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

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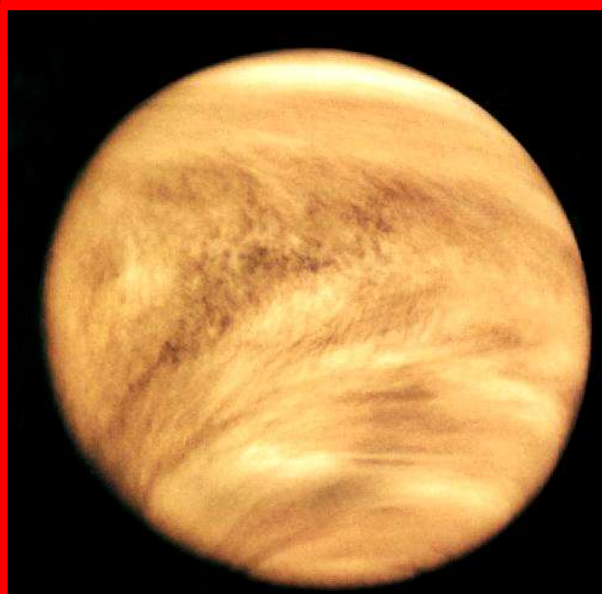
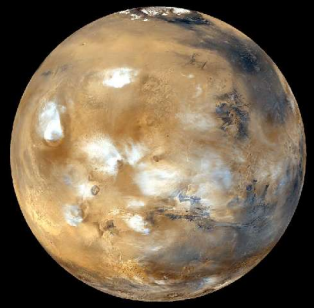
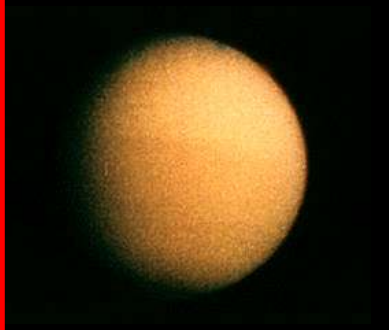
- Zonal wind observations on Venus and Titan
- The superrotation question
- Powerful tools: General Circulation Models
- Titan GCM
- Venus GCM
- Discussion based on both systems



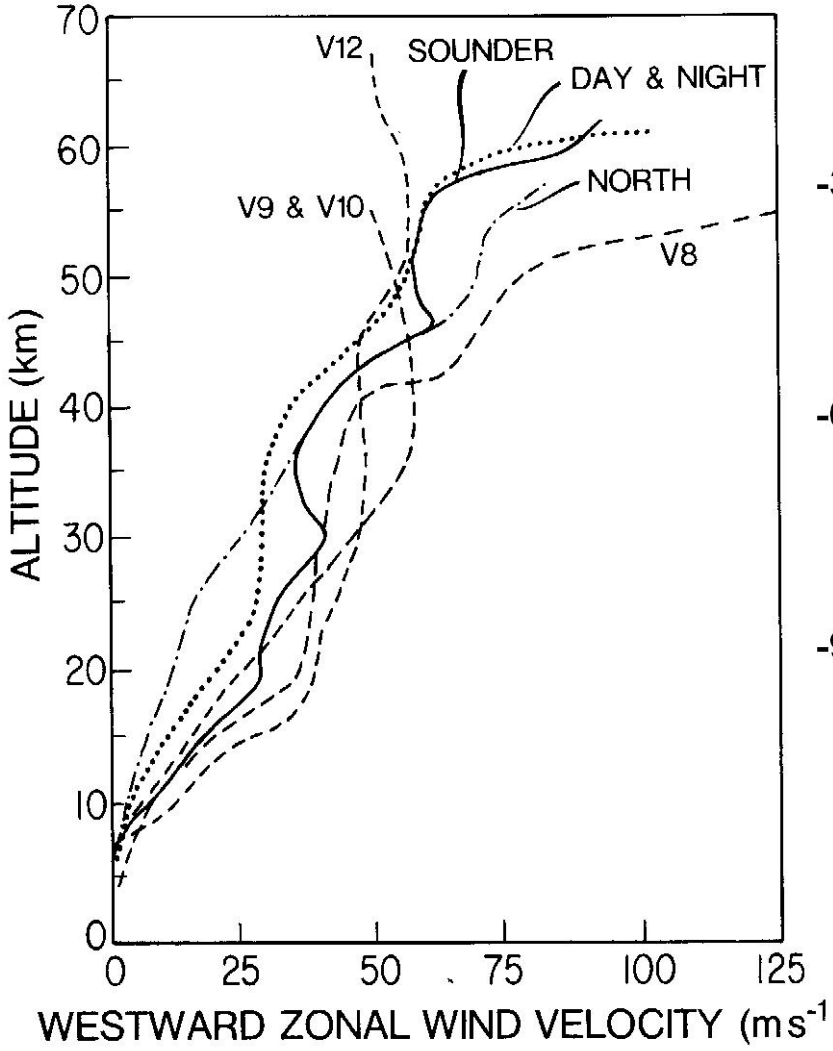


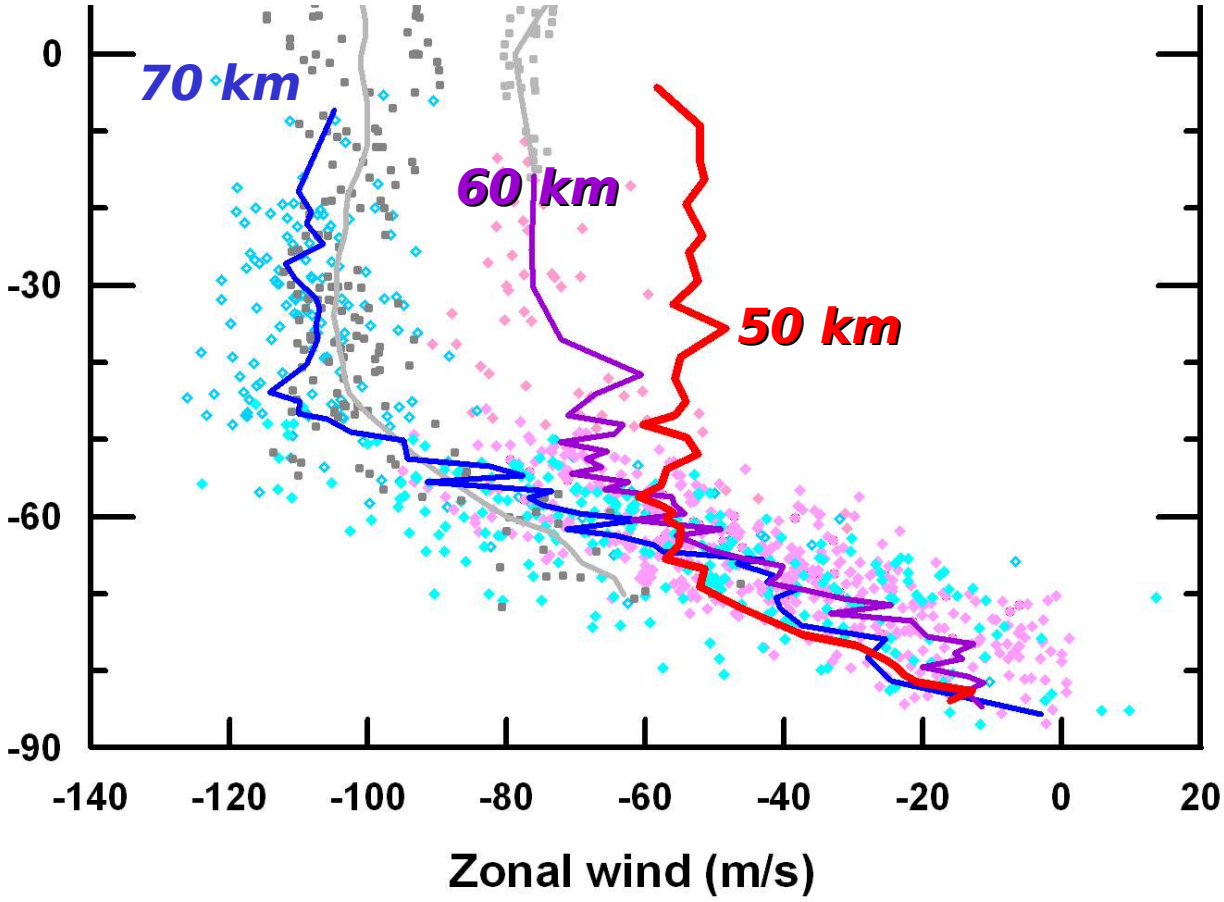


	VENUS	EARTH	MARS	TITAN
	<Ts> ~ 450 °C	<Ts> ~ 15 °C	<Ts> < -50 °C	<Ts> ~ 95 K
	CO_2~90b	CO_2~0.3 mb	CO_2 = 0.006 b	CH_4 ~ 0.06 b
	H_2O/CO_2<<1	O_2~0.2 b	N_2 = 0.0002 b	N_2 = 1.5 b
	N_2~3b	N_2~0.8 b		
Sun distance	= 0.72 AU	1 AU	1.52 AU	9.5 UA
M	= 0.81 M_{Earth}	1	0.11 M_{Earth}	0.023 M_{Earth}
ρ	= 5.25	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

