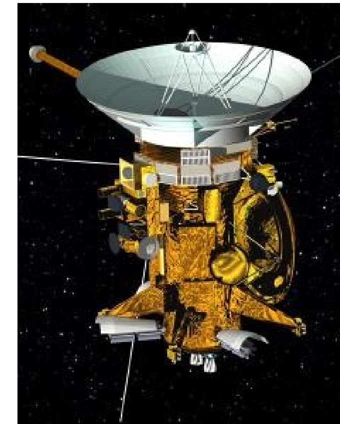


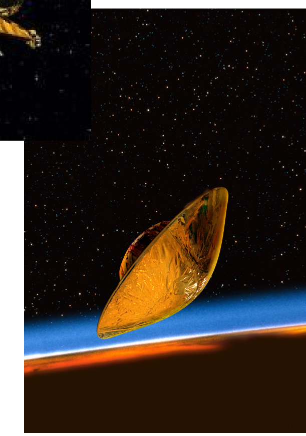
	Relative abundance
CO_2	96.5 %
N_2	3.5 %
SO_2	150 ppm
H_2O	30 ppm
Ar	70 ppm
CO	17 ppm

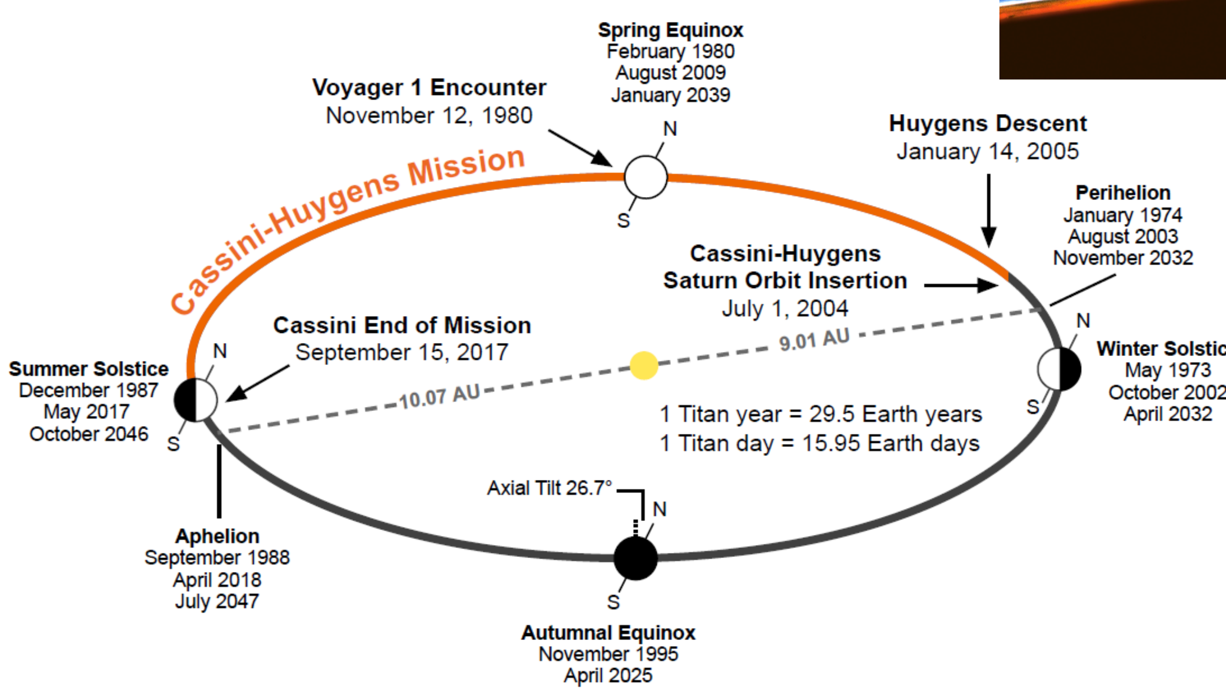
Titan : quick overview









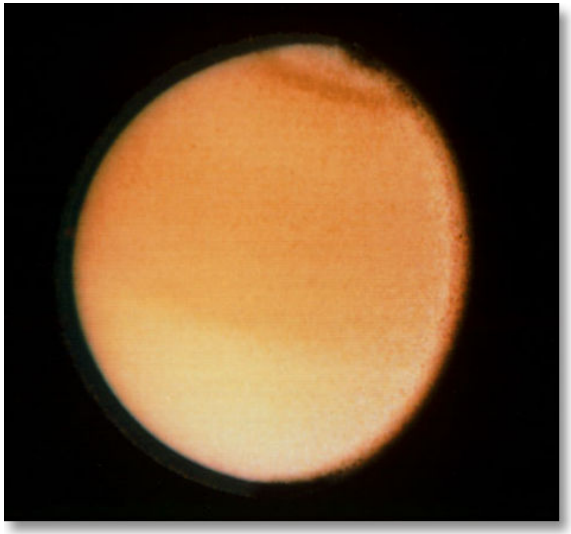


Superrotation : first observations

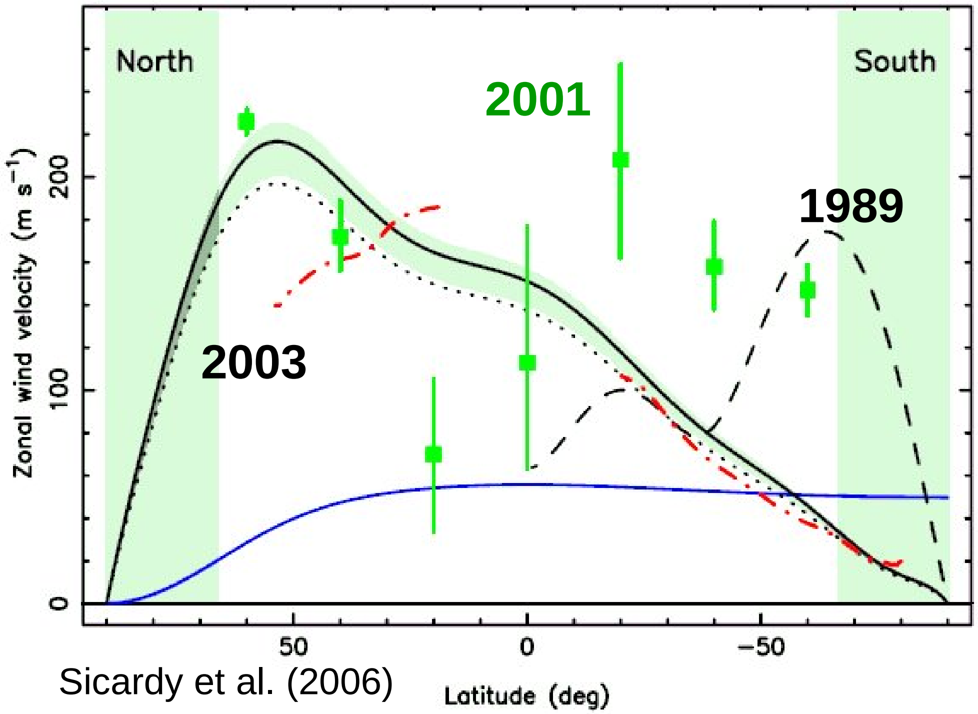
Using the UV markings at the cloud top
=> cloud-tracking zonal wind
=> rotation in 4 to 5 days (~100 m/s at ~70 km altitude)

Superrotation : first observations

Cloud-tracking
is not possible…

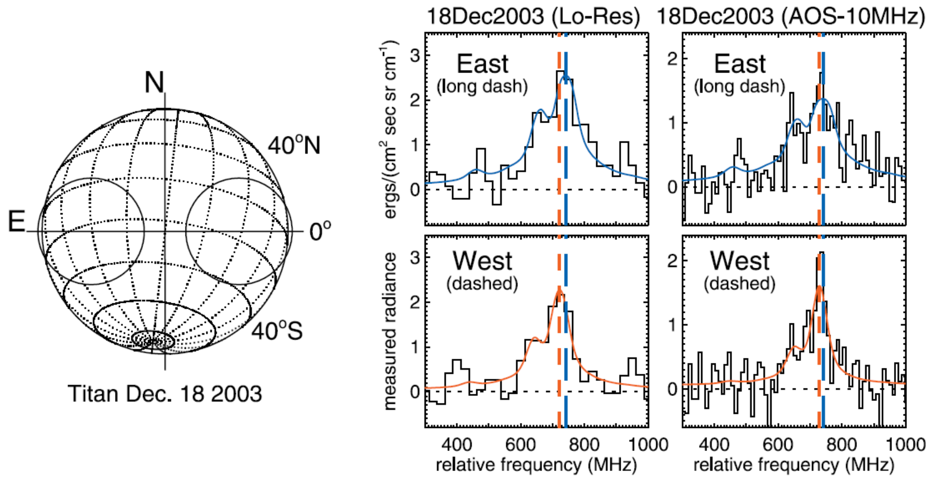


=> Stellar occultations (~0.25 mbar)



Sicardy et al. (2006)

=> Doppler shifts (~1 mbar)

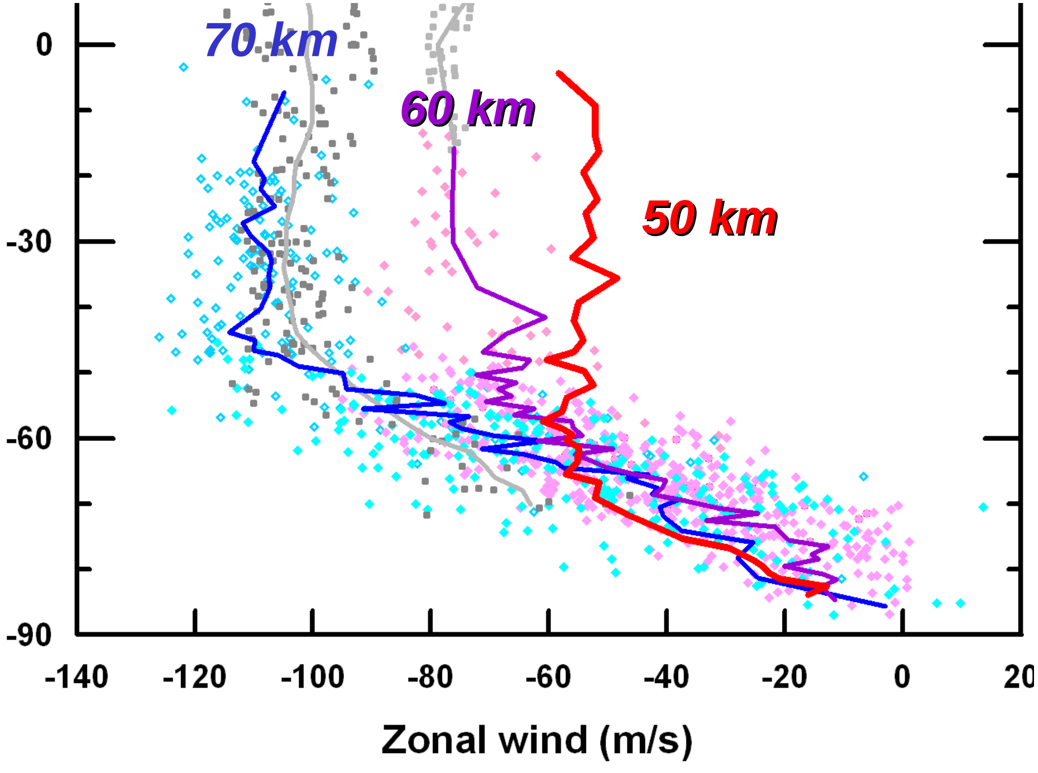


190 +- 90 m/s, centered at 20S

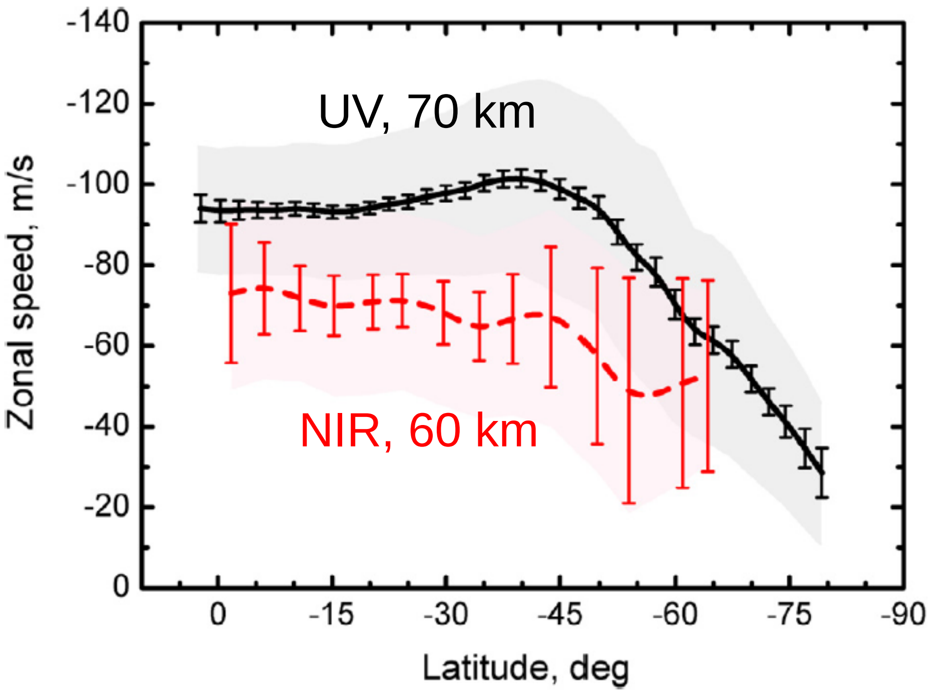
Kostiuk et al. (2005)

Venus atmosphere: superrotation

Venus Express cloud tracking



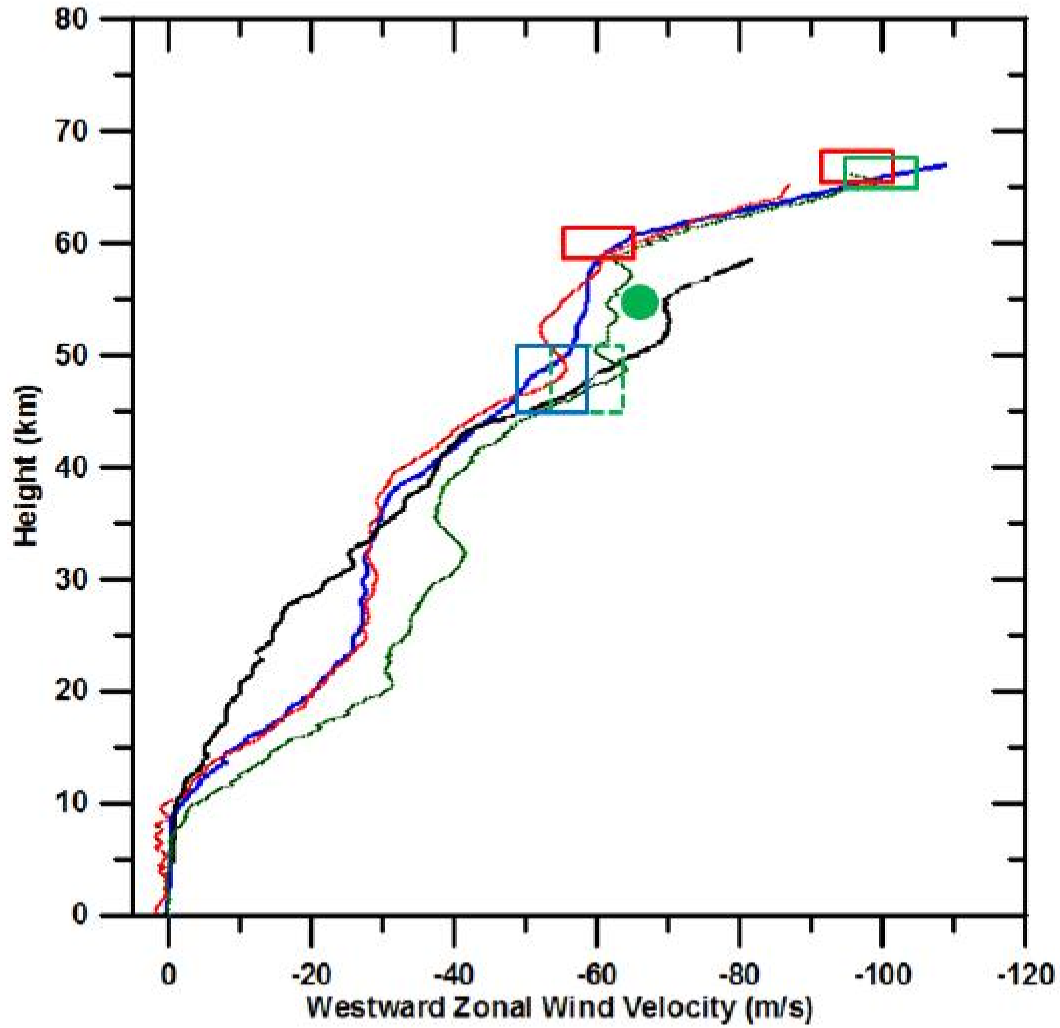
VIRTIS - Sanchez-Lavega et al. (2008)



