The mechanism of superrotation: Comparing Venus and Titan with General Circulation Models

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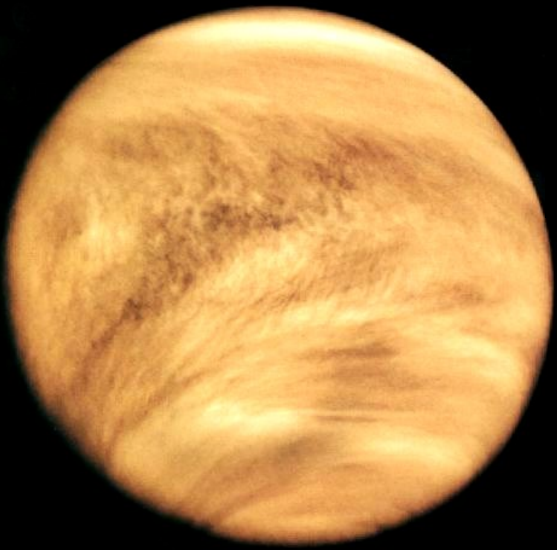
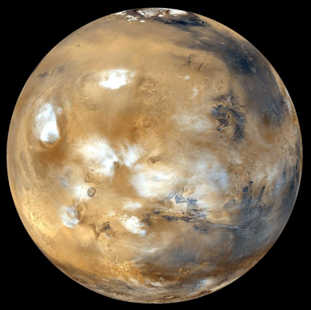
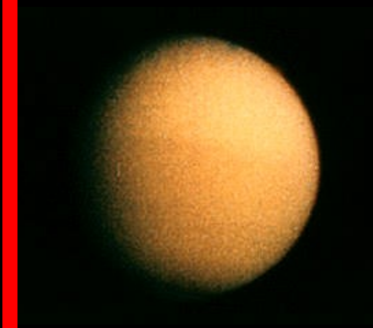
LMD, Paris



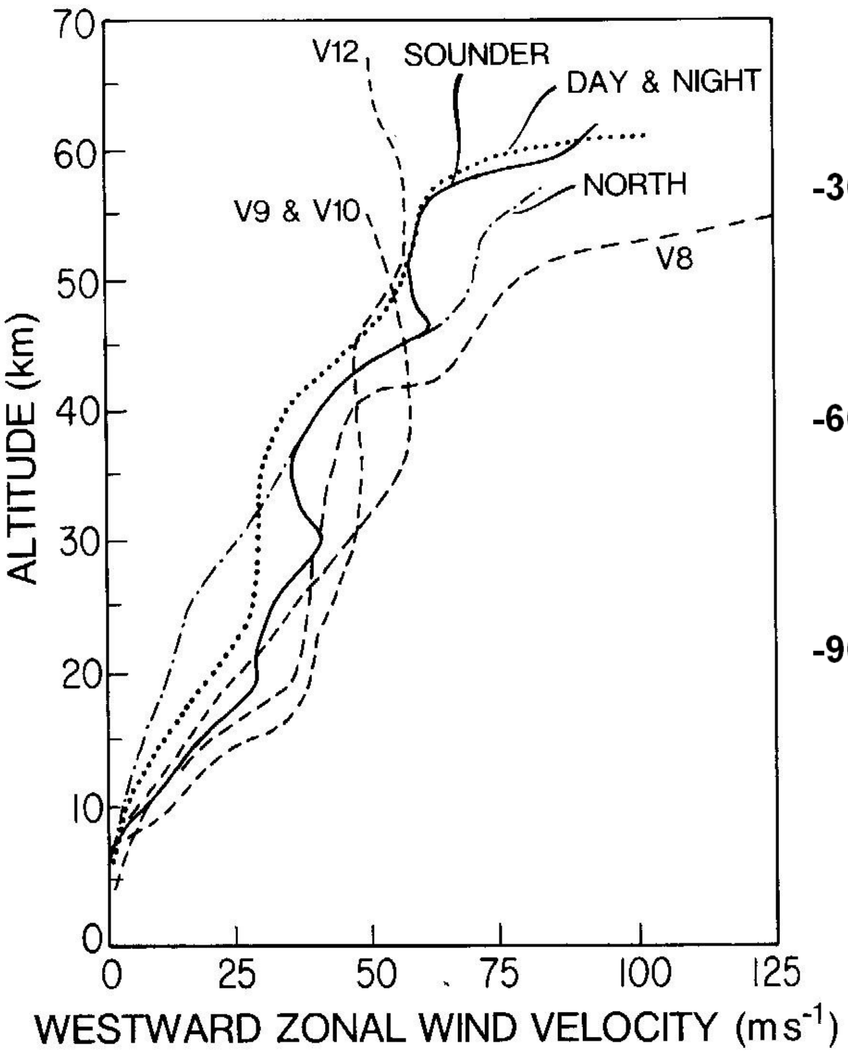


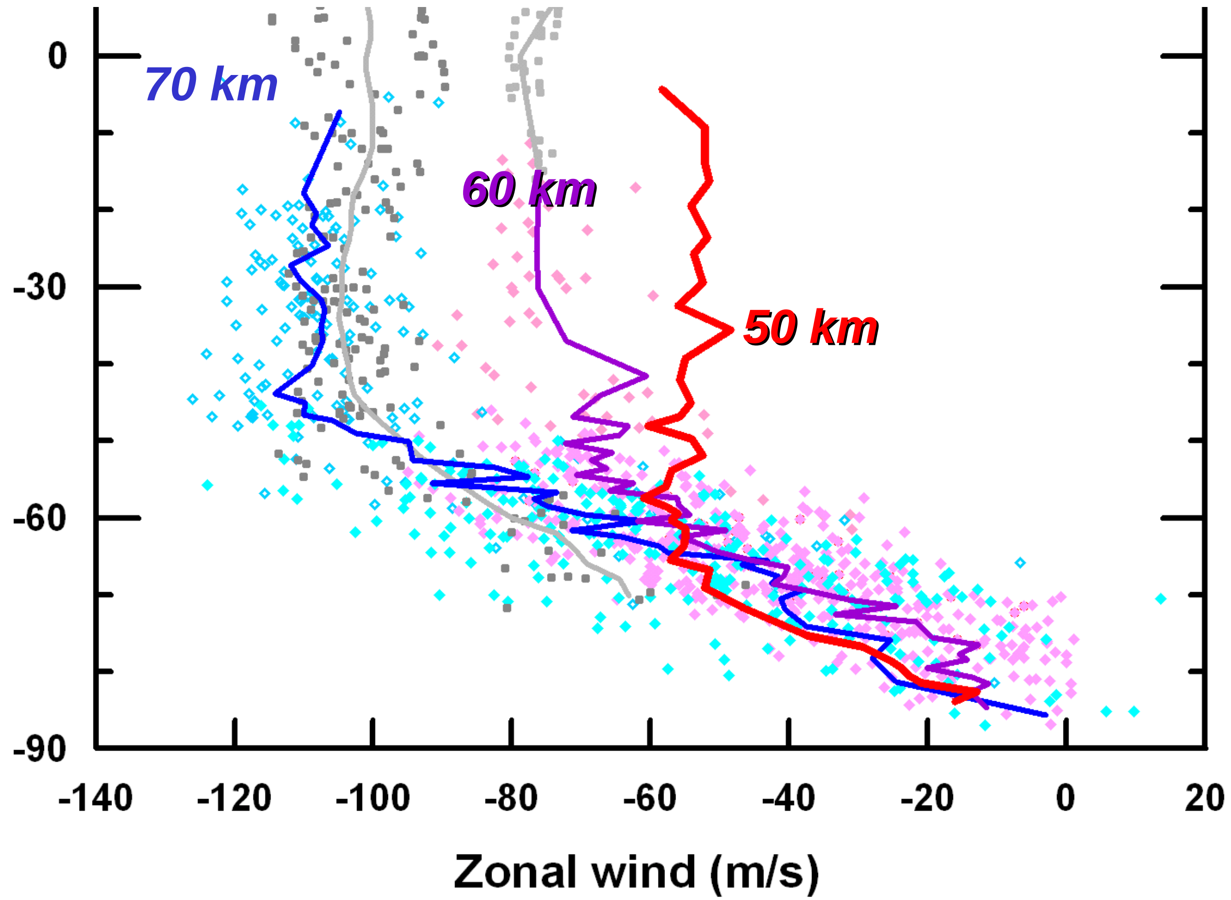


VENUS	EARTH	MARS	TITAN
<Ts> ~ 450°C	<Ts> ~ 15°C	<Ts> < -50°C	<Ts> ~ 95 K
CO_2~90b	CO_2~0.3 mb	CO_2 = 0.006 b	CH_4 ~ 0.06 b
H_2O/CO_2<<1	O_2~0.2 b	N_2 = 0.0002 b	N_2 = 1.5 b
N_2~3b	N_2~0.8 b		
Sun distance = 0.72 AU	1 AU	1.52 AU	9.5 UA
M = 0.81 M_{Earth}	1	0.11 M_{Earth}	0.023 M_{Earth}
ρ = 5.25	5.52	3.95	1.88
obliquity = 177.4°	23.5°	25.2°	26.7°
rotation = (-) 243 d	**23 h 56 m**	**24 h 37 m**	**15.94 d**
revolution = 224.7 d	365.25 d	687 d	~30 years