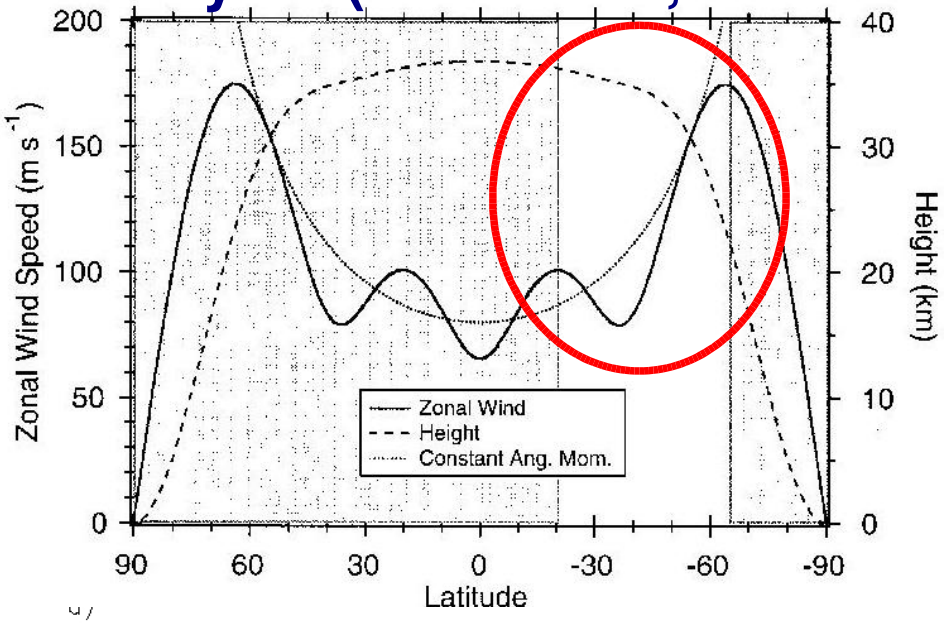




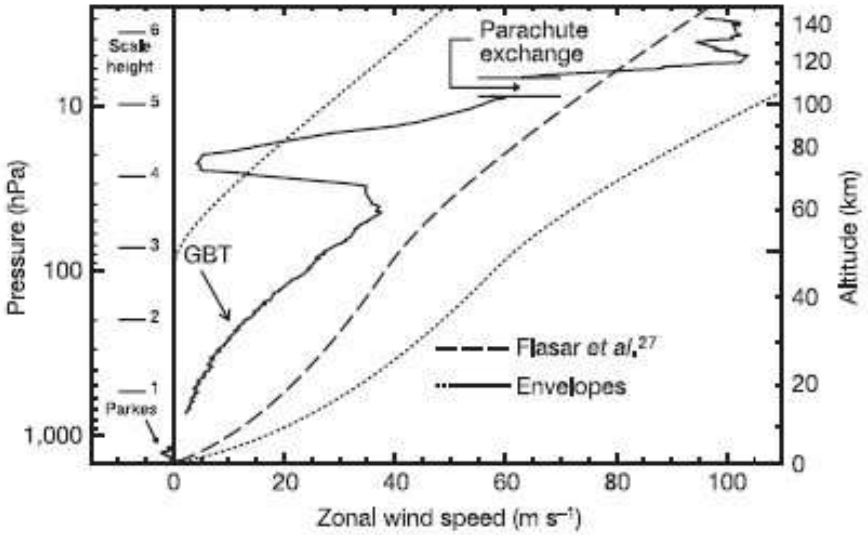
Venus Express/VIRTIS cloud tracking

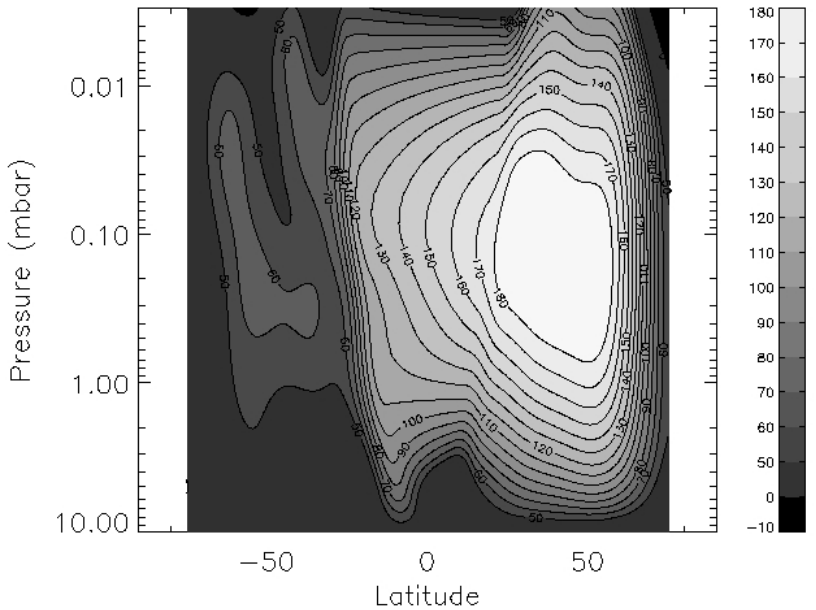
Observations of superrotation

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



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



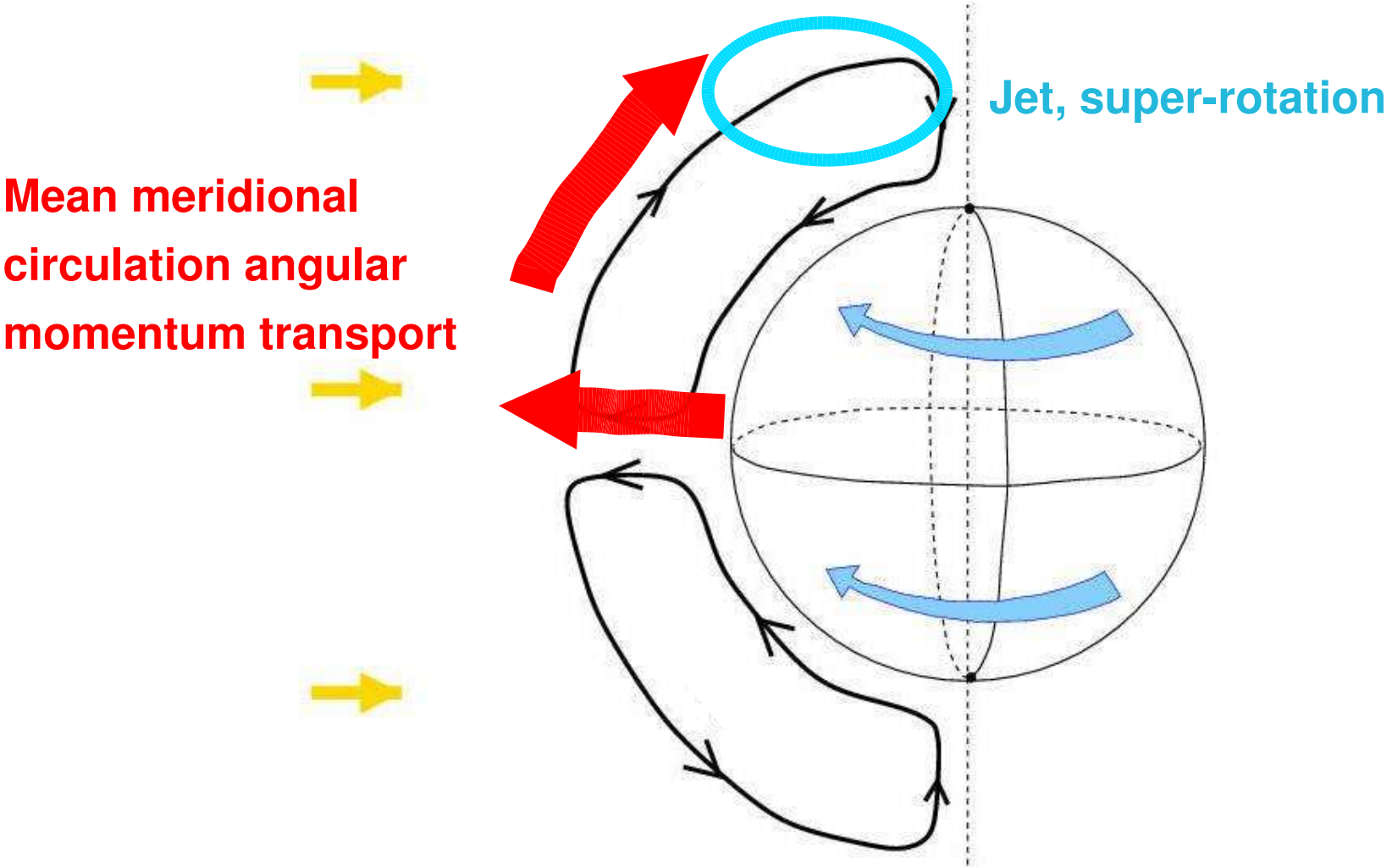


Cassini/CIRS thermal winds retrieval (Ls ~ 300°)

The superrotation question

Slow rotation:

extension of Hadley cells from equator to the poles



The superrotation question

Slow rotation:

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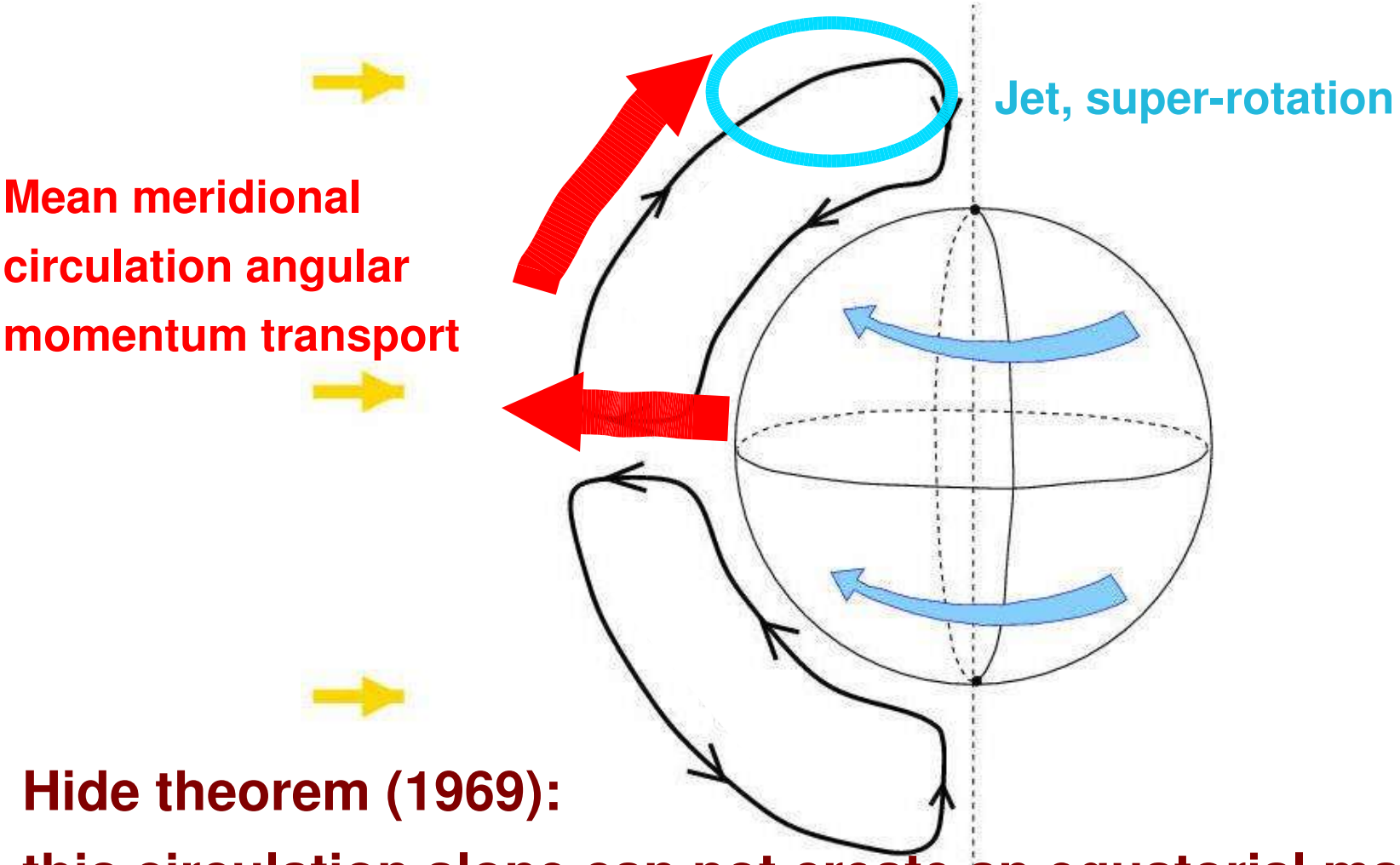


