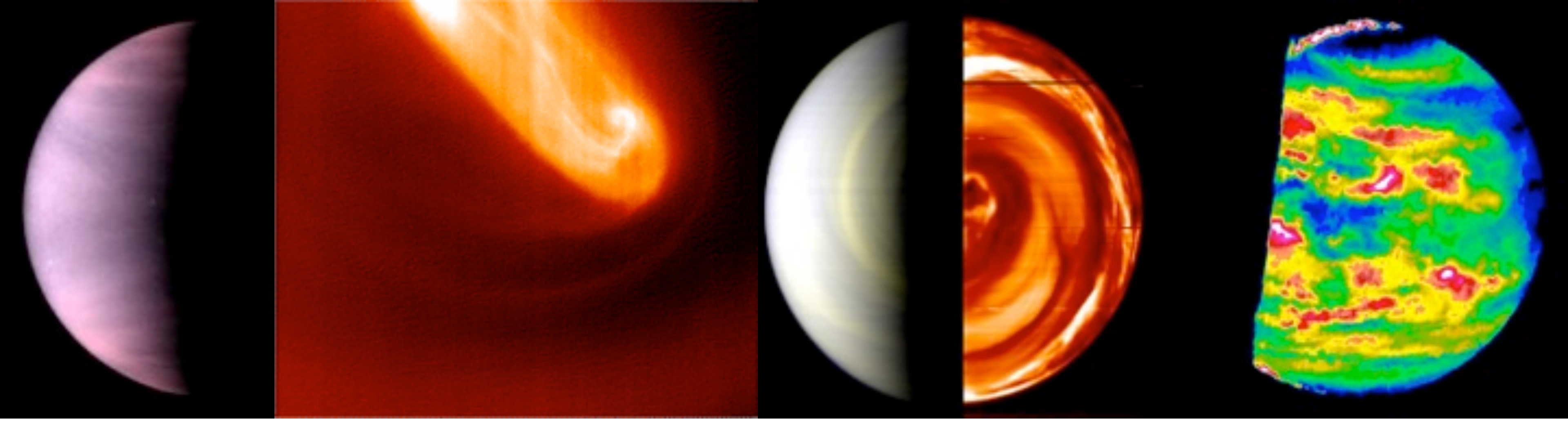


Simulating the circulation of Venus' atmosphere using OPUS-V*: *Transport barriers, radiative transfer, dynamics & Venus Express*

Joao Mendonca[1], Stephen Lewis[2] & Peter Read[1]

[1] University of Oxford, UK

[2] Now at Open University, UK

**Oxford Planetary Unified Simulation model - Venus*

GCM studies of Venus at Oxford: objectives & ongoing activities

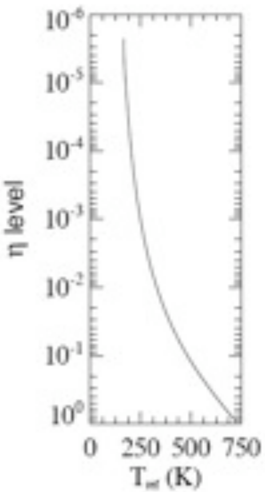
- Origin and mechanisms for global and equatorial super-rotation
- Waves and instabilities
  - Roles in general circulation?
  - Polar structures, dipole etc…
- Tracer transport & transport barriers?
- Physically-based radiative transfer
  - Net exchange scheme (Eymet et al. 2009)
- Analysis & interpretation of VEx data
  - Cyclostrophic balance?
  - Simple 'assimilation' of observed temperatures (zonal mean)?

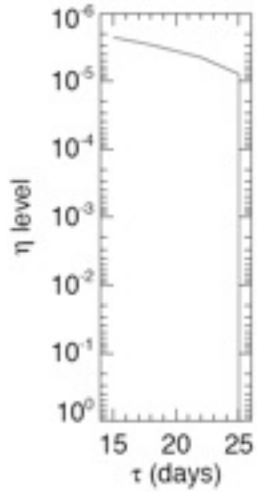
Oxford Venus GCM [OPUS-V]

- Dynamical core of UKMO Unified Model
  - Finite-difference (extended) primitive equations (White & Bromley 1995)
  - 3D time-dependent global dynamics
  - 5^o x 5^o resolution in lat x lon
  - 31 vertical levels from surface to ~80 km (0.2 hPa)
- Simplified radiative forcing
  - Relaxation to prescribed Temperature field
  - Optional diurnal cycle (relaxation to prescribed tidal structure)
- Boundary layer friction/mixing
  - Linear relaxation drag or bulk coefficient turbulence model
- Surface topography
  - Adapted from Magellan maps
- H_2SO_4 clouds and vapour transport

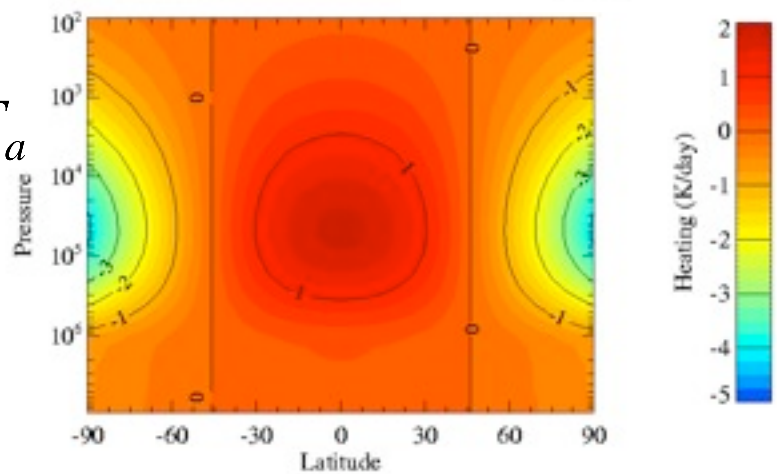
Radiative relaxation model

T_{ref}





T_a



- Relaxation towards global mean T profile PLUS
- Zonally symmetric T anomaly
- Relaxation timescale τ

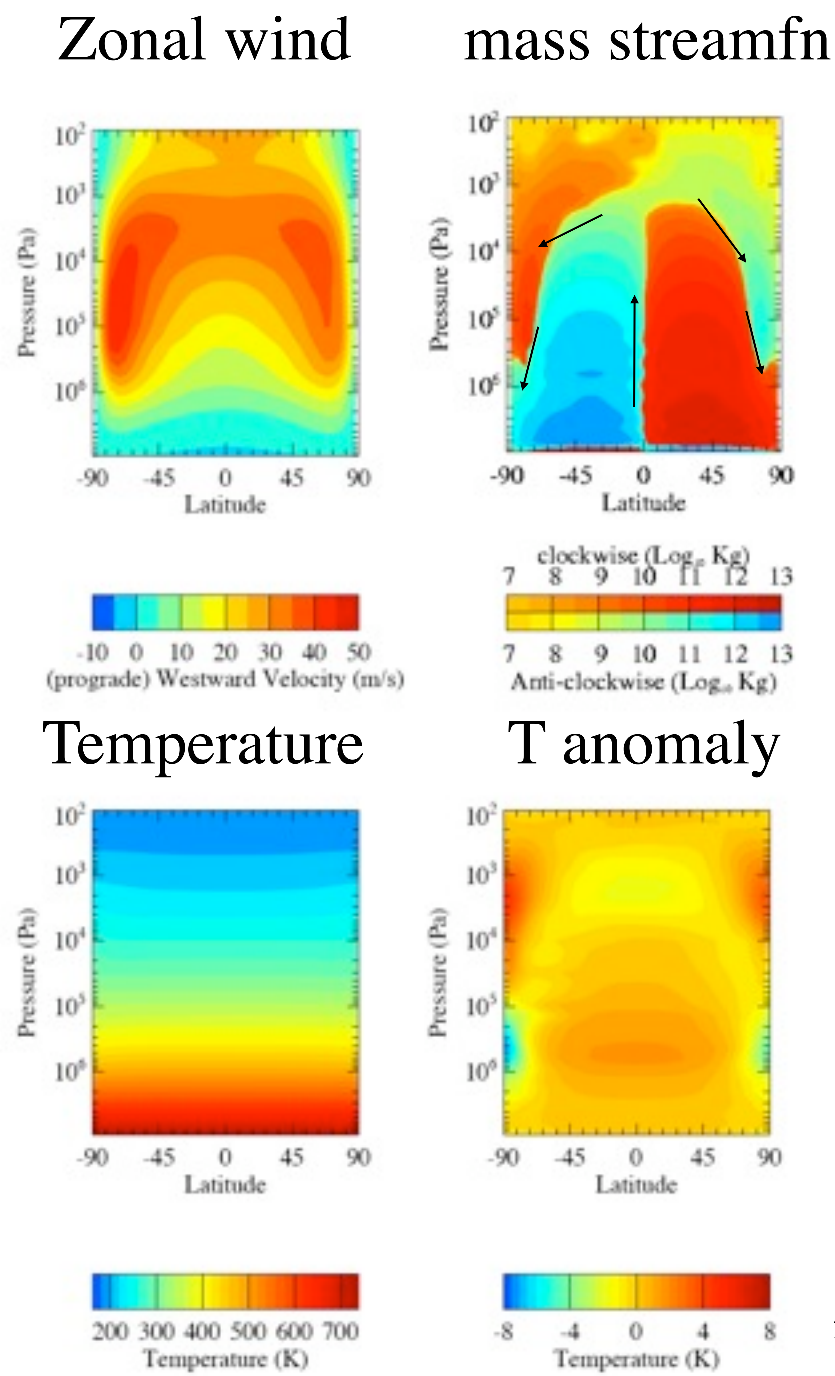
$$\frac{DT}{Dt} = -\frac{(T - T_0)}{\tau}$$

where $T_0 = T_{ref}(z) + T_a(\phi, z)$

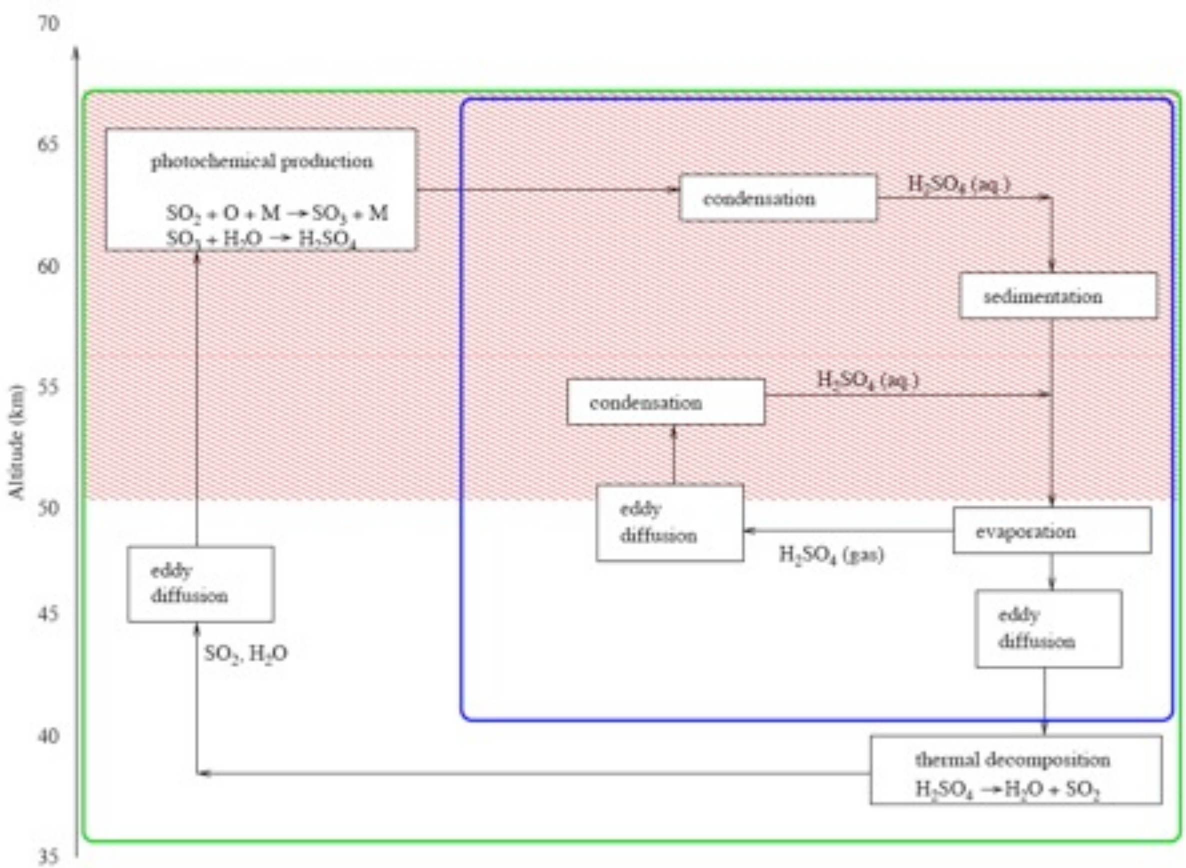
$= T_{ref}(z) + T_1(z)[\cos\phi - C]$

Venus: global circulation

- Venus planetary parameters
  - Slow (retrograde) planetary rotation
- ~"Realistic" super-rotation (~0.4-0.5 that of Venus itself!)
- Meridional circulation dominated by global Hadley cells

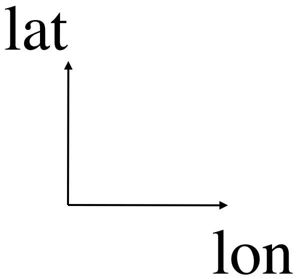


Cloud formation on Venus

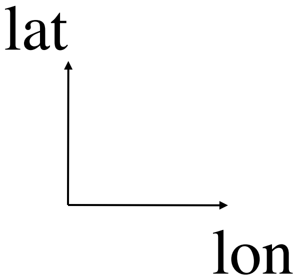


- Clouds of H_2SO_4 droplets
- Simple condensation, evaporation, advection & sedimentation included in the Venus GCM

Clouds and waves in Venus GCM (50 kPa level)



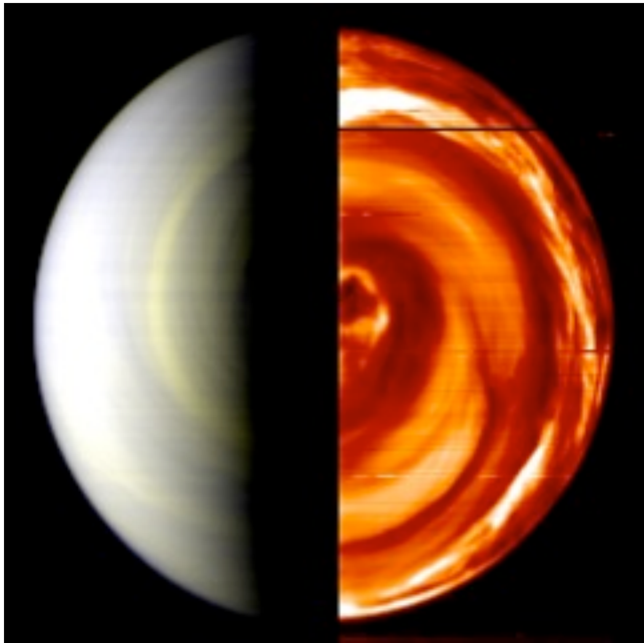
Clouds and waves in Venus GCM (50 kPa level)