VMC - Khatuntsev et al. (2013)

Venus atmosphere: superrotation

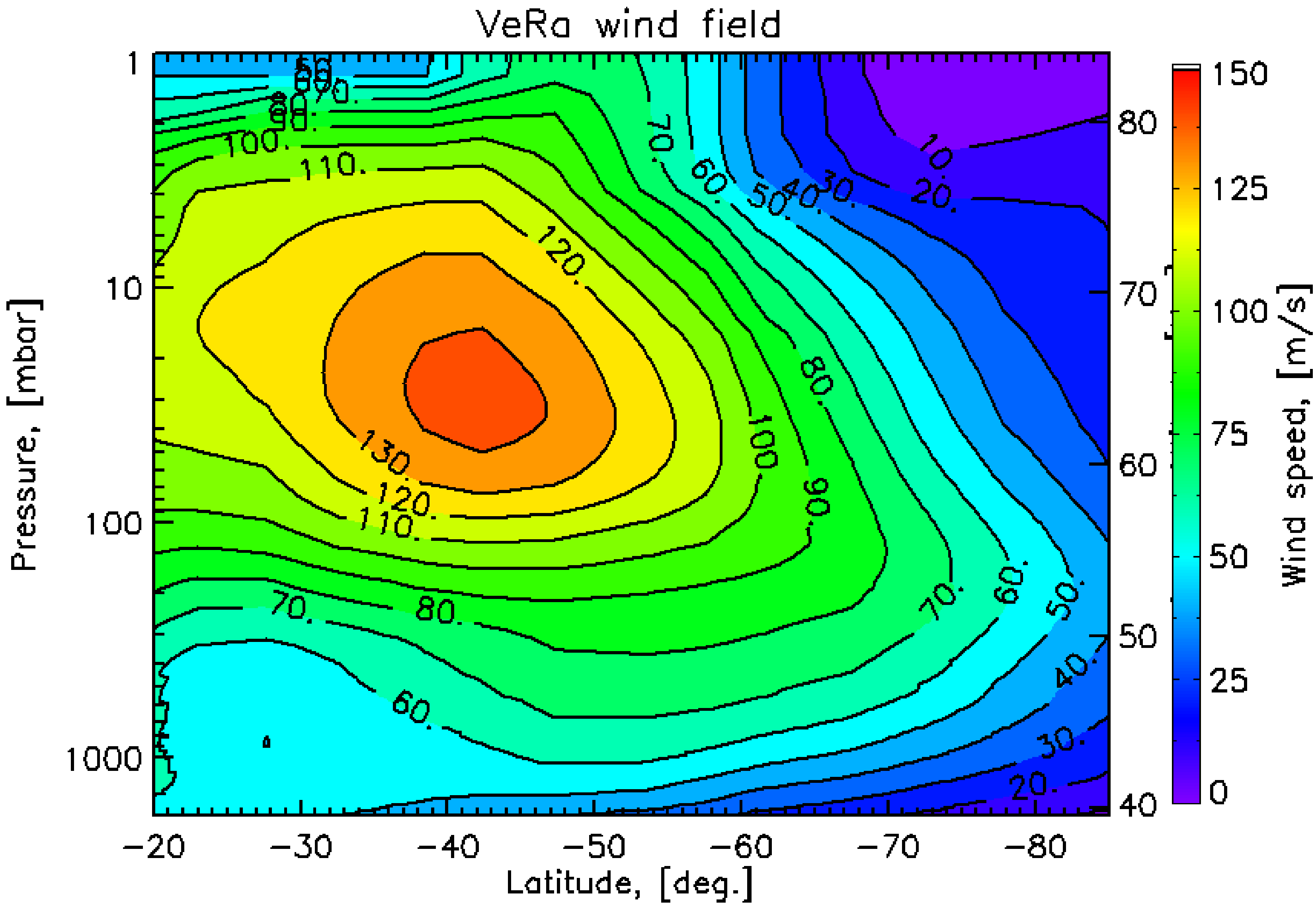
Pioneer Venus probes, VeGa ballons



Sanchez-Lavega et al. (2017)

Venus atmosphere: superrotation

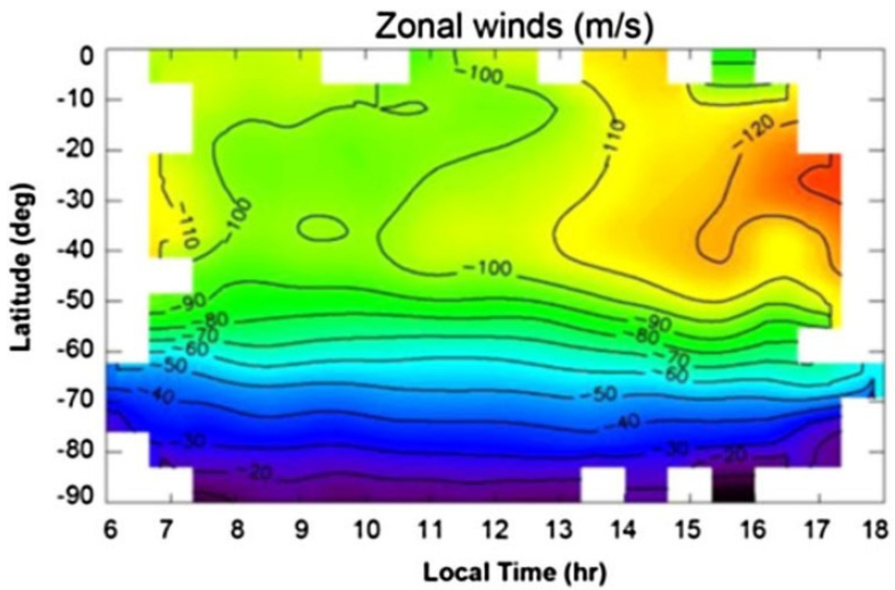
From T maps : thermal wind balance



Piccialli et al. (2012)

Variability of cloud top winds

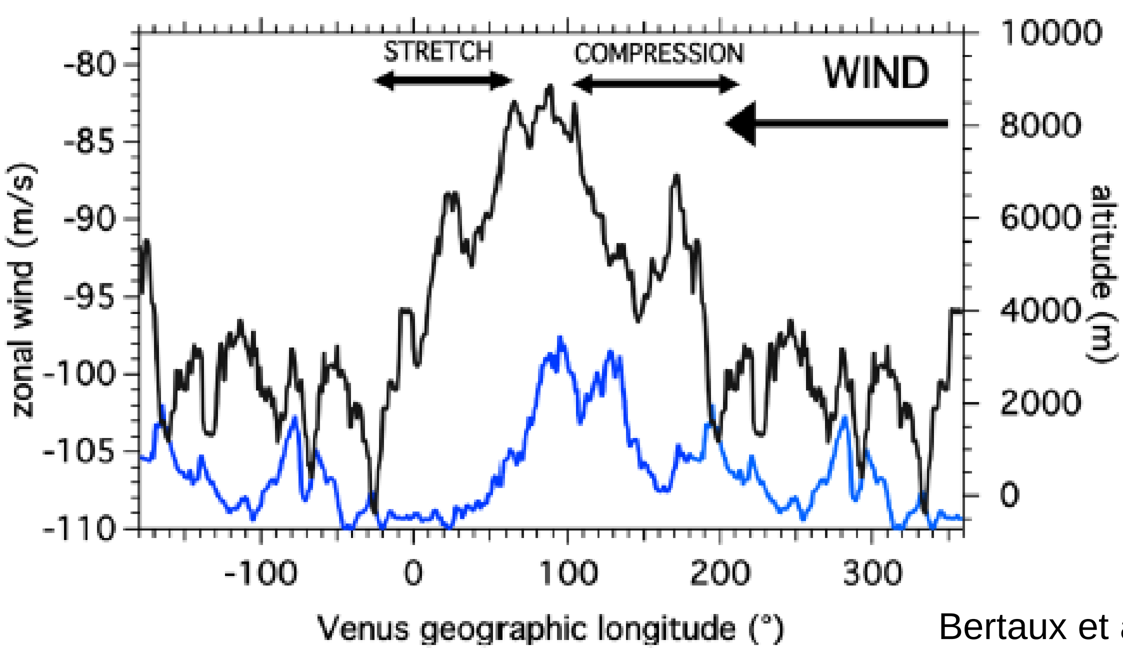
With local time



Cloud-tracking wind
Long-term average
VIRTIS (2006-2012)

Sanchez-Lavega et al. (2017)

With topography



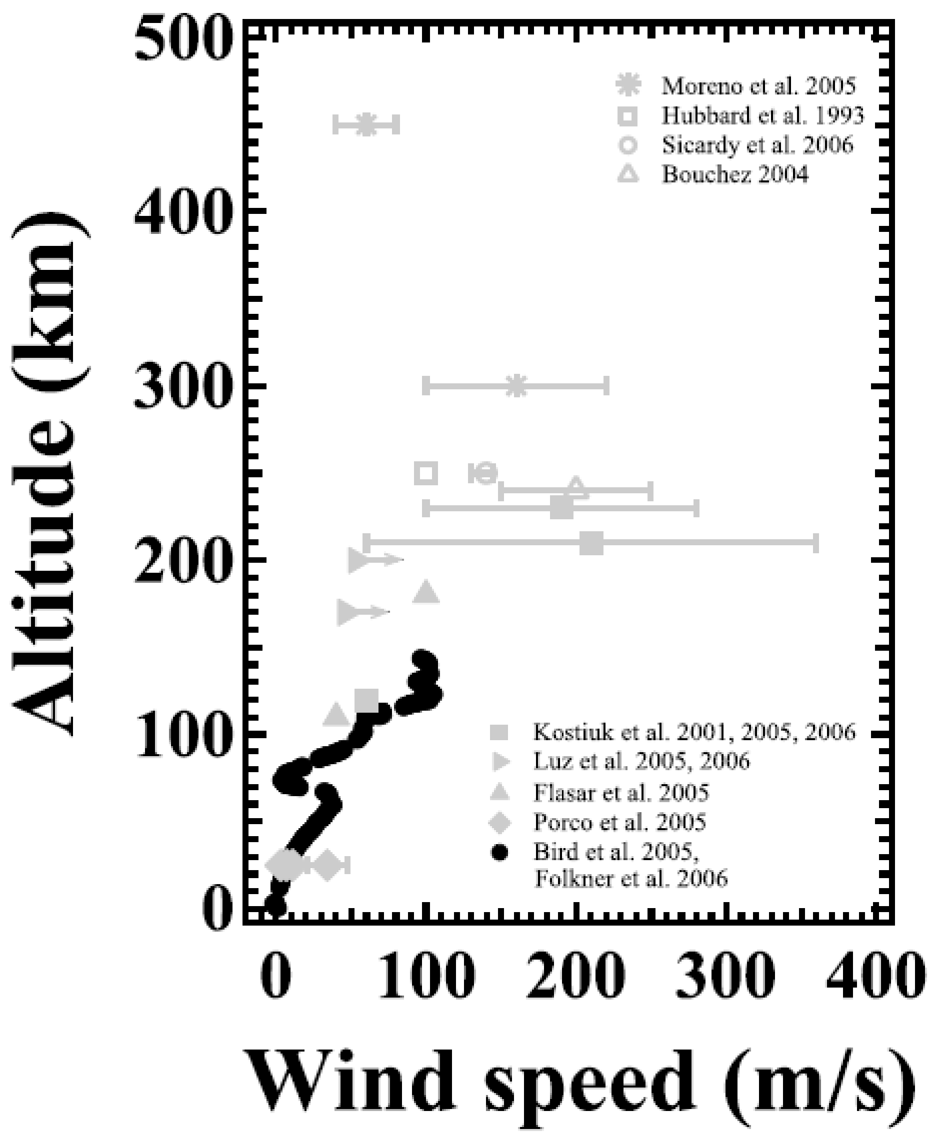
Cloud-tracking wind
<*5°S - 15°S*>

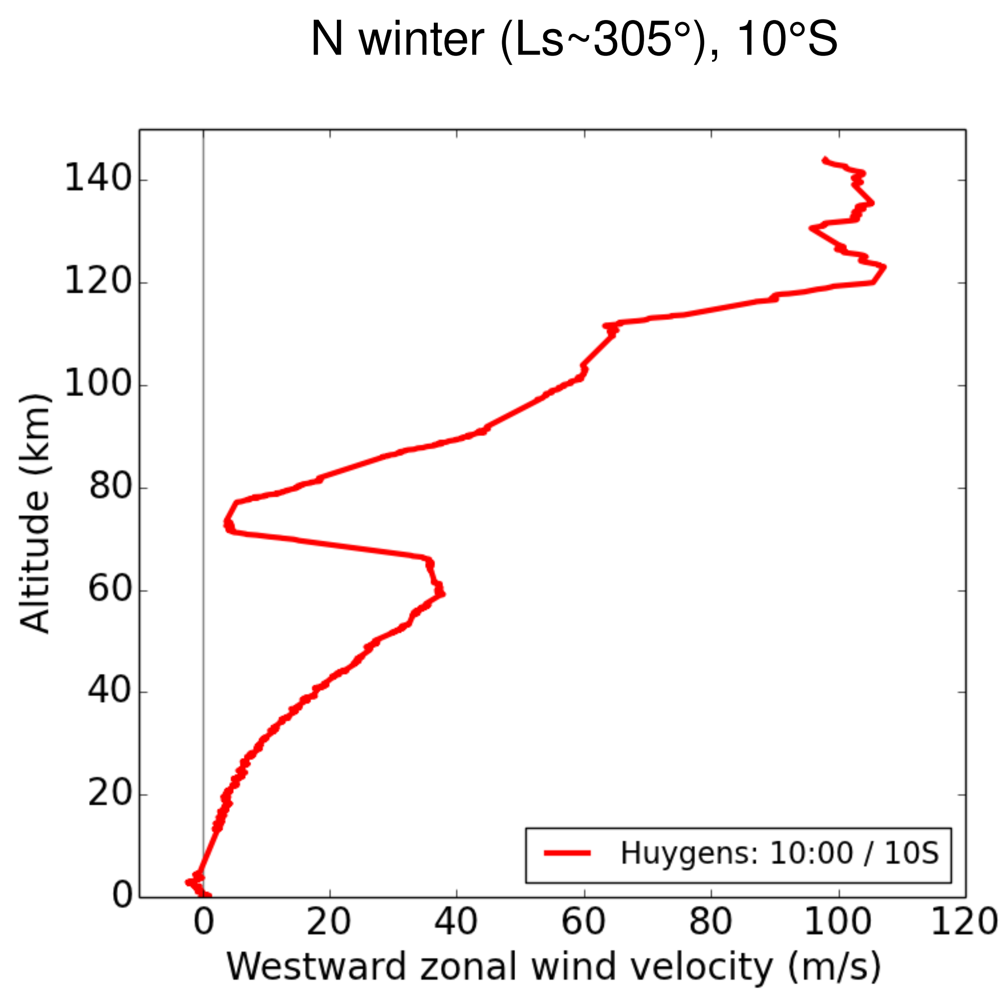
topographie

Bertaux et al. (2016)