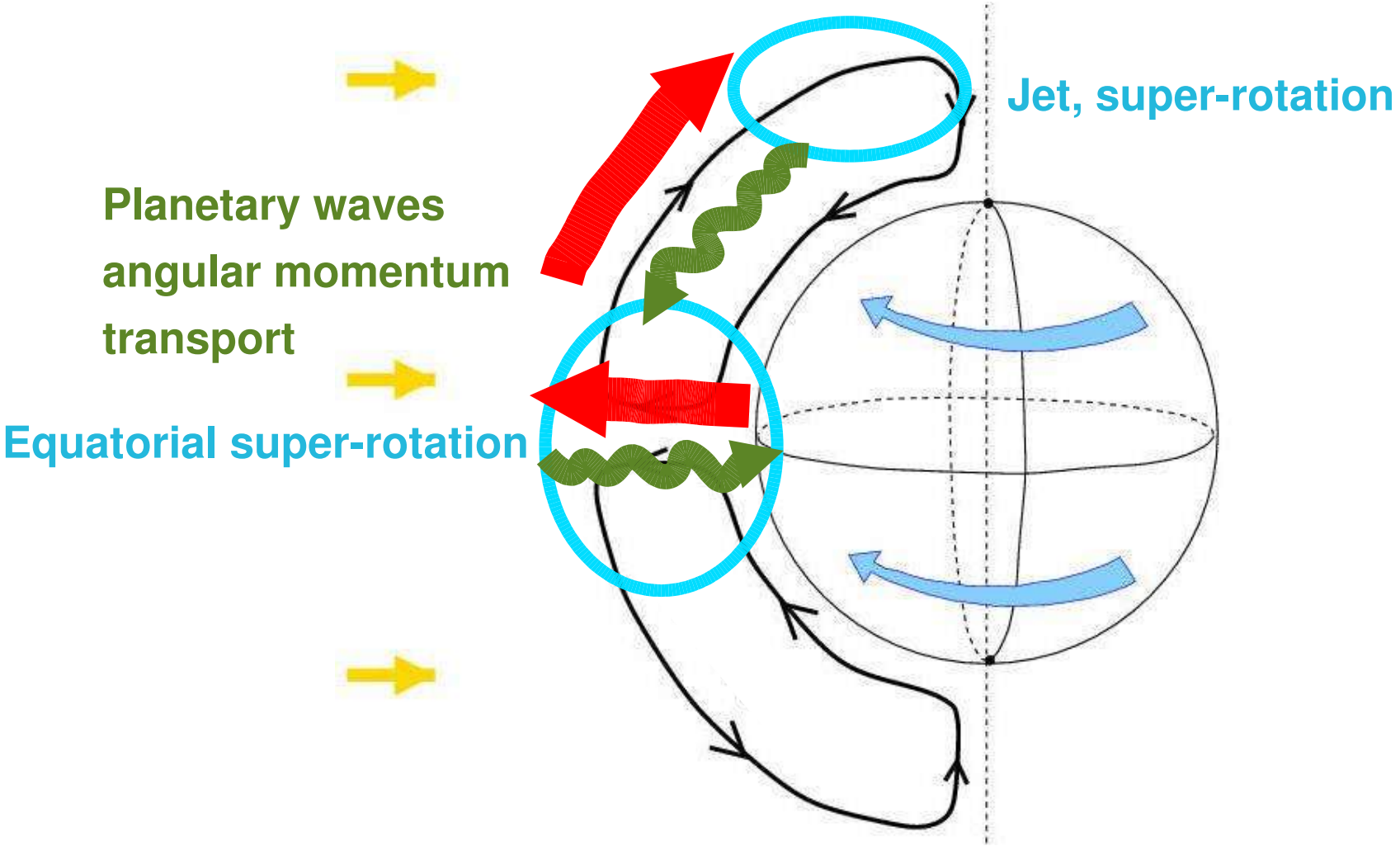
Hide theorem (1969):

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:

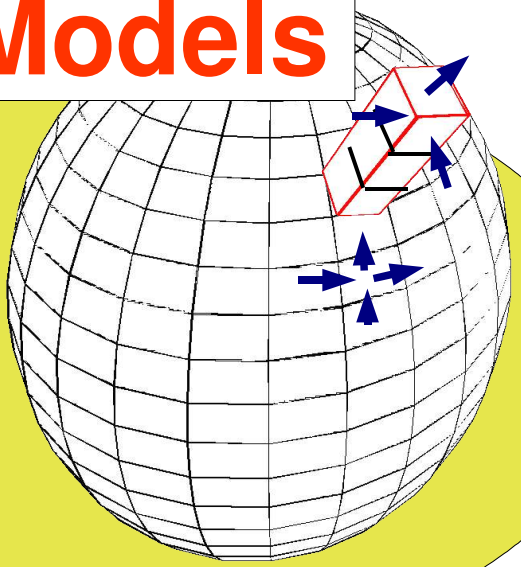
  Possible role of **gravity waves**

  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 ← $\delta_t u^*, \delta_t v^*, \delta_t T^*, \delta P^*_s$

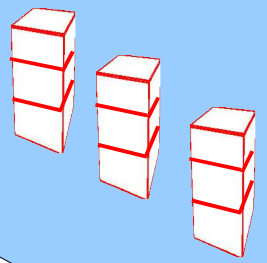
$\Delta t \sim 5$ min

$\Delta t \sim 30$ min

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

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

First LMD Titan GCM

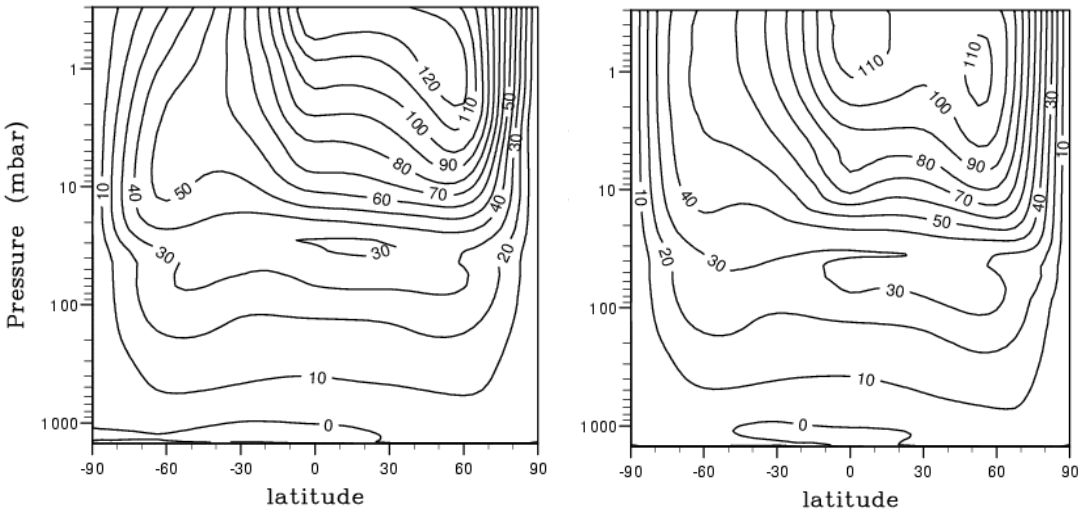
Hourdin et al. 1995

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

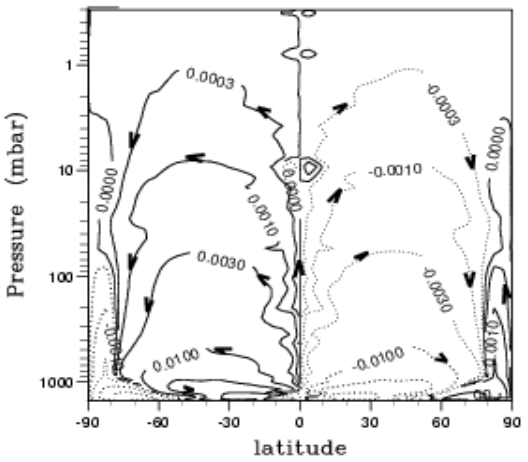
Southern summer solstice

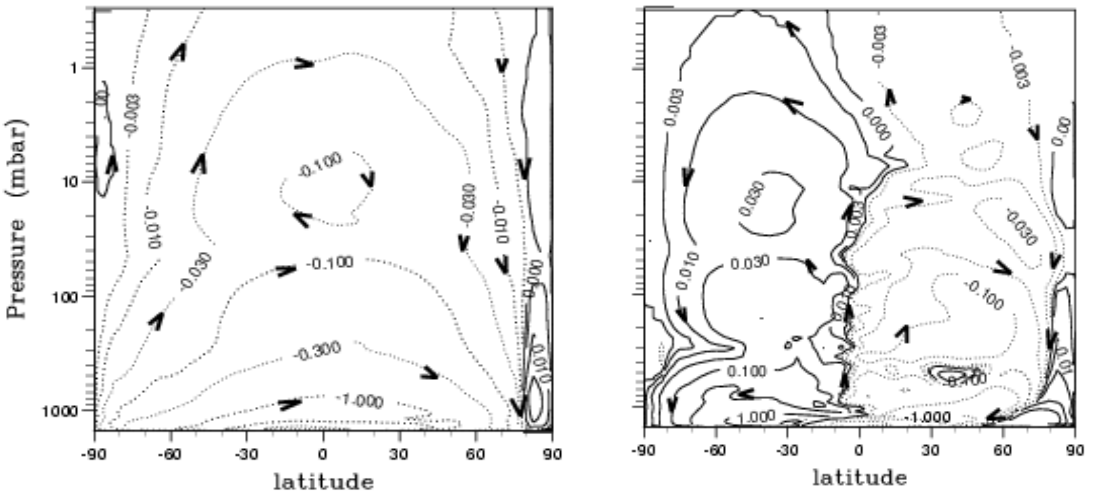
Northern spring equinox

Zonal wind (m/s)