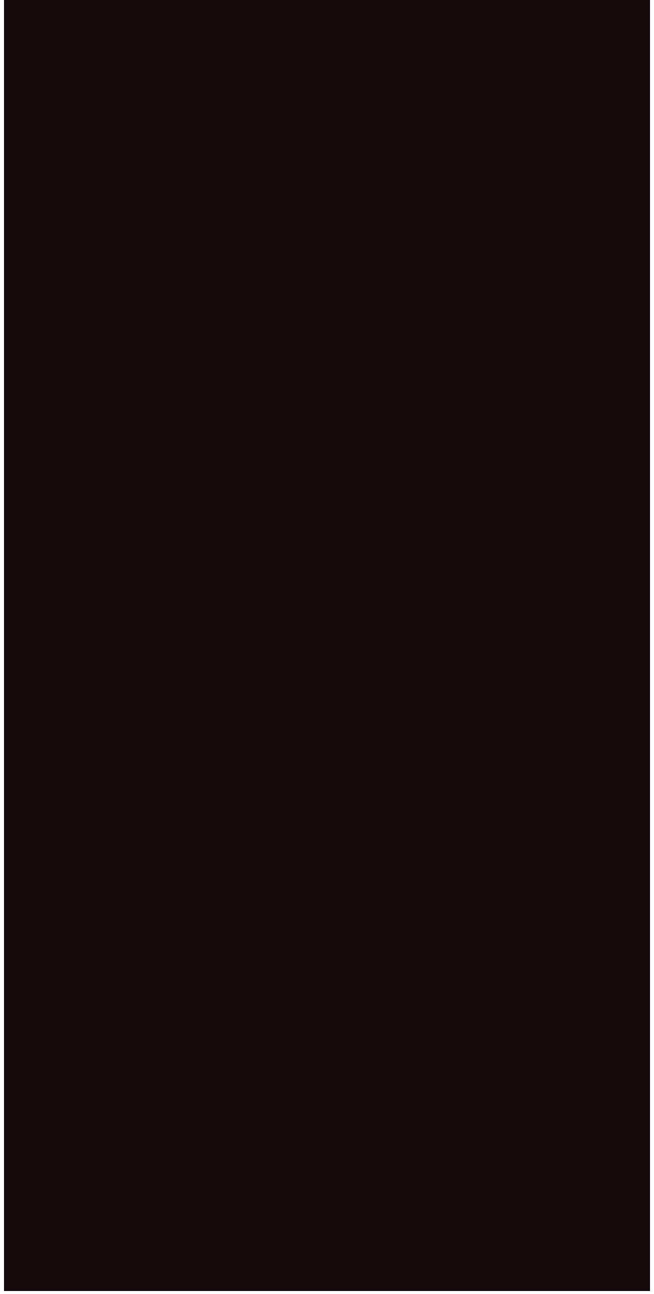


Clouds modelled near the poles

- polar vortex
- monopole eddies

-cf VEx





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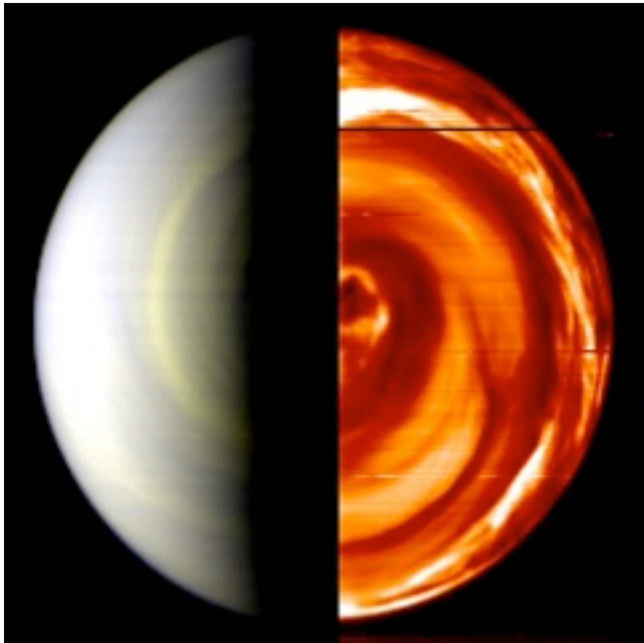
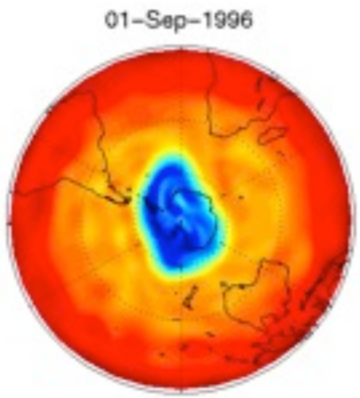


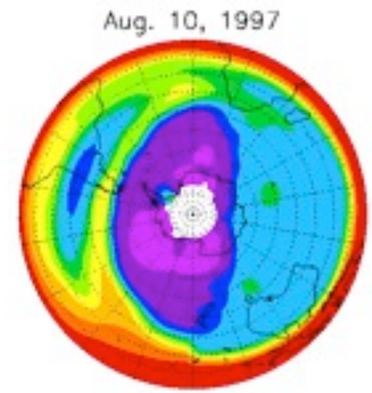
Atmospheric Transport Barrier.

. The transport barrier is a well known phenomenon in the Earth's atmosphere, and is used to explain the isolation of the Antarctic ozone hole.

From Sean Winkler's web site.

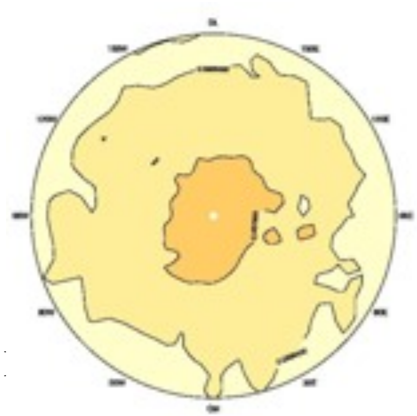


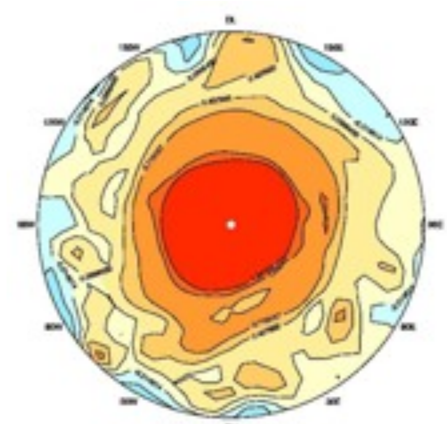
From Michael McIntyre's web site.



. The evidence for this phenomenon, which appears near the westward jets in Venus, is also observed in Mars GCM.

PV on isentropic maps.
Left: 300K
Right: 500K
The units are in 100PVU.

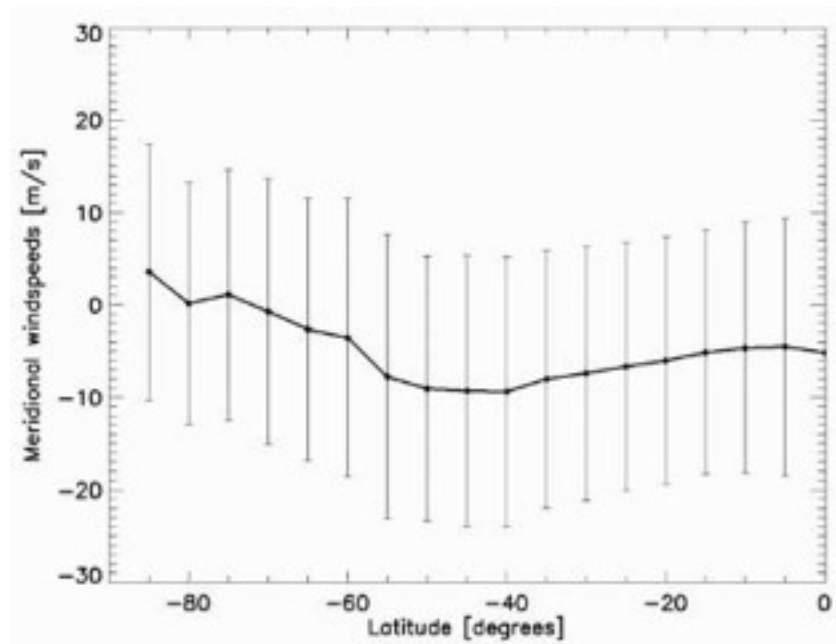




Observations

Uniformly bright at high latitudes surrounded by a sharp transition at rougly 60° .

Starts to fade at ~ 60° .



Observations

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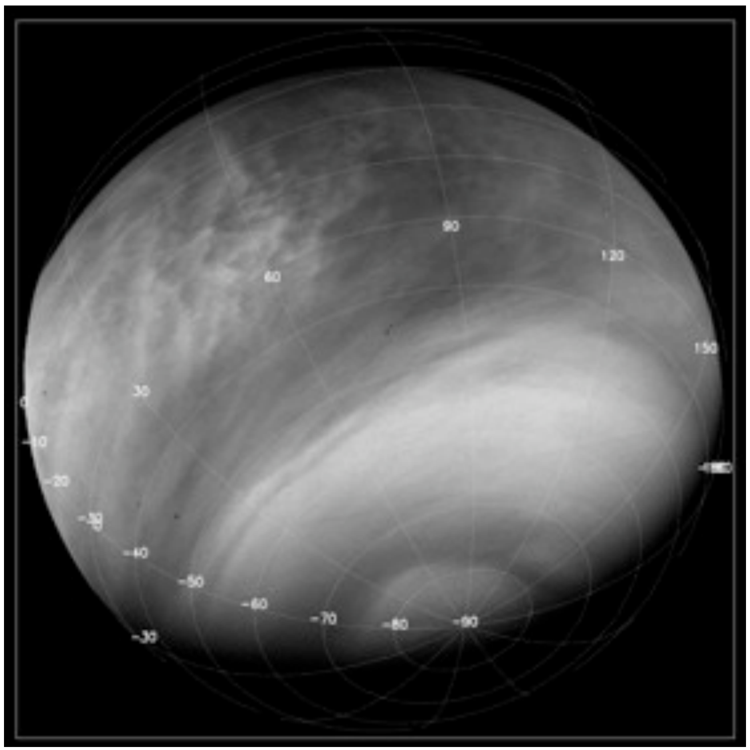

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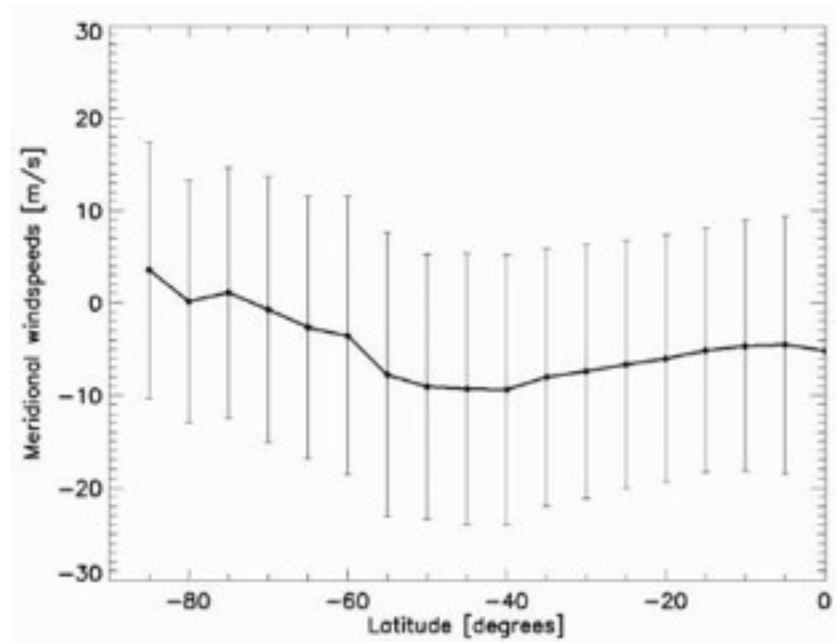

The mechanism

. In the westward jets zone, the strong gradient of the PV is associated with a large Rossby wave restoring force which inhibits meridional mixing at large scales. At small scales, the meridional shear acts to inhibit meridional mixing.

. The study of the transport barrier in the Venus GCM was analysed using the potential vorticity (PV) barrier mechanism, in the regions where the PV gradient on isentropic surfaces is relatively strong and the transport barrier is formed.

Results

Isentropic surface (right video): 864K
Pressure surface (left video): 951mBa
Altitude: 55km

Each frame is separated by one Earth's day.

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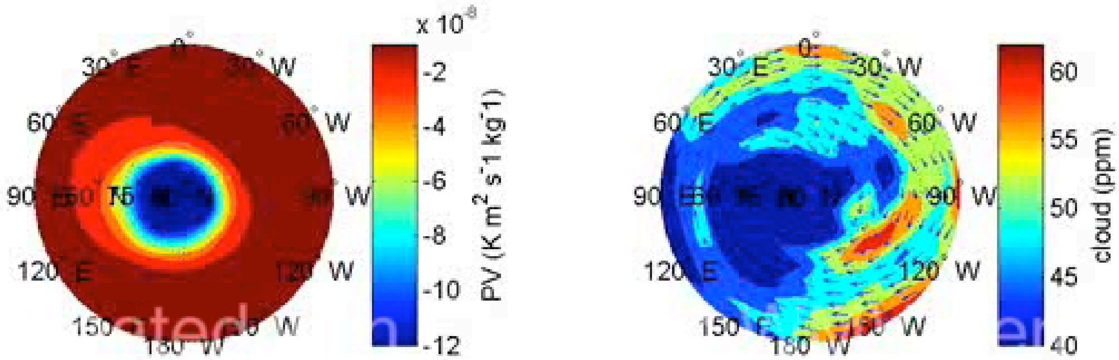


. The transport barrier that is evident in Mars and the Earth has an important role in the dynamics of the Venus atmosphere in determining the distribution of the clouds. Near the jets, meridional tracer transport is inhibited and forms a barrier that follows the dynamics of the waves.

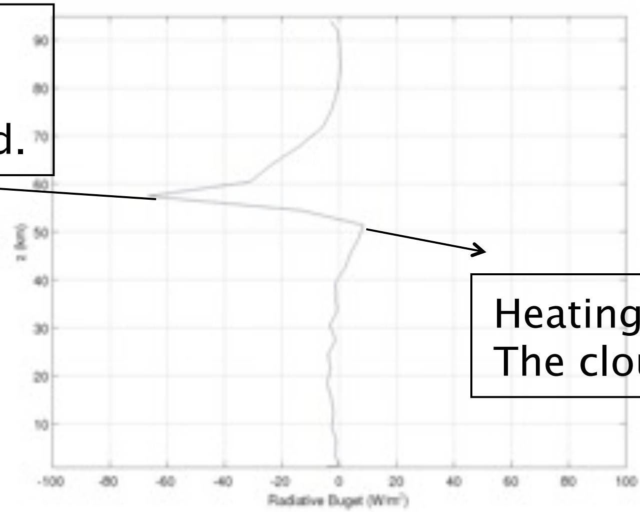
New physically-based radiative transfer parametrization in the IR

- Adapting the Net-Exchange parameterisation of thermal IR radiative transfer in Venus's atmosphere from Eymet et al. (2009)
- The parameterisation will be tested in a single column model, coupled with a short wave (Delta-Eddington) radiative heating formulation, perhaps using the scheme already present in the HadAm3 model (Earth GCM) but adapted to Venus.
- Net-Exchange Rates are evaluated from the difference in the Planck function for different layers, multiplied by an exchange factor obtained with a complex radiative transfer model (KARINE).
  - Vertical distributions of IR absorbers and scatterers in the GCM are assumed constant with time.
- Validate/recompute exchange factors using another complex radiative transfer model (NEMESIS - Irwin et al.)
- Eventually allow Lee et al. (2007) cloud model to predict distributions of absorbers and scatterers…?

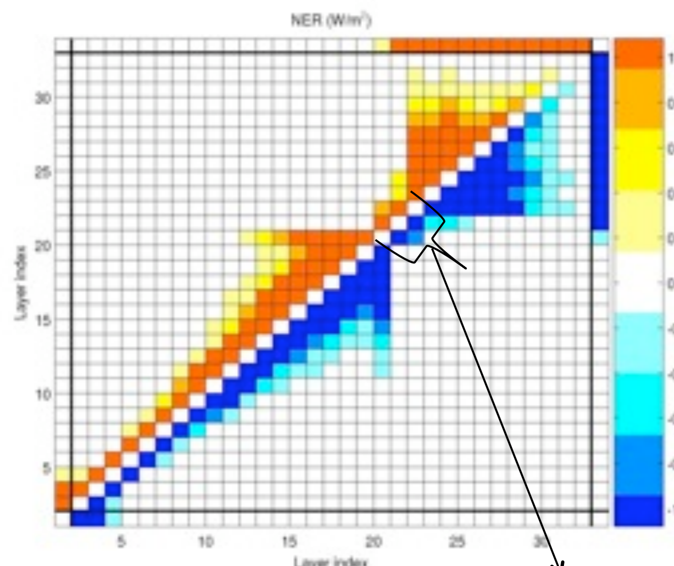
Radiative Budget and NER Matrix

Work in progress: VIRA T profile of the atmosphere was adapted to the Oxford
GCM vertical resolution (30 layers) from the Eymet et al (2009) results.

Cooling above the cloud.



Heating below The cloud



Scattering inside the cloud

Meridional study of the atmospheric dynamics.

. By studying the meridional component of the equation of motion on a spherical planet of radius a and angular velocity Ω, we analysed the contributions of different terms from the model's diagnostics. The aim was to elucidate the real nature of the atmosphere's dynamics mainly at high latitudes.

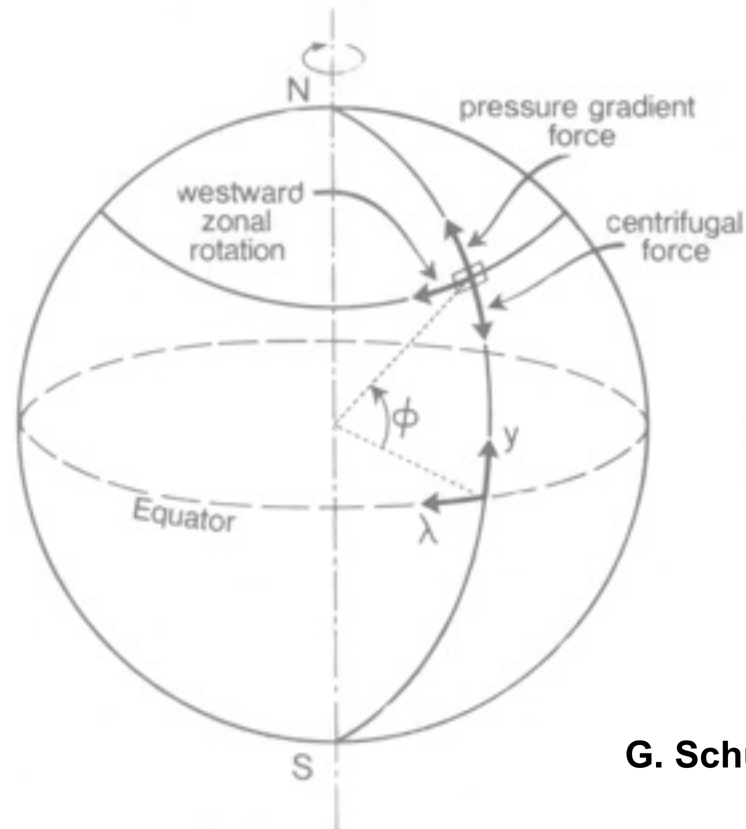
. Is the cyclostrophic balance a good approach?