Titan atmosphere: superrotation

DWE/Huygens

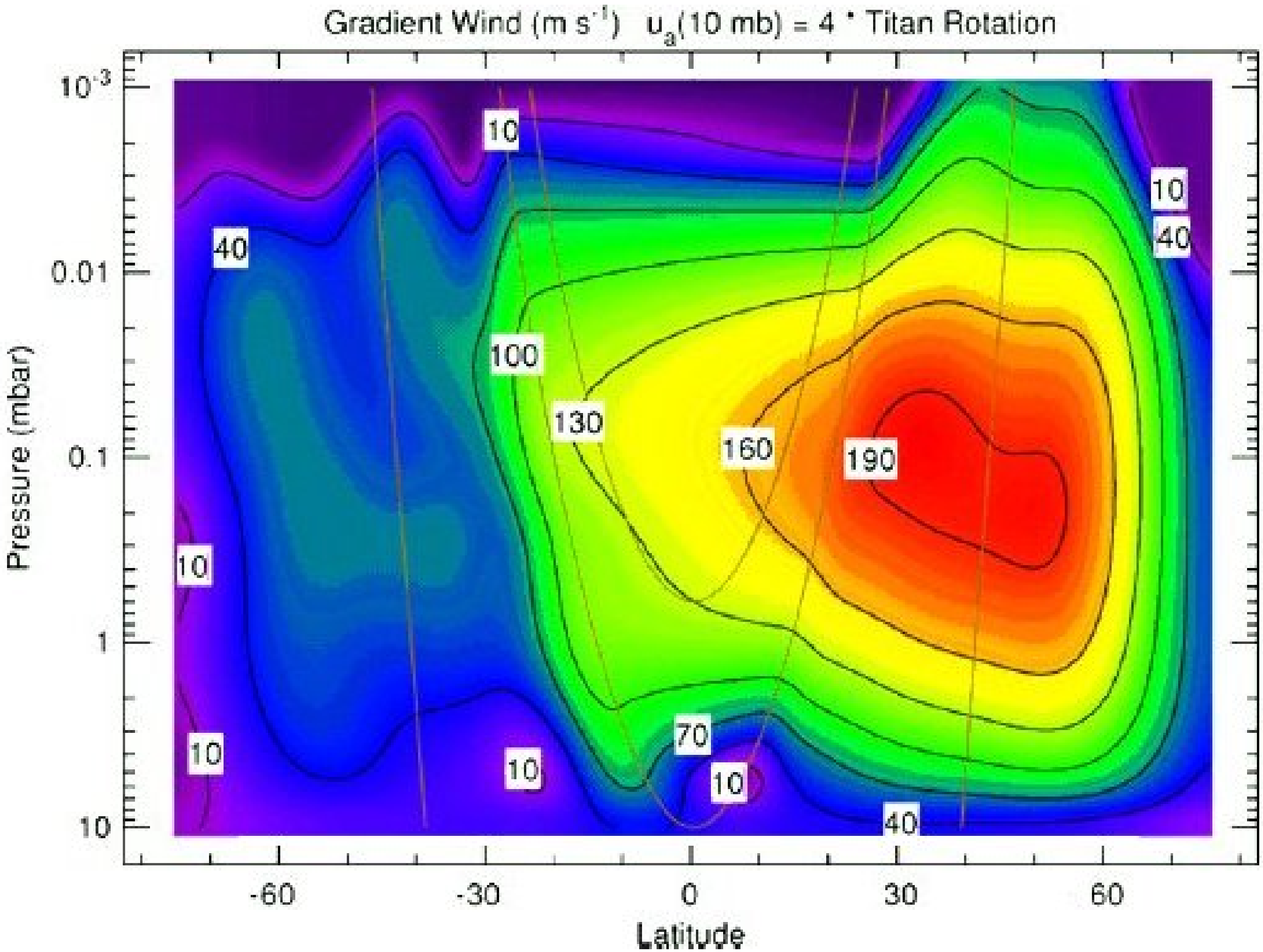




Bird et al. (2005)

Titan atmosphere: superrotation

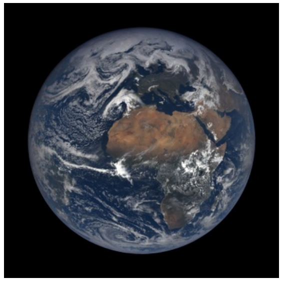
CIRS/Cassini : thermal wind balance

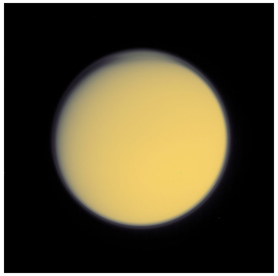


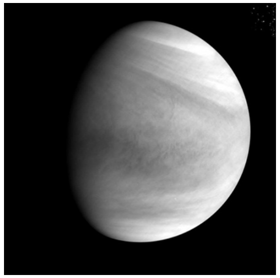
N winter (Ls~300°)

Achterberg et al. (2008)

Venus vs Titan : differences ?







Rotation periods :	1	16	243
Radiative time constants at the peak of solar heating		>> 1 Td	<< 1 Vd
Seasonal variations		yes	no

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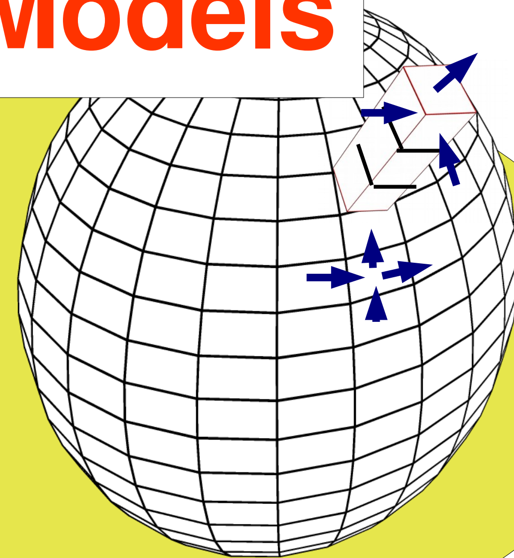
General Circulation Models



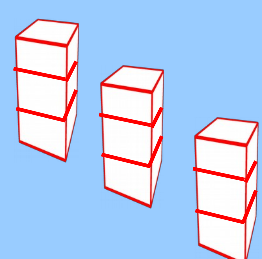
Dynamical core (3D or 2D)

- Primitive equations of meteorology
- Used for weather forecast and climate
- Depends on a few parameters only (gravity, gaz molecular mass, planetary radius, R/Cp)
- Finite differences or spherical harmonics

U^*, v^*, T^*, P^*_s ← $\delta_t u^*, \delta_t v^*, \delta_t T^*, \delta P^*_s$ ($\Delta t \sim 5$ min)

U, v, T, P_s → $\delta_t u, \delta_t v, \delta_t T, \delta P_s$ ($\Delta t \sim 30$ min)

Set of physical parameterizations specific of the planet



- radiation : main change
- subgrid scale processes
- specific processes (condensation, clouds, vegetation, ...)
- surface scheme

LMDZ versions

Earth
Mars
Titan
Venus
Idealized

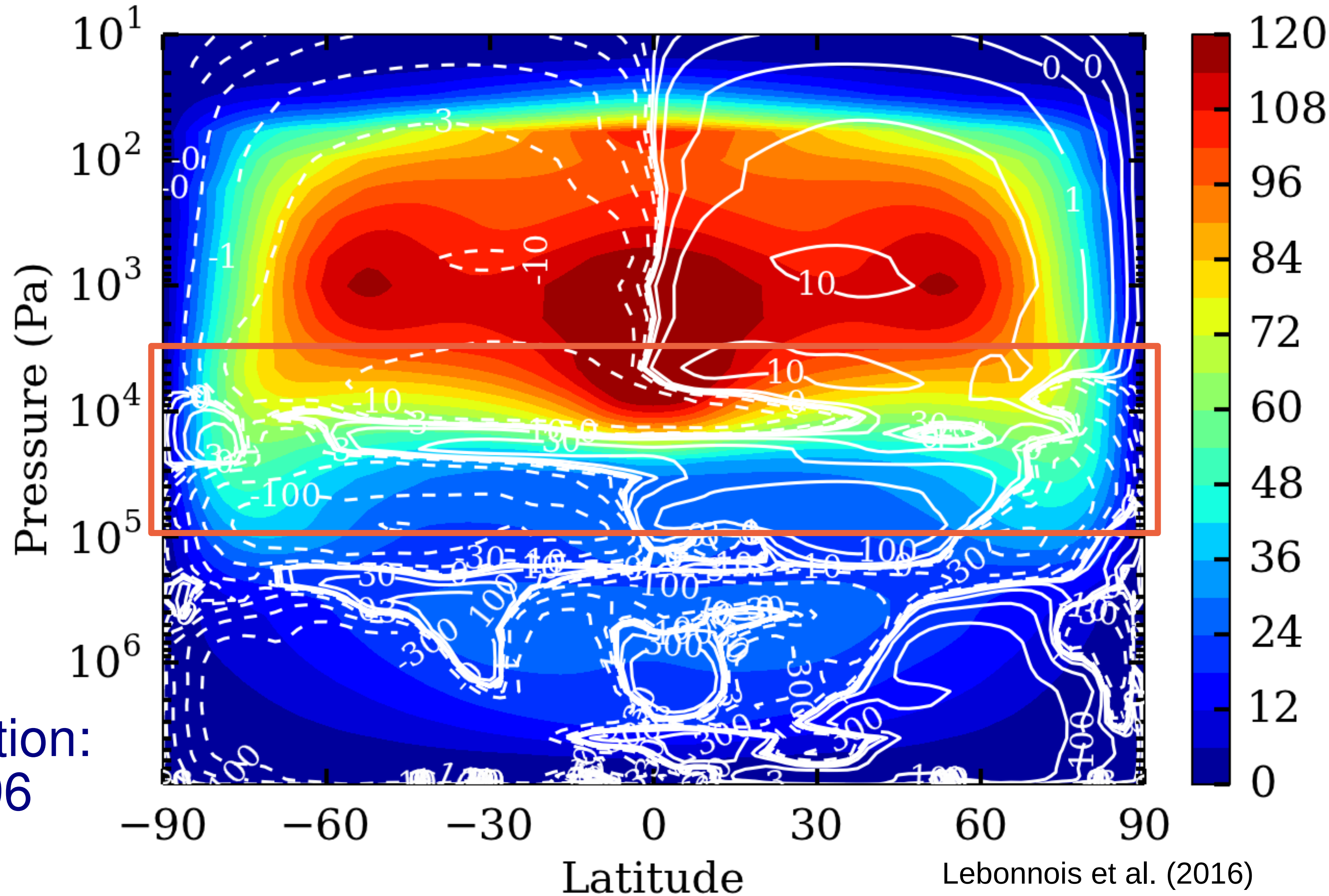
The IPSL Venus and Titan GCMs

	VENUS	TITAN
3D:	96x96x50 (0~95 km)	64x48x55 (0~500 km)
Vertical coordinates: hybrid (sigma/pressure)		
Dynamical core, transport of tracers		
Specific physics:		
radiative transfer:	NER matrix (IR)	2-stream, updated data
parameterizations (PBL: Mellor&Yamada, convection)		
	Topography	No topography
	Photochemistry	Photochemistry (radiatively coupled)
	No clouds microphysics	Haze microphysics
	Lebonnois et al., 2016	**Lebonnois et al., 2012**
	Garate-Lopez & Lebonnois, 2018	**Vatant d'Ollone et al., in prep.**

Venus superrotation

atmospheric circulation starting from rest

Clouds

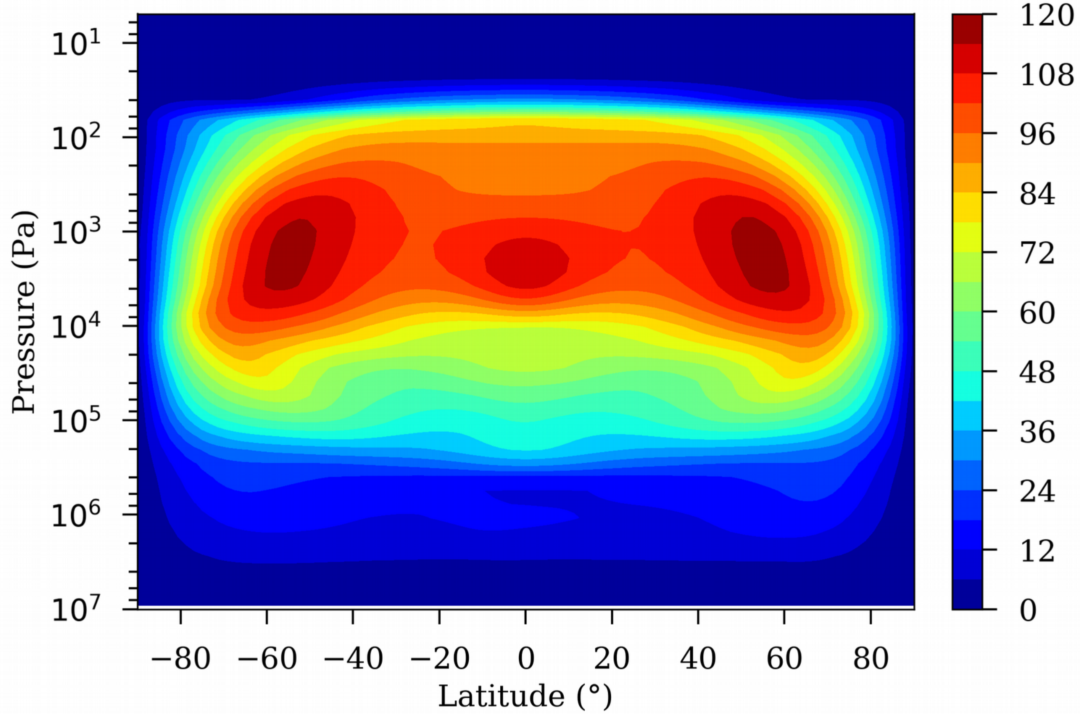


Lebonnois et al. (2016)

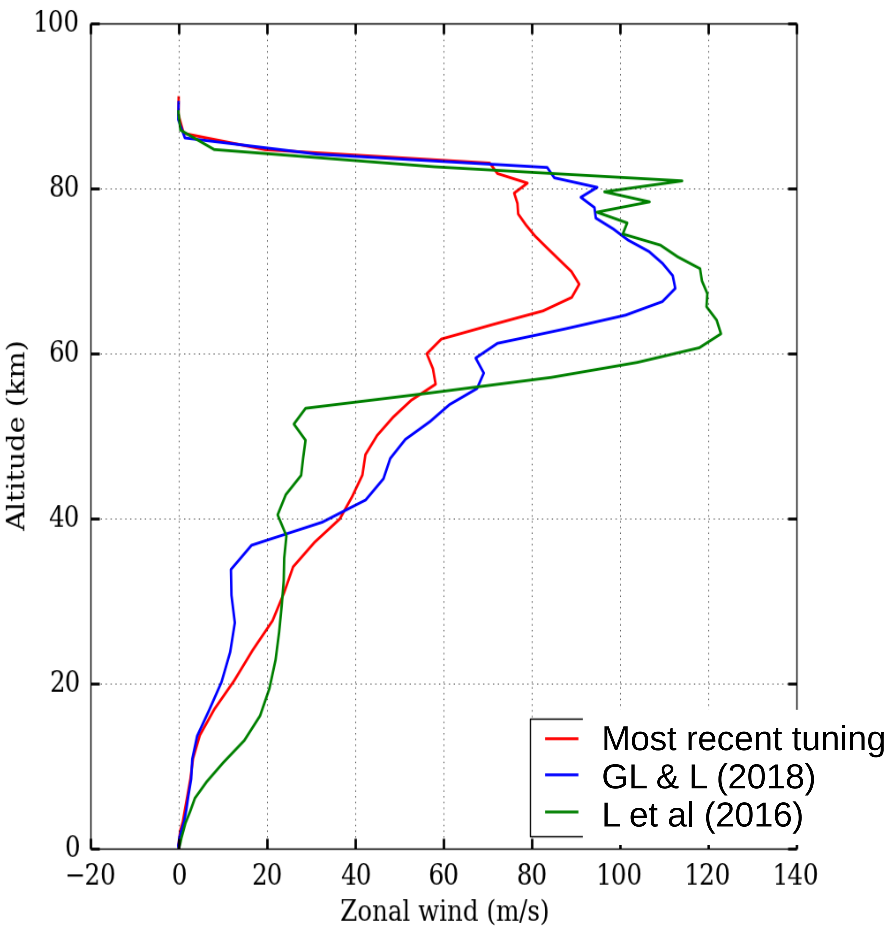
Resolution:
96x96

Mean zonal wind and stream function after 300 Vdays
(Topography, diurnal cycle)