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





First LMD Titan GCM

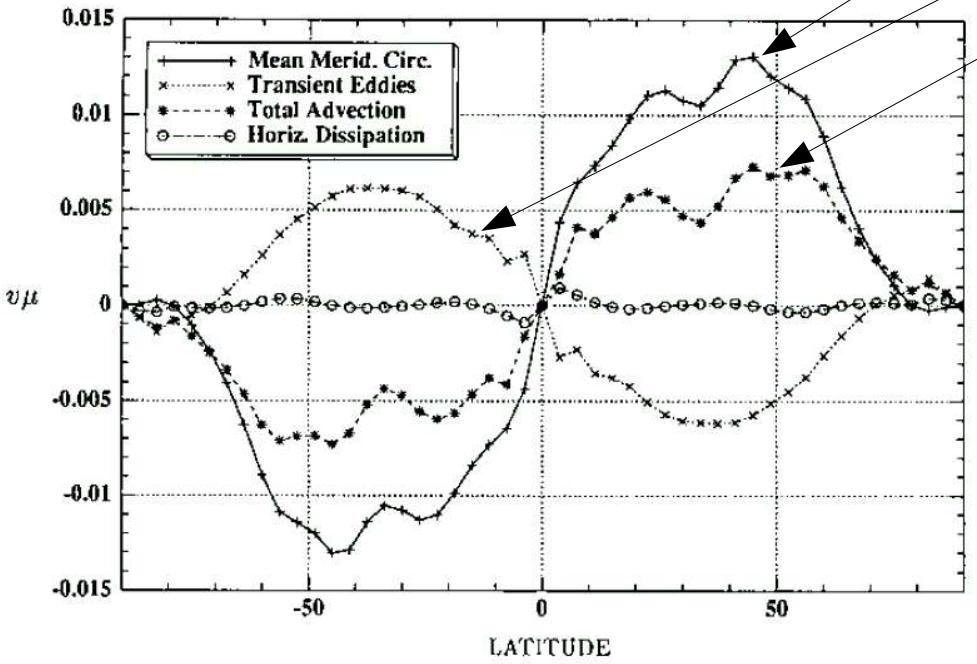
Hourdin et al. 1995

annual mean

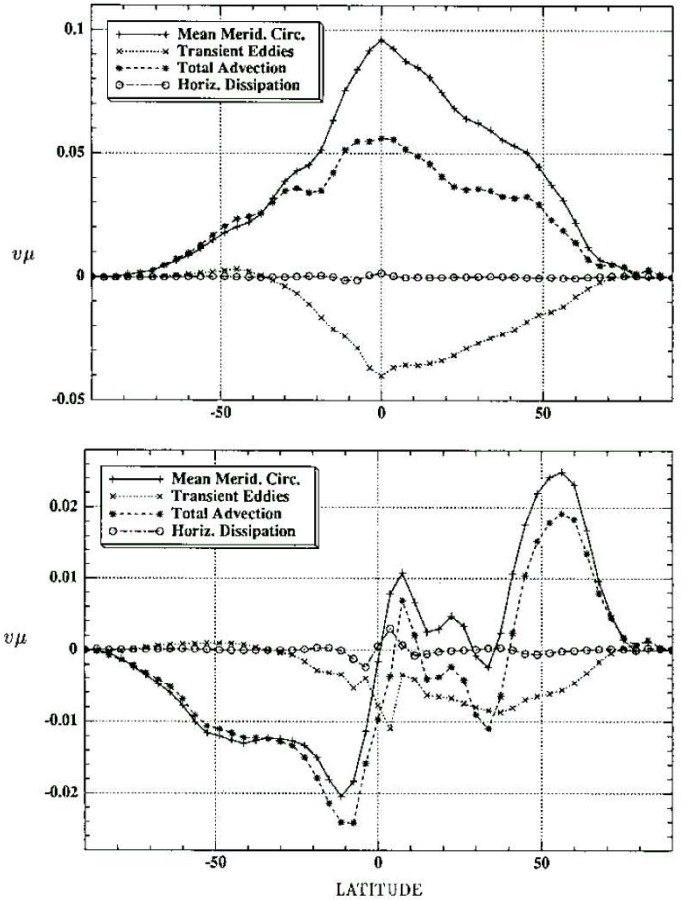
Mean meridional circulation

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

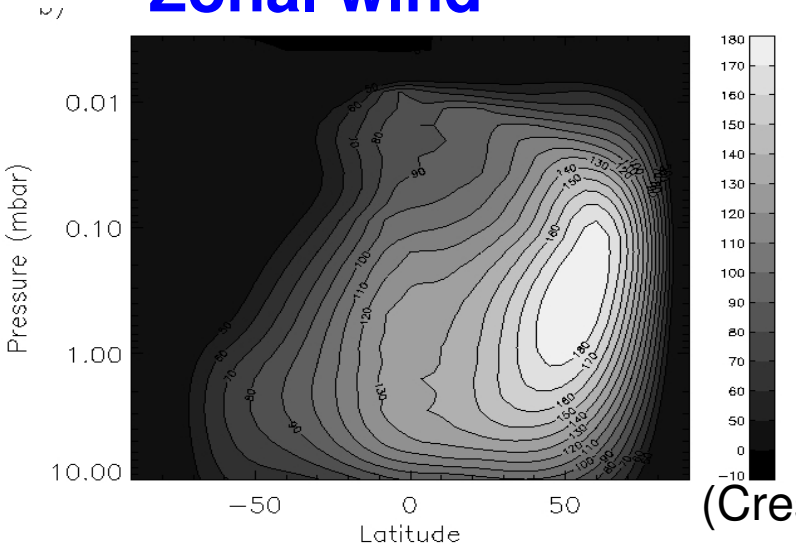
1. Study of the mixing properties of barotropic planetary waves in Titan stratosphere (Luz et Hourdin 2003).
2. Development of a parameterization (Luz et al., 2003).

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

Coupling with haze and chemistry

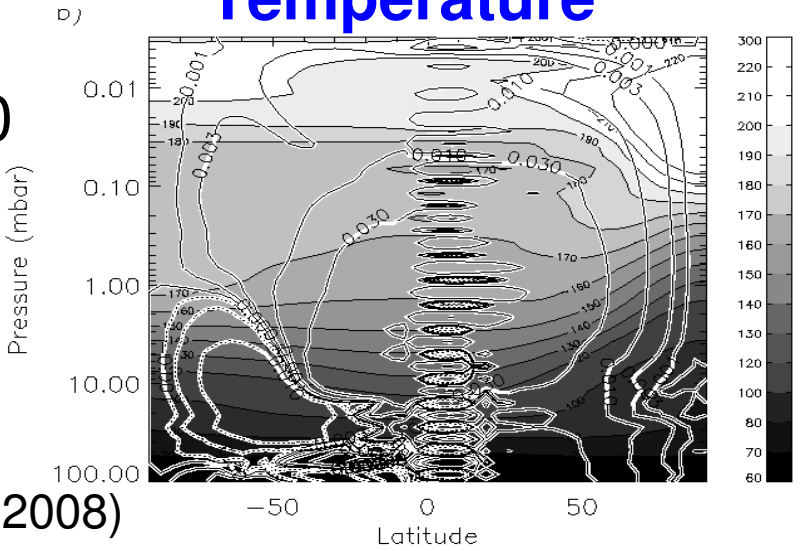
2D Climate Model

Zonal wind



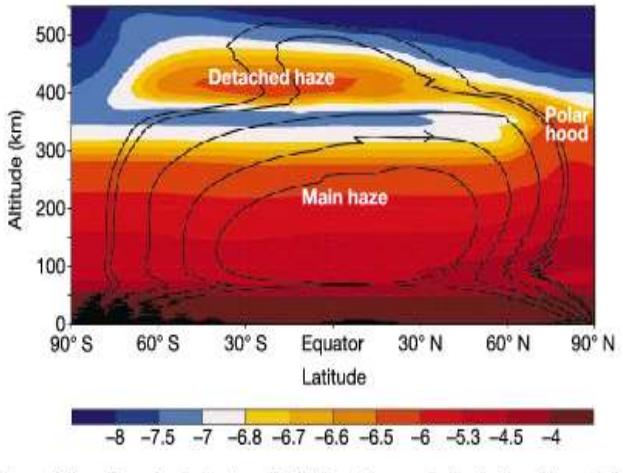
Ls=300

Temperature

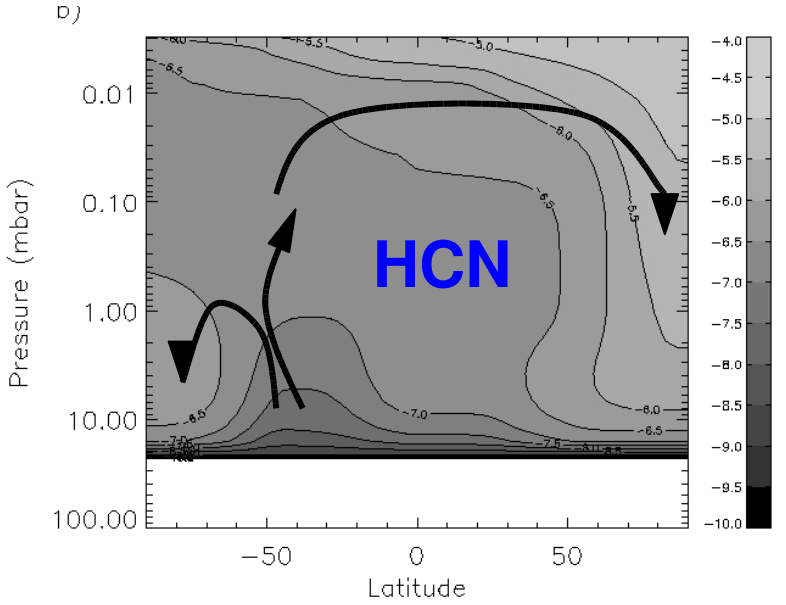


(Crespin et al. 2008)