Observations of superrotation

Pioneer Venus and Venera probes

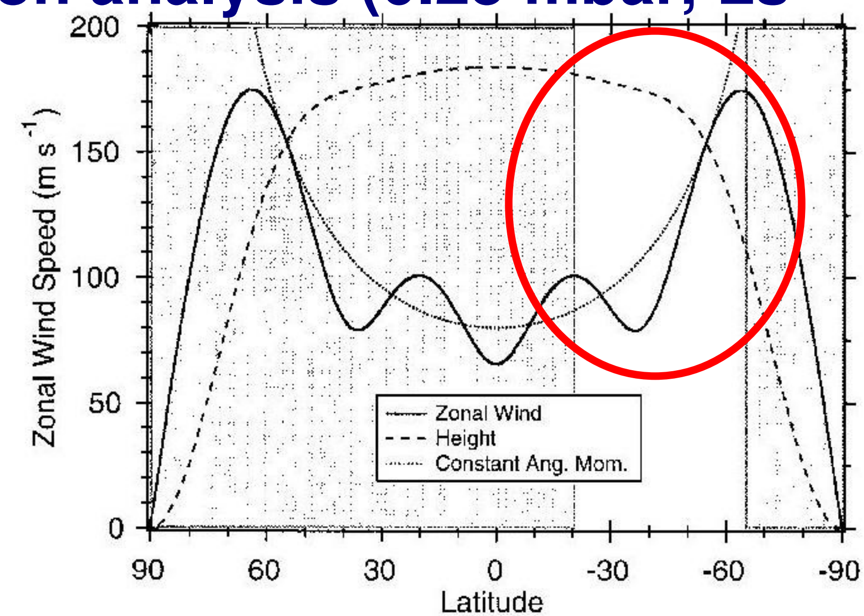




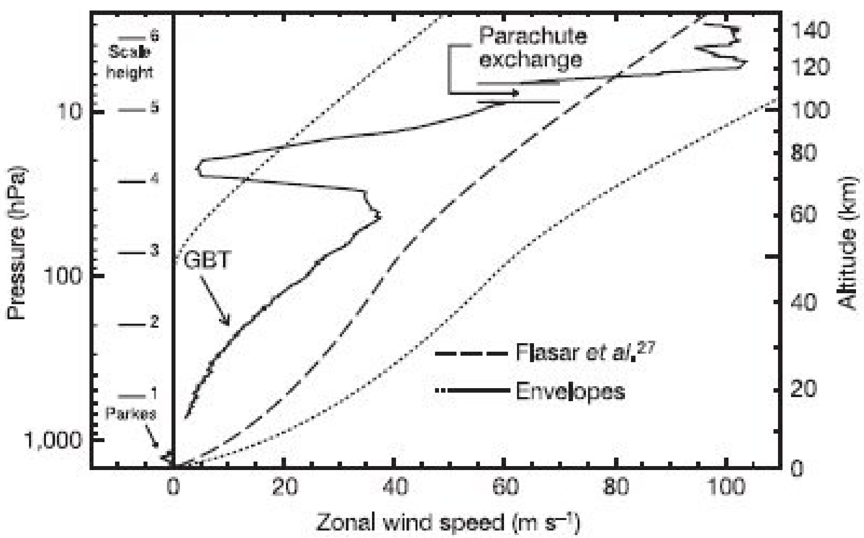
Venus Express/VIRTIS cloud tracking

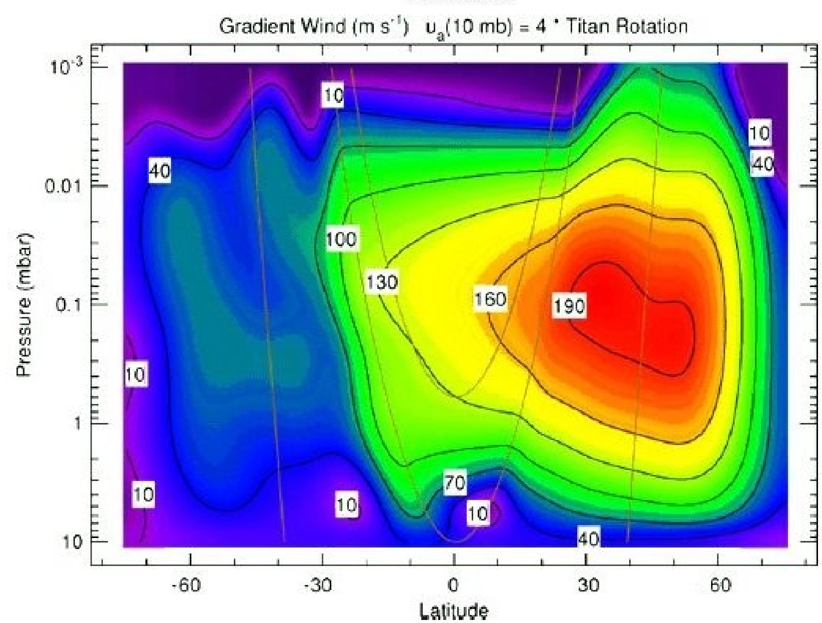
Observations of superrotation

Stellar occultation analysis (0.25 mbar, Ls ~ 128°)



Huygens/DWE vertical profile at 10°S (Ls ~ 300°)



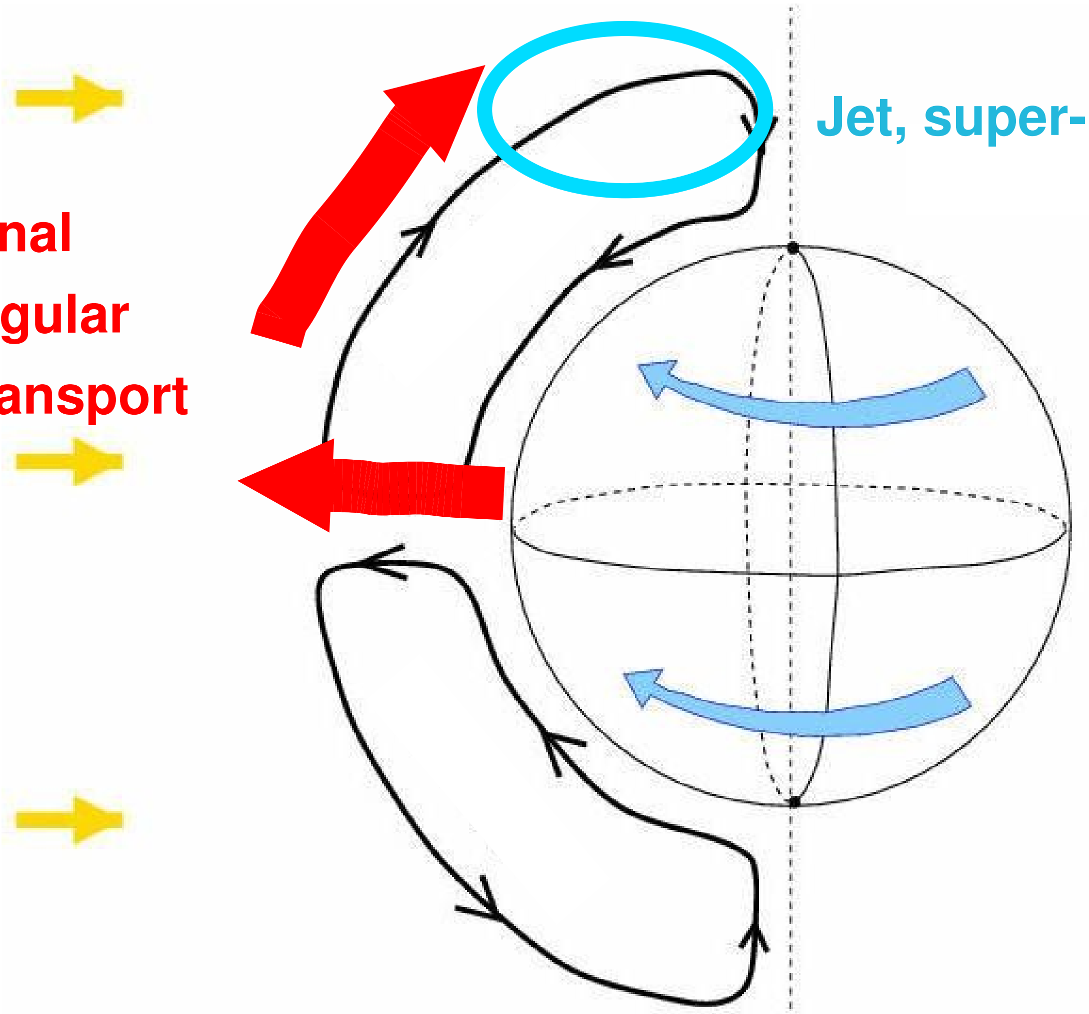


Cassini/CIRS thermal winds retrieval (Ls ~ 300°)

The superrotation question

Slow rotation:

extension of Hadley cells from equator to the poles

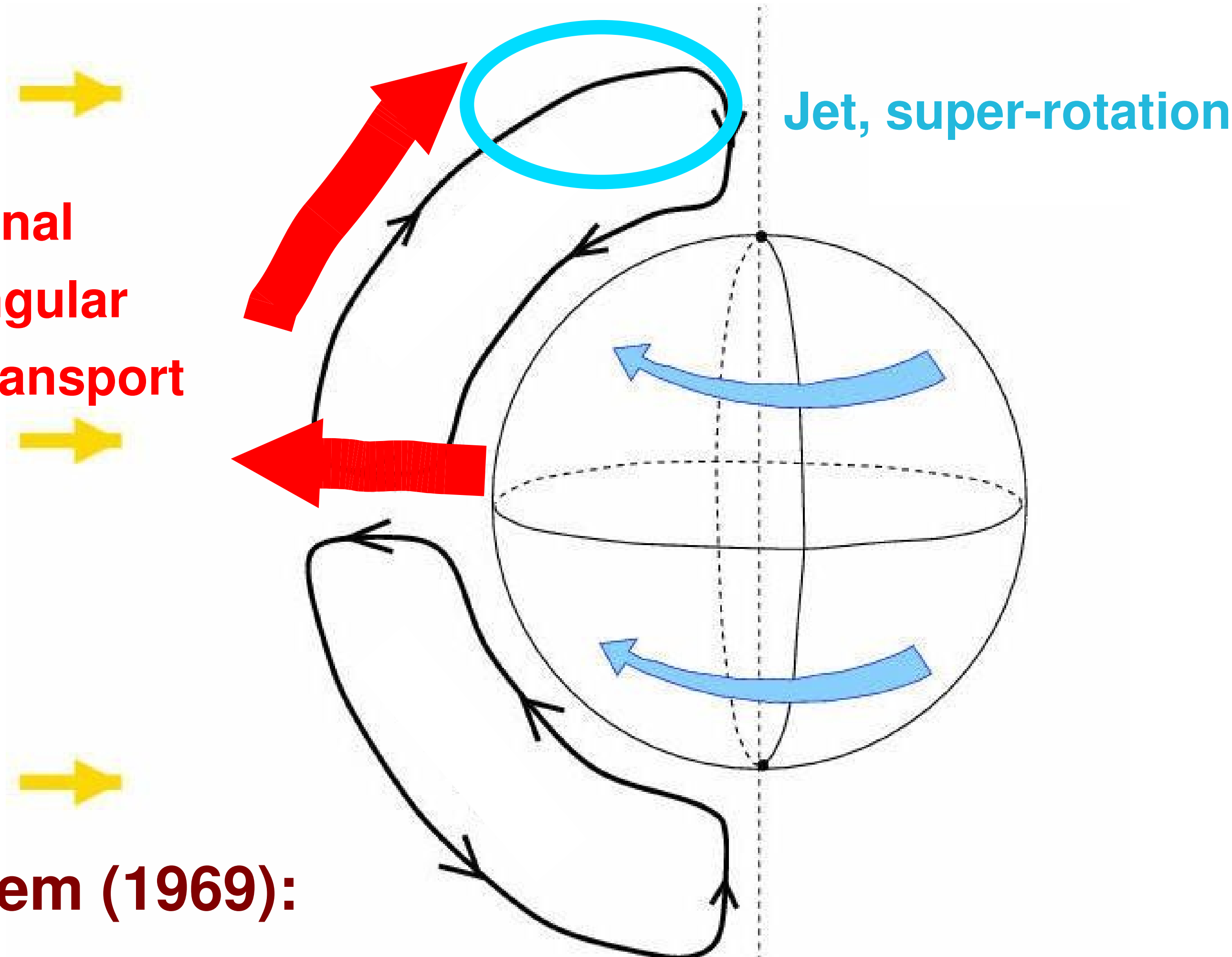


The superrotation question

Slow rotation:

extension of Hadley cells from equator to the poles

Mean meridional circulation angular momentum transport



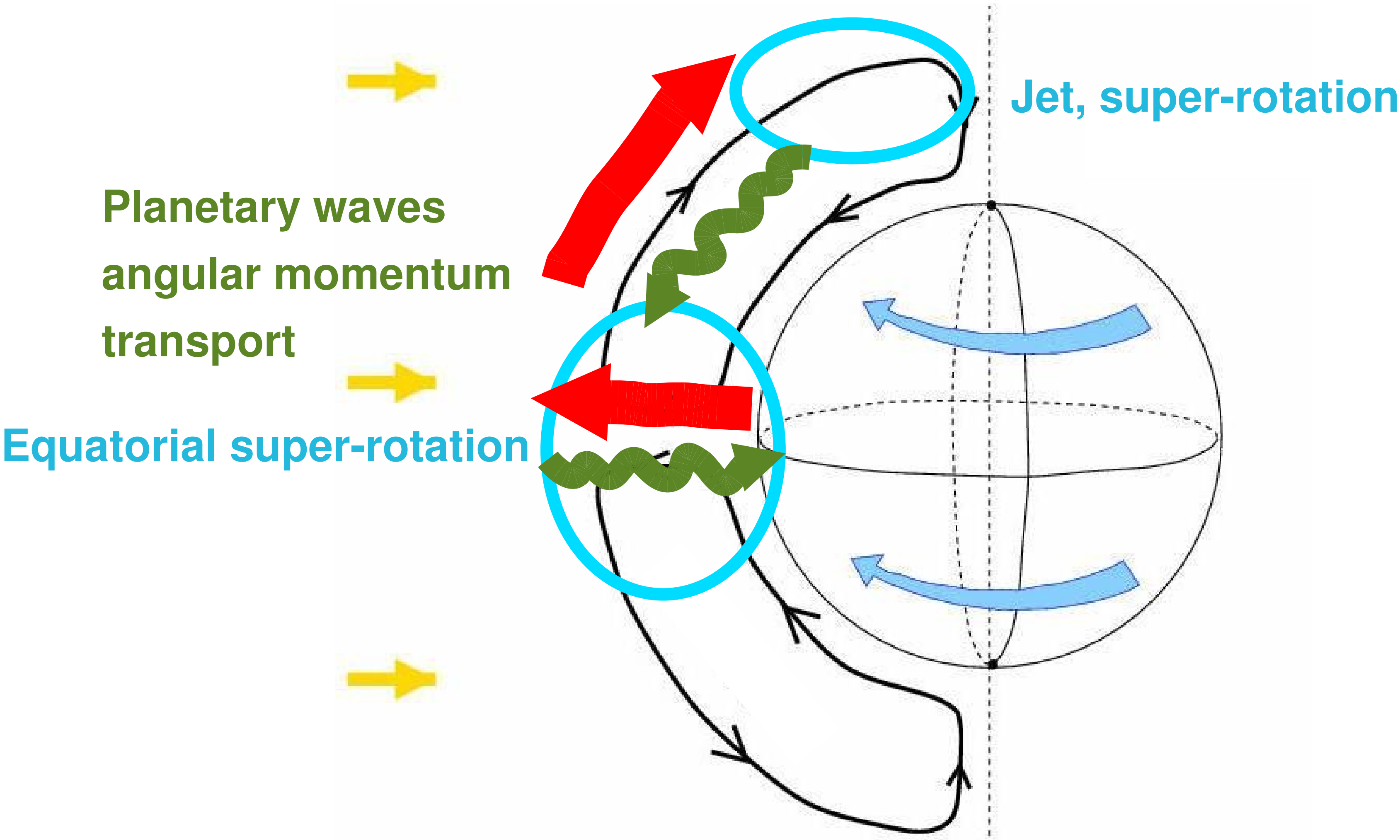
Hide theorem (1969):

this circulation alone can not create an equatorial maximum

The superrotation question

Superrotation at the equator:

need for non-axisymmetric planetary waves



The superrotation question

- Gierasch 1975; Rossow and Williams 1979:

  GRW mechanism: **unstable high-latitude jets**

  Horizontal transport by **waves** from poles to equator

- Newman and Leovy 1992, Takagi and Matsuda 2007:

  Possible role of **thermal tides**

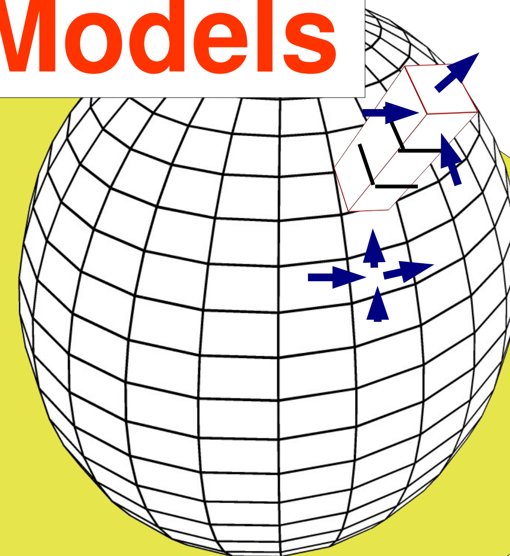
  Vertical transport of angular momentum

- Leovy 1973, Hou and Farrel 1987:

  Possible role of **gravity waves**

  Vertical transport of angular momentum

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

$\Delta t \sim$ 30 min

U, v, T, P_s → $\delta_t u, \delta_t v, \delta_t T, \delta P_s$

LMDZ versions

Earth

Mars

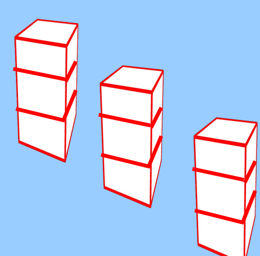
Titan

Venus

Idealized

Set of physical parameterizations

specific of the planet



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

First LMD Titan GCM

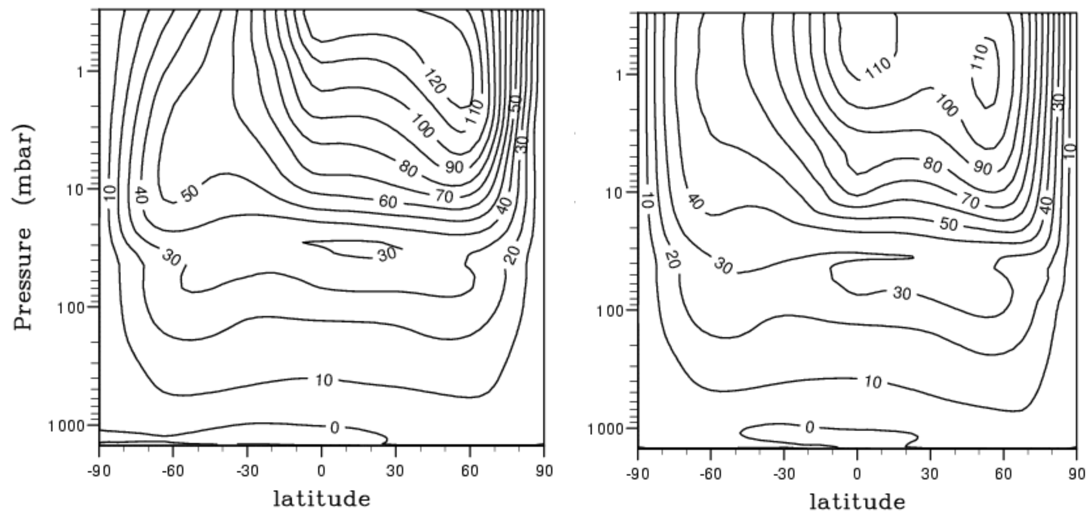
Hourdin et al. 1995

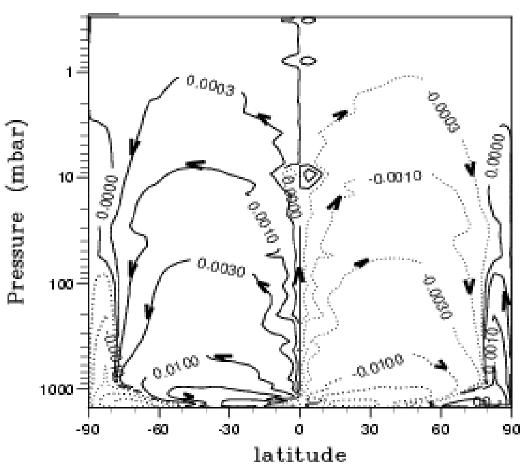
- Three-dimensional
- Fixed homogeneous haze and composition
- Surface to ~250 km

Southern summer solstice

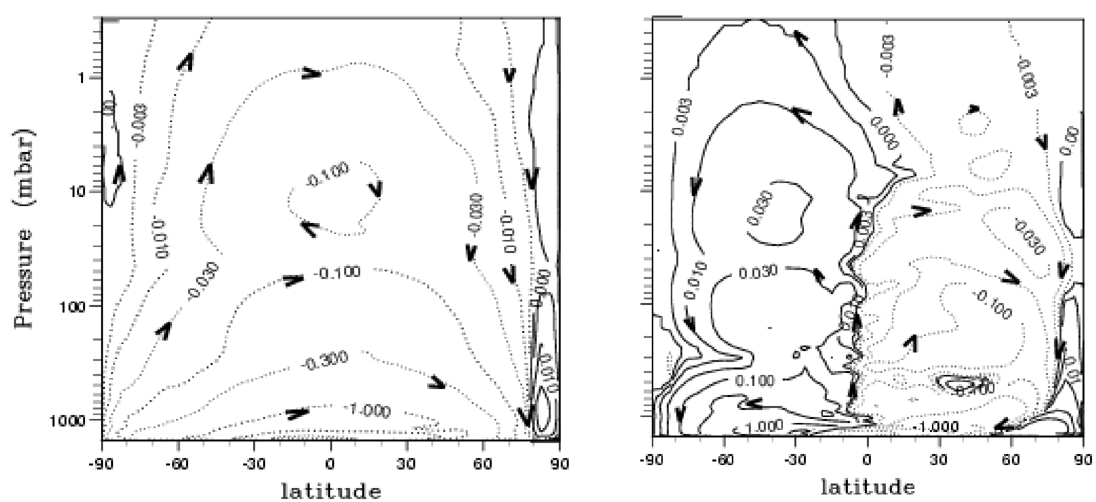
Northern spring equinox

Zonal wind (m/s)