Venus superrotation



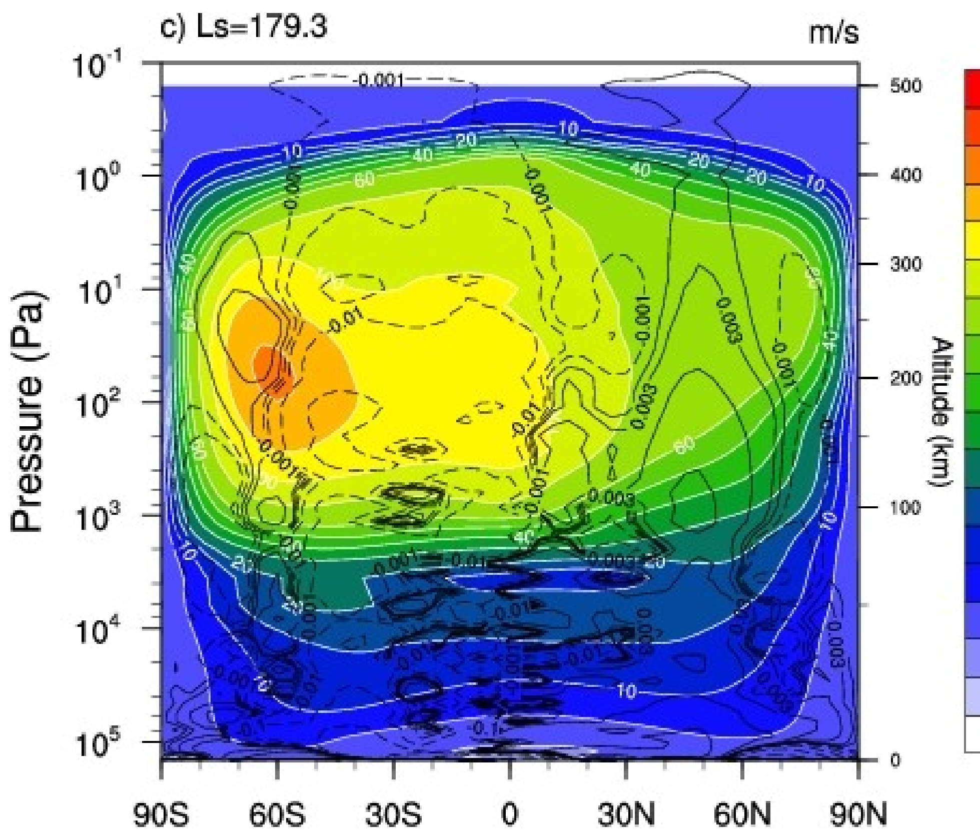
Garate-Lopez & Lebonnois (2018)



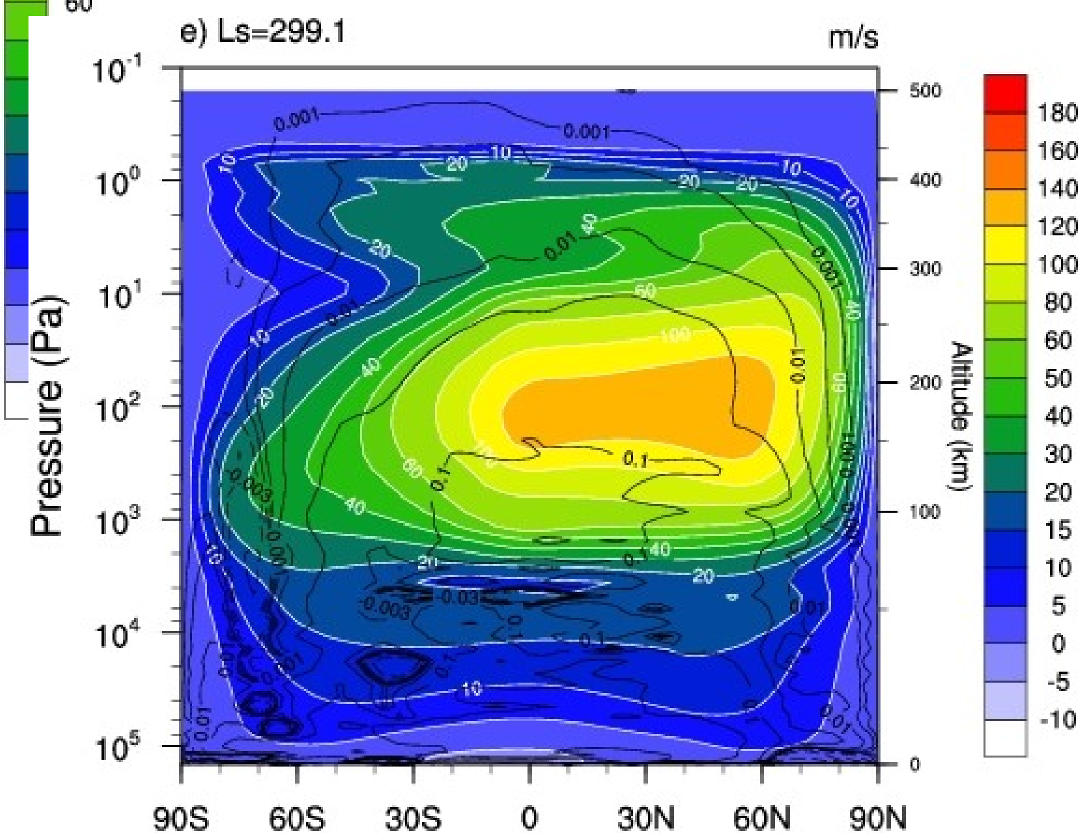
Details are sensitive to modeling parameters...

Titan superrotation

Started from 2D-CM simulations, interactive haze



Lebonnois et al. (2012)



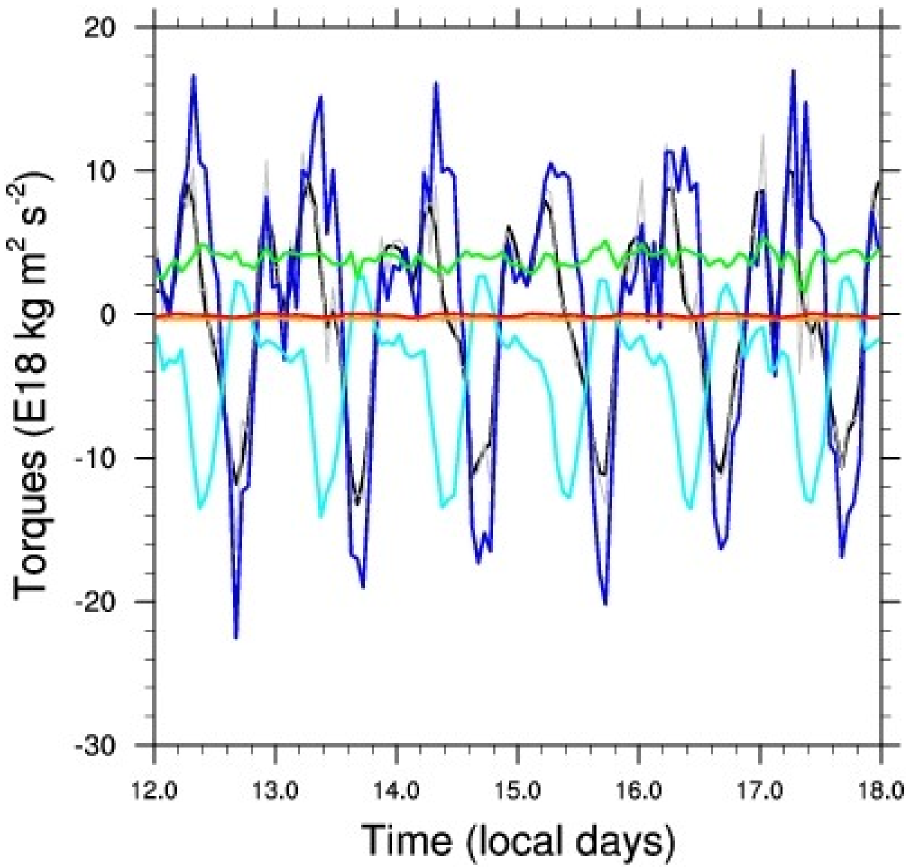
Mean zonal wind and stream function after 12 Titan years

Angular Momentum Conservation

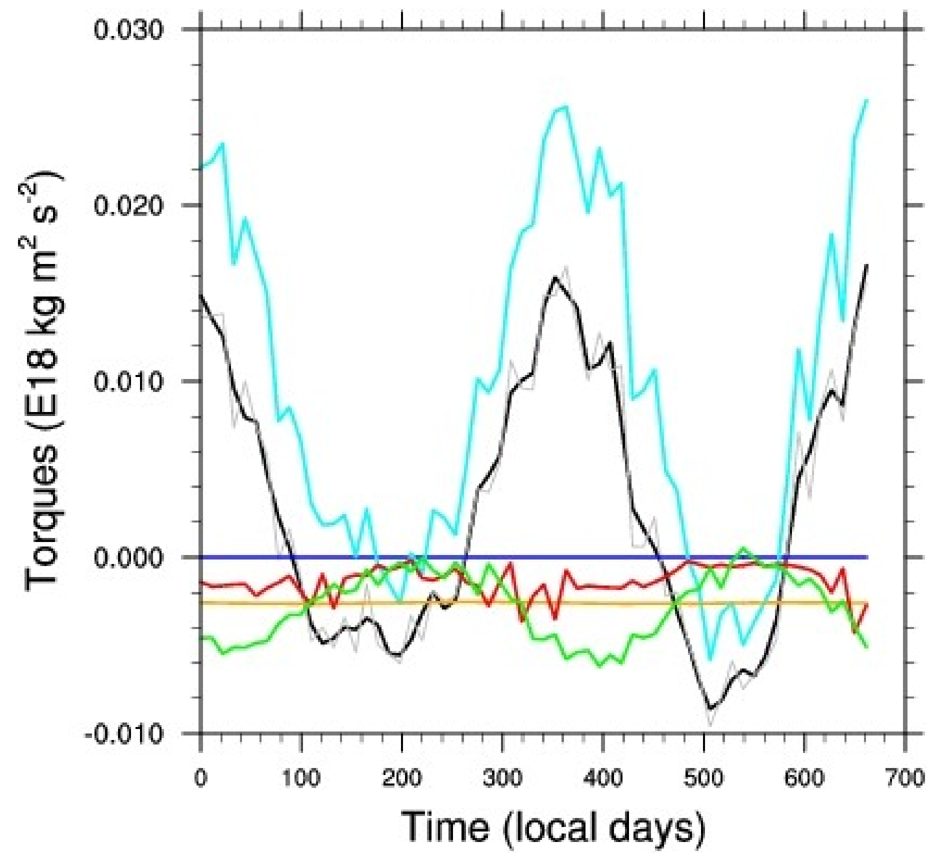
VENUS

Mountain torque
Friction torque
Sponge layer
Horizontal dissipation
Dynamical core

Total dM/dt



TITAN



$$\frac{dM}{dt} = T + F + S + D + \epsilon$$

Lebonnois et al. (2012b)

Modeling superrotation

Modeling Titan and Venus superrotation has been a long-lasting problem

Pioneer period : 1970s, 1980s

First Titan GCM with superrotation : Del Genio et al (1993), Hourdin et al (1995)

Early Venus GCMs, mostly with simplified radiative forcing (2000s)
=> difficulties to get superrotation

After 2010, successful GCMs
=> for Titan : Newman et al (2011), Lebonnois et al (2012), Lora et al (2015)
=> for Venus :
Lebonnois et al (2010, 2016), Sugimoto et al (2014a,b), Mendonca and Read (2016)

Sources of difficulties ? Unclear…
- Angular momentum conservation problems
- horizontal and/or vertical resolution (crucial role of wave activity)
- excessive vertical mixing

Importance of **comparison between several GCMs** to ensure **robustness** of conclusions

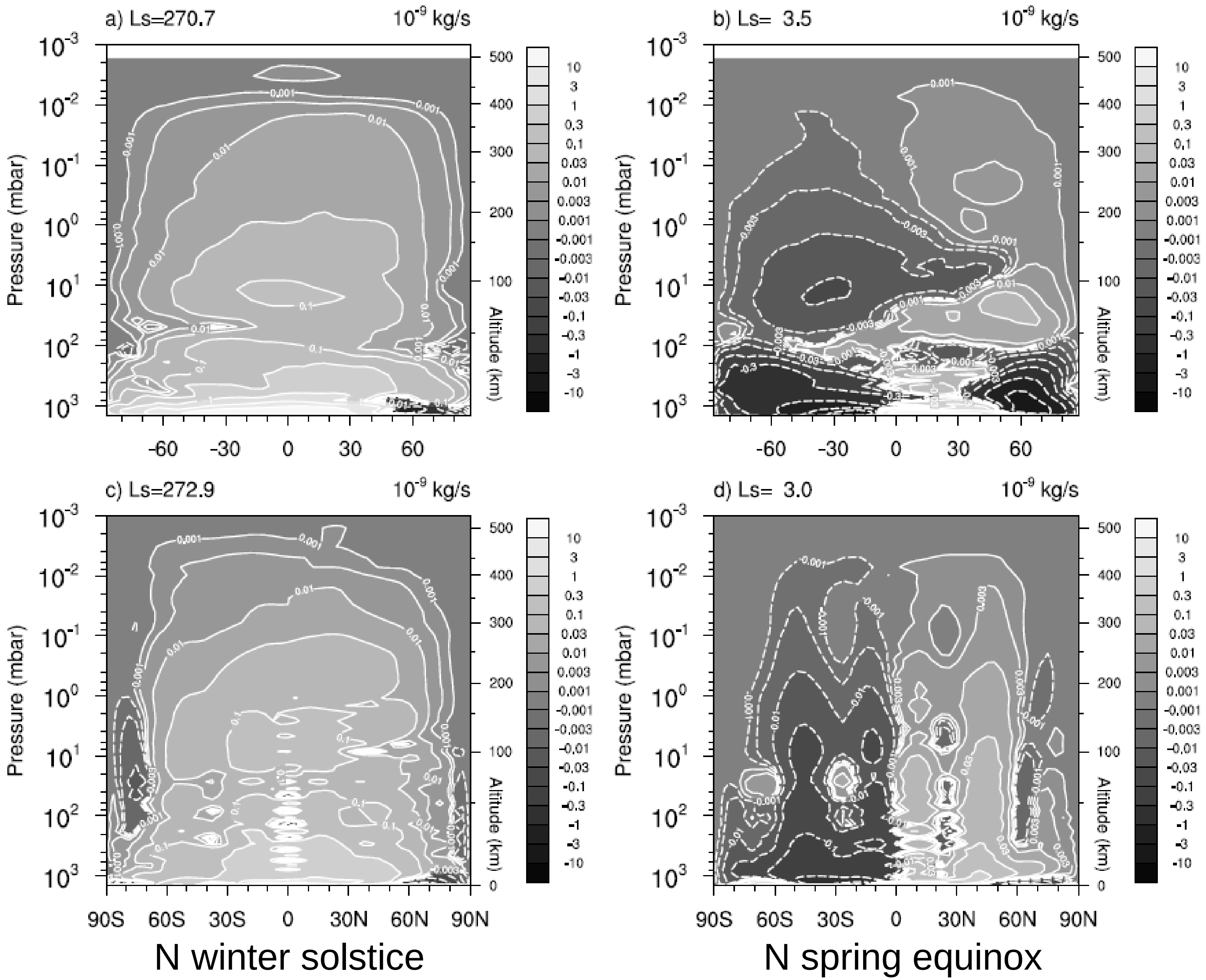
Example : Titan GCMs comparison

Titan WRF

(Newman et al, 2011)