Haze opacity



(Rannou et al. 2002)



Back to 3D GCM

- 48x32x55 (0~500 km)

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

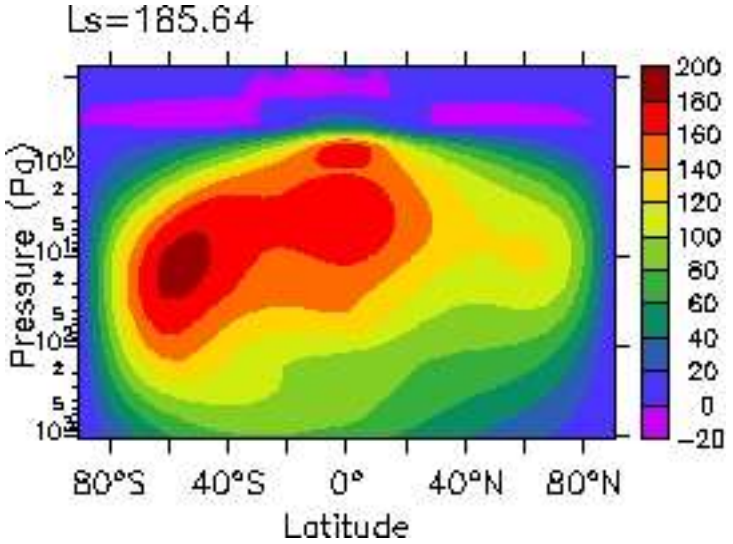
- Starting from 2D simulation

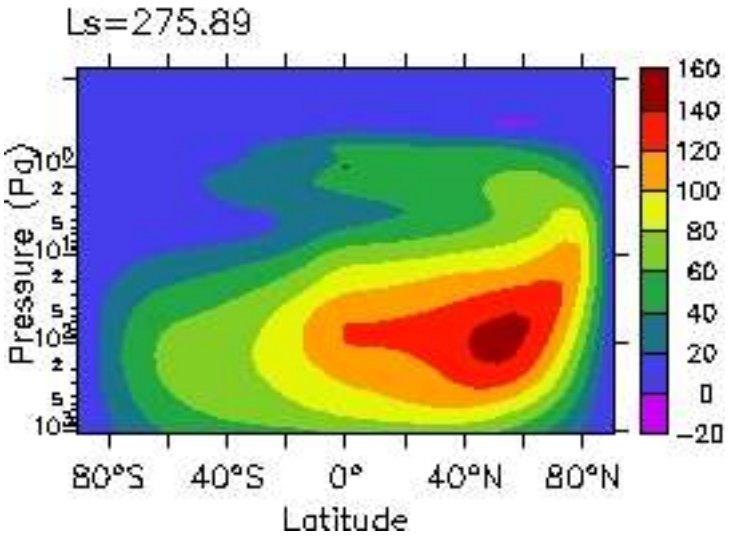
- 2 Titan years run only :
  first results, to be confirmed