Cyclostrophic balance

Cyclostrophic balance:

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

Leovy, 1973



G. Schubert, 1983

u = zonal velocity

a = Venus radius

y = poleward pointing cartesian coordinate

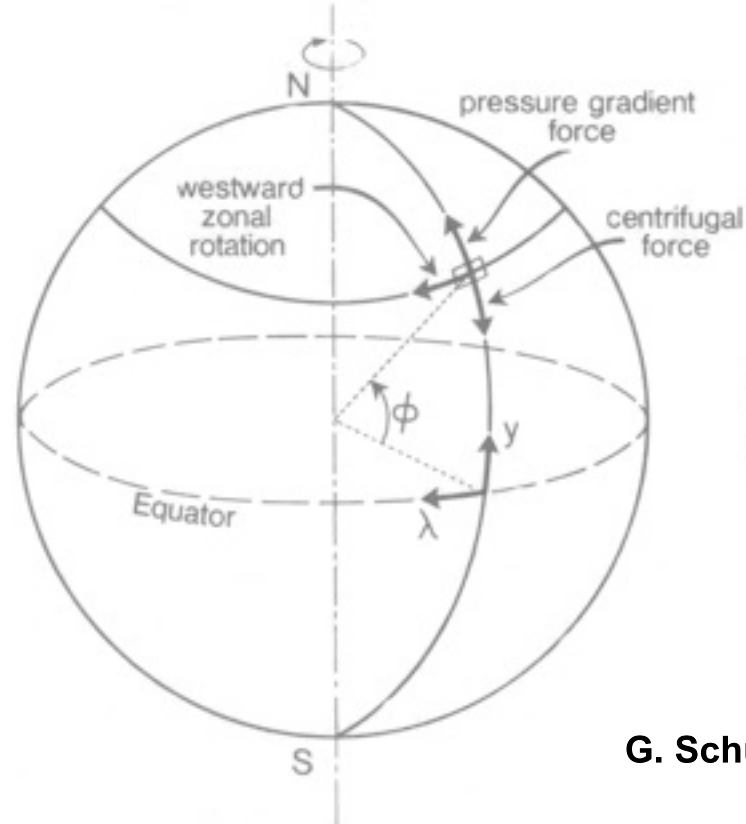
$$\xi = -\ln\frac{P}{P_{ref}}$$

Cyclostrophic balance

Cyclostrophic balance:

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

Leovy, 1973



G. Schubert, 1983

u = zonal velocity

a = Venus radius

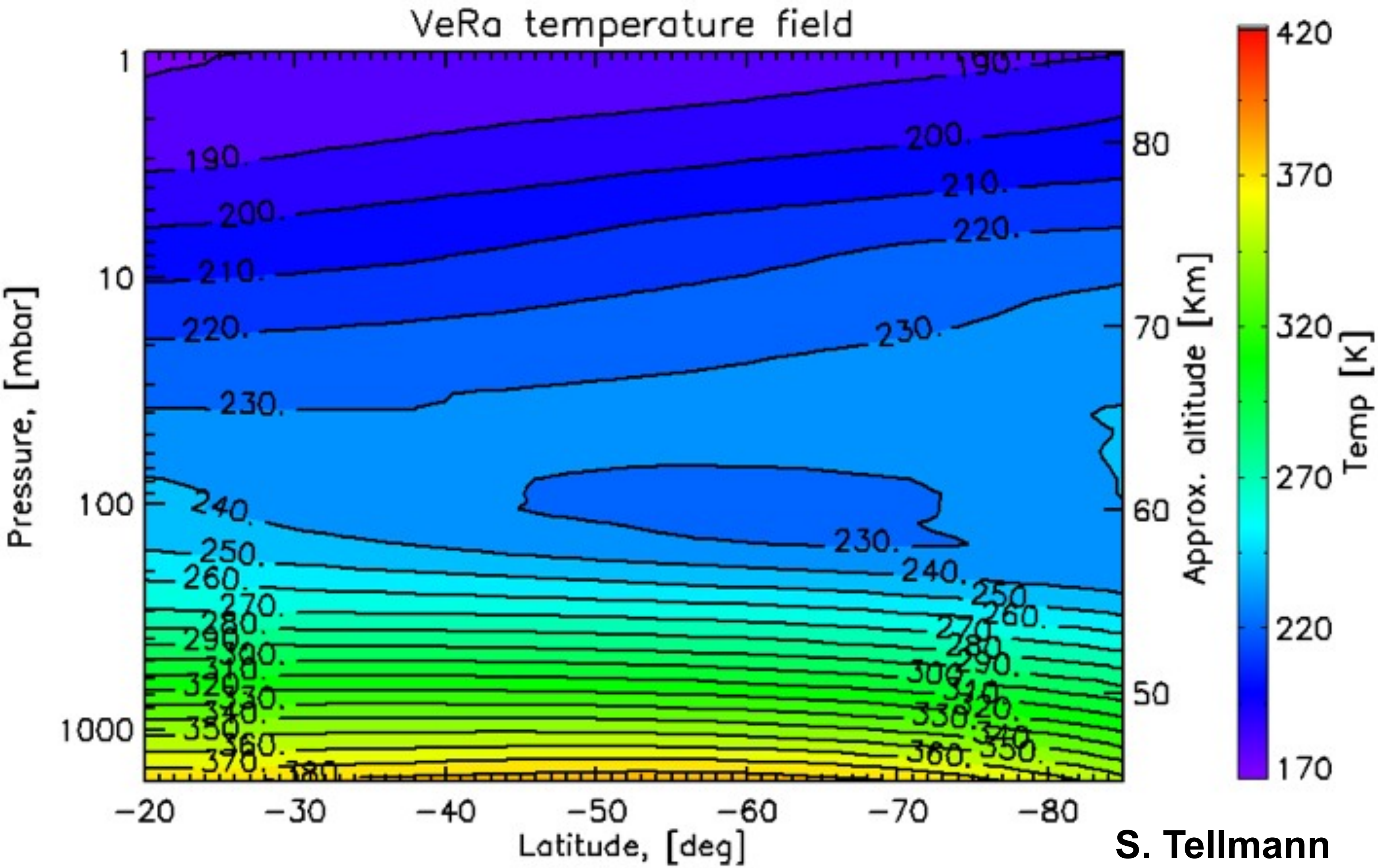
y = poleward pointing cartesian coordinate

$$\xi = -\ln\frac{P}{P_{ref}}$$

Thermal wind equation:

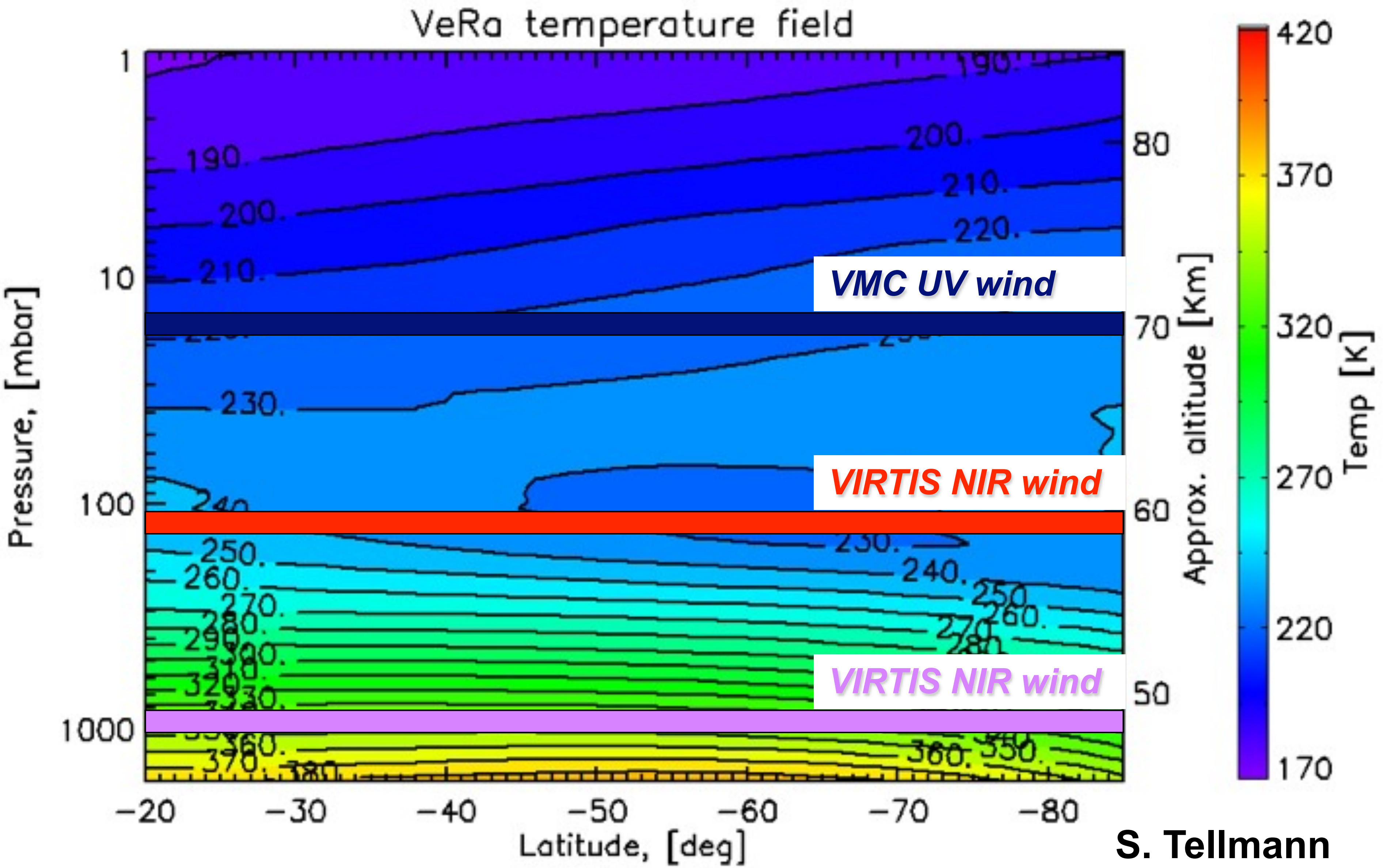
$$\boxed{2u\frac{\partial u}{\partial \xi} = -\frac{R}{\tan\phi}\frac{\partial T}{\partial \phi}}$$

VeRa – Temperature field



S. Tellmann

VeRa – Temperature field



S. Tellmann

VIRTIS Temperature at isobaric levels

(Picciali et al. 2008)

$$\boxed{2u\frac{\partial u}{\partial \xi} = -\frac{R}{\tan\phi}\frac{\partial T}{\partial \phi}}$$

VIRTIS Temperature at isobaric levels

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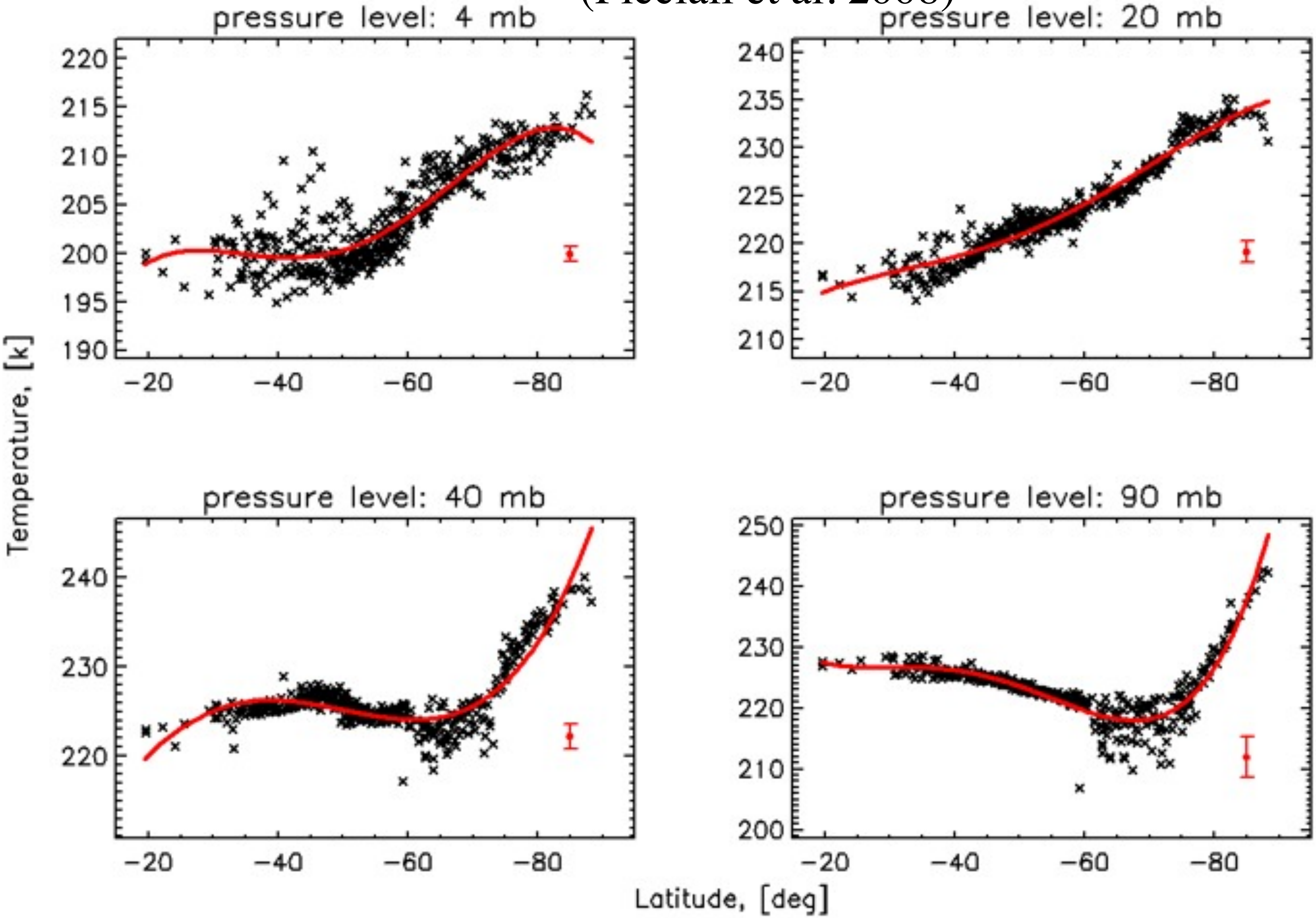
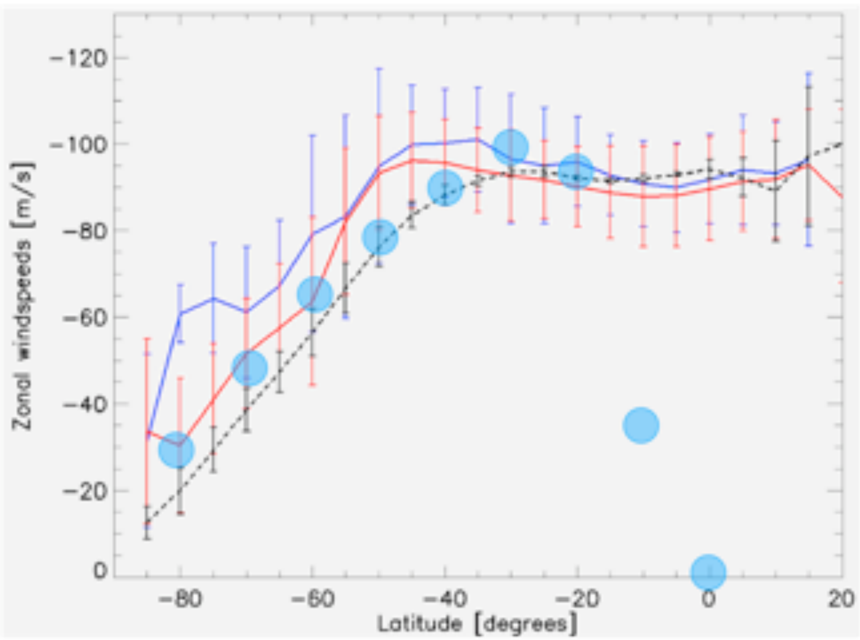
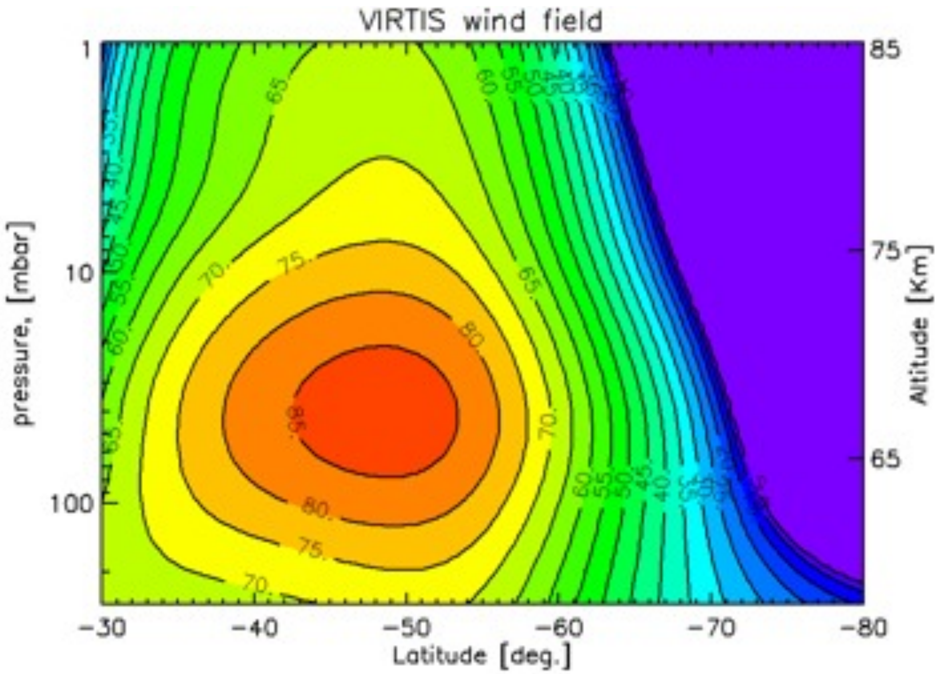


Venus atmospheric super-rotation

R. Moissl, S. Limaye, I. Khatuntsev



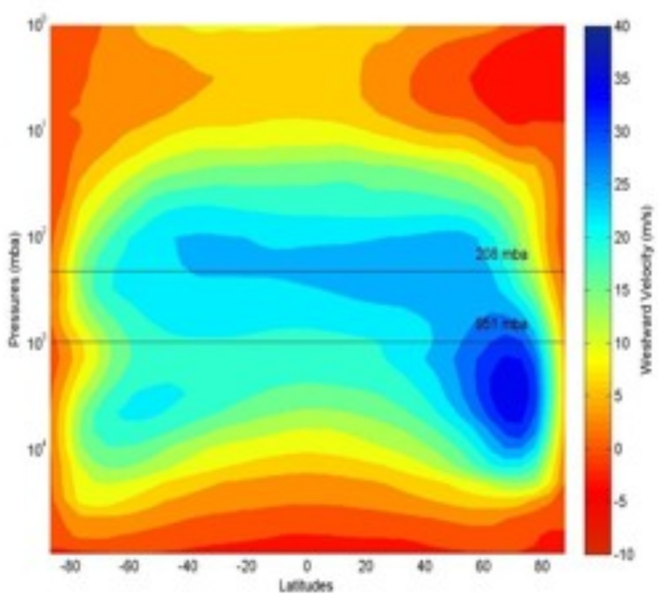
Picciali et al.