IPSL Titan GCM

(Lebonnois et al, 2012)



Mean meridional circulation

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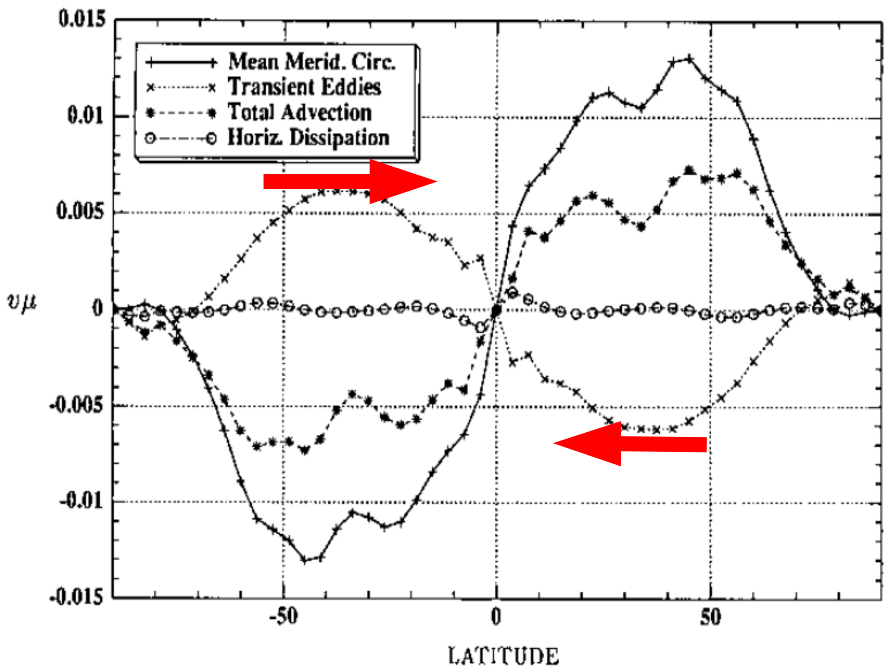
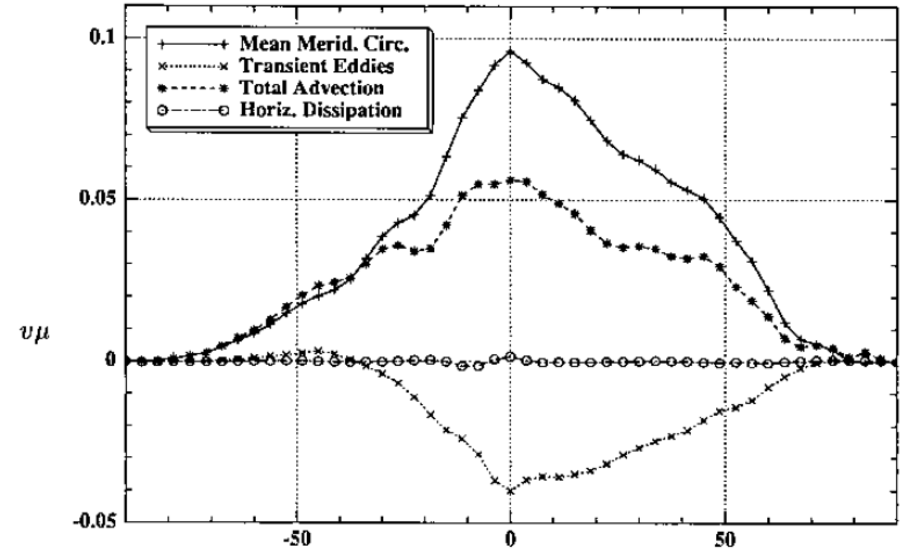
Titan : Angular momentum budget

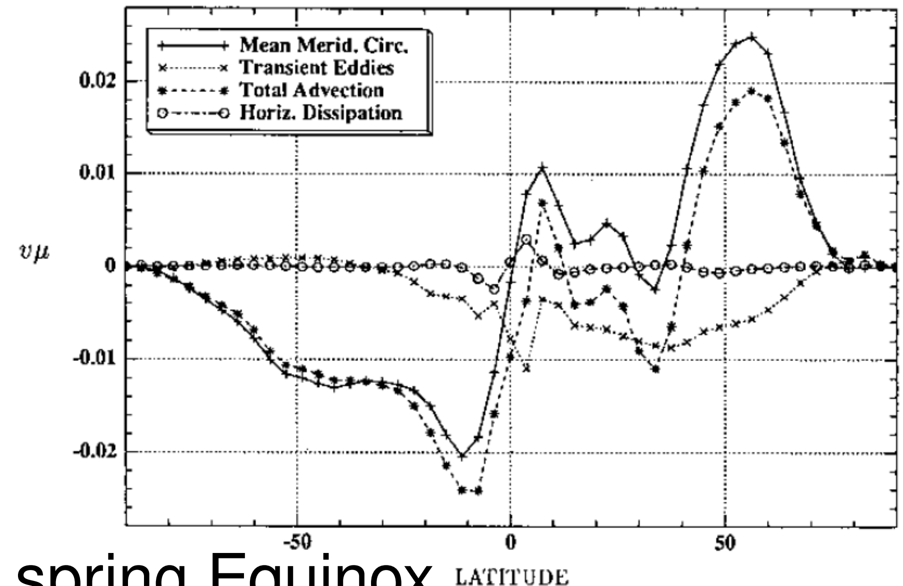
(Hourdin et al. 1995)

N winter Solstice

Annual mean







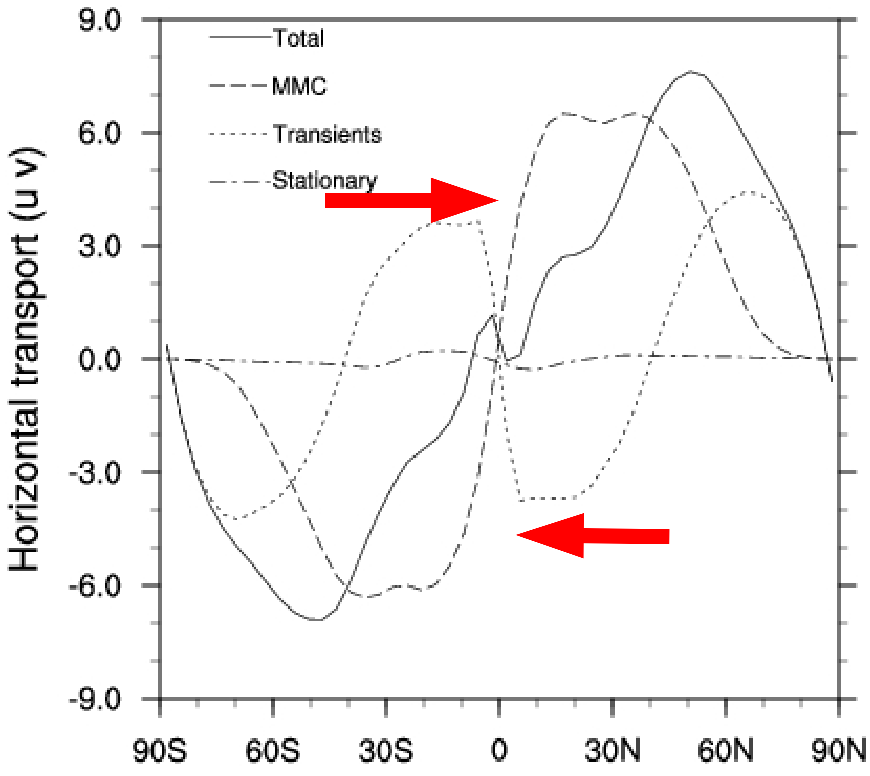
N spring Equinox

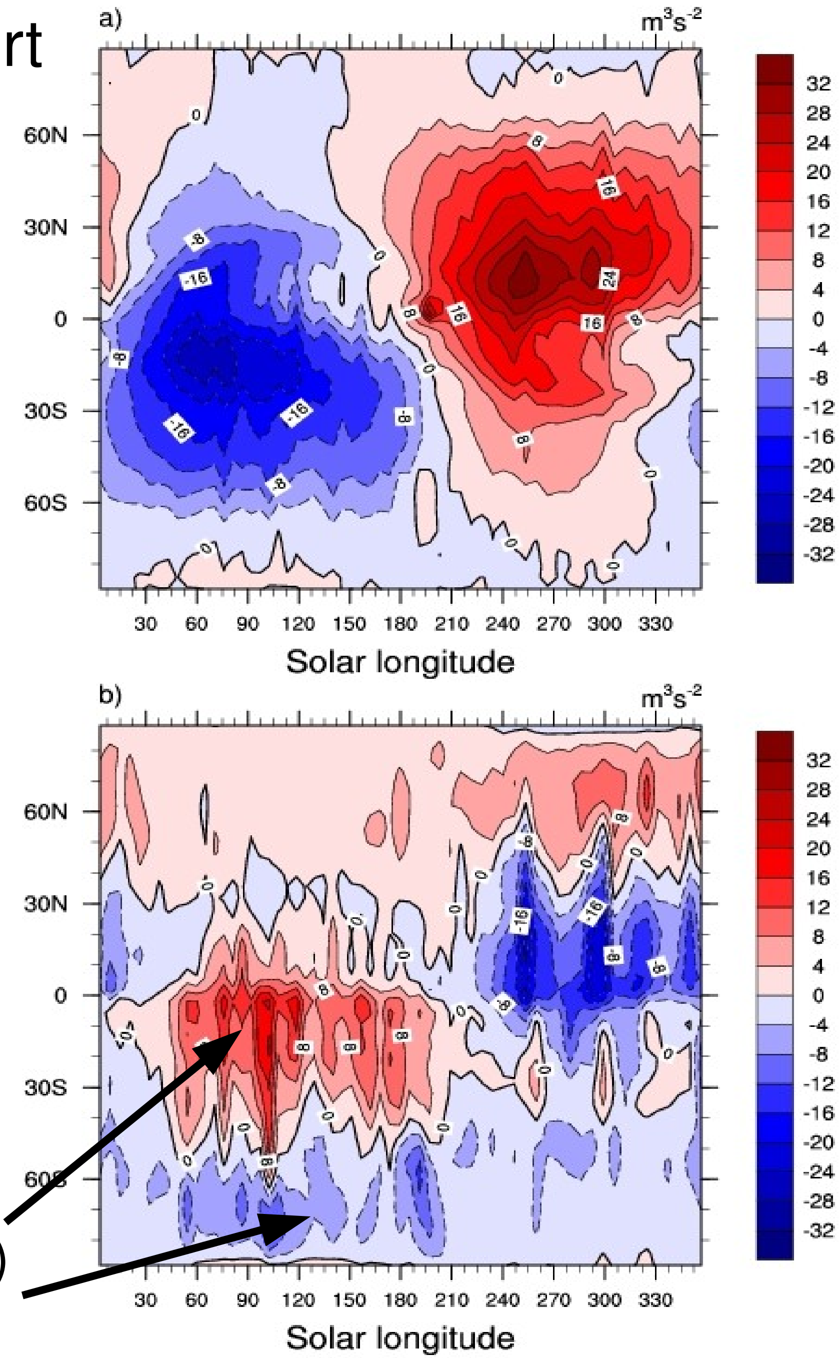
Titan : Angular momentum budget

(Lebonnois et al. 2012)

MMC transport

Annual mean





Transients transport

Barotropic waves (stratosphere)

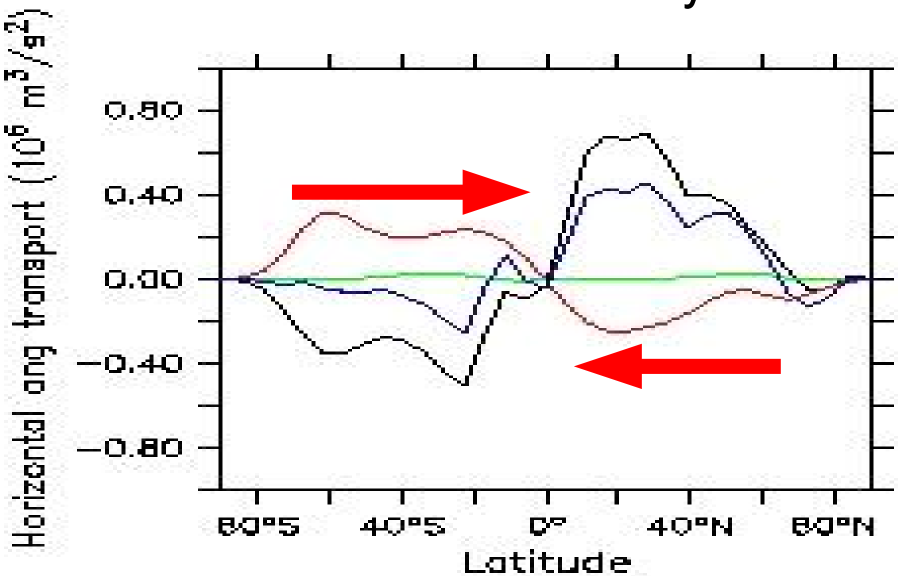
Baroclinic waves ? (troposphere)

Venus : Angular momentum budget

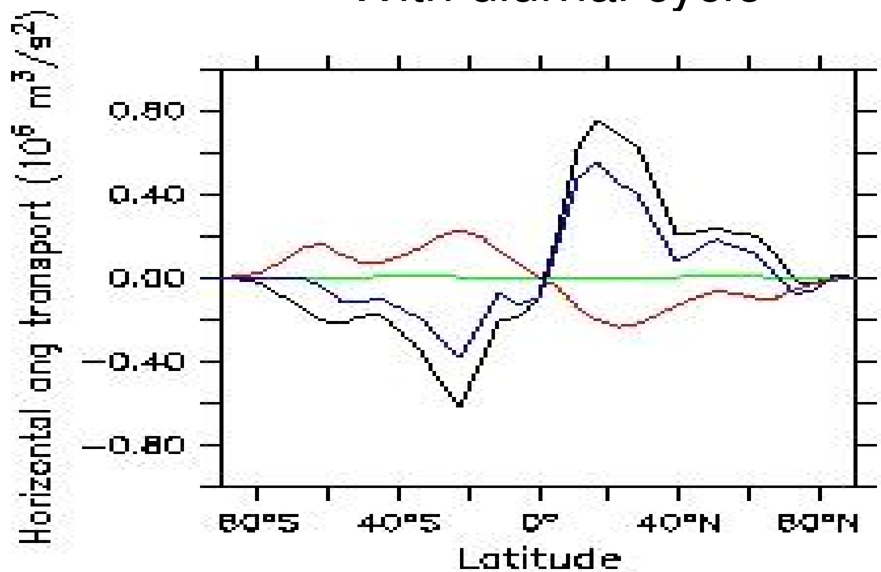
(Lebonnois et al. 2010)