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

Back to 3D GCM

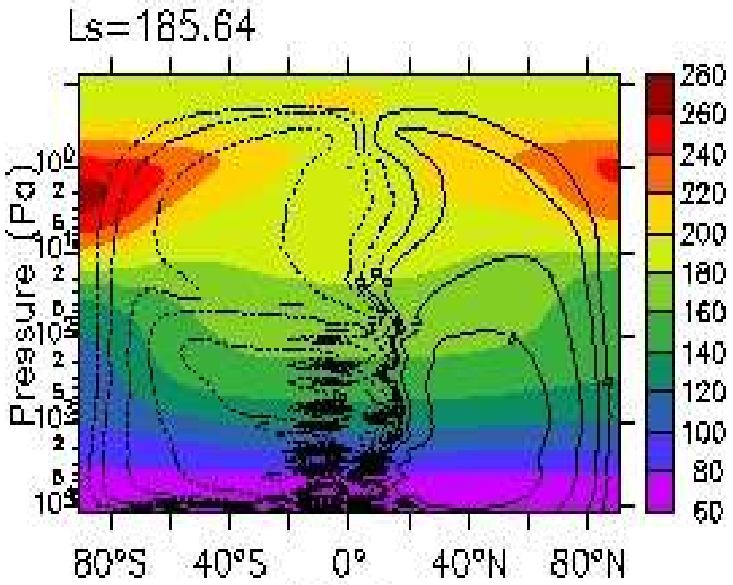
Mean zonal wind

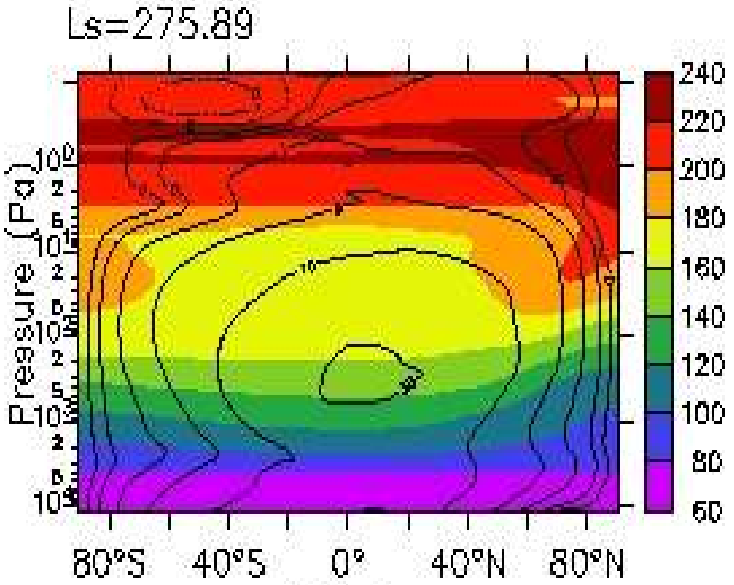




N fall equinox

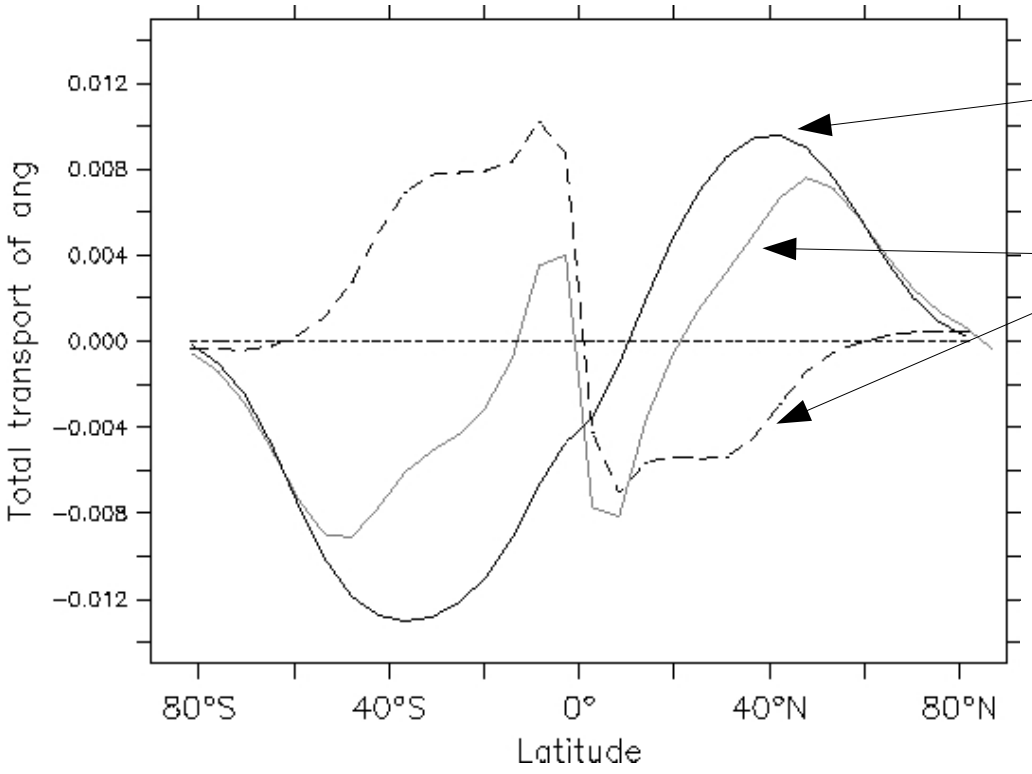
N winter solstice





Mean temperature and stream function

Momentum transport



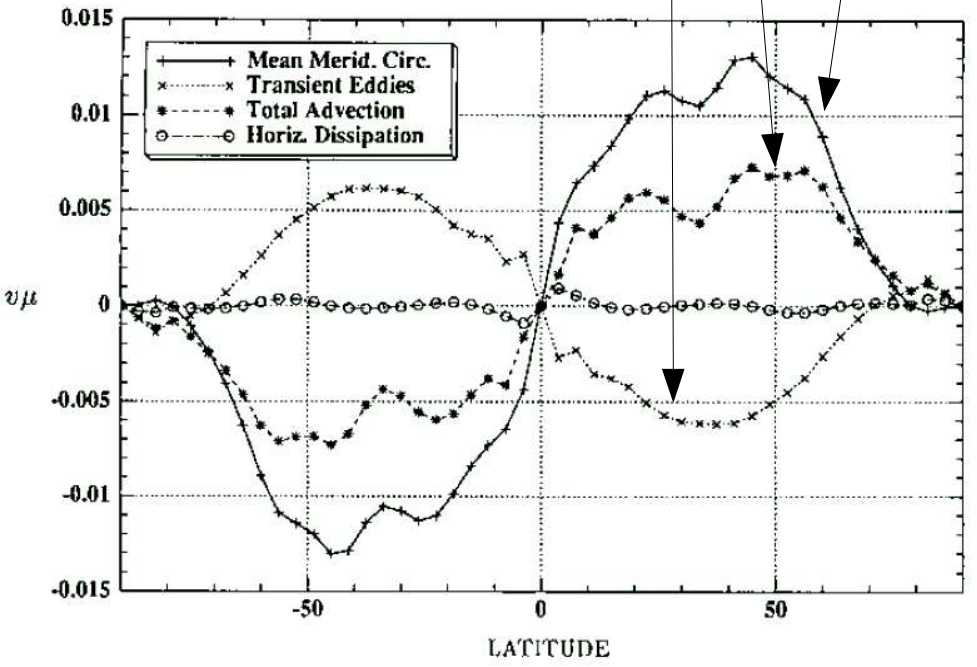
3D, annual mean

Mean meridional circulation

Transients

Total advection

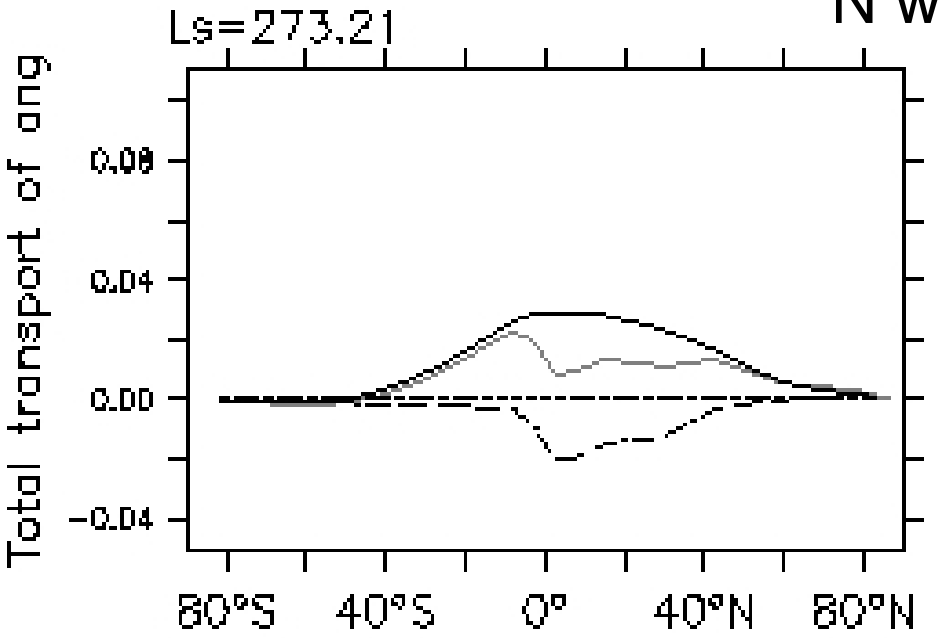
Hourdin et al. 1995, annual mean

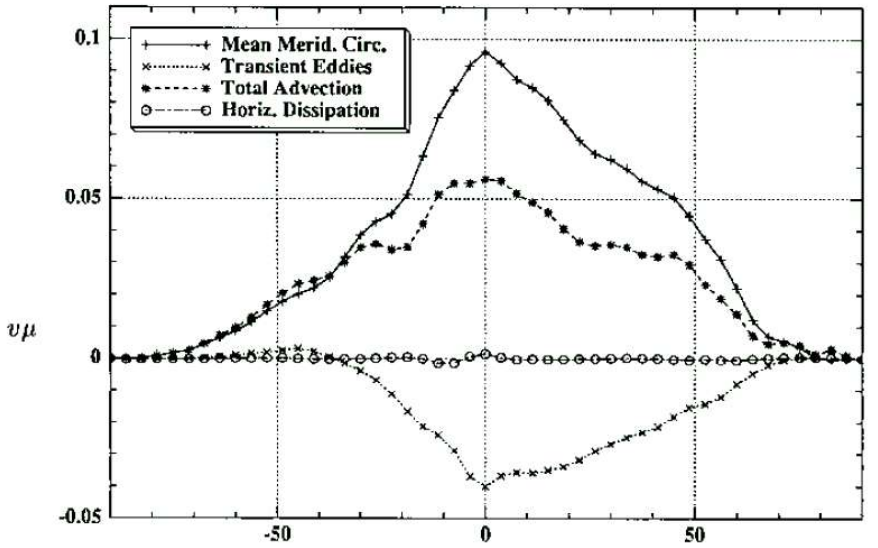


⇒ **GRW mechanism**

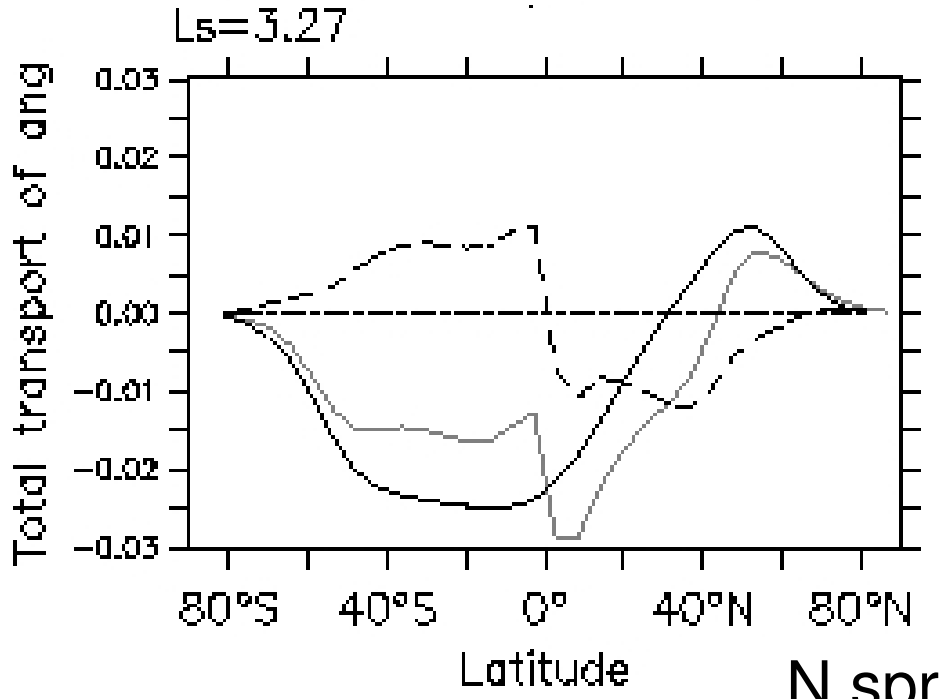
Momentum transport

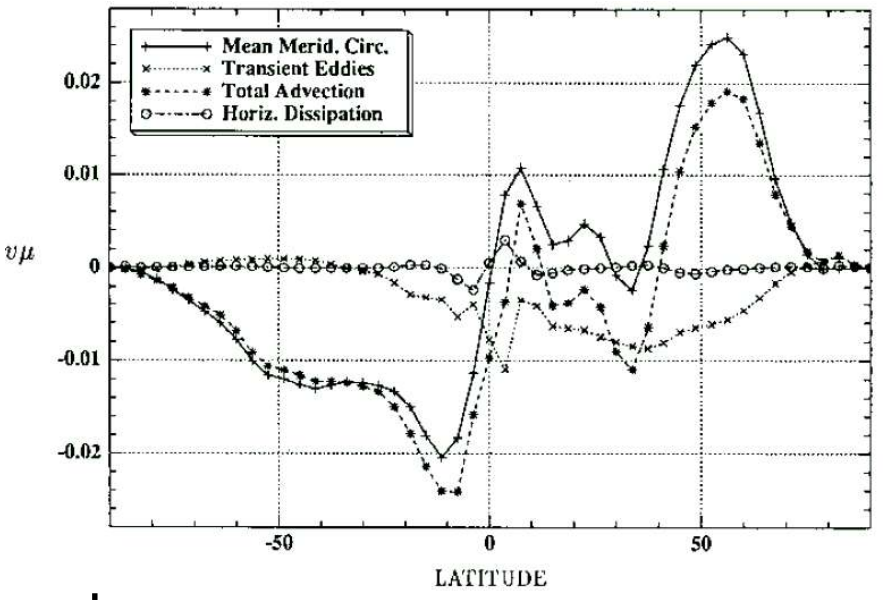
N winter solstice





Hourdin et al. 1995





N spring equinox

LMD VENUS GCM

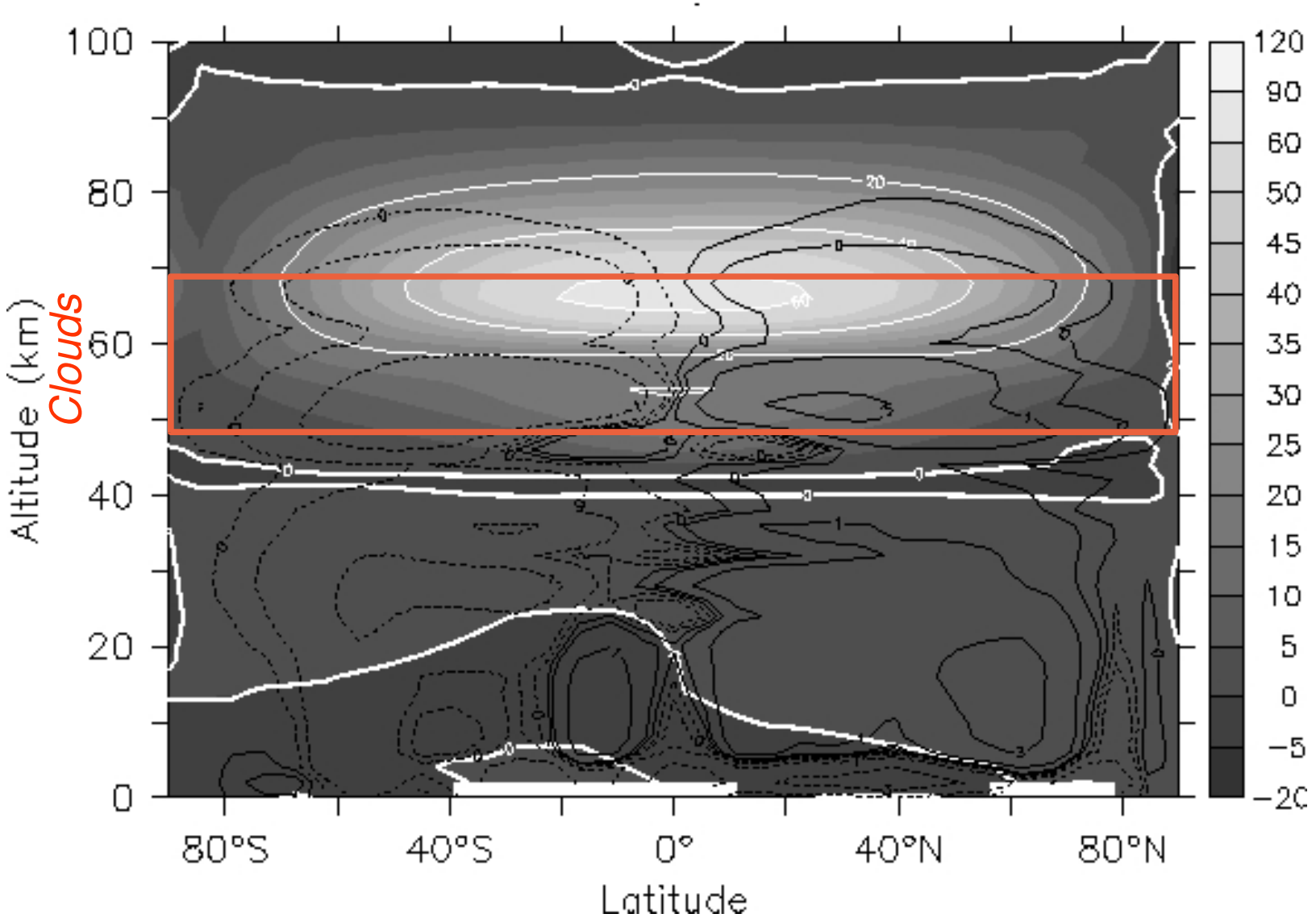
- Three-dimensional: 48x32x50 (0~95 km)
- Vertical coordinates: hybrid (sigma/pressure)