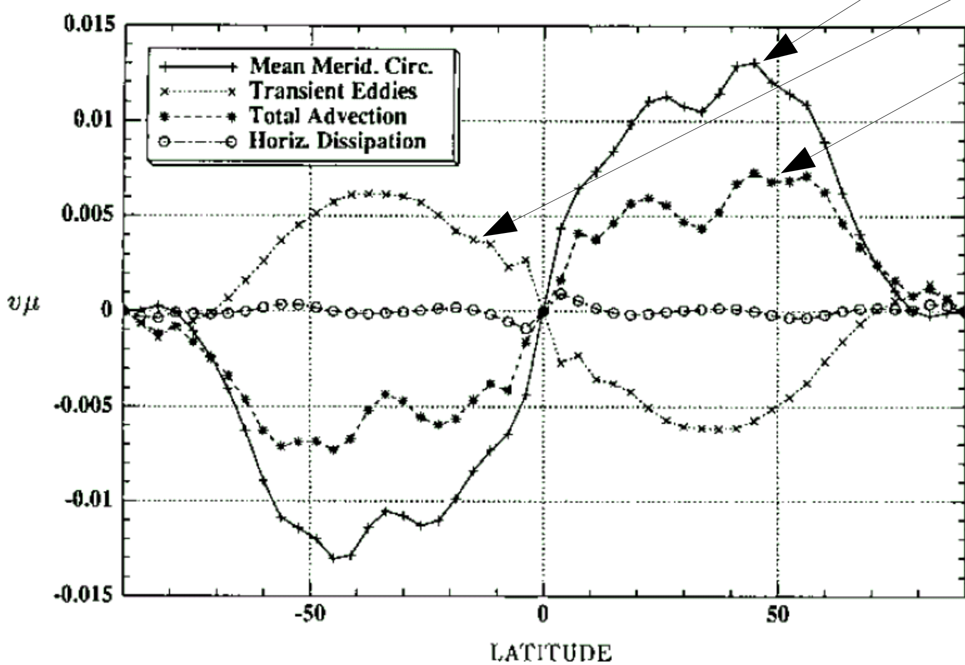
Stream function of the Mean Meridional Circulation (Mt / s)



First LMD Titan GCM

Hourdin et al. 1995

annual mean

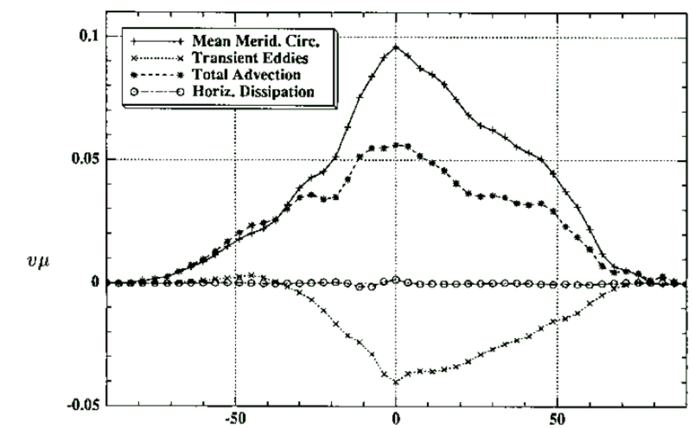


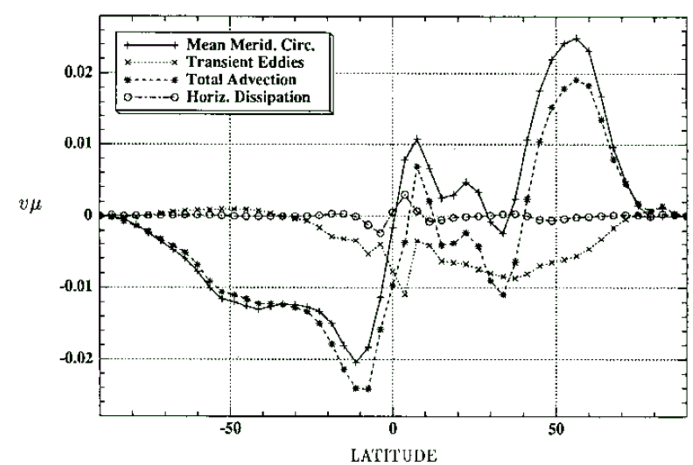
Mean meridional circulation

Transients

Total advection

N winter solstice





N spring equinox

⇒ **GRW mechanism**

Coupling with haze and chemistry

2D Climate Model

- **Barotropic waves have to be parameterized**
- Coupled haze and composition
- Surface to ~500 km

Important step :

Development of a parametrization of latitudinal mixing by waves.

PhD work of David Luz

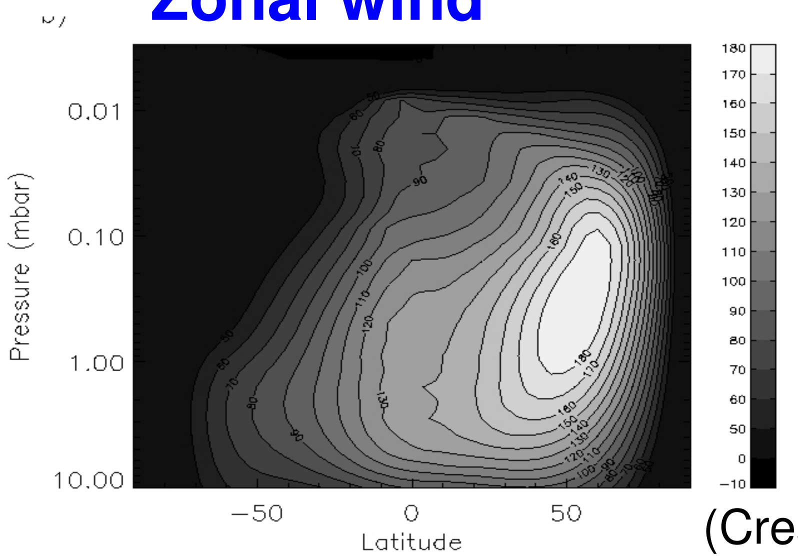
1. Study of the mixing properties of barotropic planetary waves in Titan stratosphere (Luz et Hourdin 2003).
2. Development of a parameterization (Luz et al., 2003).

Done with a 2D longitude-latitude "shallow water" model.

Coupling with haze and chemistry

2D Climate Model

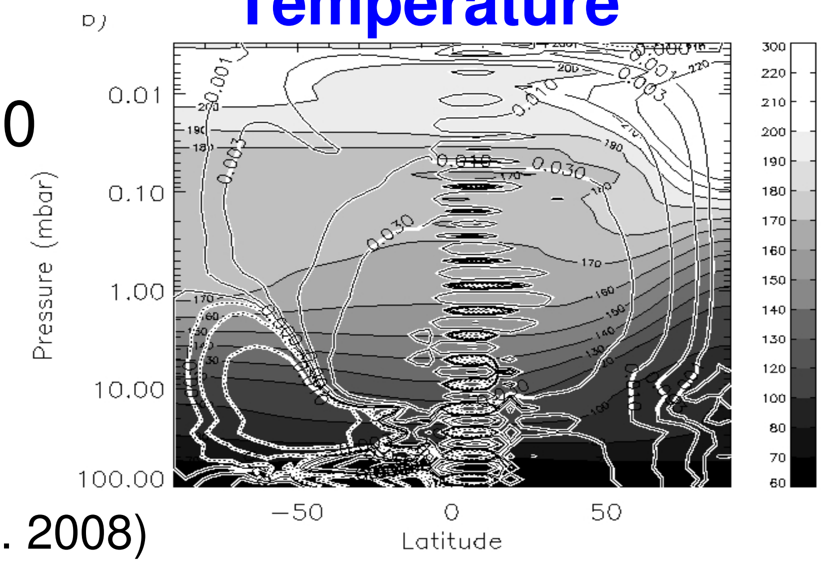
Zonal wind



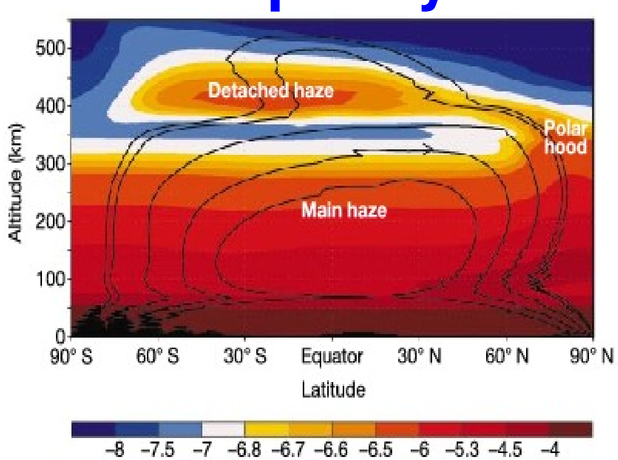
Ls=300

(Crespin et al. 2008)

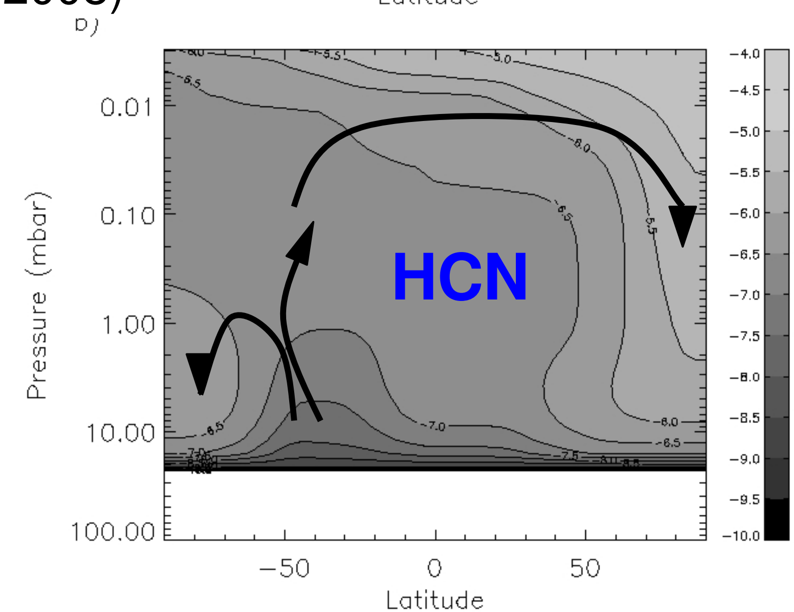
Temperature



Haze opacity



(Rannou et al. 2002)



Back to 3D GCM

- 48x32x55 (0~500 km)

- Haze microphysics coupled
- No clouds microphysics coupled
- No photochemistry coupled
- Diurnal cycle