Resolution: 48x32

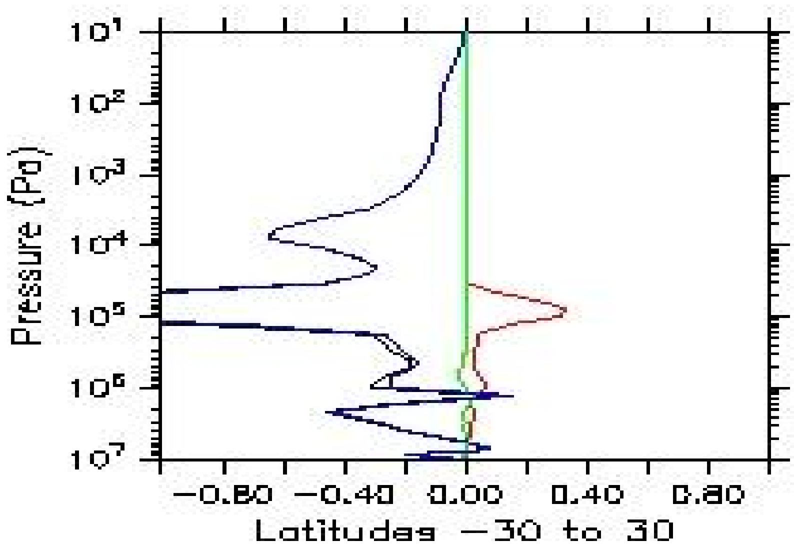
Without diurnal cycle

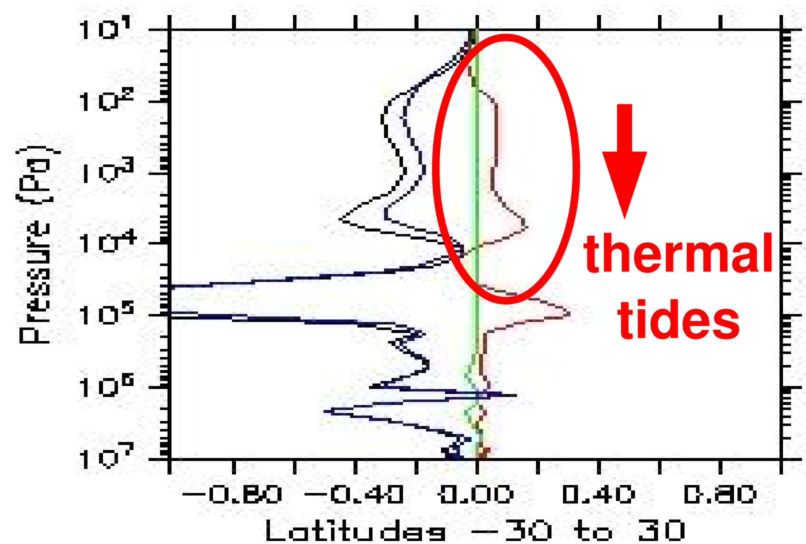


With diurnal cycle



Vertical transport between 30°N and 30°S

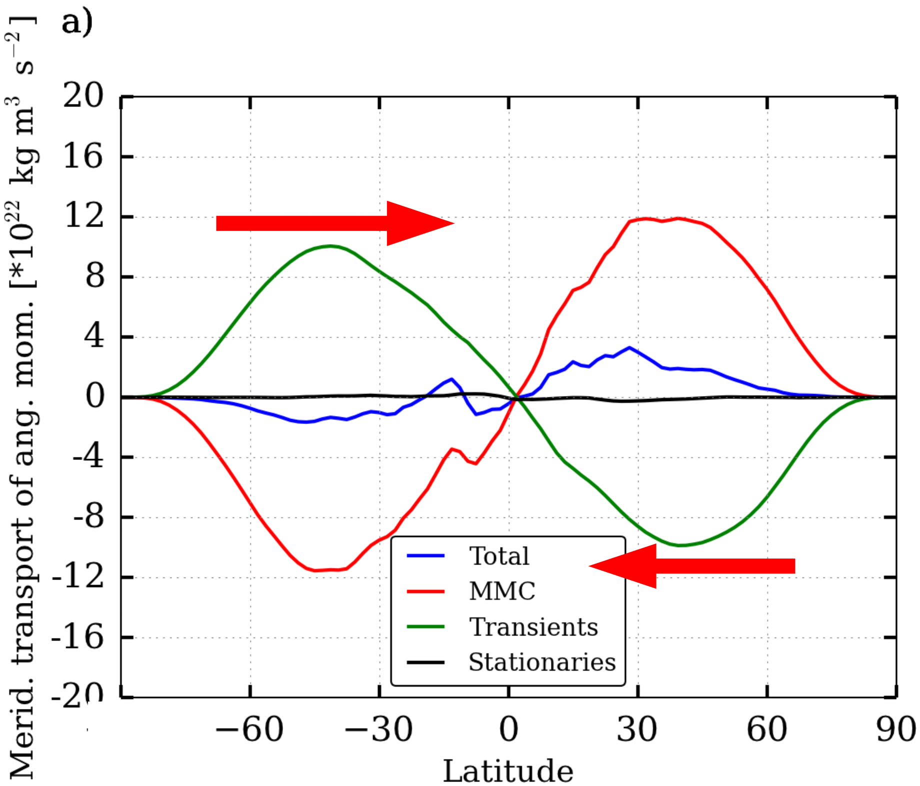




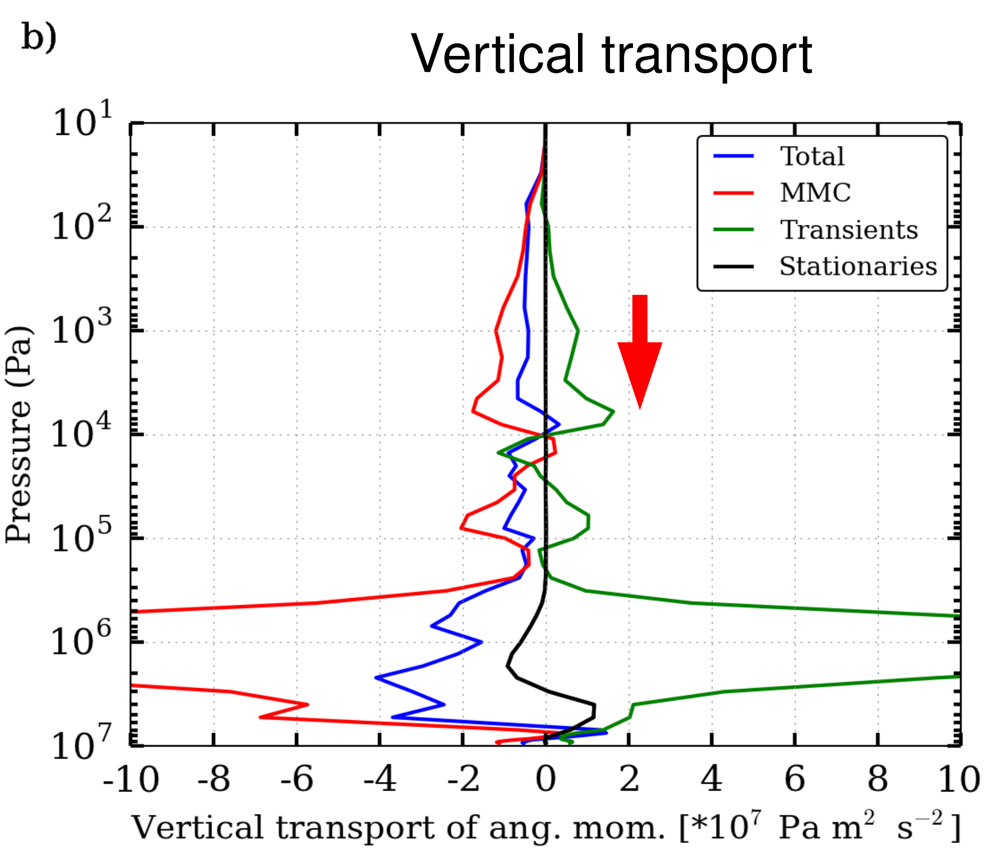
Venus : Angular momentum budget

(Lebonnois et al. 2016)

Resolution: 96x96



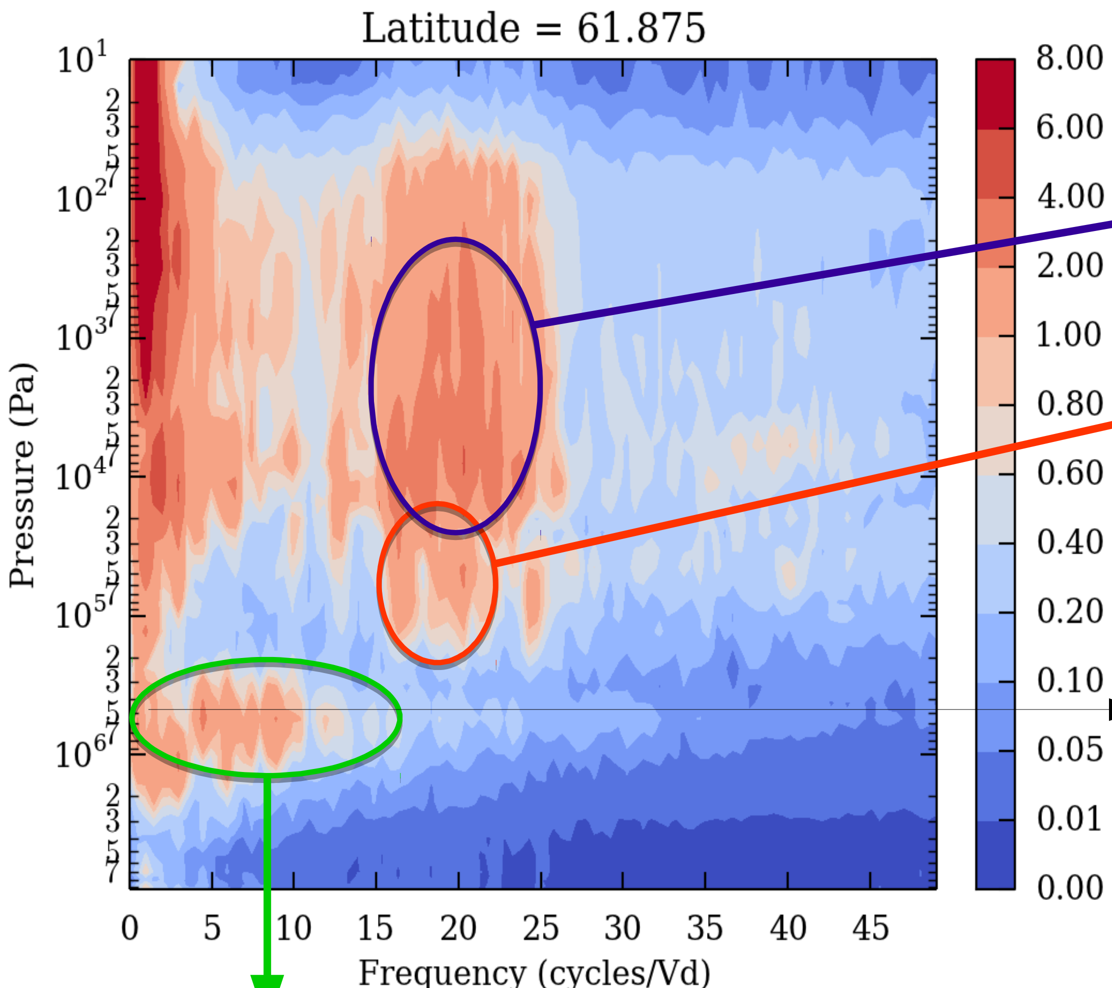
Horizontal transport



Venus : Wave activity

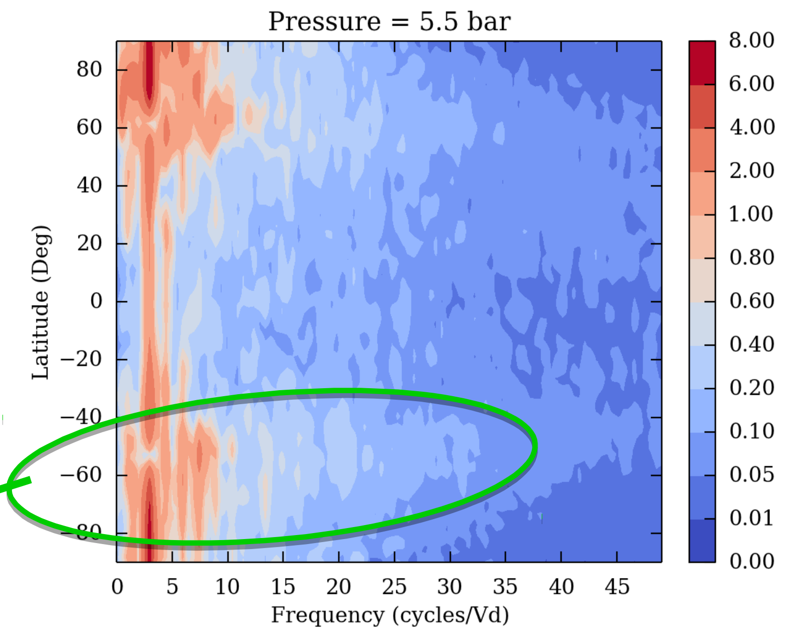
Most recent simulation, still under analysis...

FFT of zonal wind time series



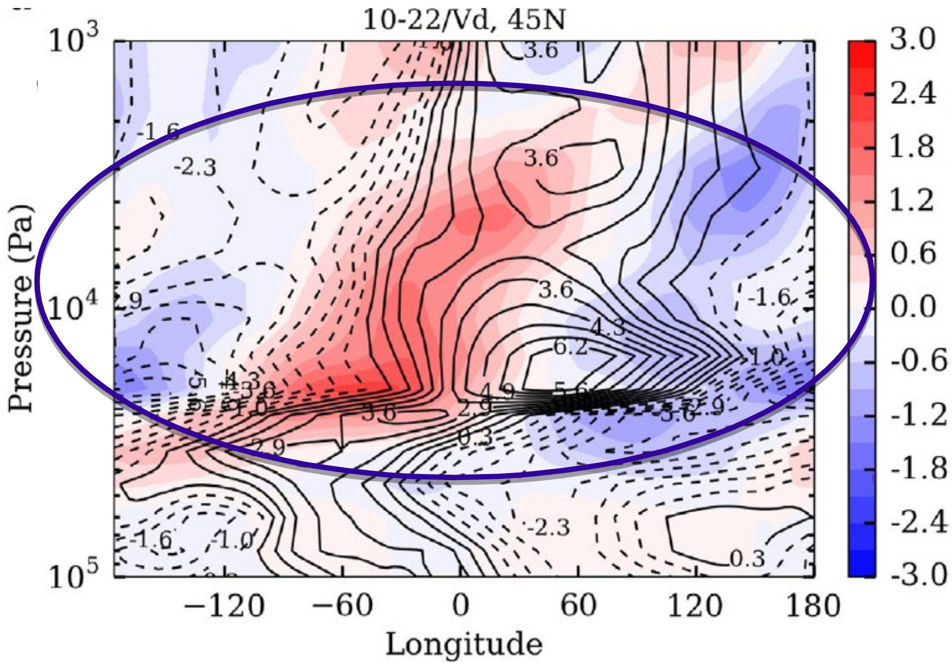
Dominant baroclinic activity,

Baroclinic activity, contributes to cloud-base equatorial zonal wind



Inertio-gravity waves, contributes to deep atmosphere zonal wind

Venus : Angular momentum budget

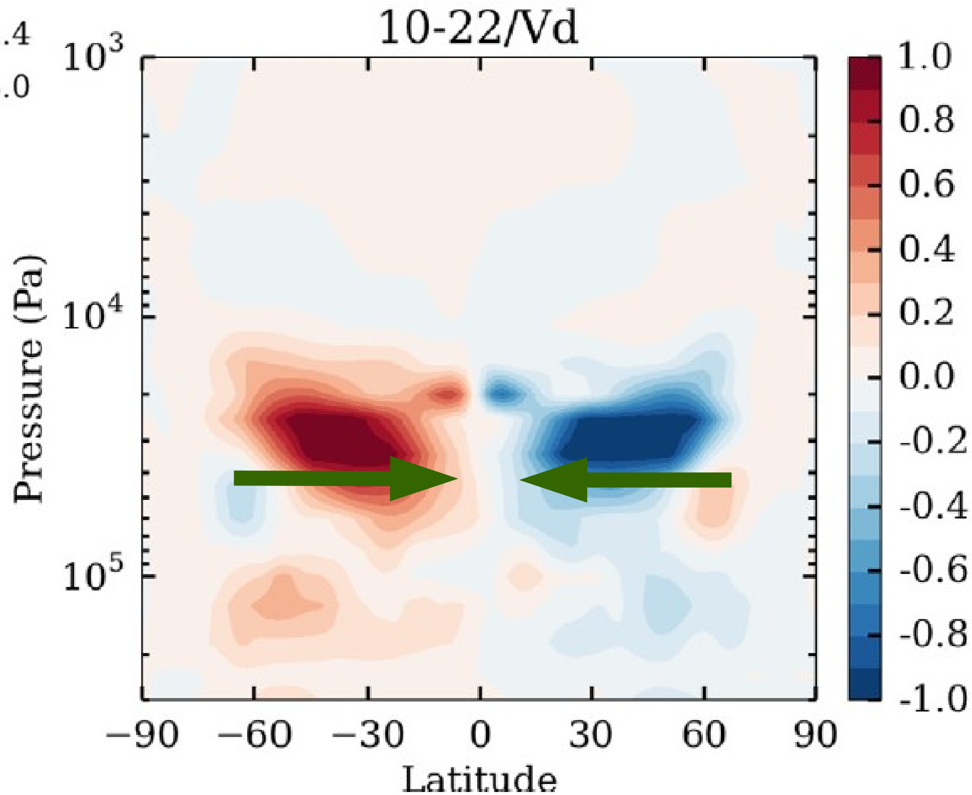


Lebonnois et al (2016)