- Cloud-tracked winds show velocities ~100 m s^{-1}
  - Rotation period ~ 4 days, cf surface period of 240 days
- Cyclostrophic thermal winds -> mid-latitude jets above clouds?
  - **Decrease towards equator…..???**

Results (OPUS-V)

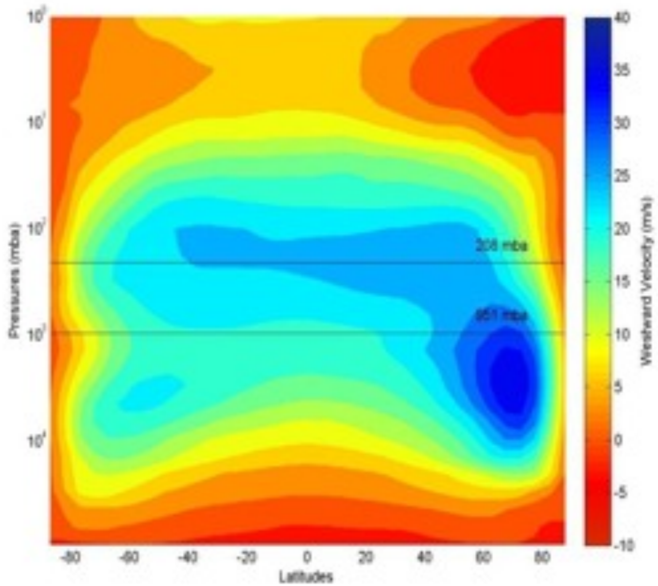
$$RESIDUAL + \frac{u^2 \tan\vartheta}{a} + \frac{wv}{a} + u2\Omega\sin\vartheta = -\frac{1}{a}\frac{\partial\Phi}{\partial\vartheta}$$

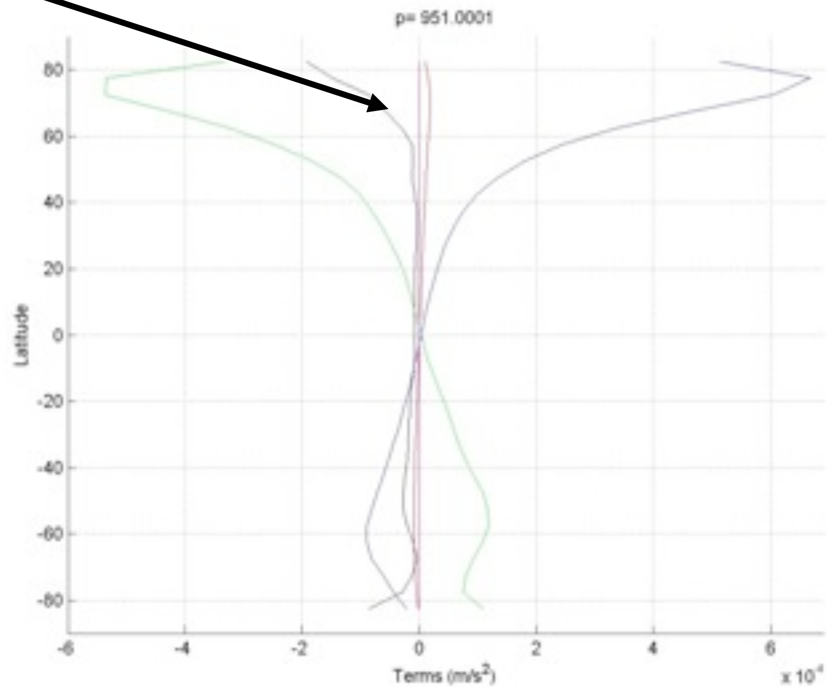


Each variable v, w, u and Φ, was averaged over longitude and over time .

Results (OPUS-V)

$$RESIDUAL + \frac{u^2 \tan\vartheta}{a} + \frac{wv}{a} + u2\Omega\sin\vartheta = -\frac{1}{a}\frac{\partial\Phi}{\partial\vartheta}$$





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Results (OPUS-V)

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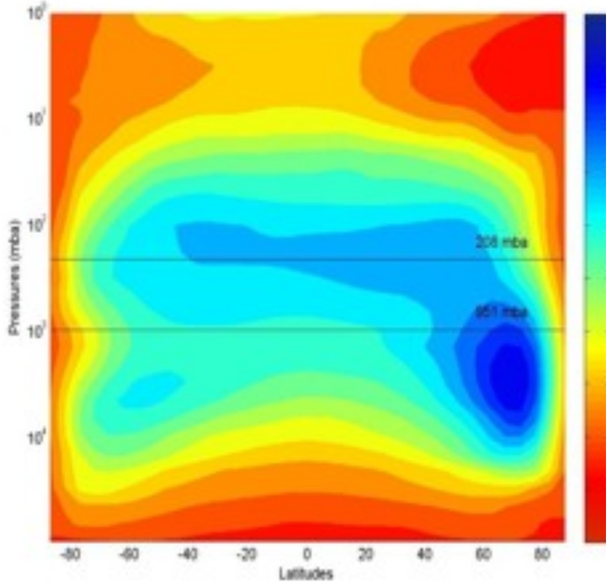
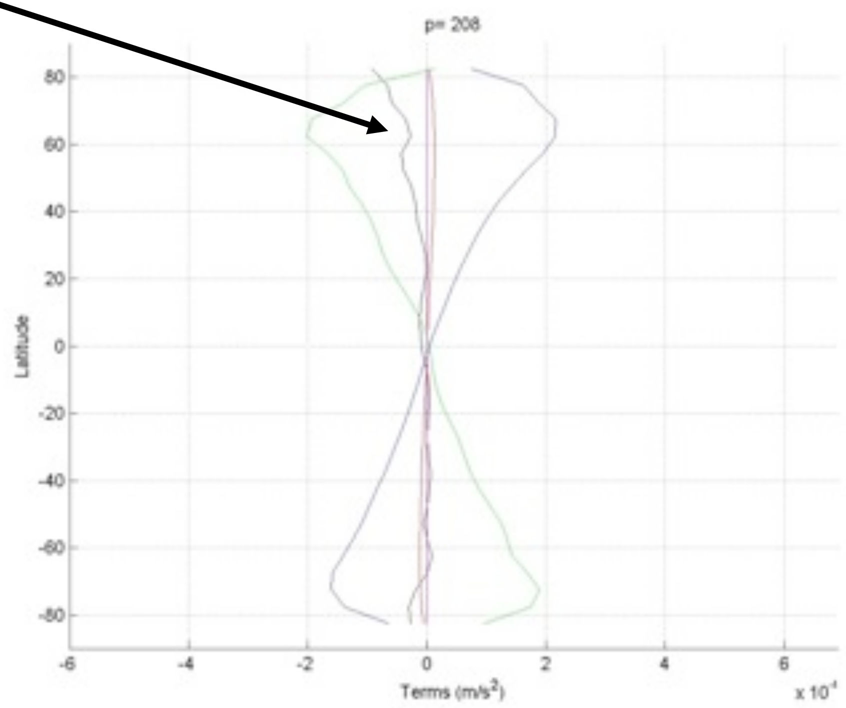
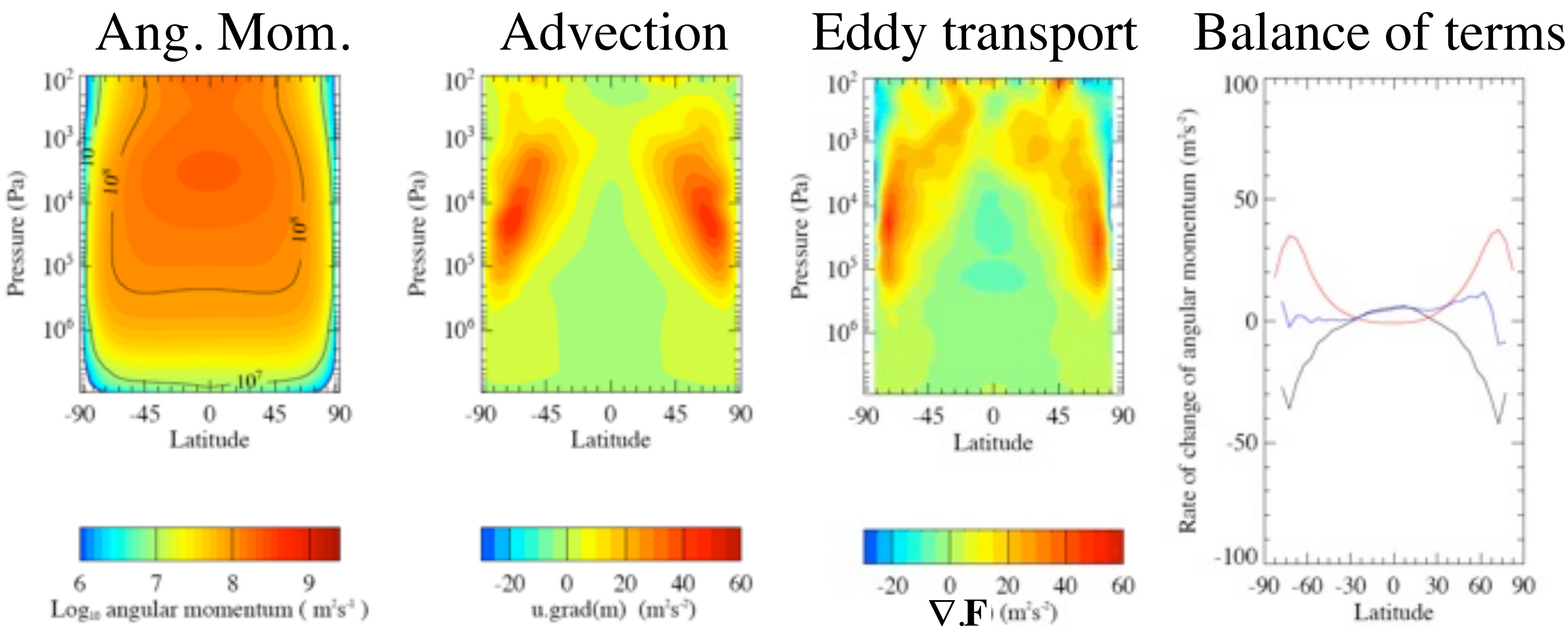




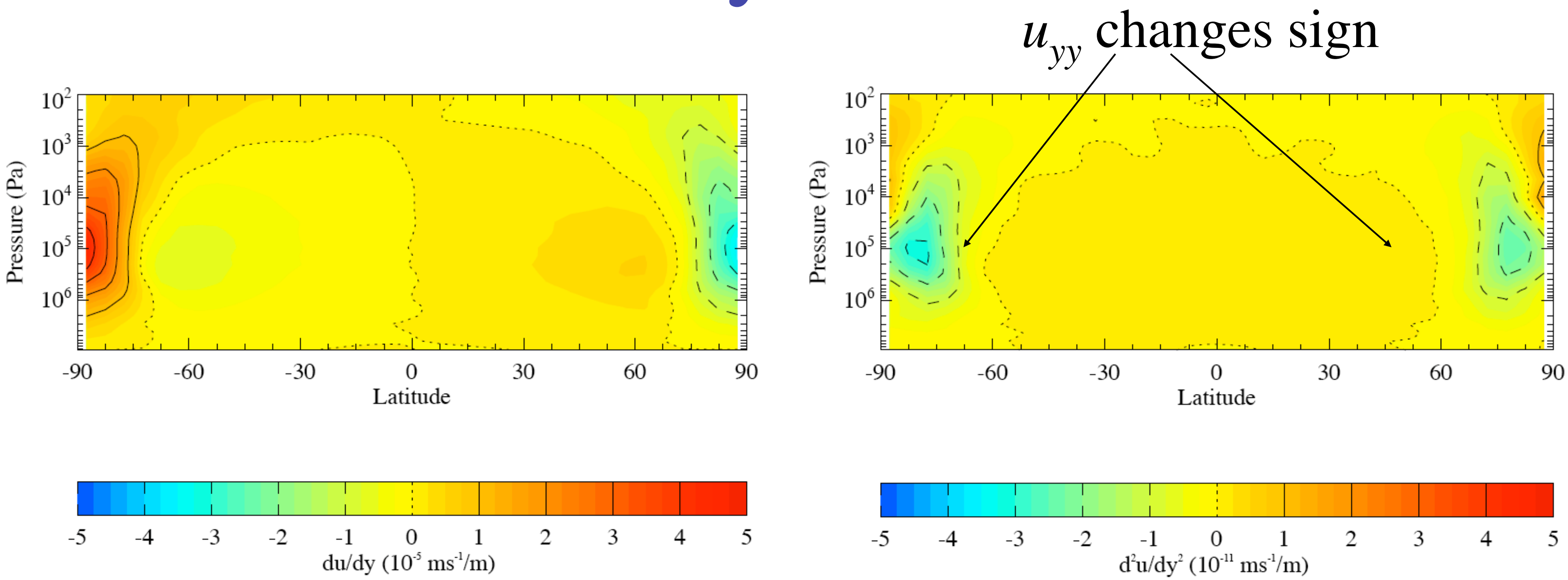
Each variable v, w, u and Φ, was averaged over longitude and over time .

Angular momentum budget



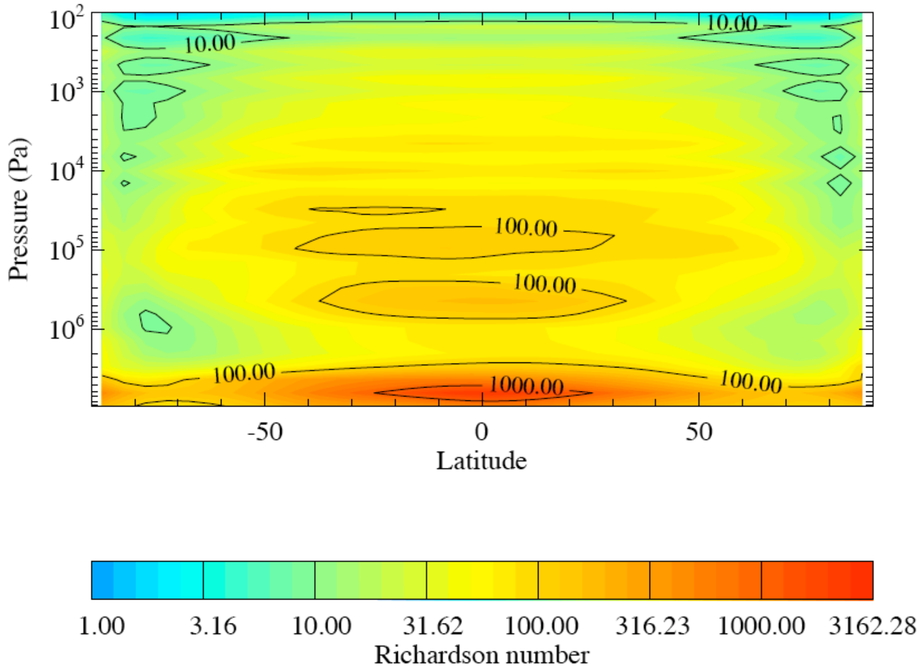
- Transport of angular momentum by Hadley circulation is balanced by eddy transports due mainly to MRG waves
- Broadly consistent with Gierasch-Rossow-Williams conceptual model
- ORIGIN of AM-transporting waves? - Barotropic instability…..