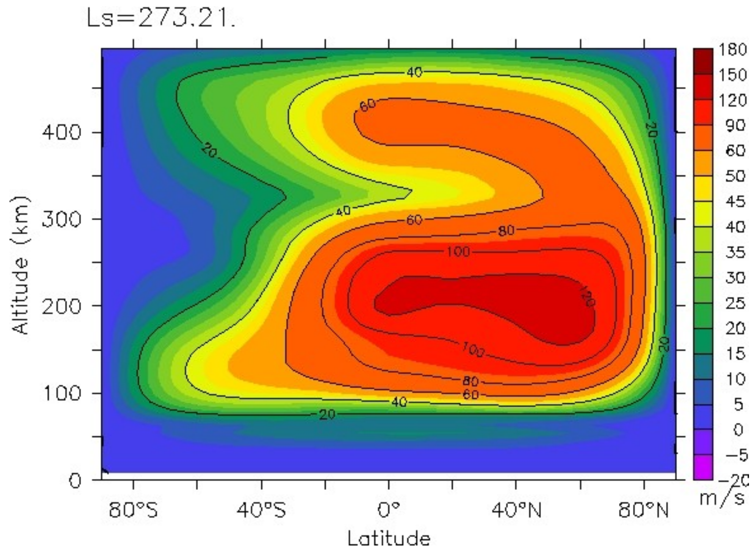
- Starting from 2D simulation

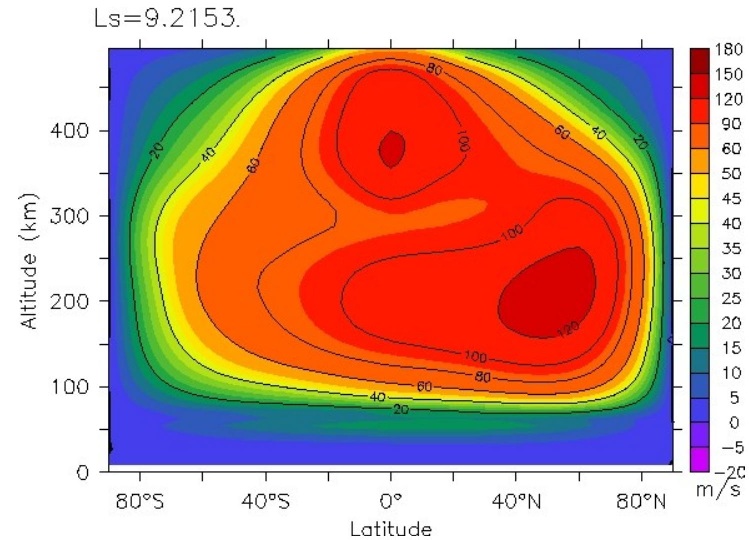
- 5 Titan years run

- Structure obtained similar to old Hourdin et al. (1995) 3D simulations

Back to 3D GCM

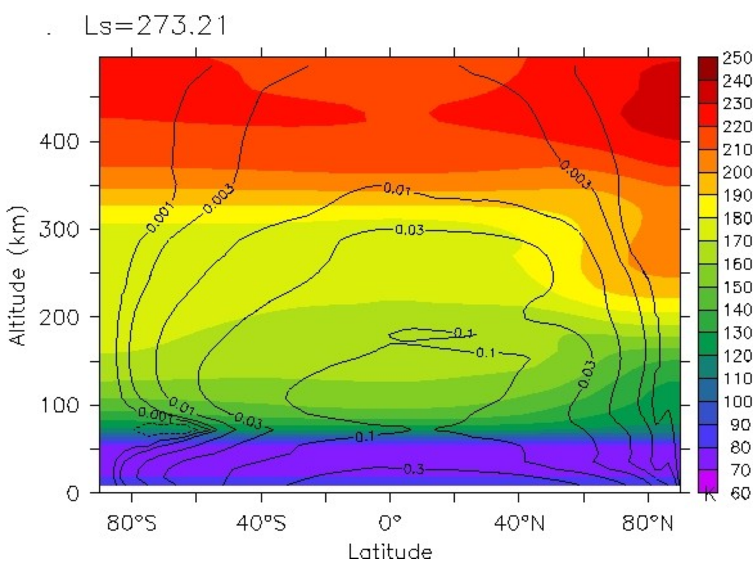
Mean zonal wind

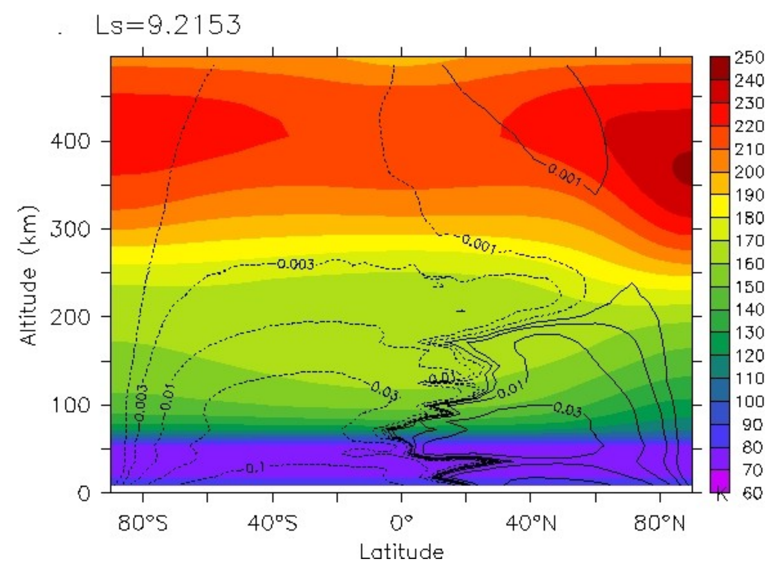




N winter solstice

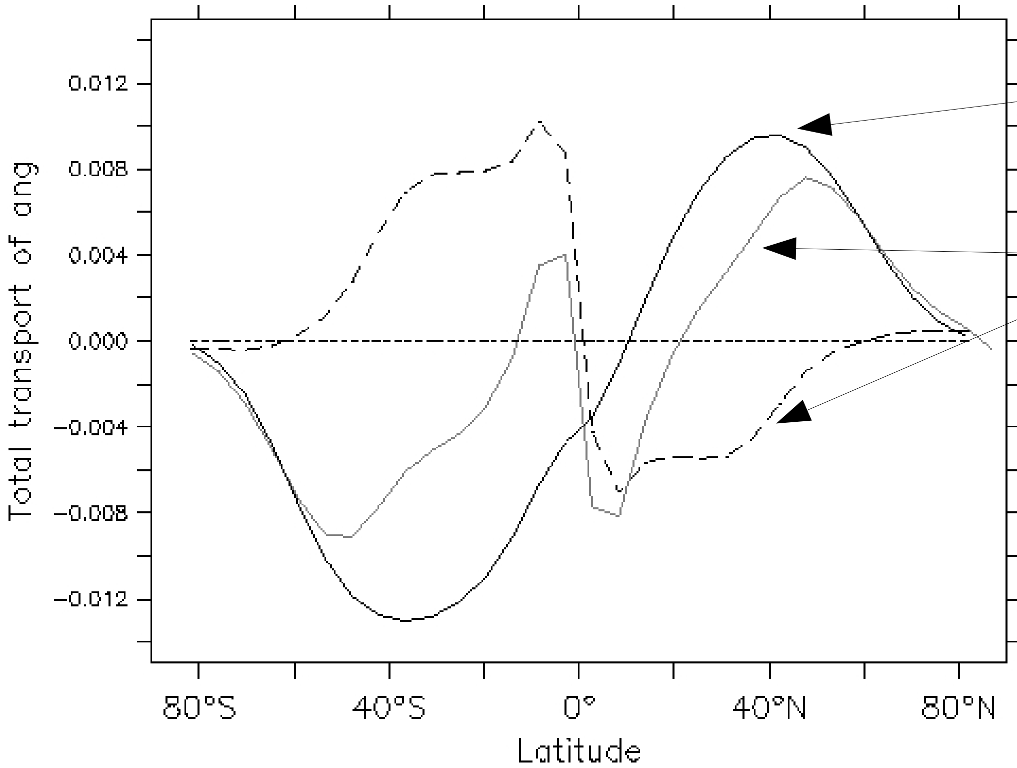
N spring equinox





Mean temperature and stream function

Momentum transport

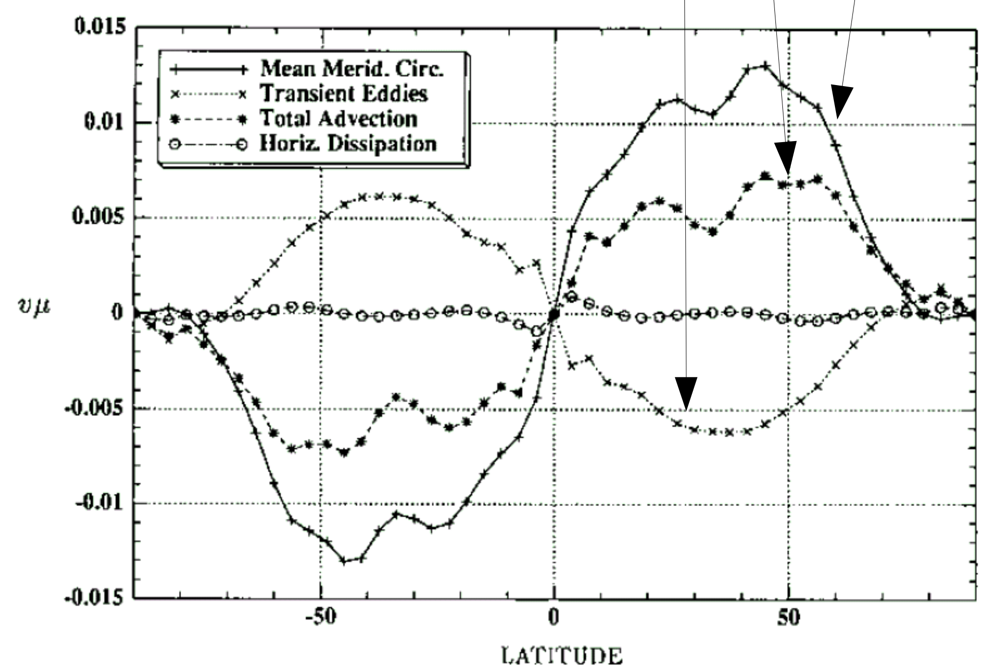


Mean meridional circulation

Transients

Total advection

Hourdin et al. 1995,
annual mean

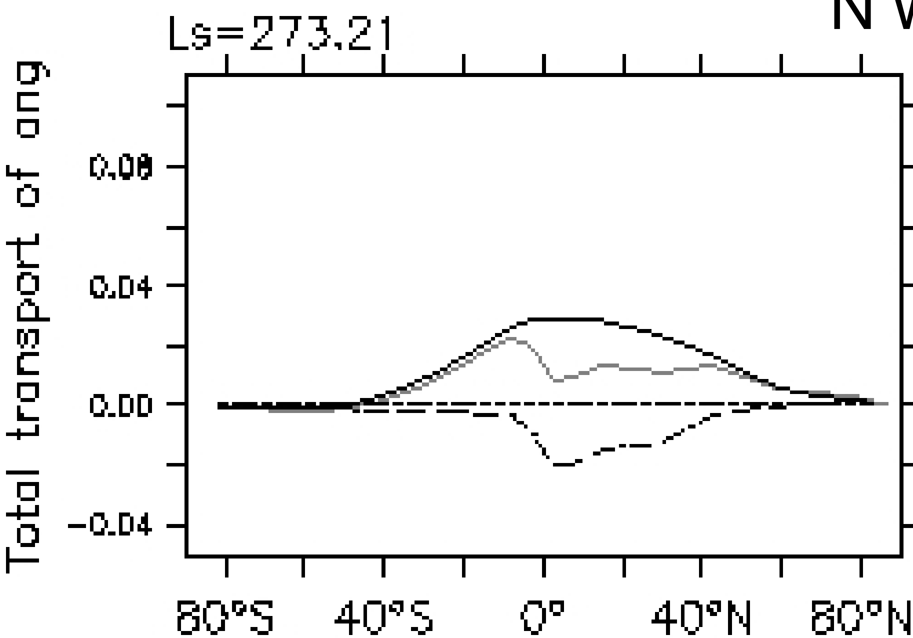