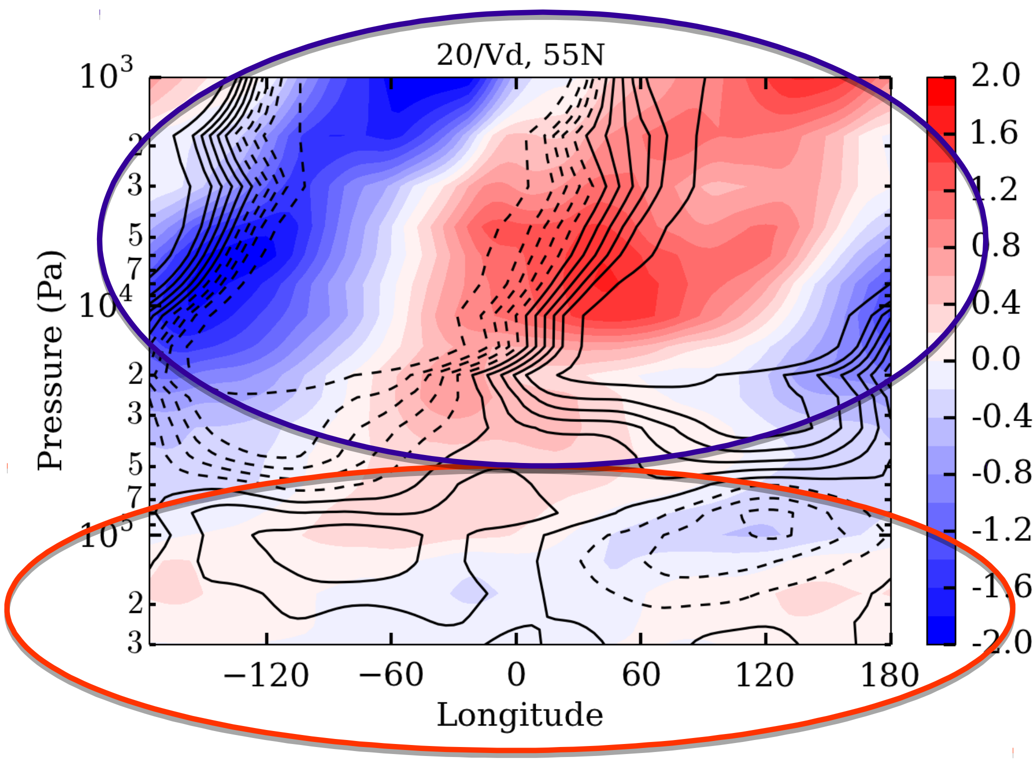
Baroclinic waves

Meridional wind and temperature anomalies

Horizontal transport of angular momentum



Venus : Angular momentum budget

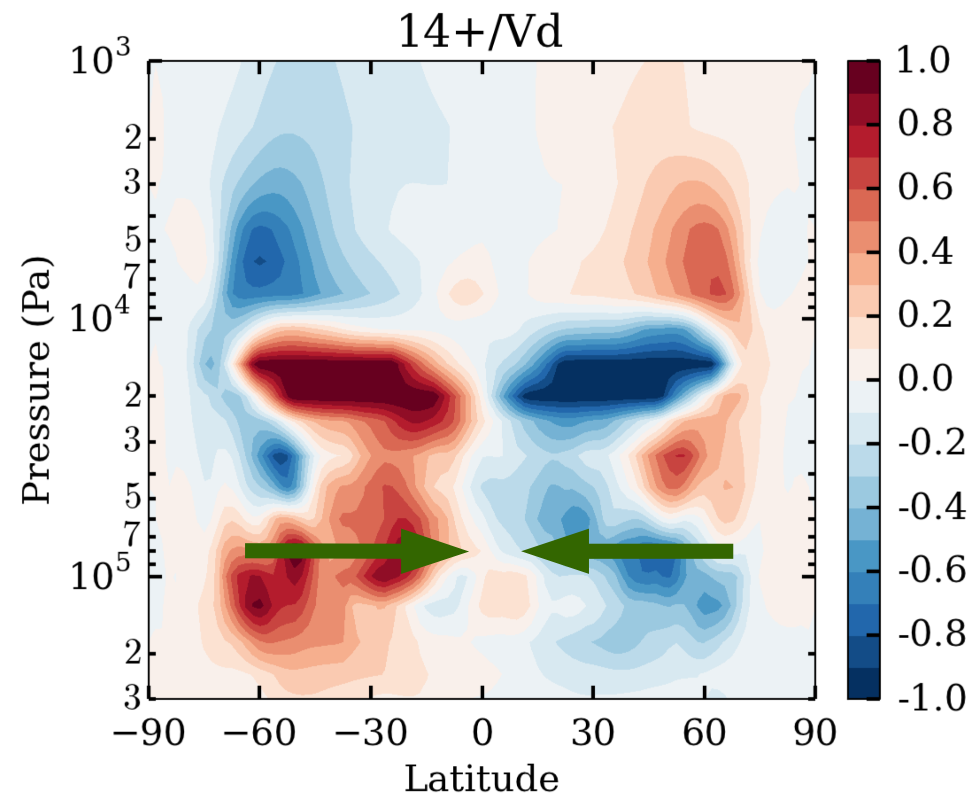


Cloud base baroclinic waves

Meridional wind and temperature anomalies

Most recent simulation

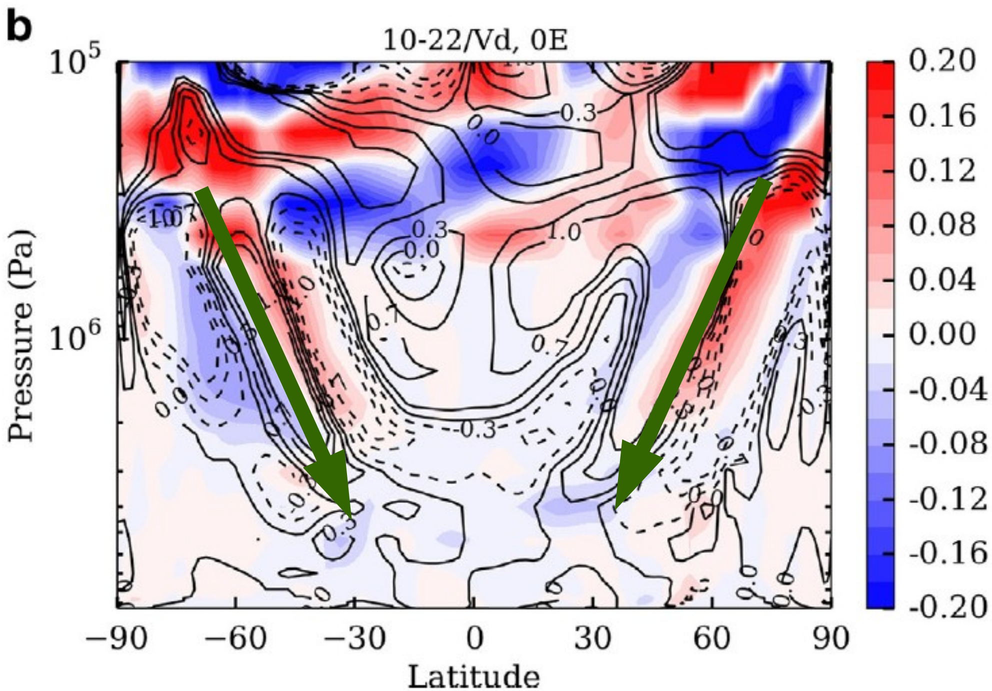
Horizontal transport of angular momentum

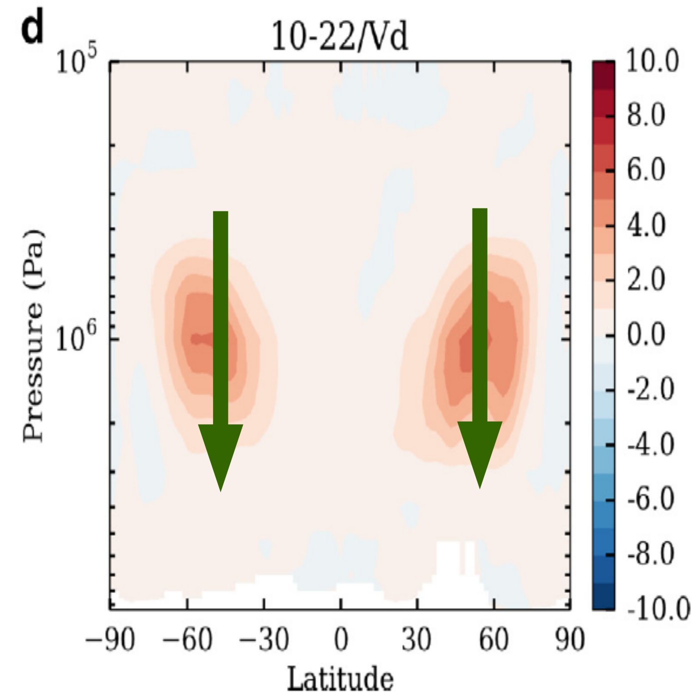


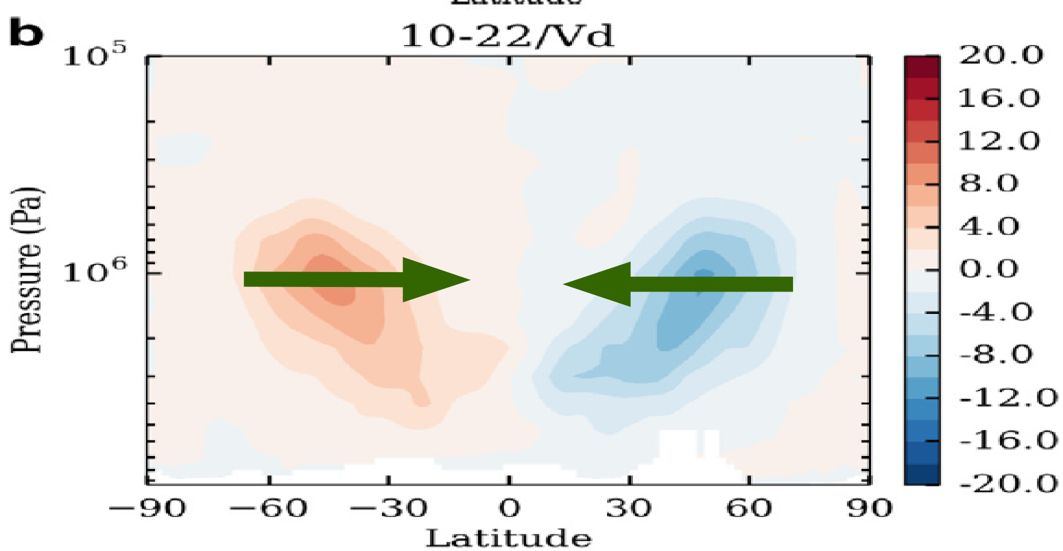
Venus : Angular momentum budget

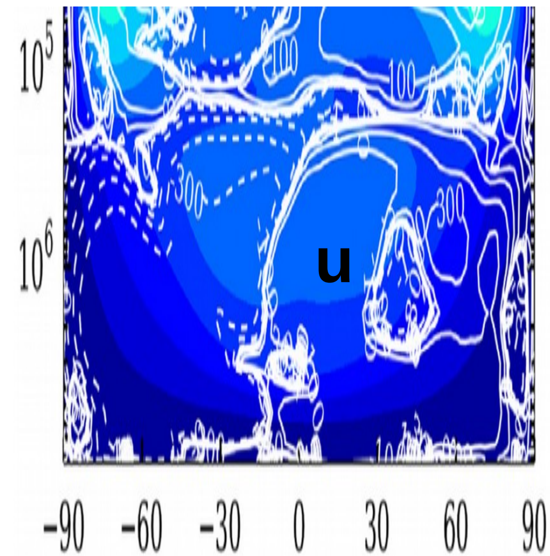
Inertio-gravity waves

Lebonnois et al (2016)