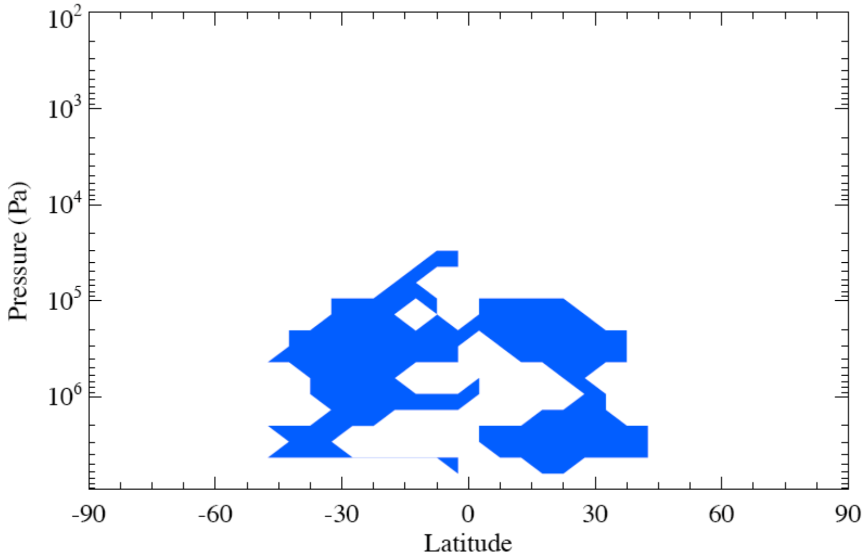
Instability indicators



- Relative vorticity concentrated over polar caps
- Horizontal vorticity gradient changes sign around $\pm 60^{o}$ latitude
- BAROTROPIC INSTABILITY……

Instability indicators

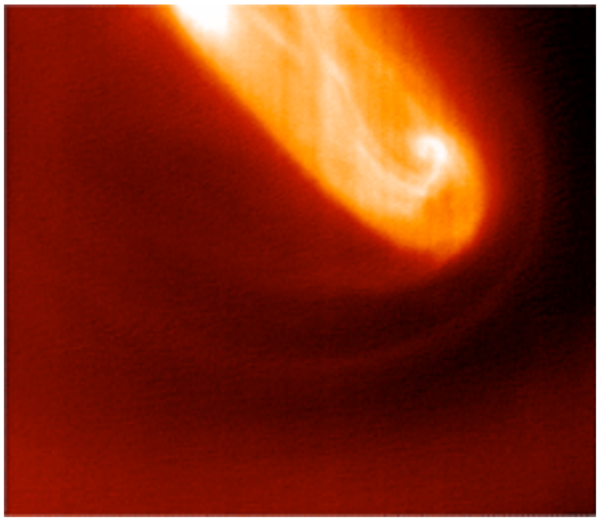


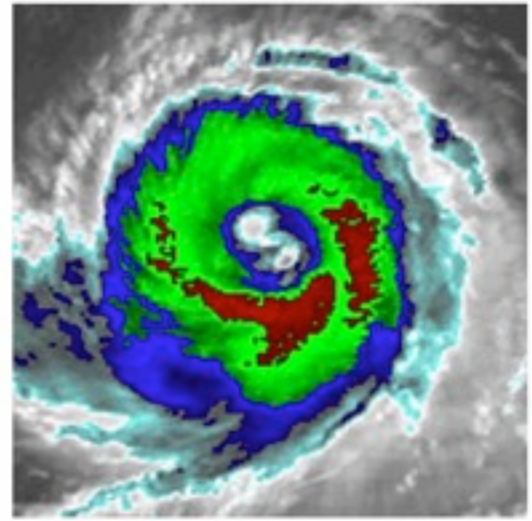


f.q

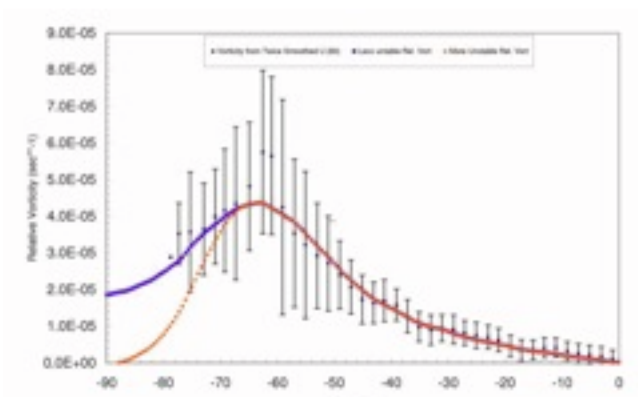
- Richardson number $R_i = N^2 / (\frac{du}{dz})^2$ >3 almost everywhere
- *f.q* tends to be negative near equator
  - INERTIAL INSTABILITY possible…..?

Venus's "dipole"?

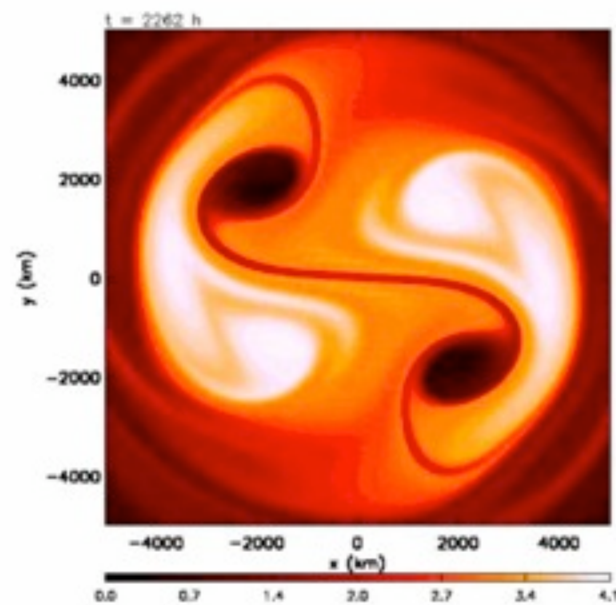




Hurricane Howard (1998)



Limaye et al. GRL (2009)



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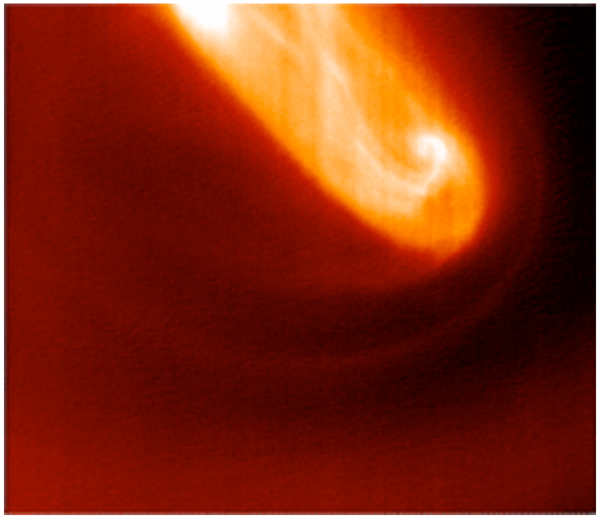
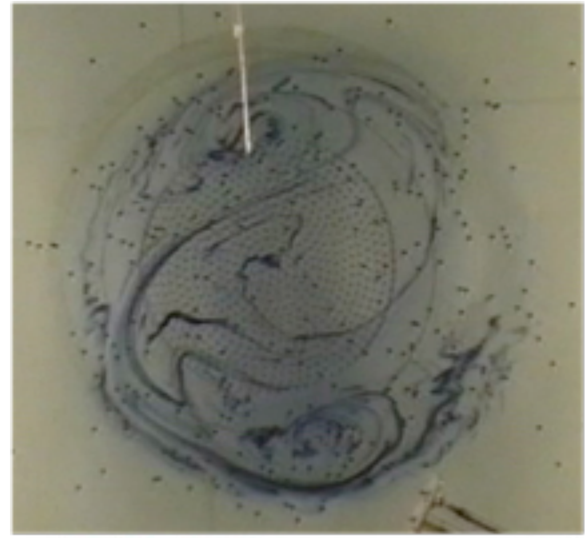
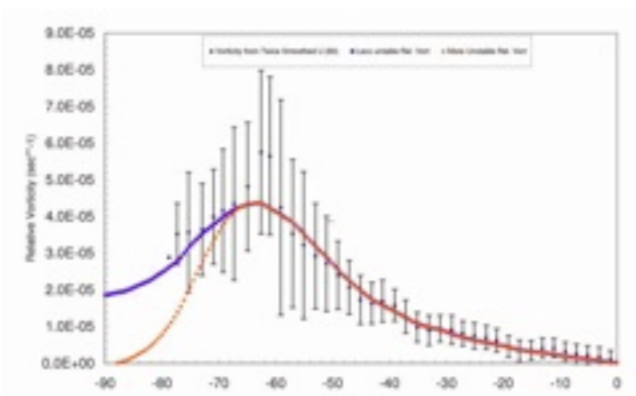
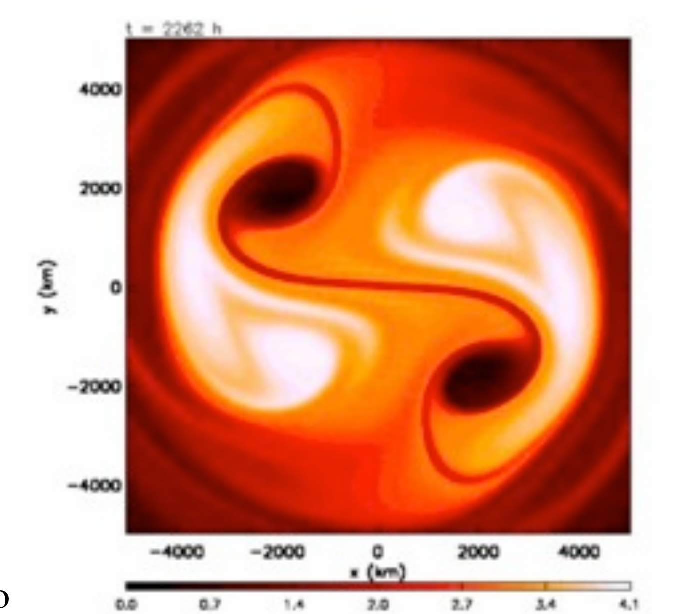




Montabone et al. (2009)



Limaye et al. GRL (2009)



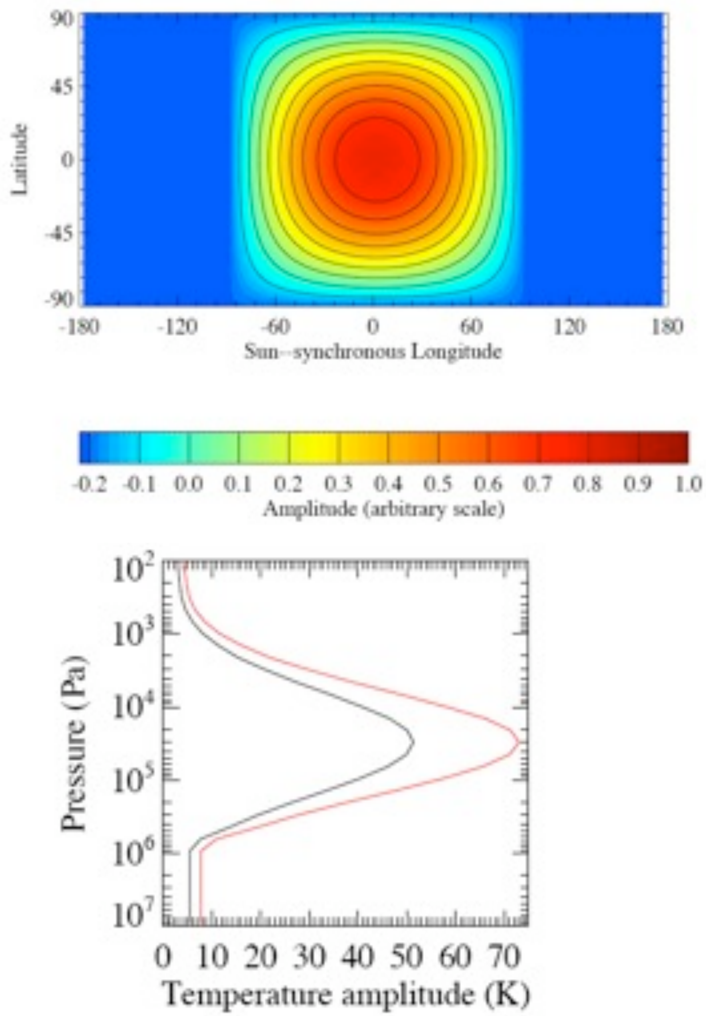
Dominant balances for zonal

- At the altitudes analysed, the results so far show that the equation of motion is dominated mainly by three terms: the centrifugal acceleration, the geopotential gradient and a residual.
- The residual contribution may be due to the variability of the flow with time, and seems to be related to the turbulent zone near the jets dominated by eddy momentum fluxes.
- Possibility to correct the cyclostrophic balance by adding a correction term parametrizing eddy momentum fluxes?
  - Mixing length scheme?

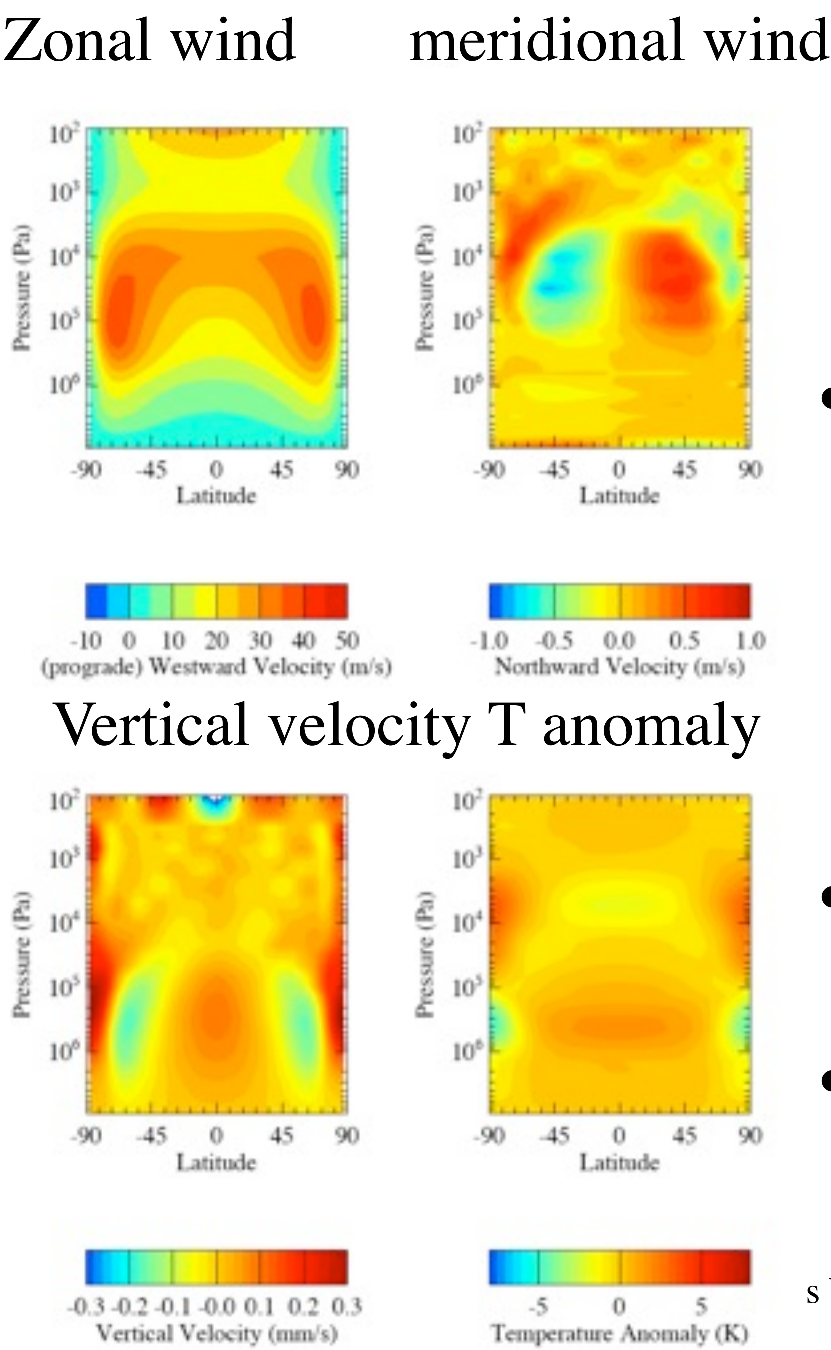
$$\overline{u'v'} \approx -K\frac{\partial \overline{u}}{\partial y}; \text{ so that } \frac{\partial}{\partial y}\left(\overline{u'v'}\right) \approx -K\frac{\partial^2 \overline{u}}{\partial y^2}$$

  - **NB How to define/determine *K*?**
- Simple "assimilation"?
  - Newtonian relaxation of SGCM towards *observed* $\overline{T}(y,z)$