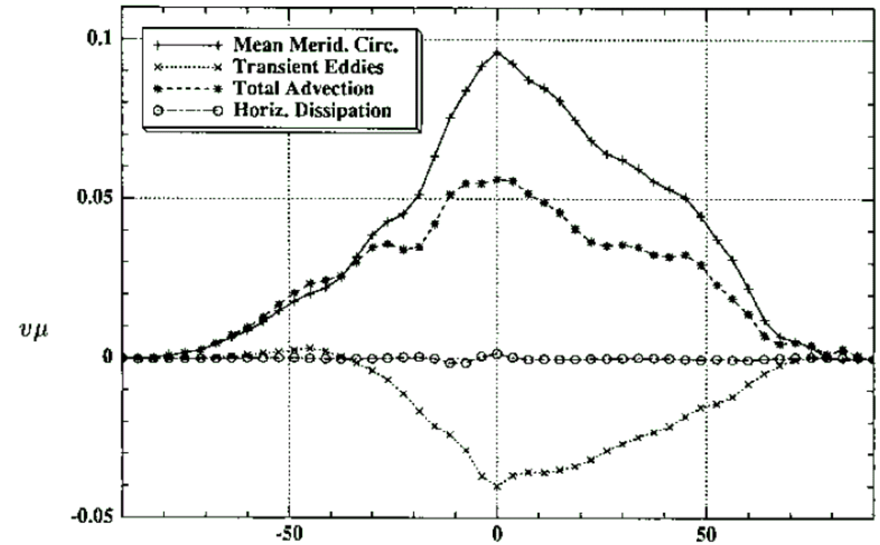
3D, annual mean

⇒ GRW mechanism

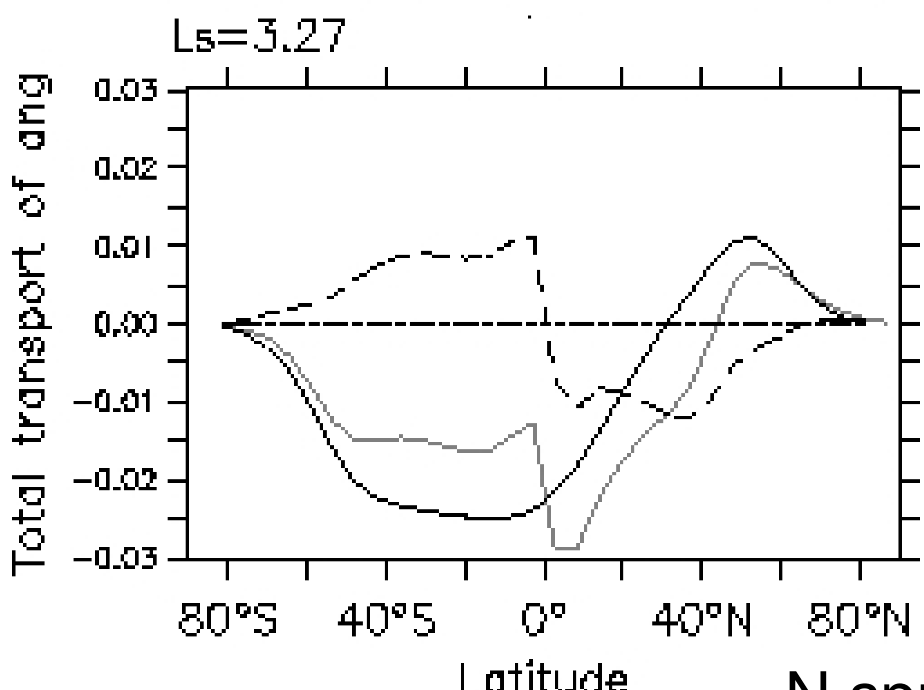
Momentum transport

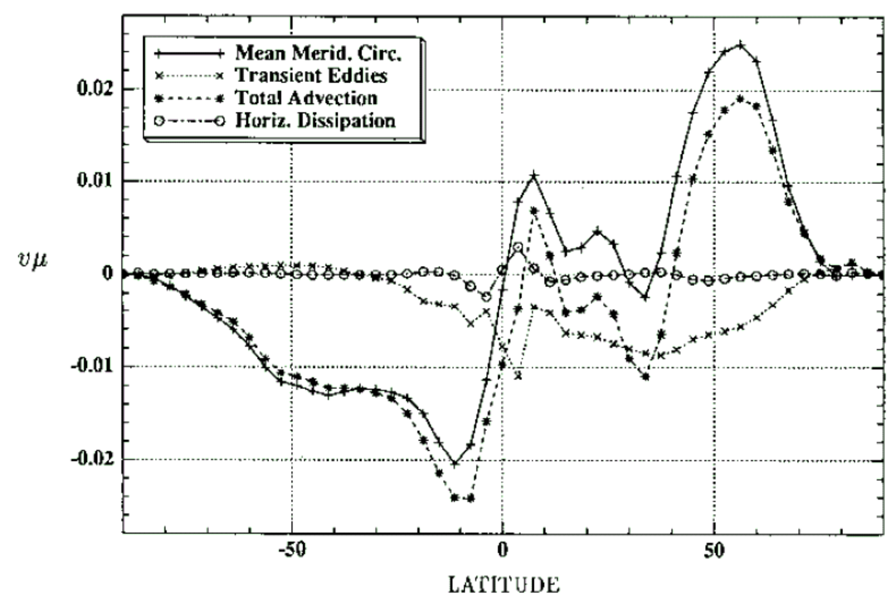
N winter solstice





Hourdin et al. 1995





N spring equinox

LMD VENUS GCM

- Three-dimensional: 48x32x50 (0~95 km)
- Vertical coordinates: hybrid (sigma/pressure)

- Dynamical core, transport of tracers

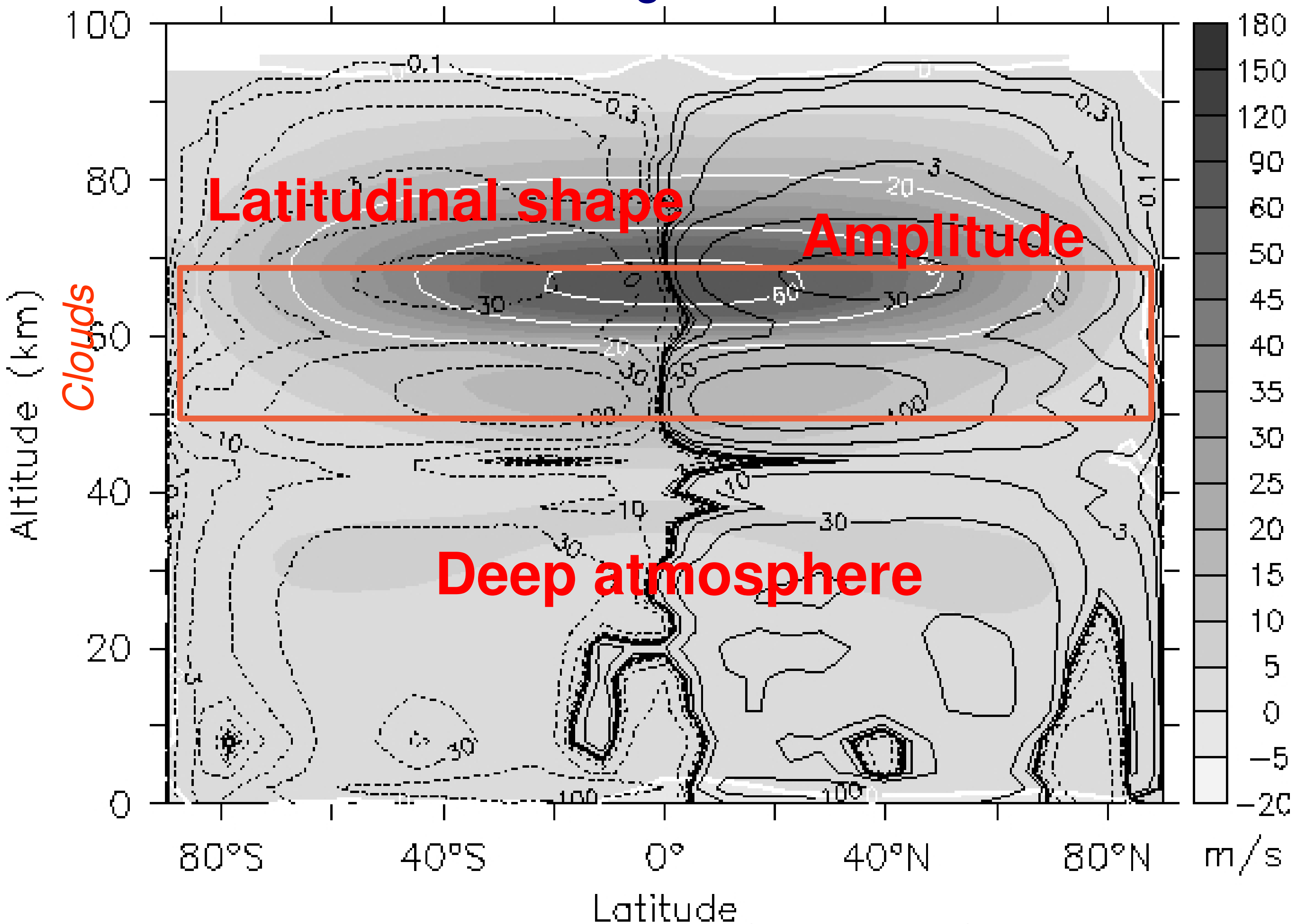
- Specific physics:
  - radiative transfer: Net Exchange Rates matrix
  - parameterizations (sub-grid processes, boundary layer, convection, turbulence)
  - topography
  - no clouds microphysics