- 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

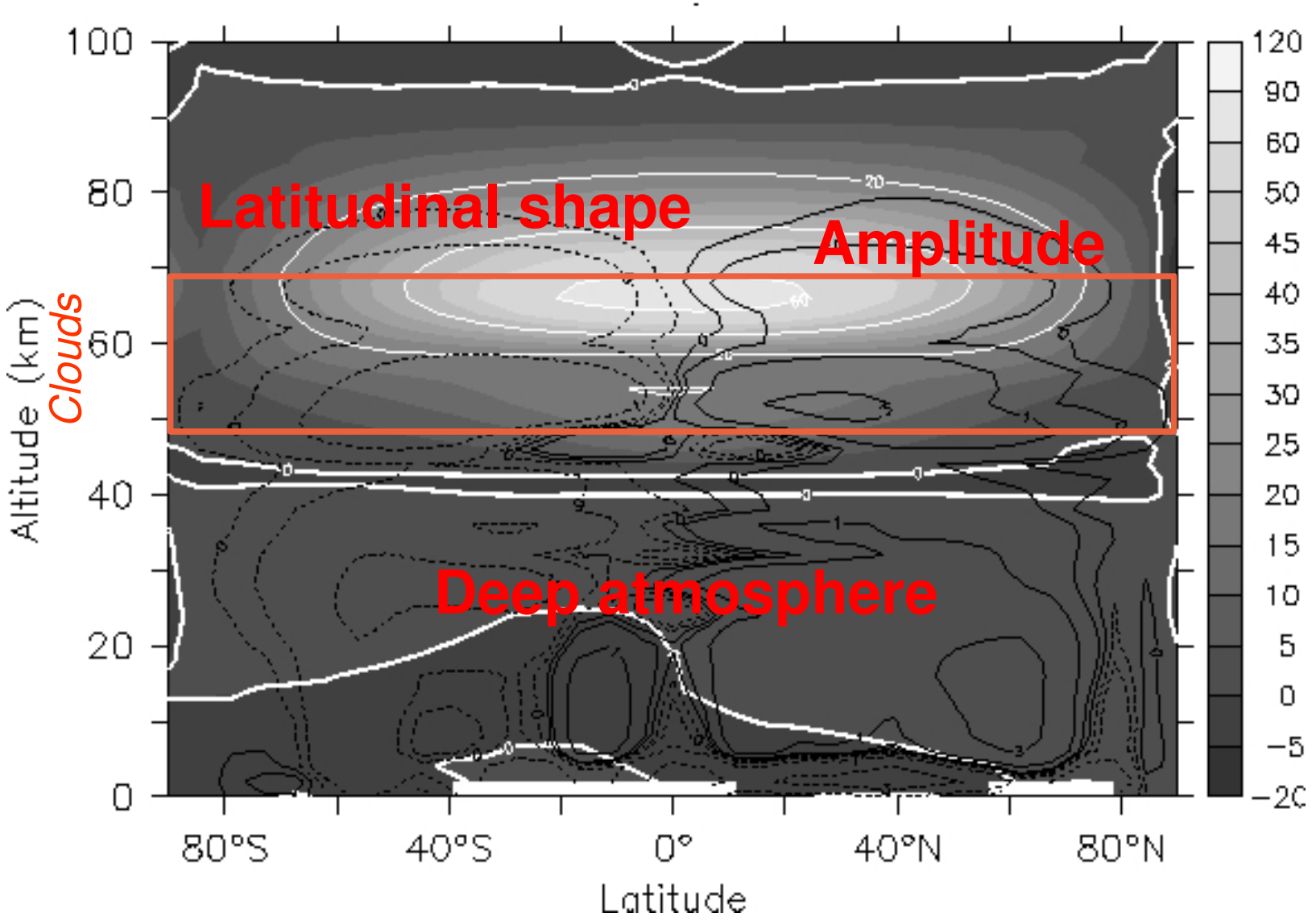
- No photochemistry

Venus Superrotation



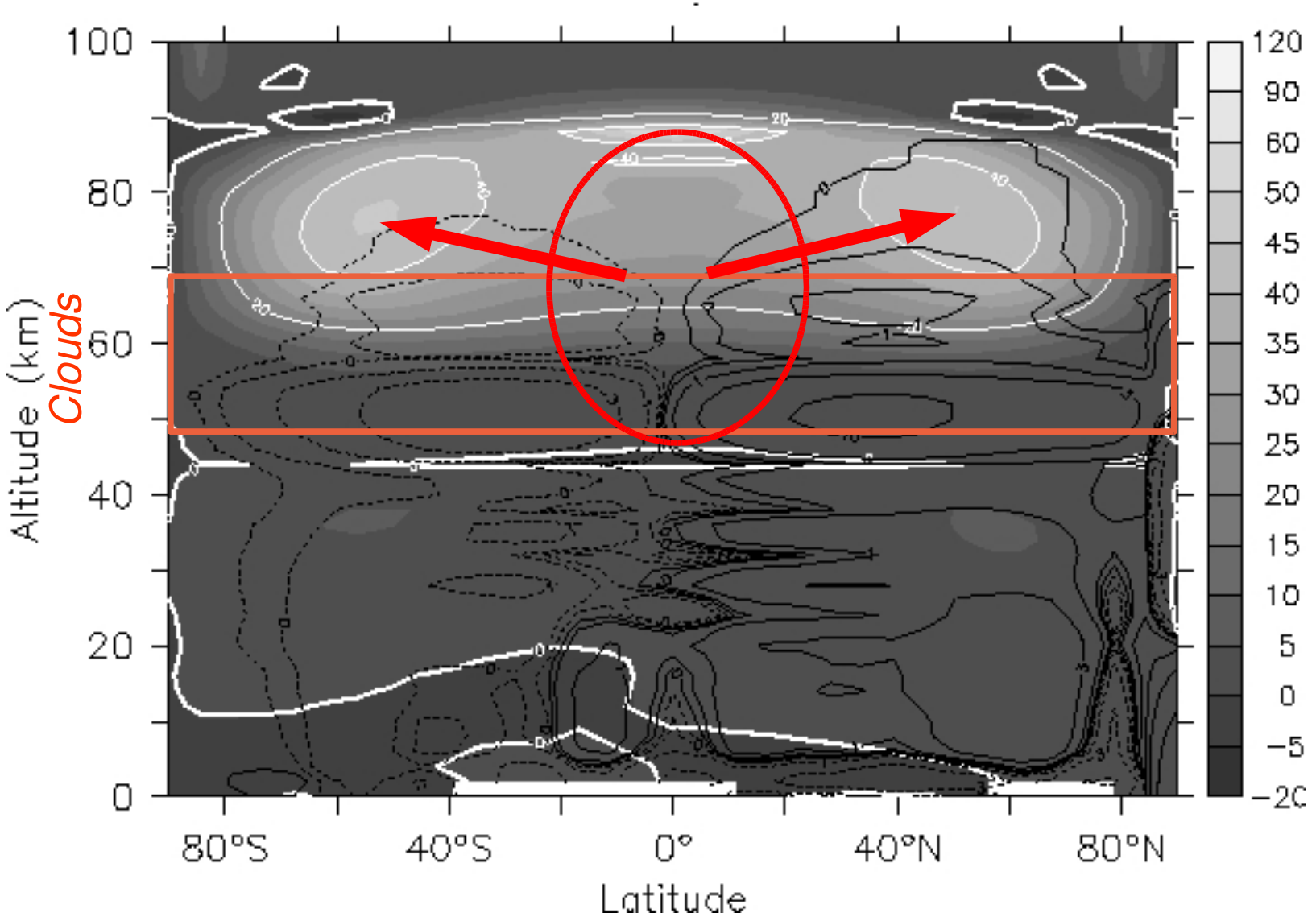
Mean zonal wind and stream function after 250 Vdays
(Topography, diurnal cycle)

Venus Superrotation



Mean zonal wind and stream function after 250 Vdays
(Topography, diurnal cycle)