Venus: diurnal effects



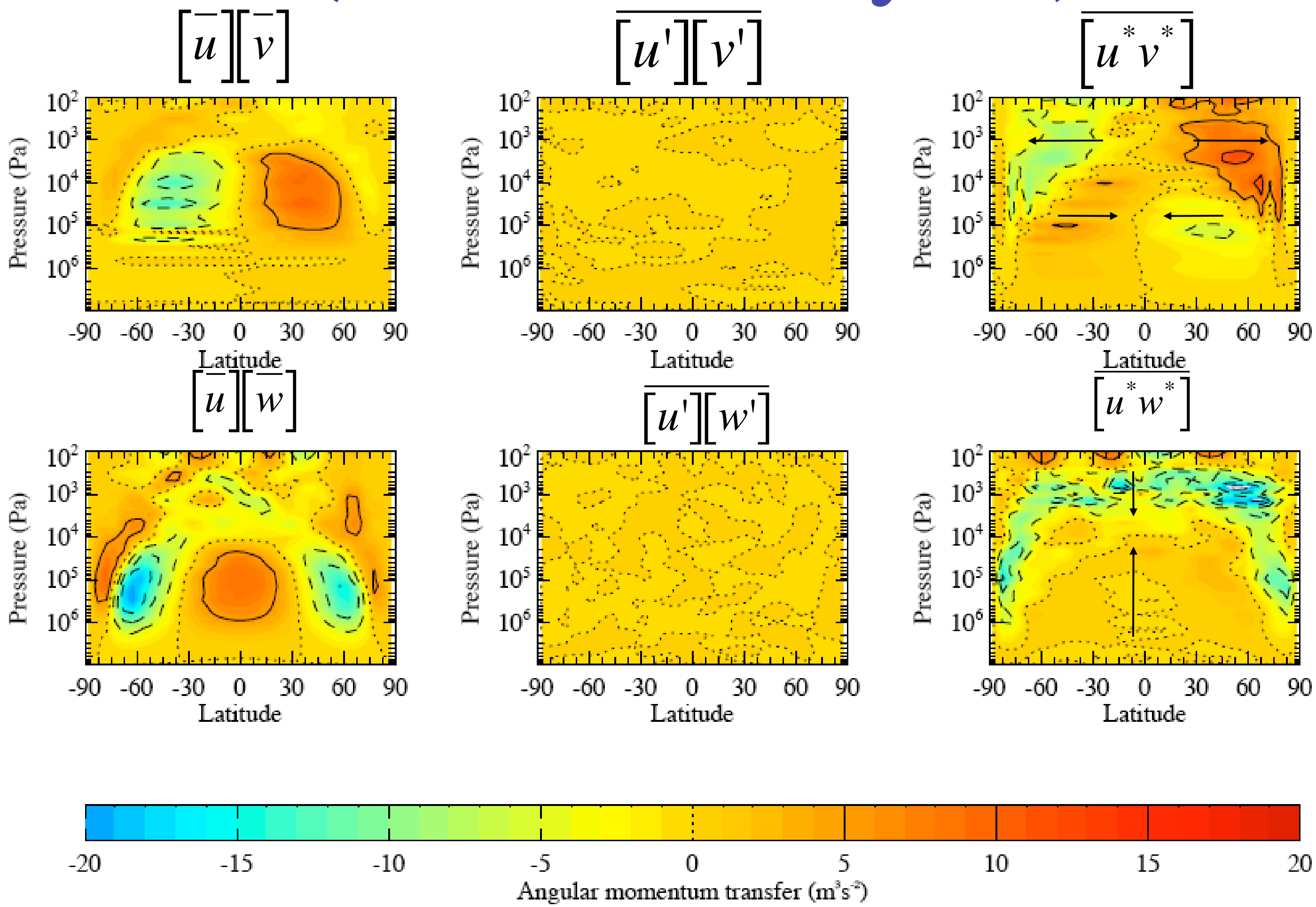
- Simple diurnal tidal forcing
- Sinusoidal form in lat and longitude
  - Positive only!
- Vertical distribution concentrated near cloud layers
  - Cf main diabatic heating/cooling



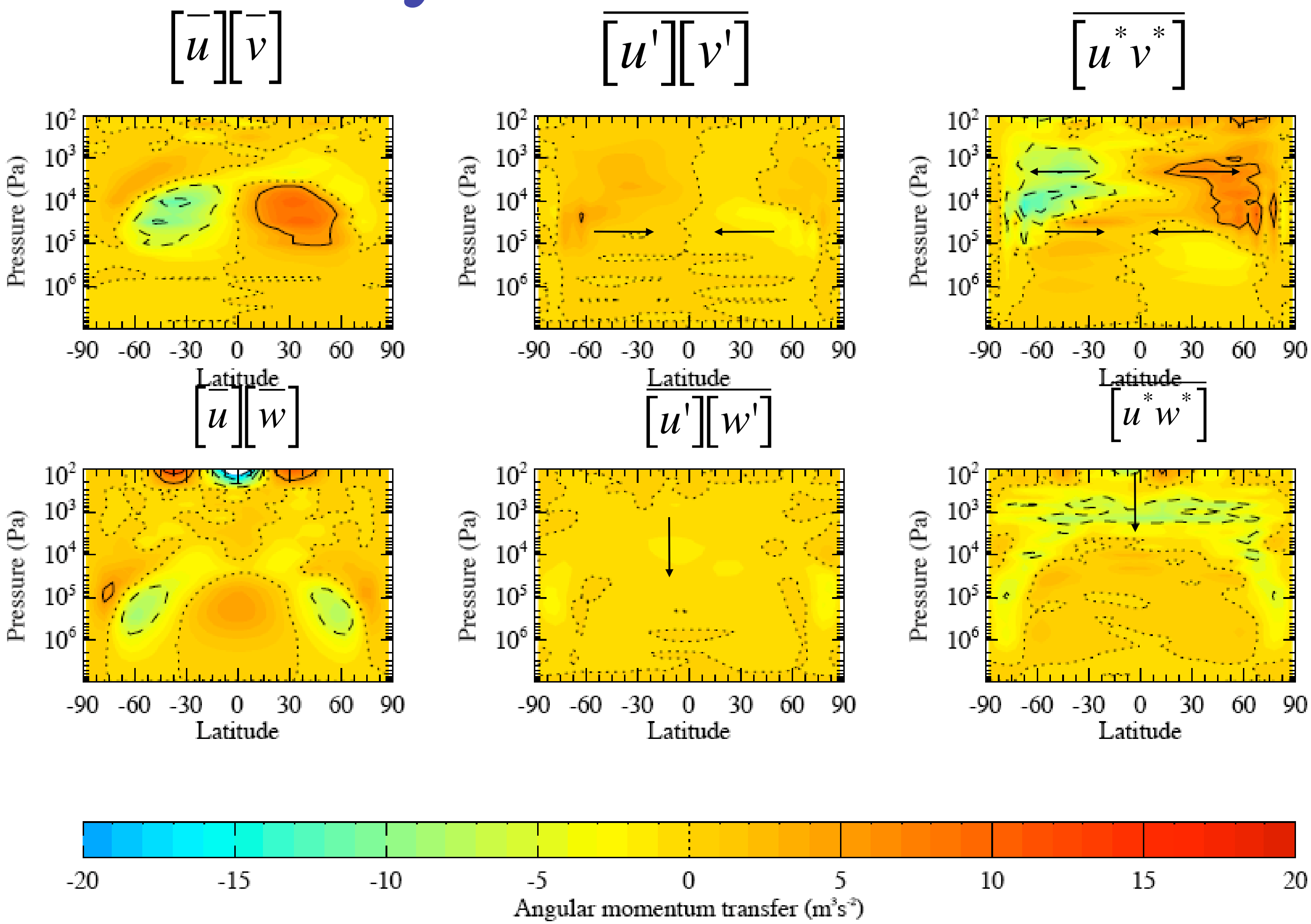
Venus: global circulation+

- Venus planetary parameters
  - Slow (retrograde) planetary rotation
  - Now with realistic topography
- ~Realistic super-rotation (~0.5 that of Venus itself!)
- Overall circulation not greatly affected by topography….?

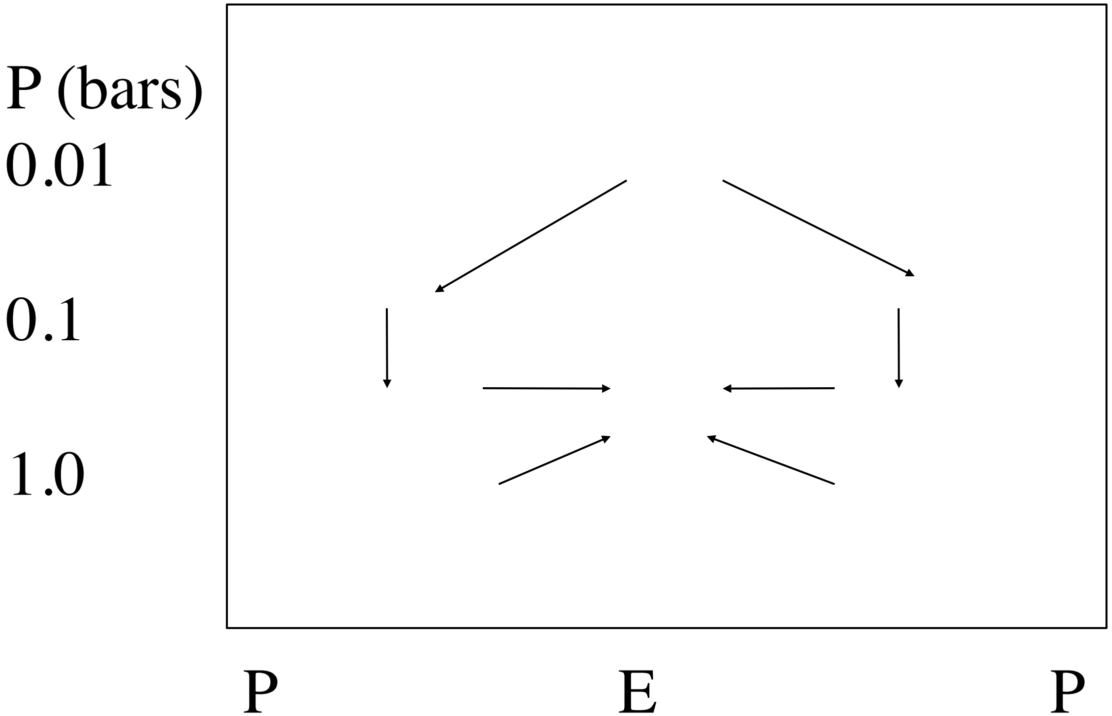
Momentum transports (no diurnal cycle)



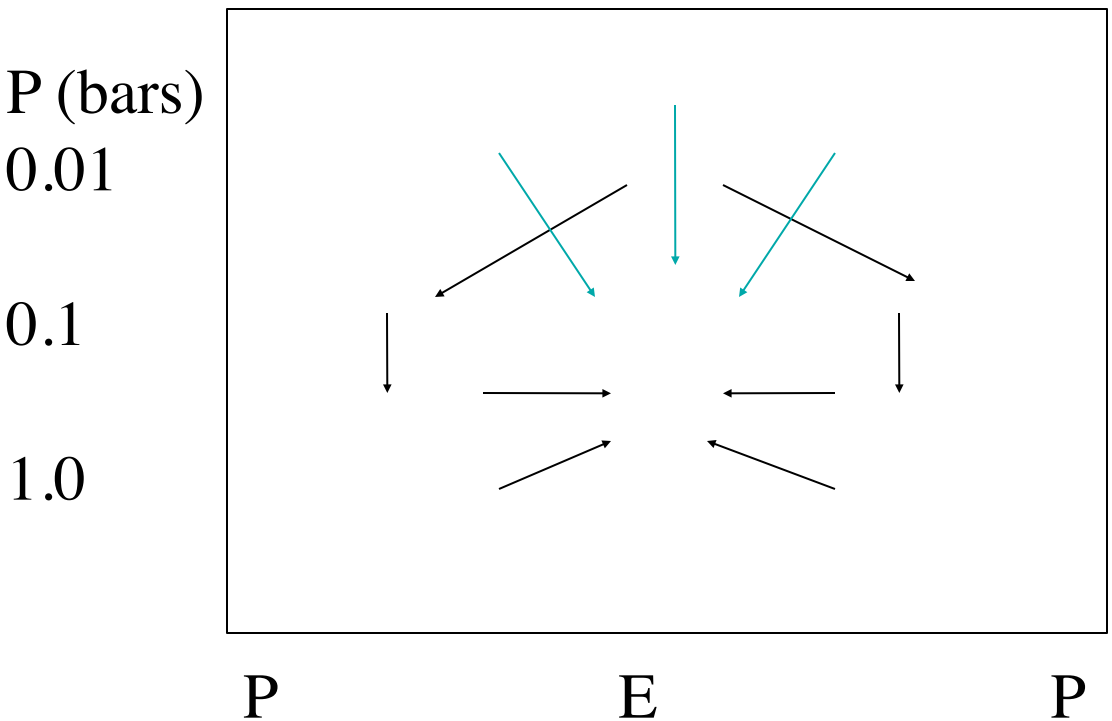
Momentum transports (+diurnal cycle: solar-fixed coords)



Schematic momentum transport (no diurnal cycle)



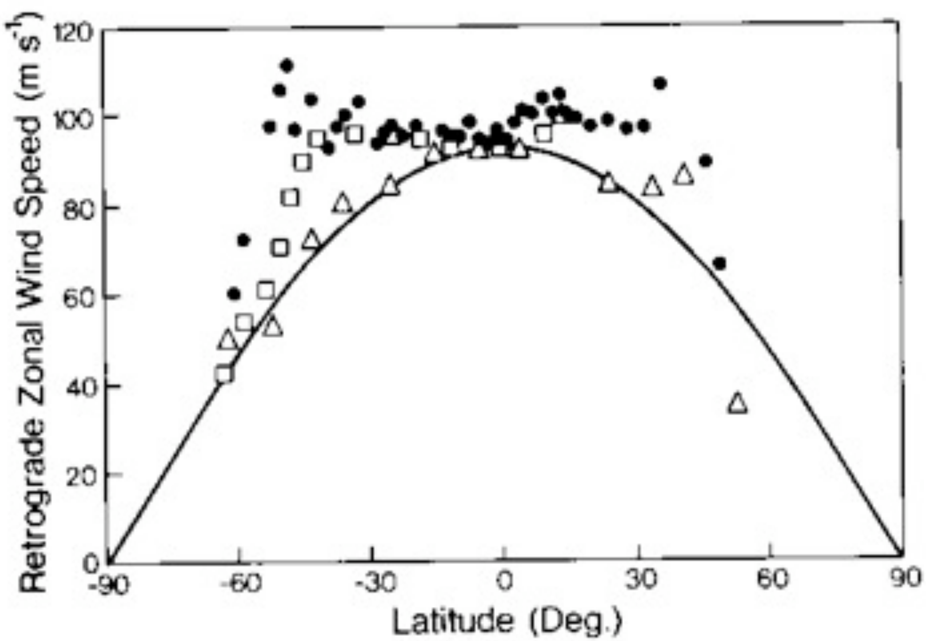
Schematic momentum transport (+ diurnal cycle)

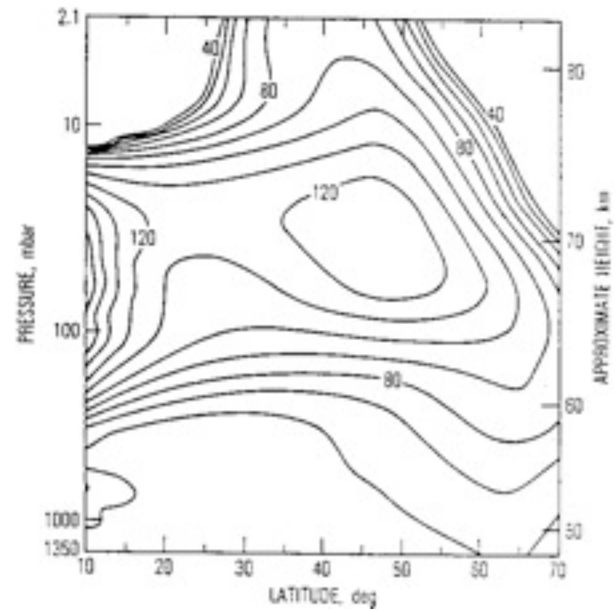


Conclusions

- SGCM simulations under Venus-like conditions produces large super-rotation
  - Barotropic instability of mid-latitude jets
  - Momentum transports consistent with Gierasch-Rossow-Williams mechanism
  - Diurnal cycle/tides reinforce GRW super-rotation?
- Cloud features dominated by passive transport of H_2SO_4 aerosol
  - Possible transport barrier at ~60^o polewards of jet core
- Radiative transfer scheme under development
  - Similarities to LMD IR scheme but some differences?
- Interactions with VEx observers to evaluate dynamical