- No photochemistry

Lebonnois et al., JGR, 2010

Venus Superrotation

Starting from rest

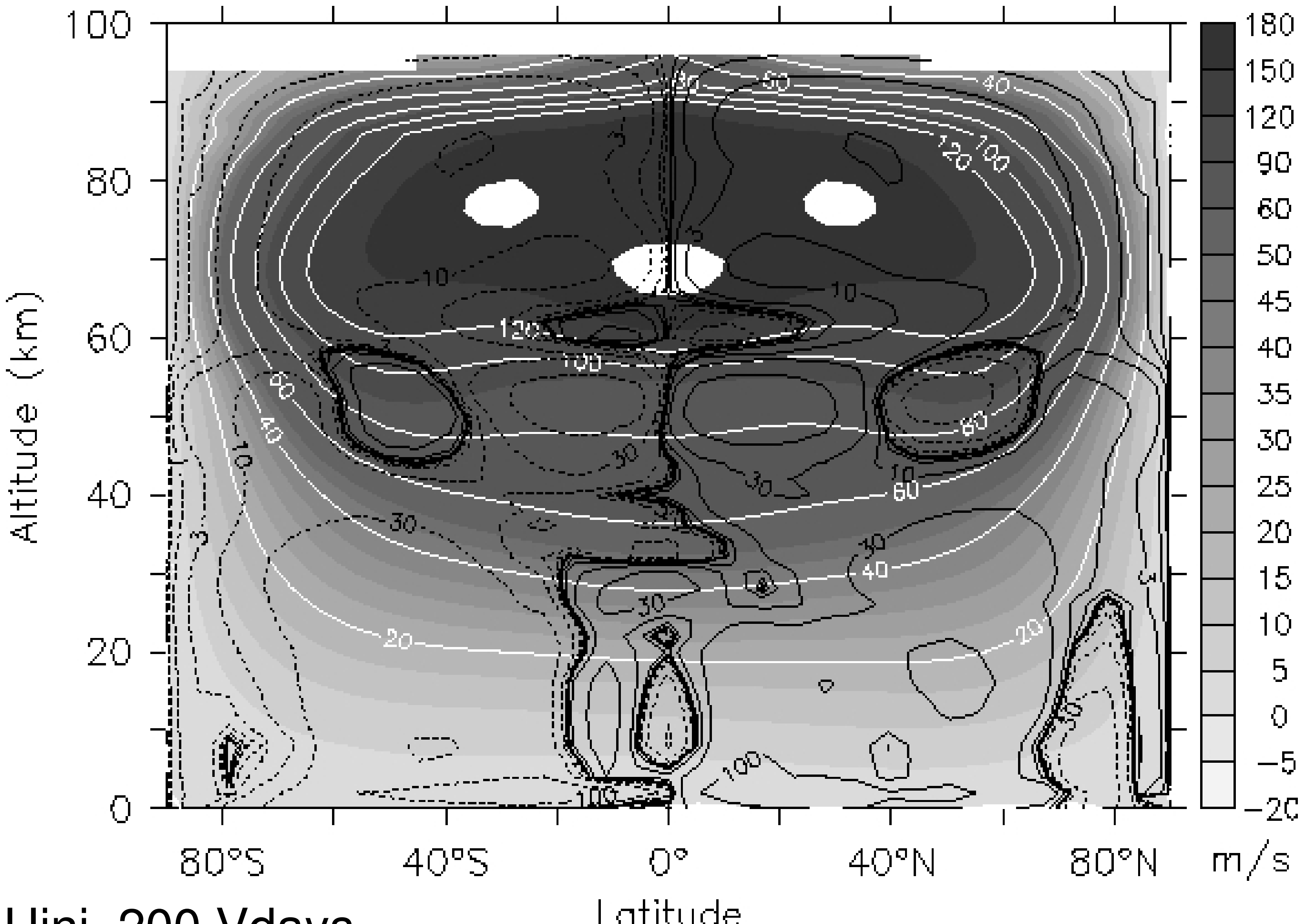


Mean zonal wind and stream function after 350 Vdays

(Topography, diurnal cycle)

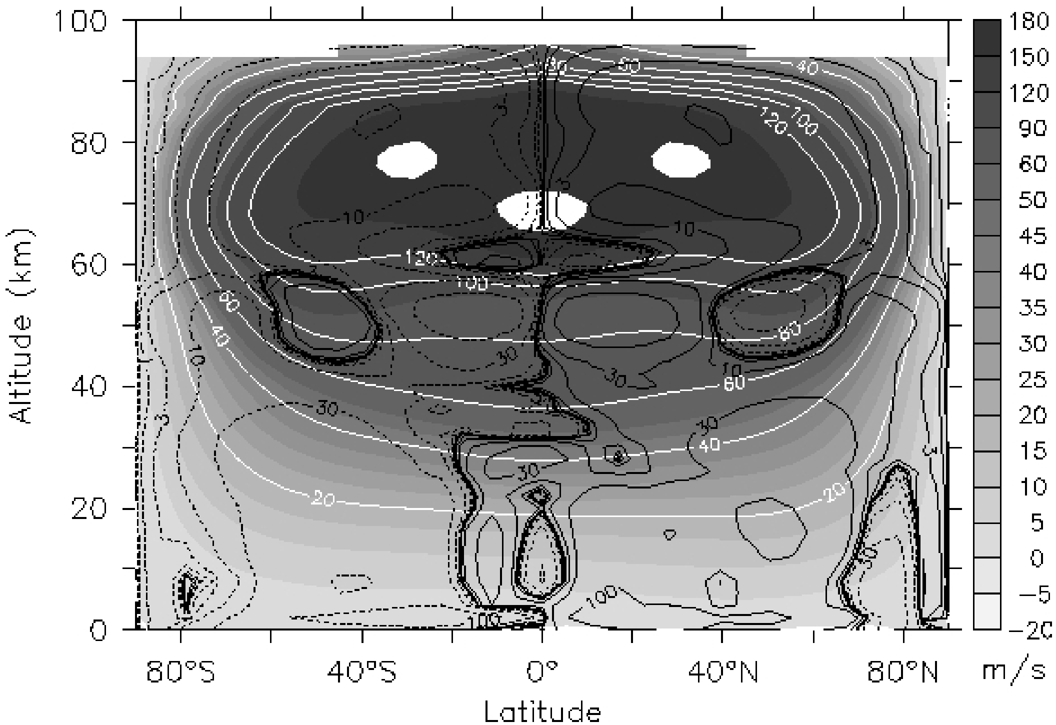
Initial conditions

Starting from a zonal wind profile close to observations



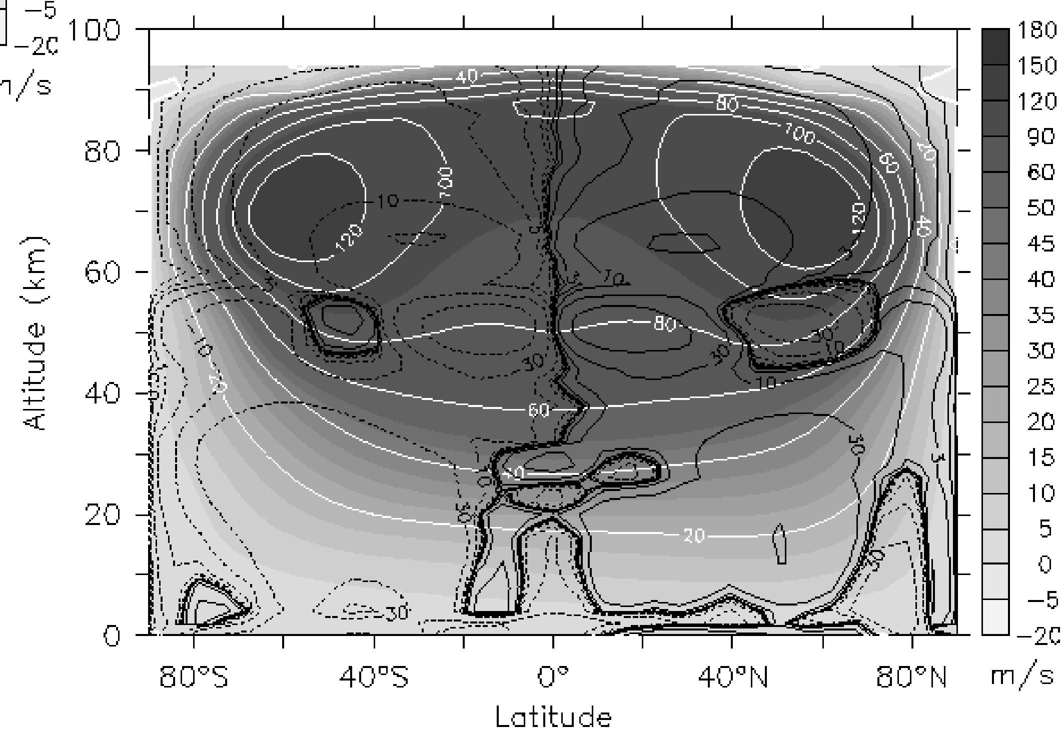
Uini, 200 Vdays

Role of the diurnal cycle



Uini With diurnal cycle

Undc Without diurnal cycle

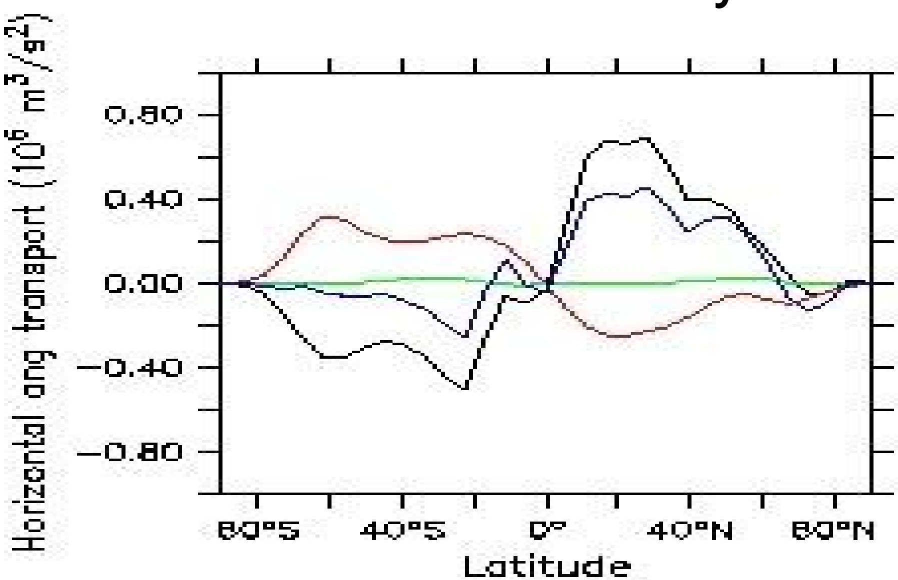


Influence of thermal tides in angular momentum transport:

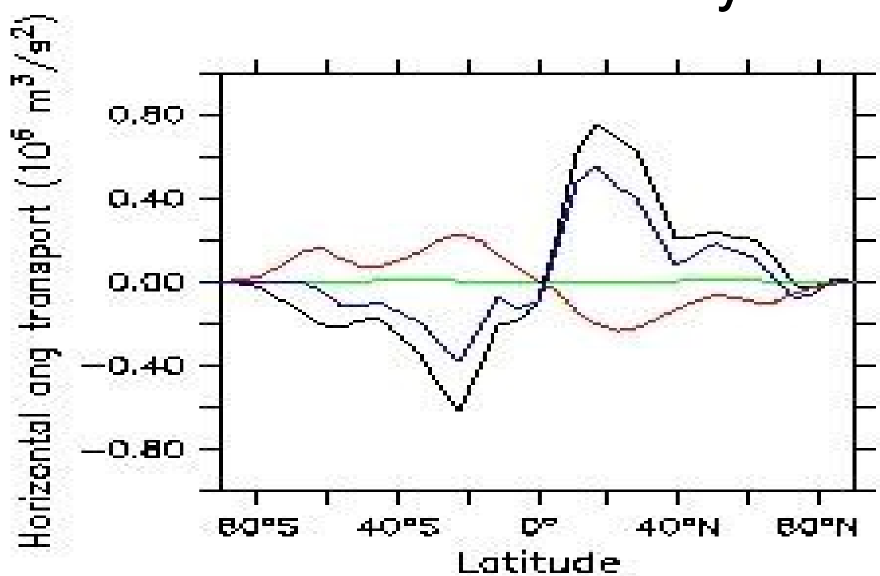
downward transport in the equatorial 64-90 km region.