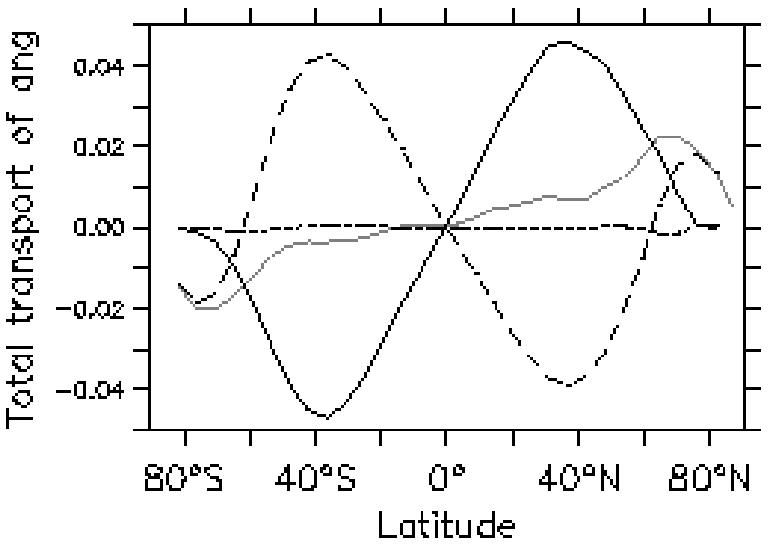
Role of the diurnal cycle



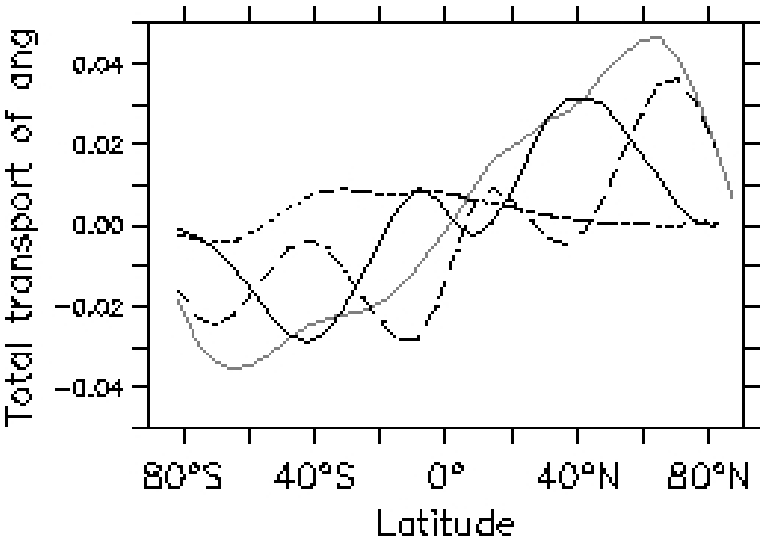
Mean zonal wind and stream function after +50 Vdays
(Topography, no diurnal cycle)

Angular momentum transport

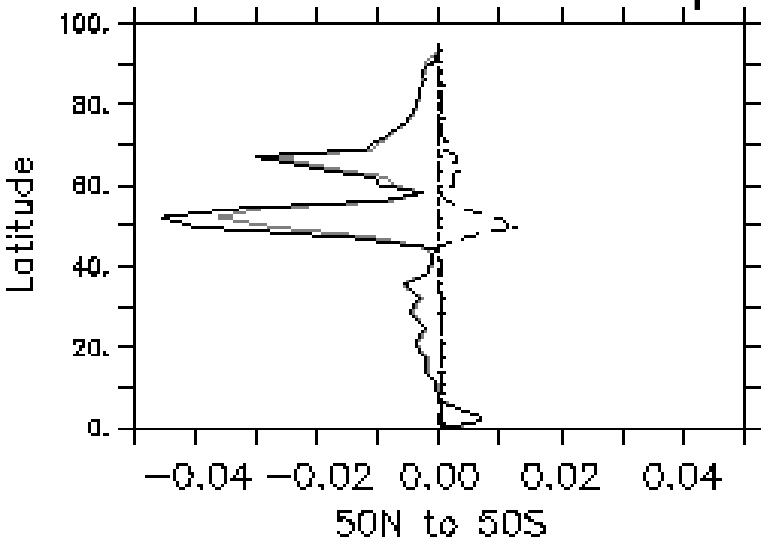
Without diurnal cycle

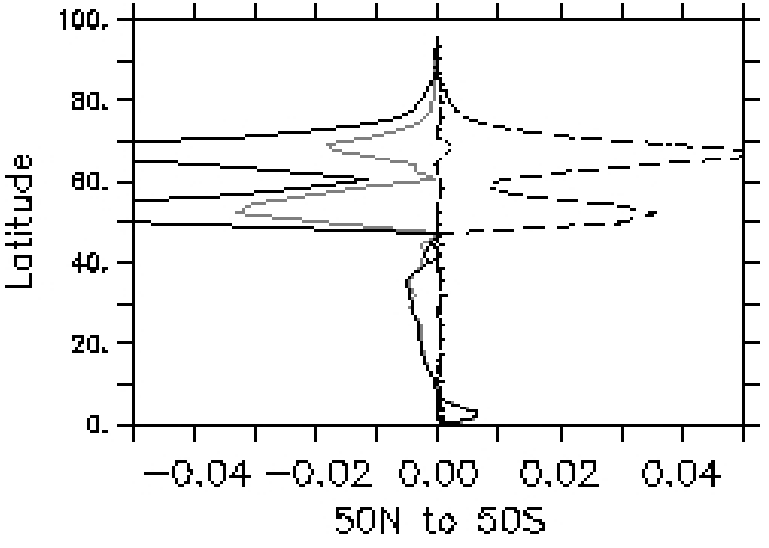


With diurnal cycle



Vertical transport between 50°N and 50°S

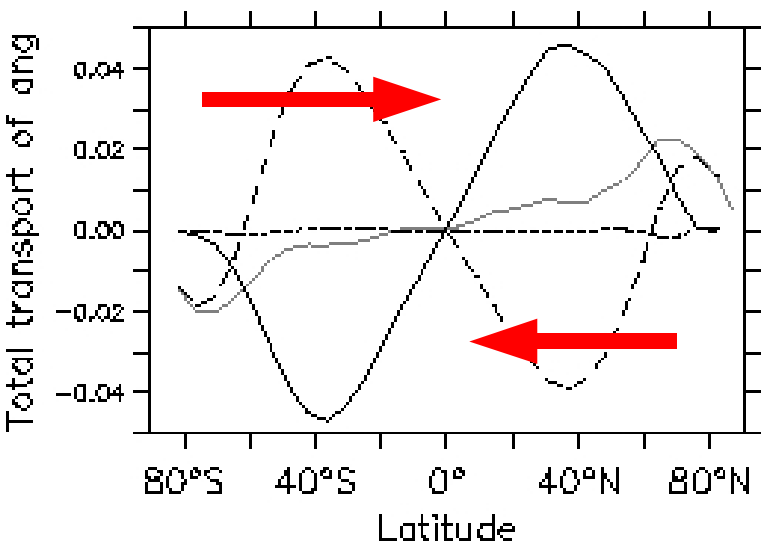




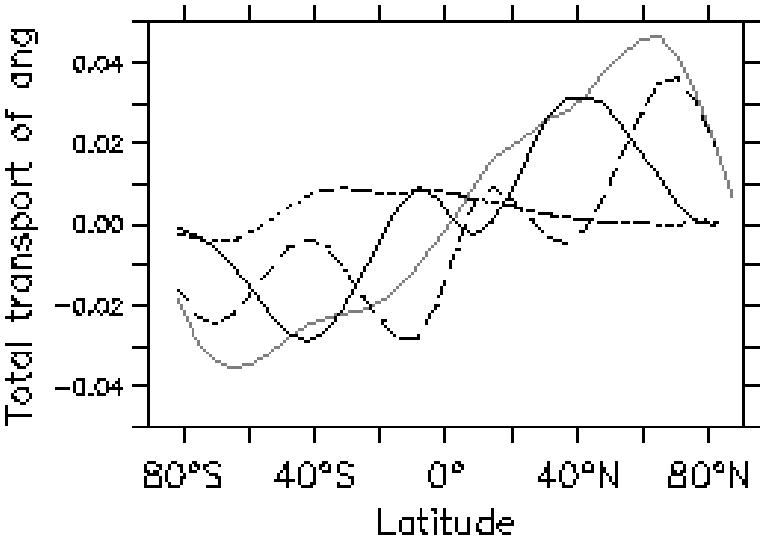
Angular momentum transport

Role of waves

Without diurnal cycle



With diurnal cycle



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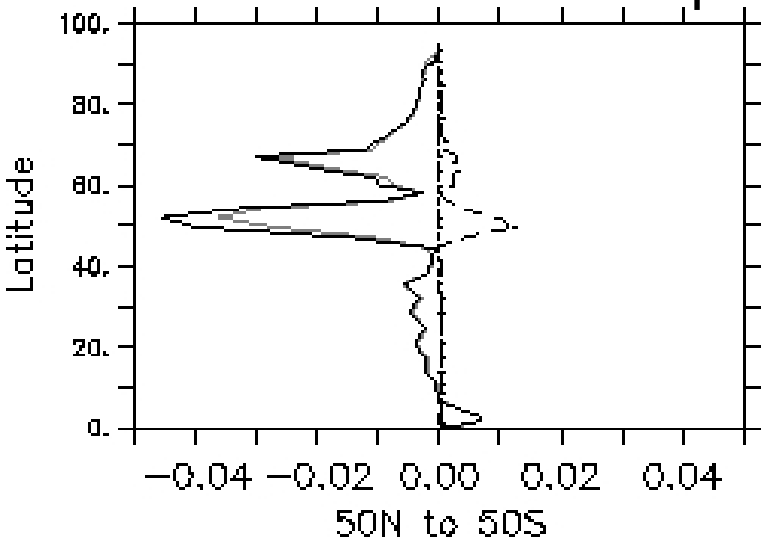

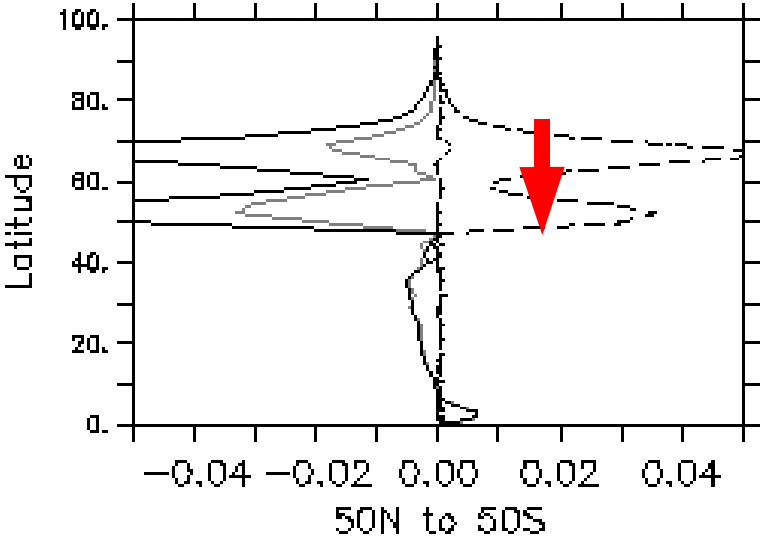

Discussion

- 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. Role of thermal tides ?

- Venus: the question of the deep atmosphere is still pending...

What is missing ? Gravity waves forcing ?

Why is this problem not present in Titan's model ?