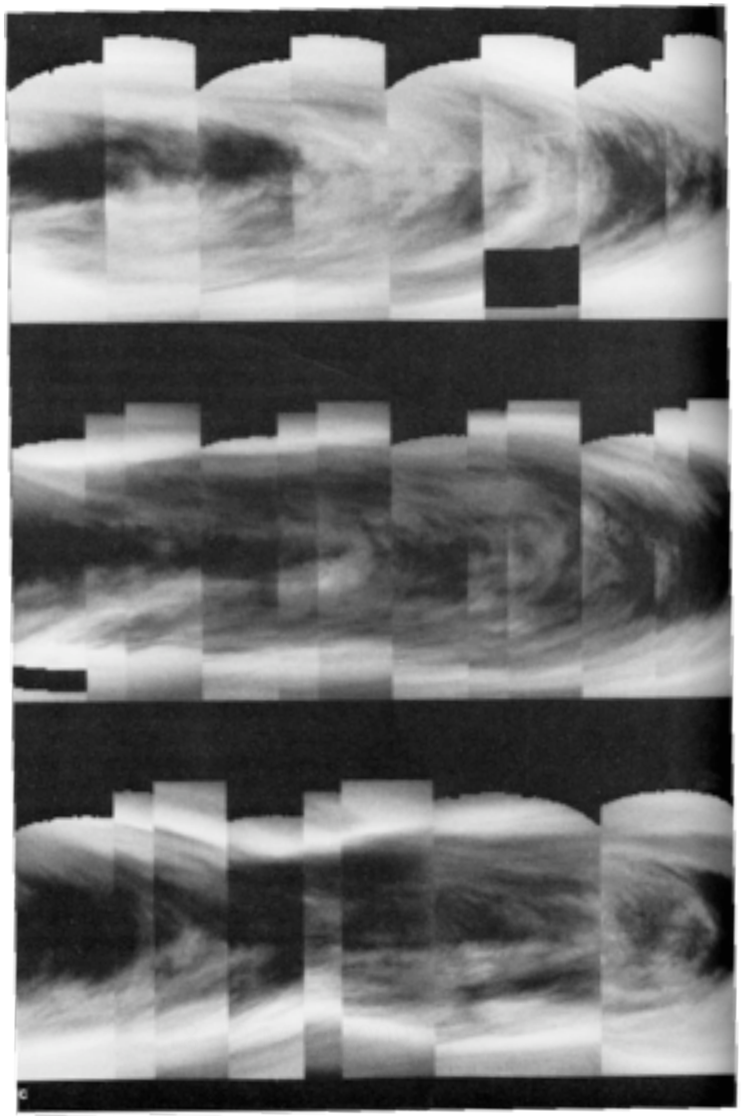
Venus atmospheric super-rotation



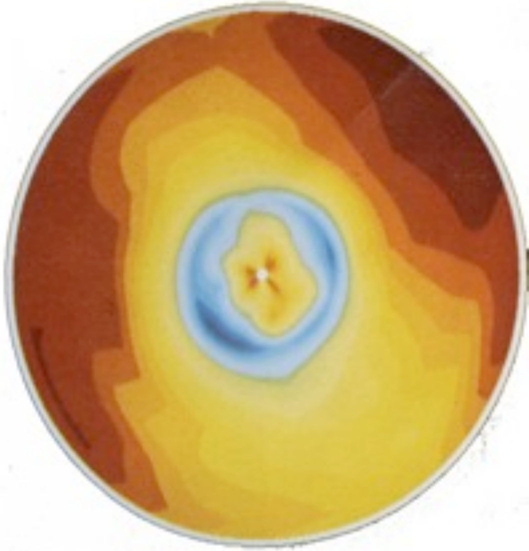


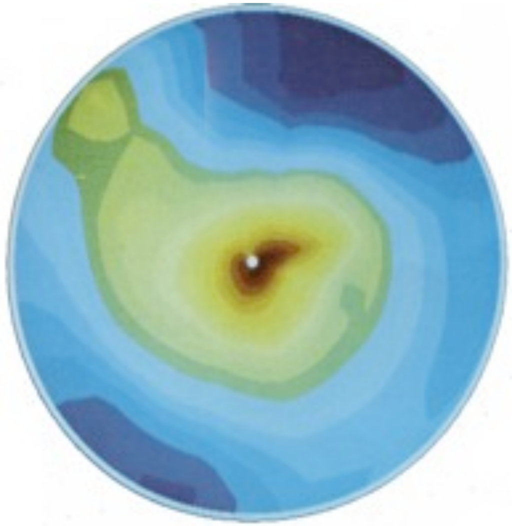
- Cloud-tracked winds show velocities ~100 m s^{-1}
  - Rotation period ~ 4 days, cf surface period of 240 days
- Cyclostrophic thermal winds -> mid-latitude jets above clouds

Venus - clouds & waves

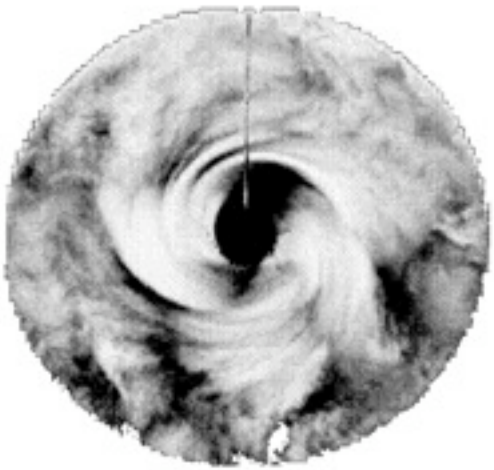


Pioneer Venus IR polar maps





Mariner 10 Polar clouds



Super-rotation: Gierasch conceptual model (1975)

P E P

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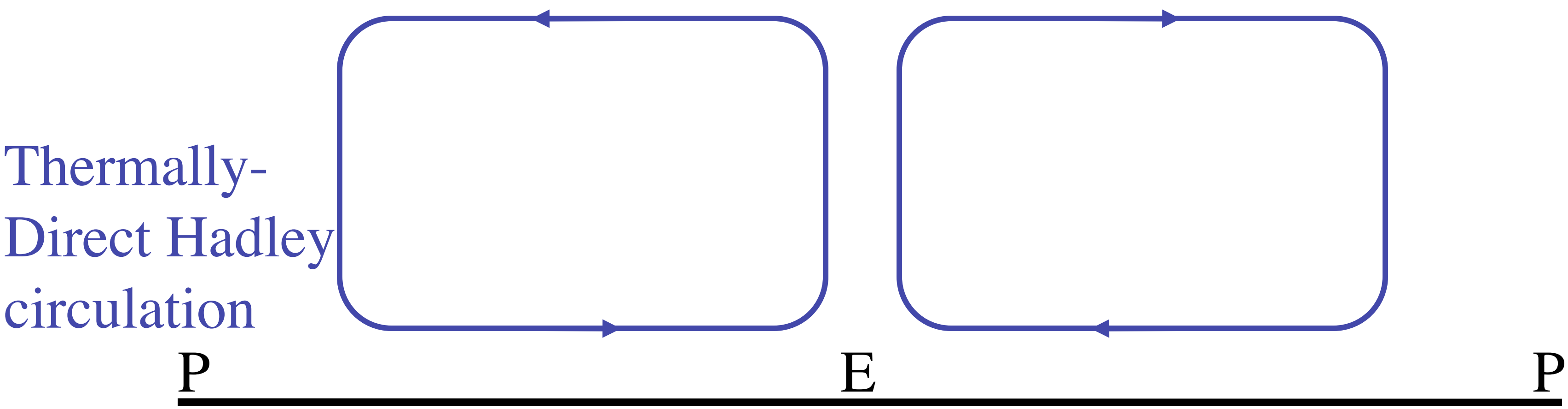

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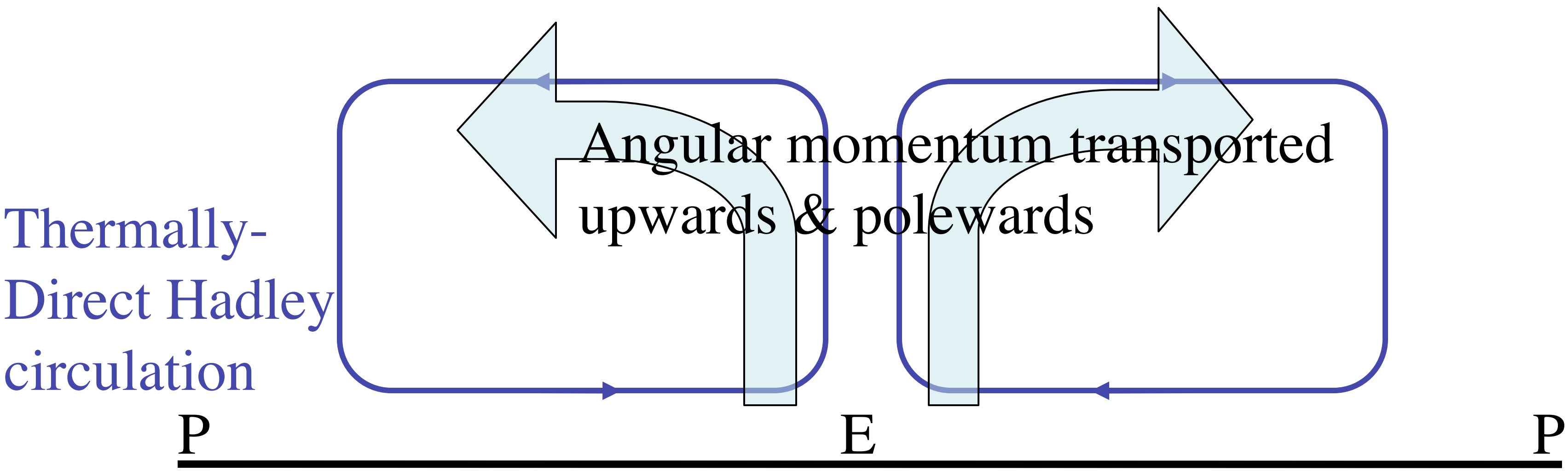

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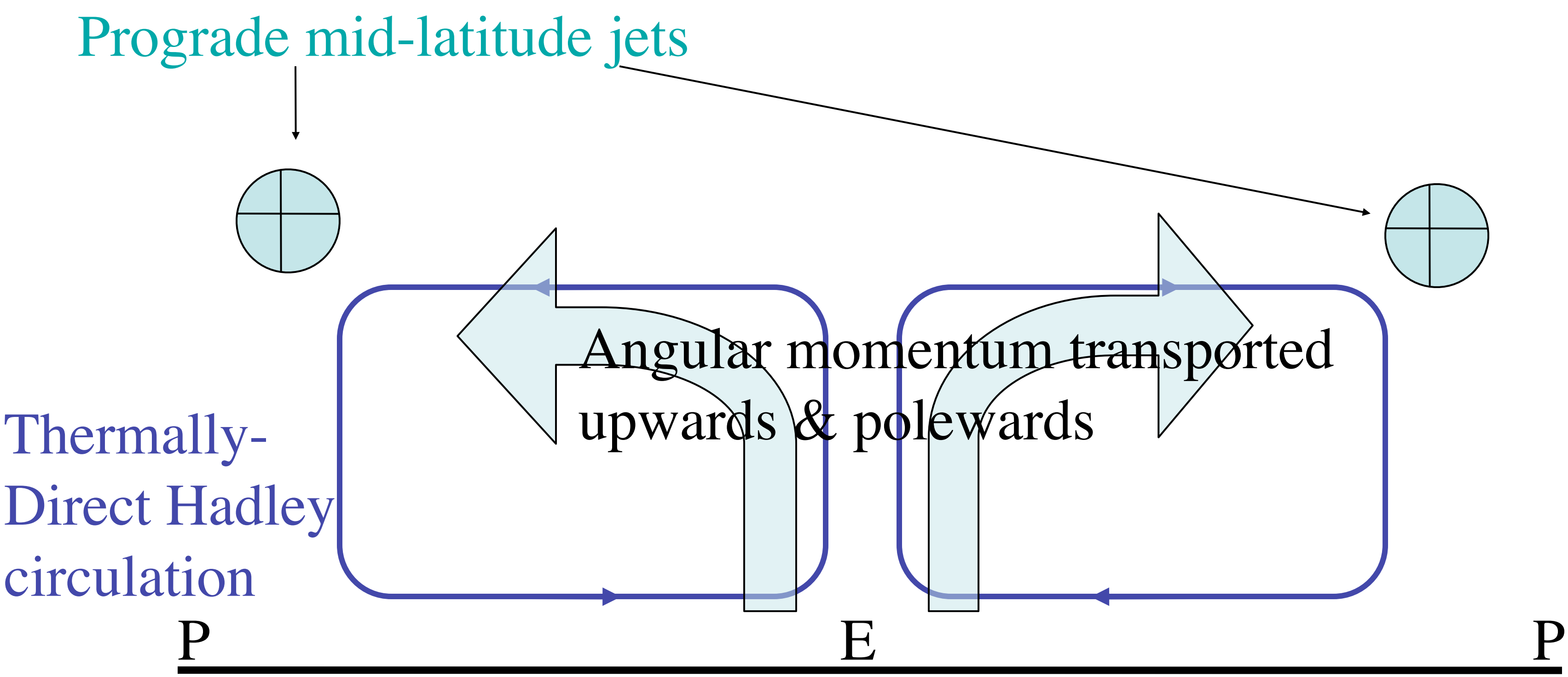

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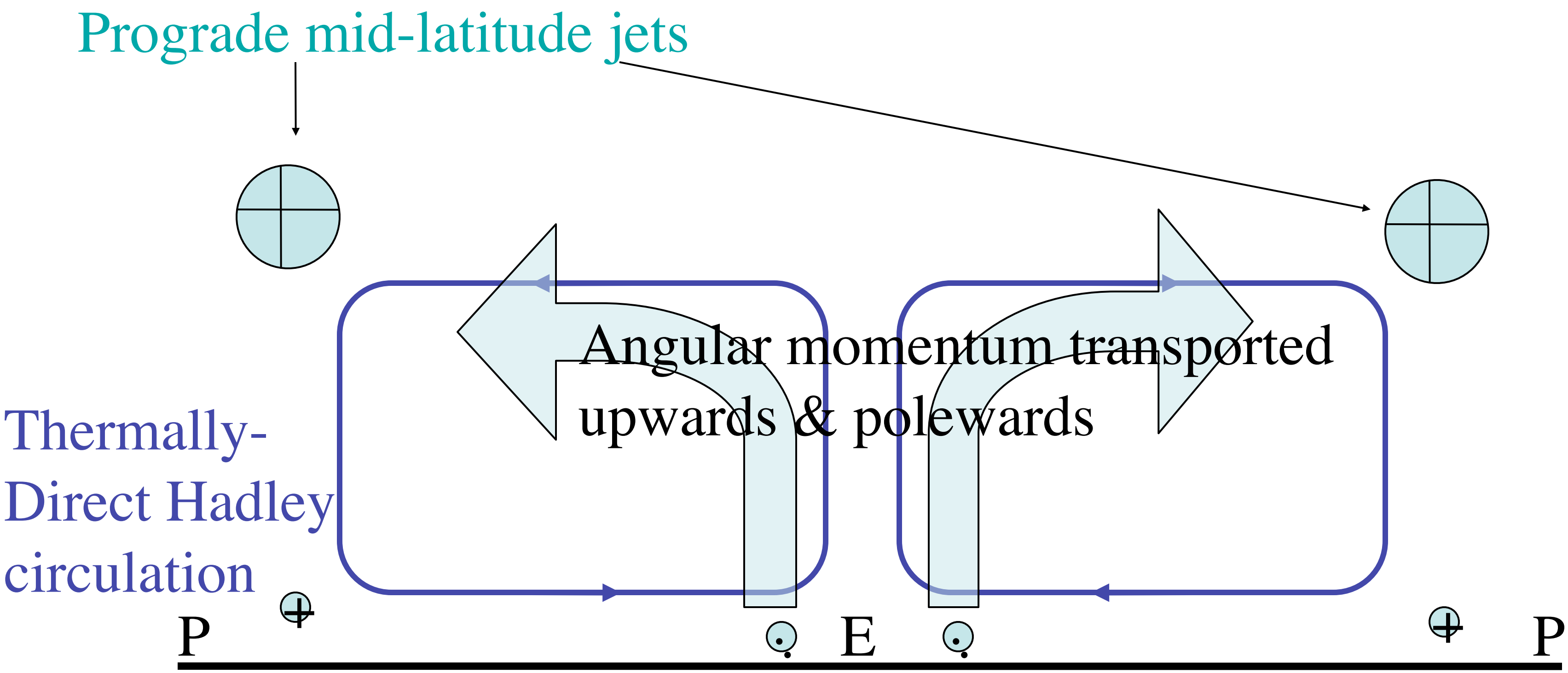