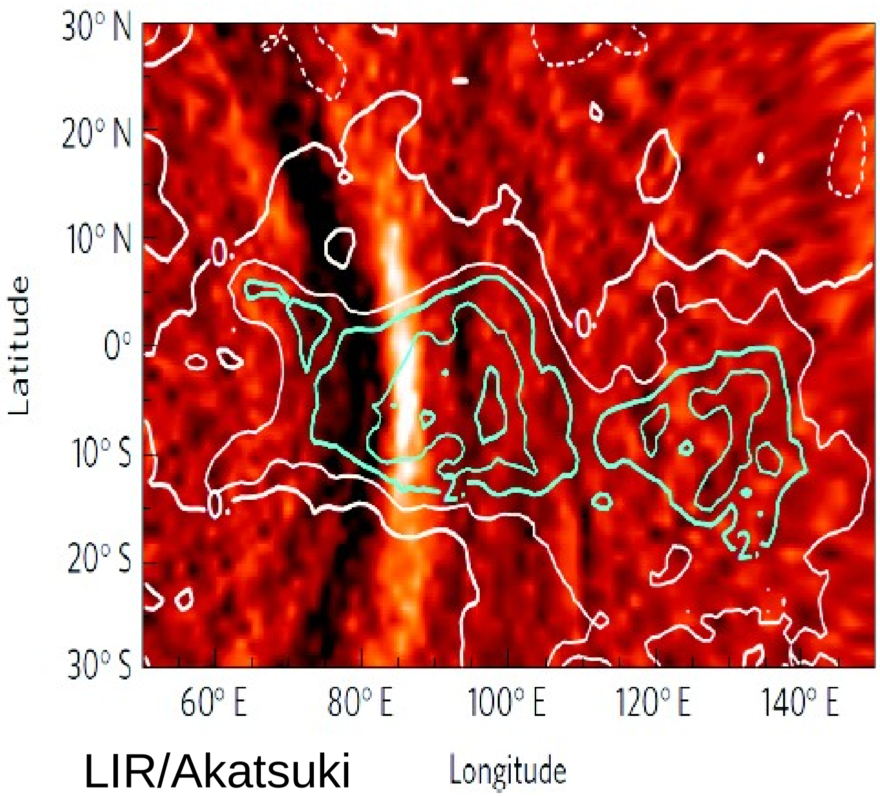




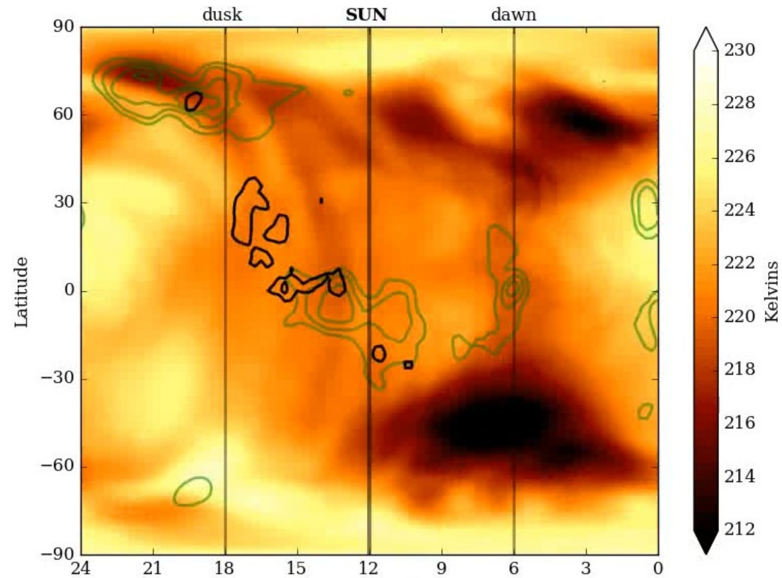
Venus : Surface interactions

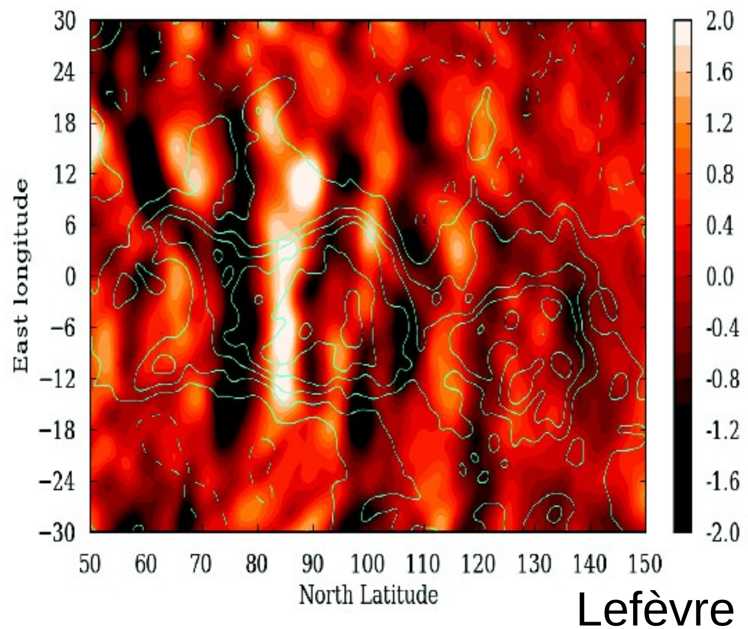
Navarro et al (2018)

Orographic gravity waves



LIR/Akatsuki





Lefèvre et al, 2019

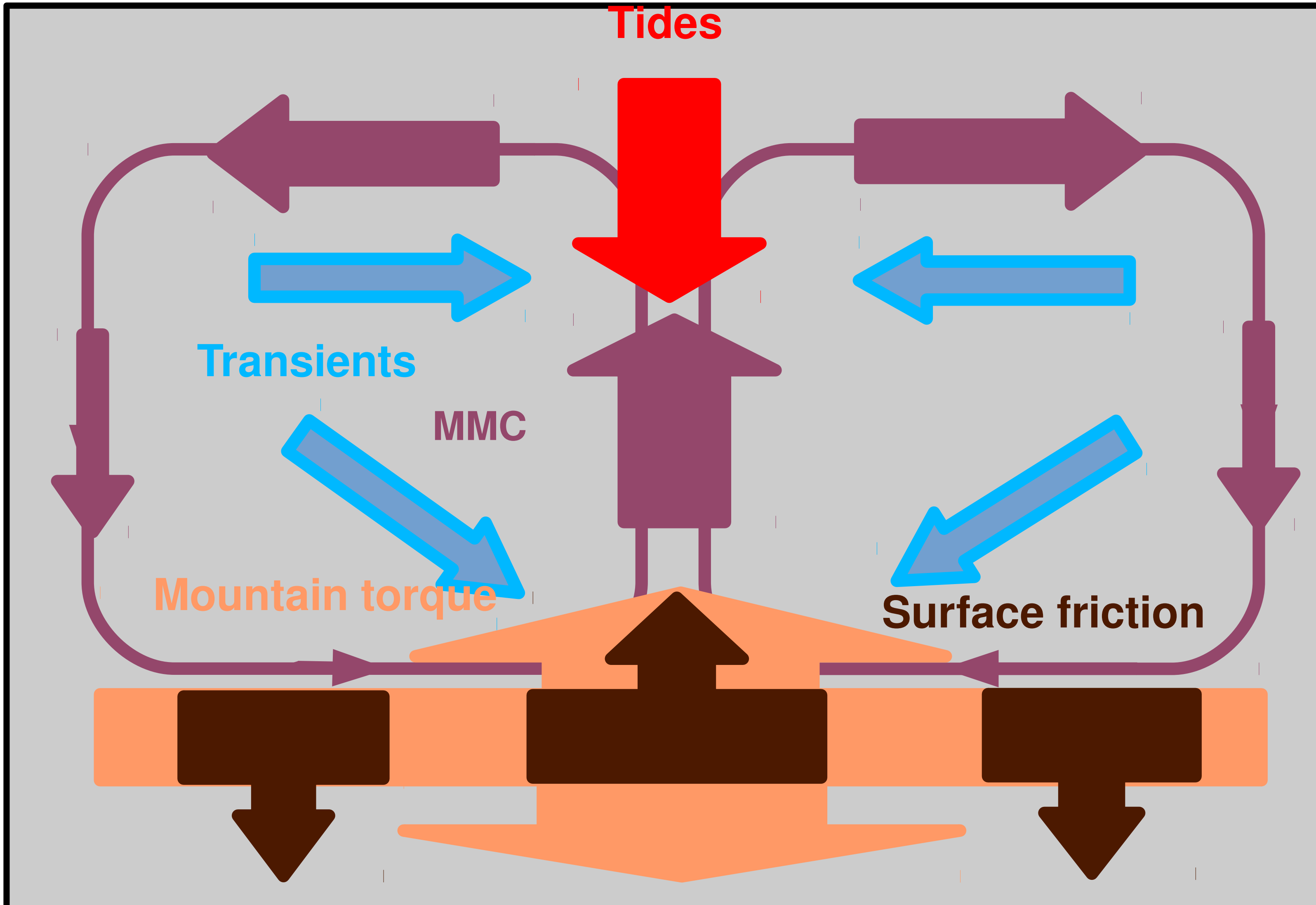
Venus orographic GW => impact on zonal wind ?

=> ang mom exchange with surface, LOD var ?

- Superrotation in the Solar System: Venus and Titan
  - First observations
  - Characteristics
  - Differences between Venus and Titan
- Tools to undertand: Global Climate Models
  - The IPSL Venus & Titan GCMs
  - Angular momentum budgets
- **Summary**
  - **Mechanisms**
  - **Similarities and differences between Venus and Titan**

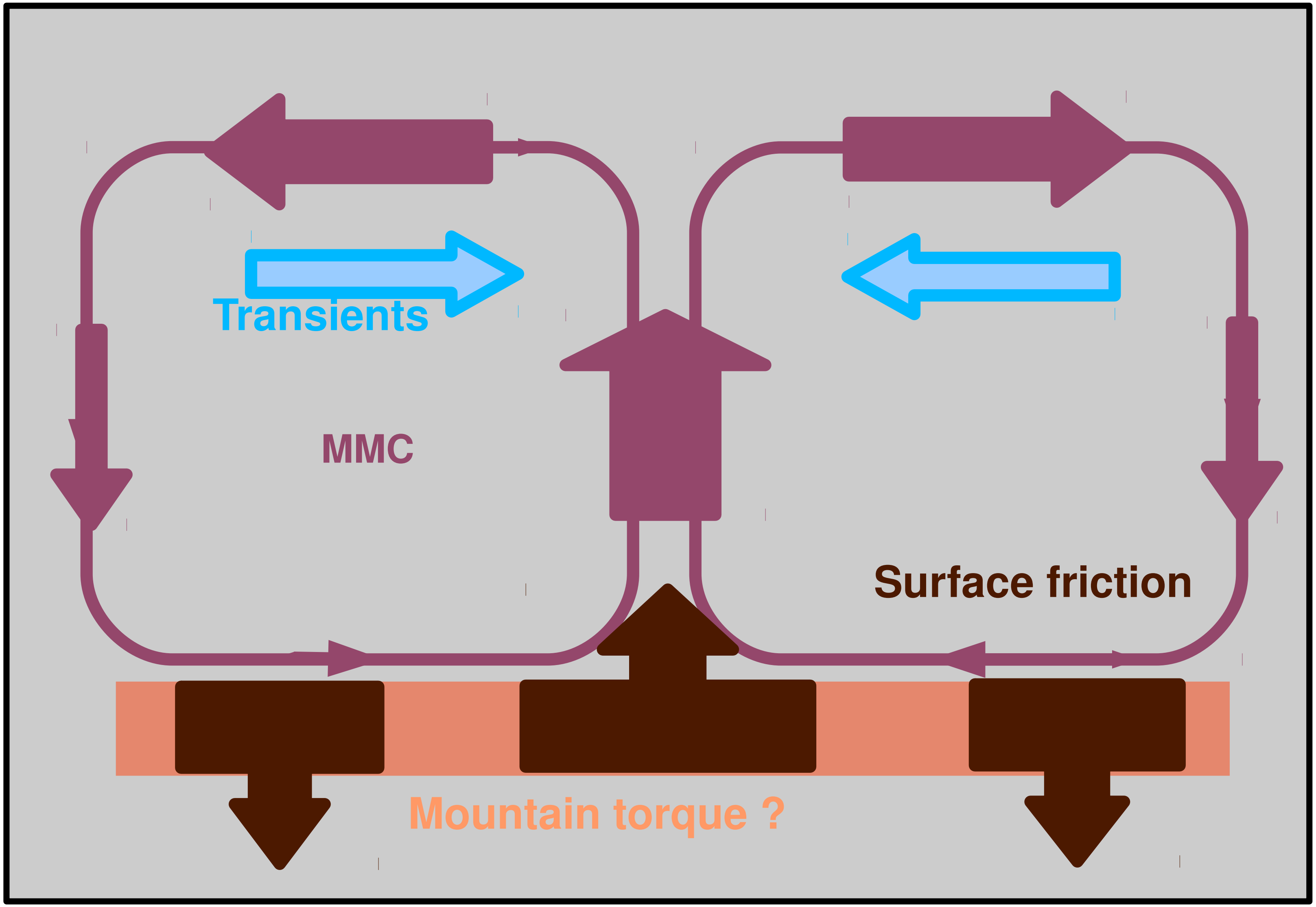
Summary

Venus:
Gierasch-Rossow-Williams (GRW),
but with tides and inertio-gravity waves



Summary

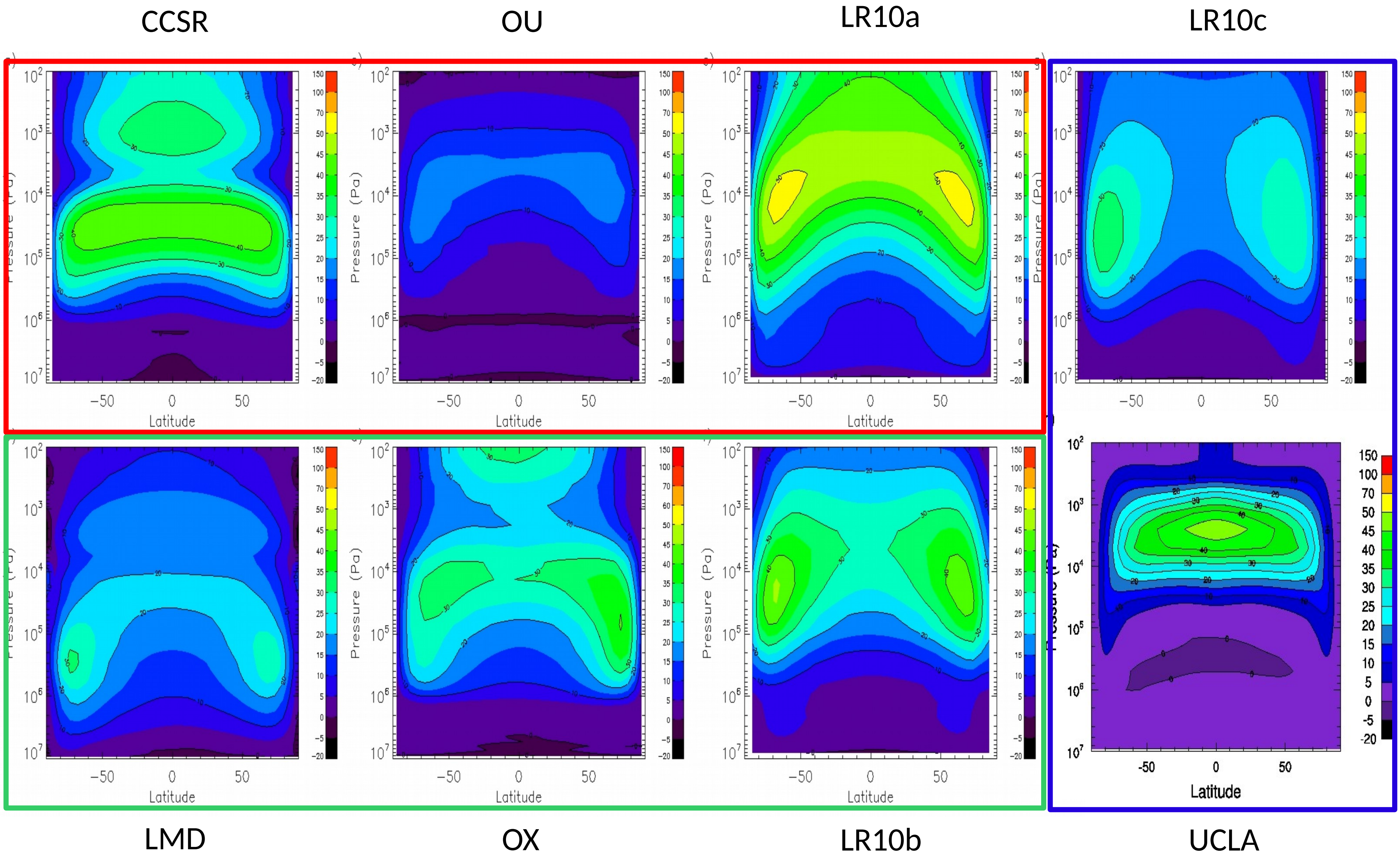
Titan:
Gierasch-Rossow-Williams (GRW), in annual average
Seasonal variation, from one hemisphere to the other



A subtle balance

A kind of Held-Suarez exercise for simplified forcing Venus GCMs
It illustrates the sensitivity of the balance

Lebonnois et al (2013)



Mean zonal wind field

Conclusion

Zonal wind field results from subtle balance between mean meridional circulation and wave momentum transport

Wave activity plays a crucial role in the redistribution of angular momentum

Depending on the atmospheric properties, different type of waves can participate to this balance
=> tides, planetary-scale horizontal waves, inertio-gravity waves

Robust interpretation needs to be confirmed by observations and comparisons between several GCMs