Angular momentum transport

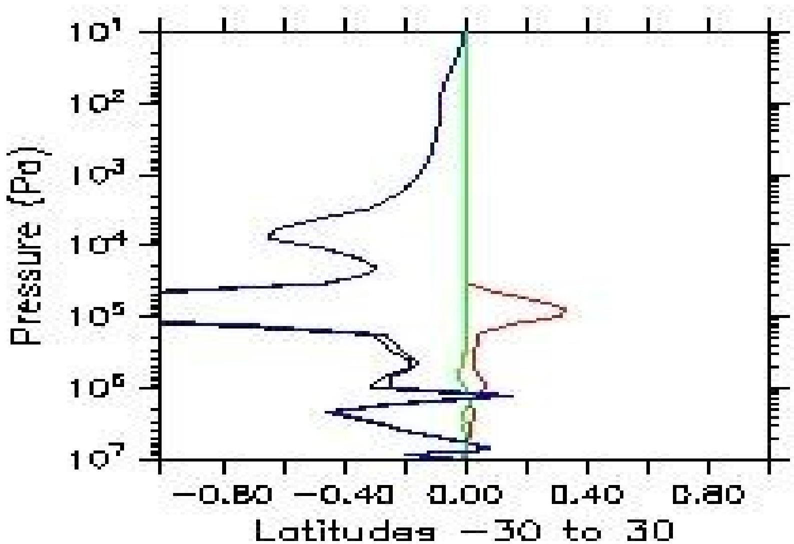
Without diurnal cycle

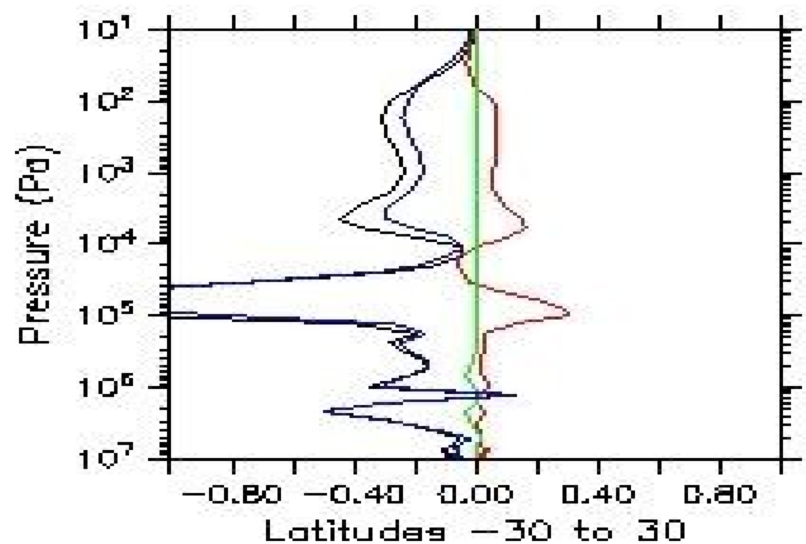


With diurnal cycle



Vertical transport between 30°N and 30°S

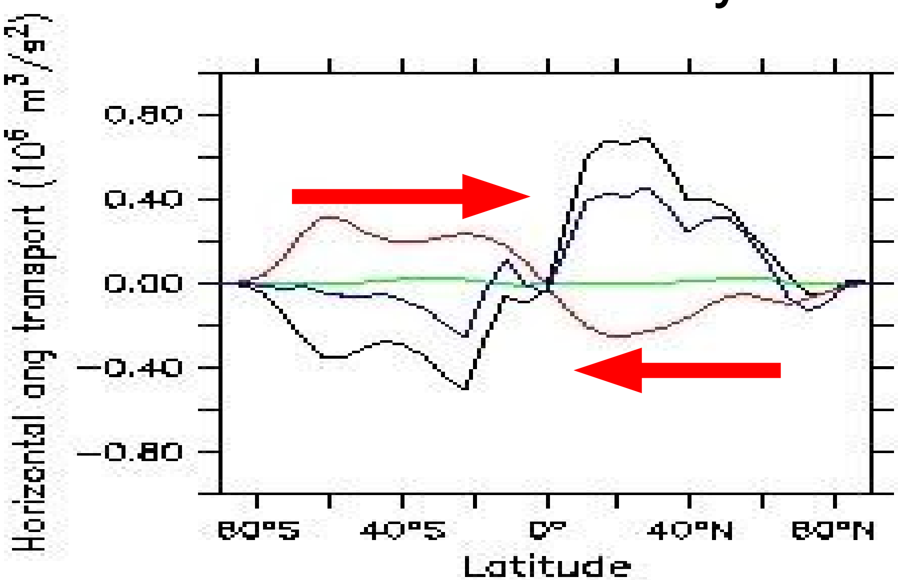




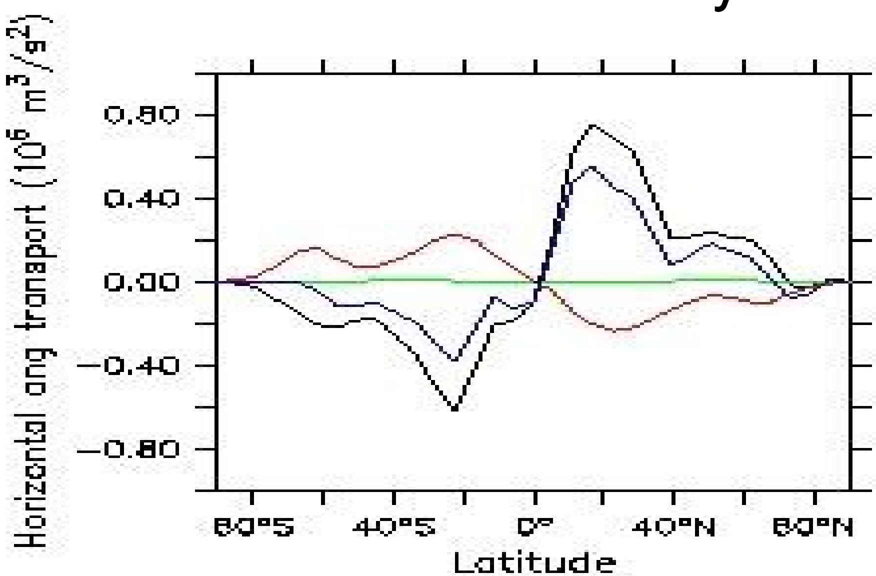
Angular momentum transport

Role of waves

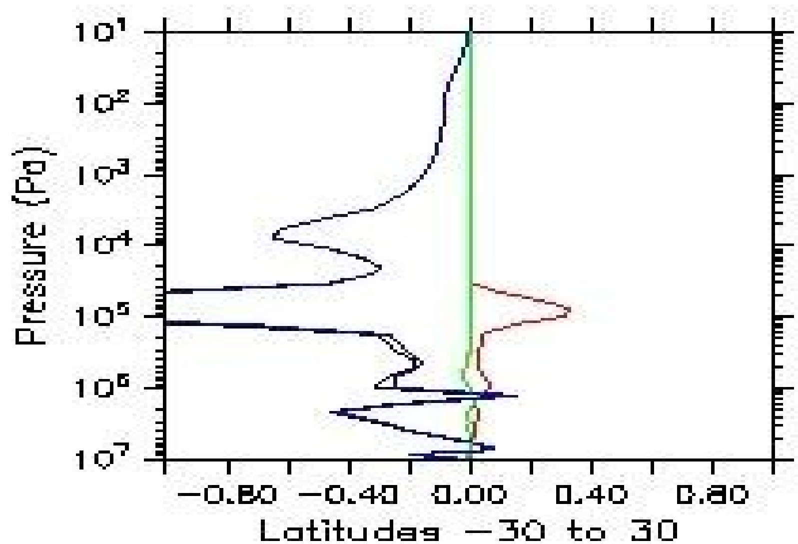
Without diurnal cycle

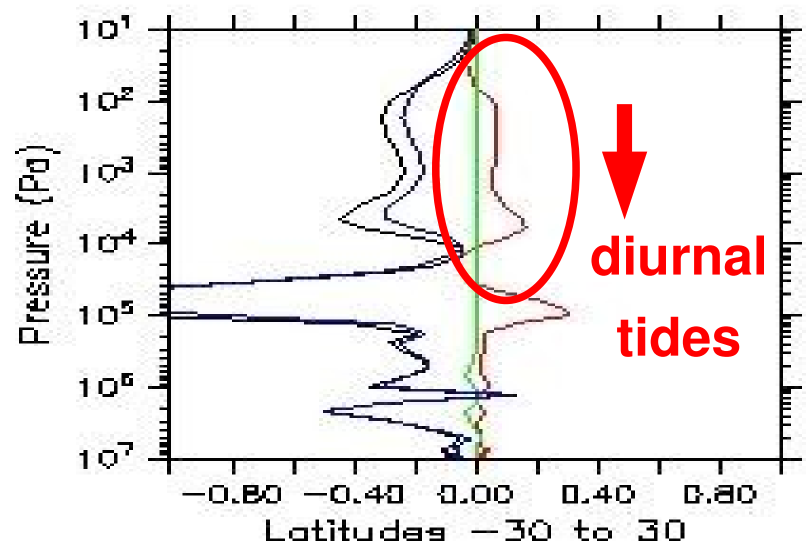


With diurnal cycle



Vertical transport between 30°N and 30°S





Discussion

- The superrotation problem is a difficult and sensitive one: many GCM have tried and failed to produce superrotation either for Venus or Titan, some succeed. Why ?

- Meridional circulation resulting from slow rotation.

- Titan vs Venus: the influence of seasonal variations.

- Non-axisymmetric angular momentum transport

  Venus: vertical transport in the equatorial region generated by thermal tides.

  Titan: unstable jet generating horizontal transport by waves. No role from thermal tides (radiative timescales).

- Venus: the question of the deep atmosphere is still pending...
What is missing ? Gravity waves forcing ?
Relation with Titan's model ?