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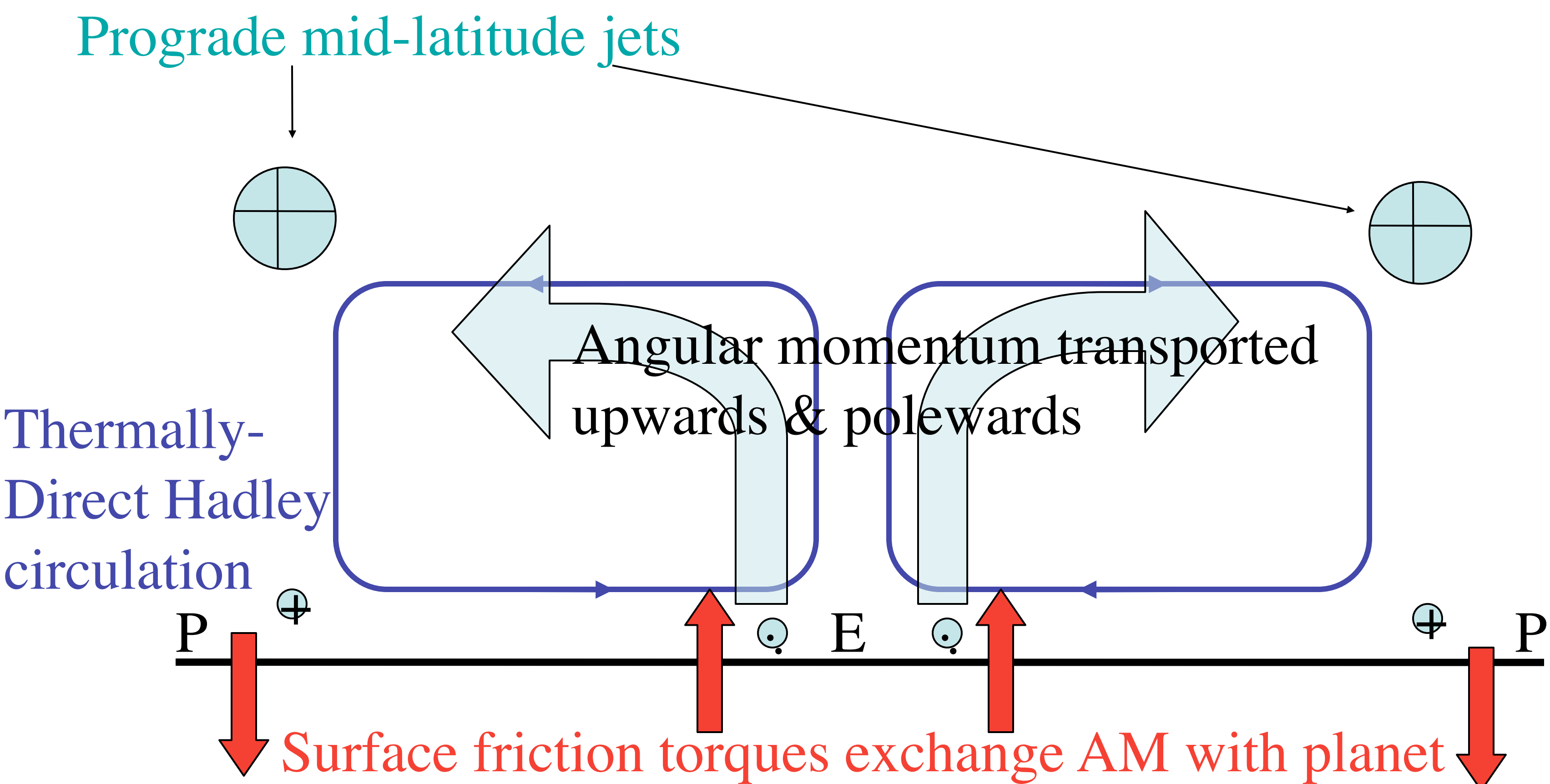

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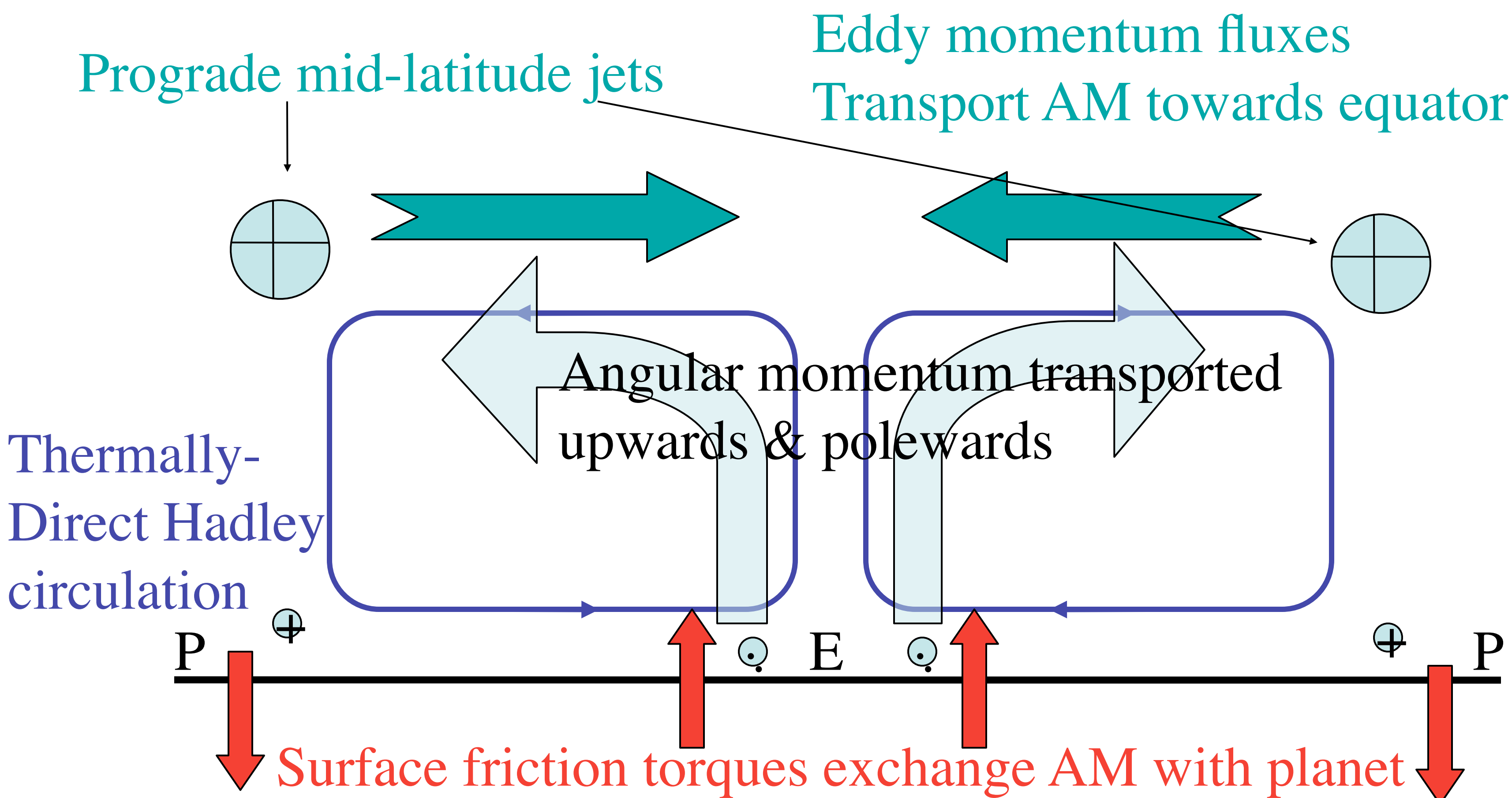
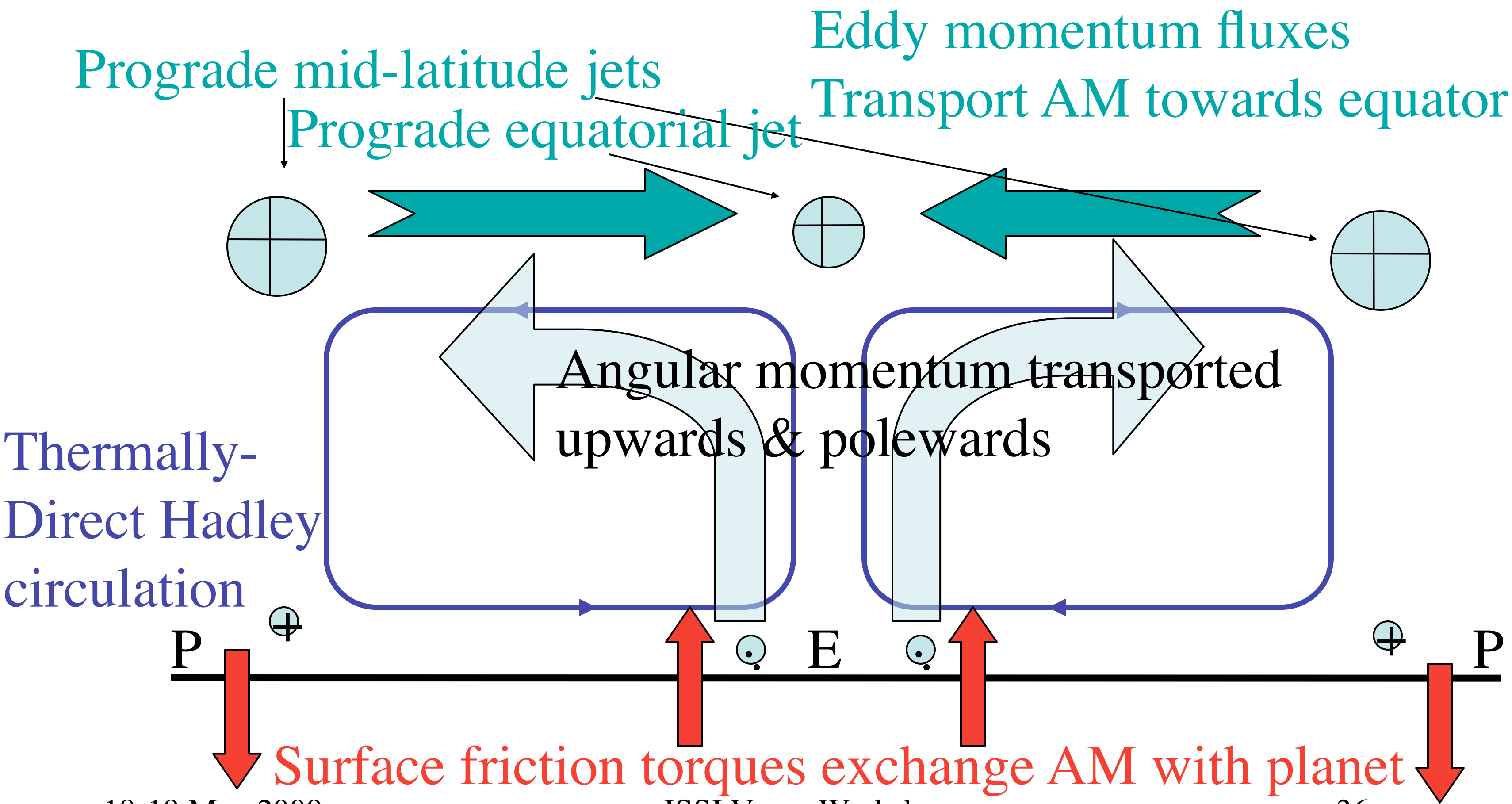


Super-rotation: Gierasch conceptual model (1975)



Super-rotation: an alternative to Gierasch (1975) cf Earth's QBO?

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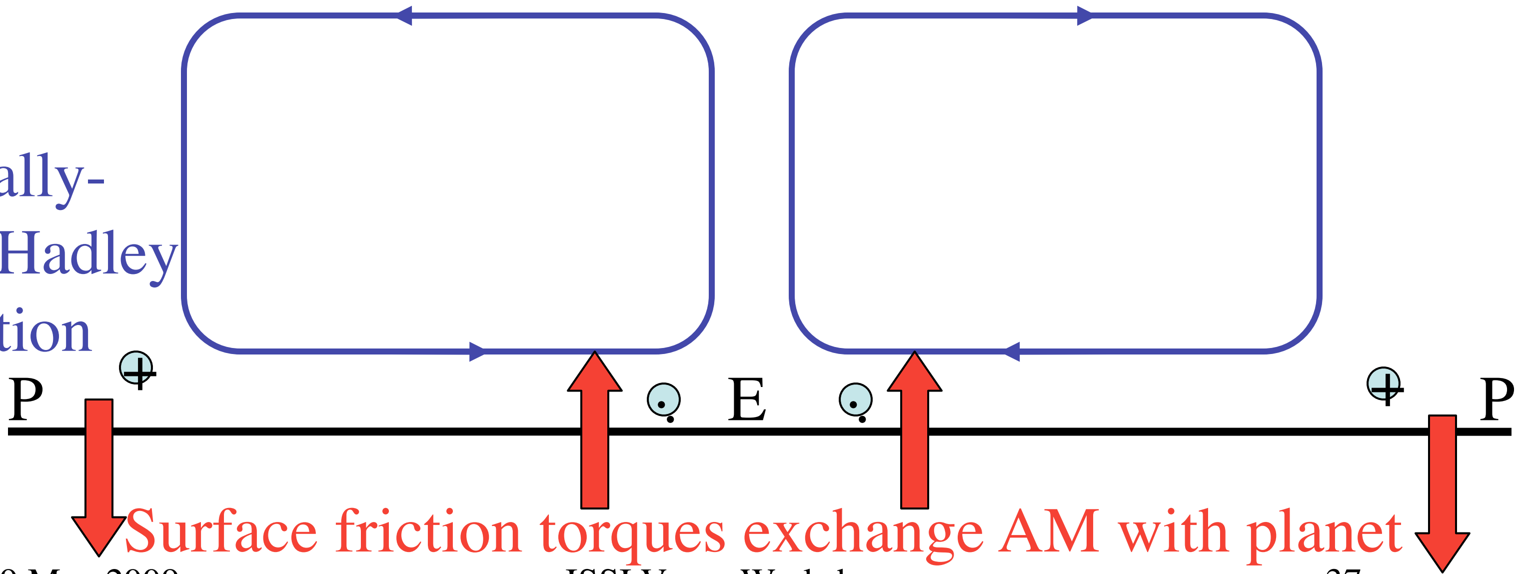
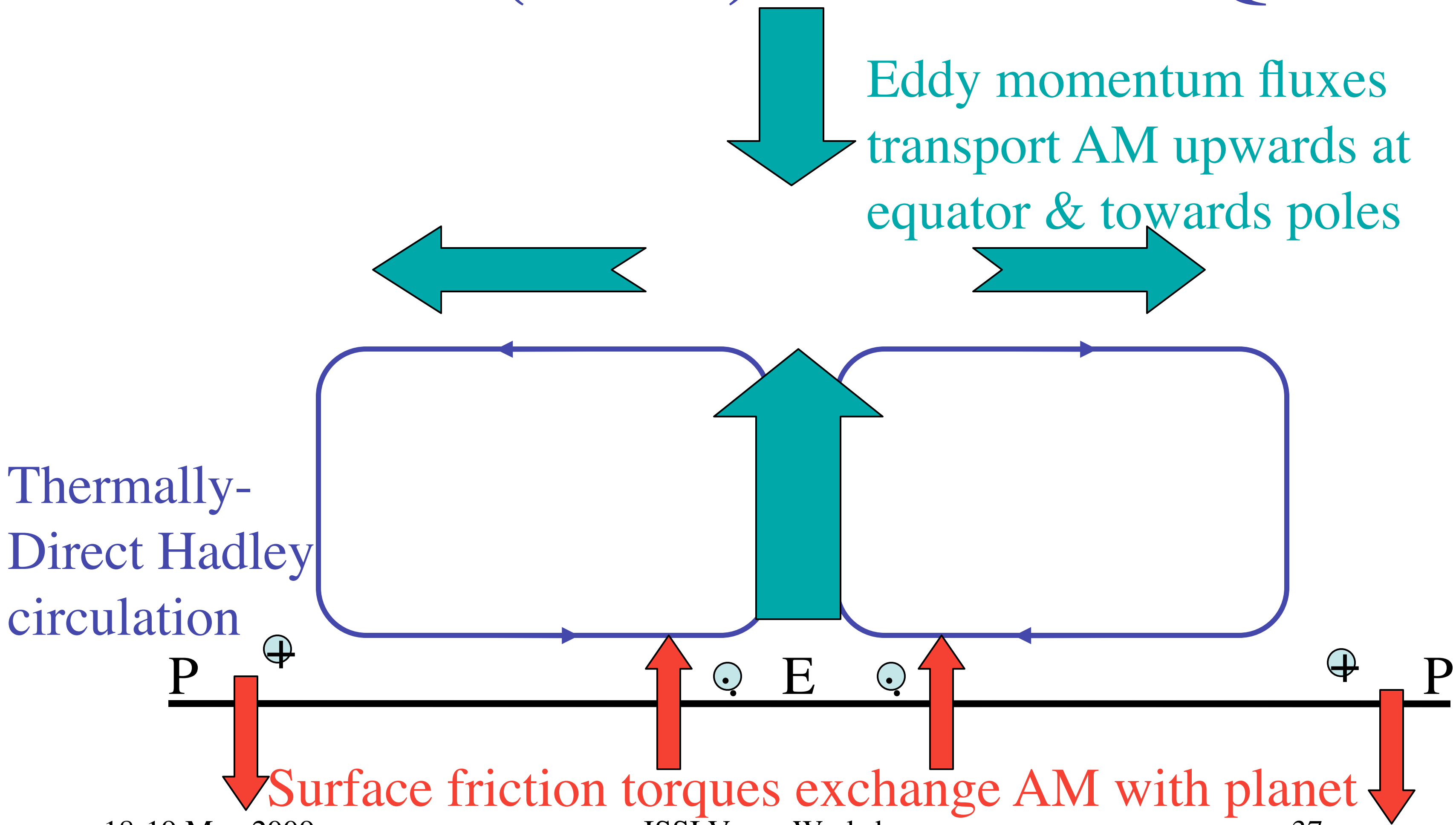
Thermally-Direct Hadley circulation



Surface friction torques exchange AM with planet

Super-rotation: an alternative to Gierasch (1975) cf Earth's QBO?



Super-rotation: an alternative to Gierasch (1975) cf Earth's QBO?