

Producing and Understanding the
Super-rotation in a Simple
Numerical Model of Venus.

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Outline

- Model Description
 - Newtonian cooling and linear friction schemes
- Results and Analysis
 - Zonal mean state
 - Waves
 - Super-rotation and Eliassen-Palm fluxes
- Summary & Conclusions

Model Outline

- Based on the UKMO Unified Model (Earth AGCM),
- $5^{\circ} \times 5^{\circ}$ horizontal resolution, 3km vertical resolution (0-90km),
- Flat topography, no diurnal cycle, no active clouds, no radiation .
- Arakawa B grid, η (hybrid) vertical levels
- Horizontal diffusion (no vertical diffusion),
- Linearized cooling and friction,
- diurnal cycle and topography experiments have been run.

Linearized Friction

- Rayleigh friction on horizontal wind fields on the lowest layer.

- $$\frac{d\vec{u}}{dt} = -\frac{\vec{u}}{\tau}$$
$$\vec{u} = (u, v)$$
$$\tau = 32 \text{ days}$$

Linearized Cooling

- Newtonian cooling on full temperature field

$$\frac{dT}{dt} = -\frac{T - T_0}{\tau_N}$$

$$T_0 = \bar{T}(Z) + T'(Z) * \cos(\phi)$$

$$\tau_N = 25 \text{ days}$$

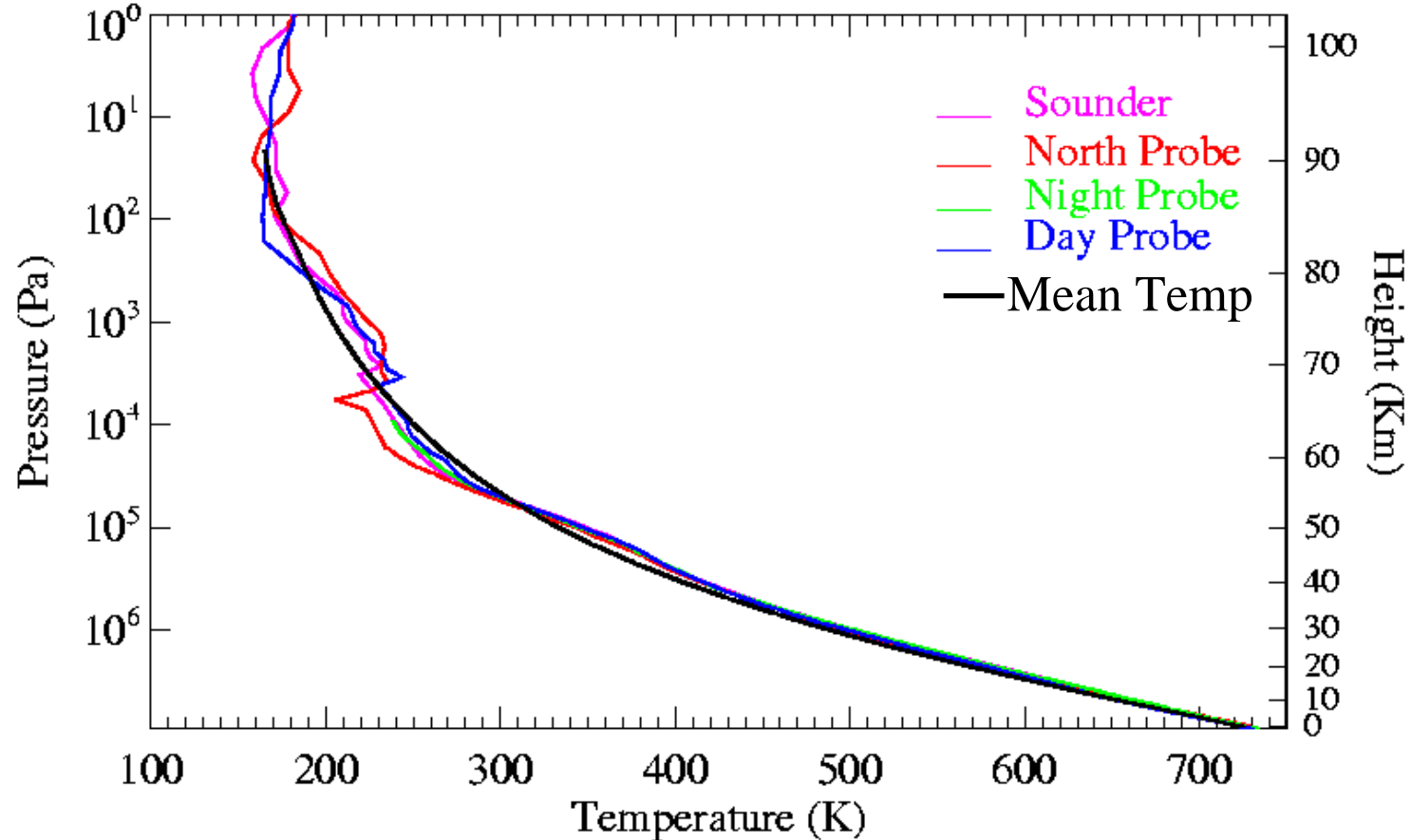
Global Mean

Latitudinal
dependence

$$T_0 = \bar{T}(Z) + T'(Z) * \cos(\phi)$$

Linearized Cooling

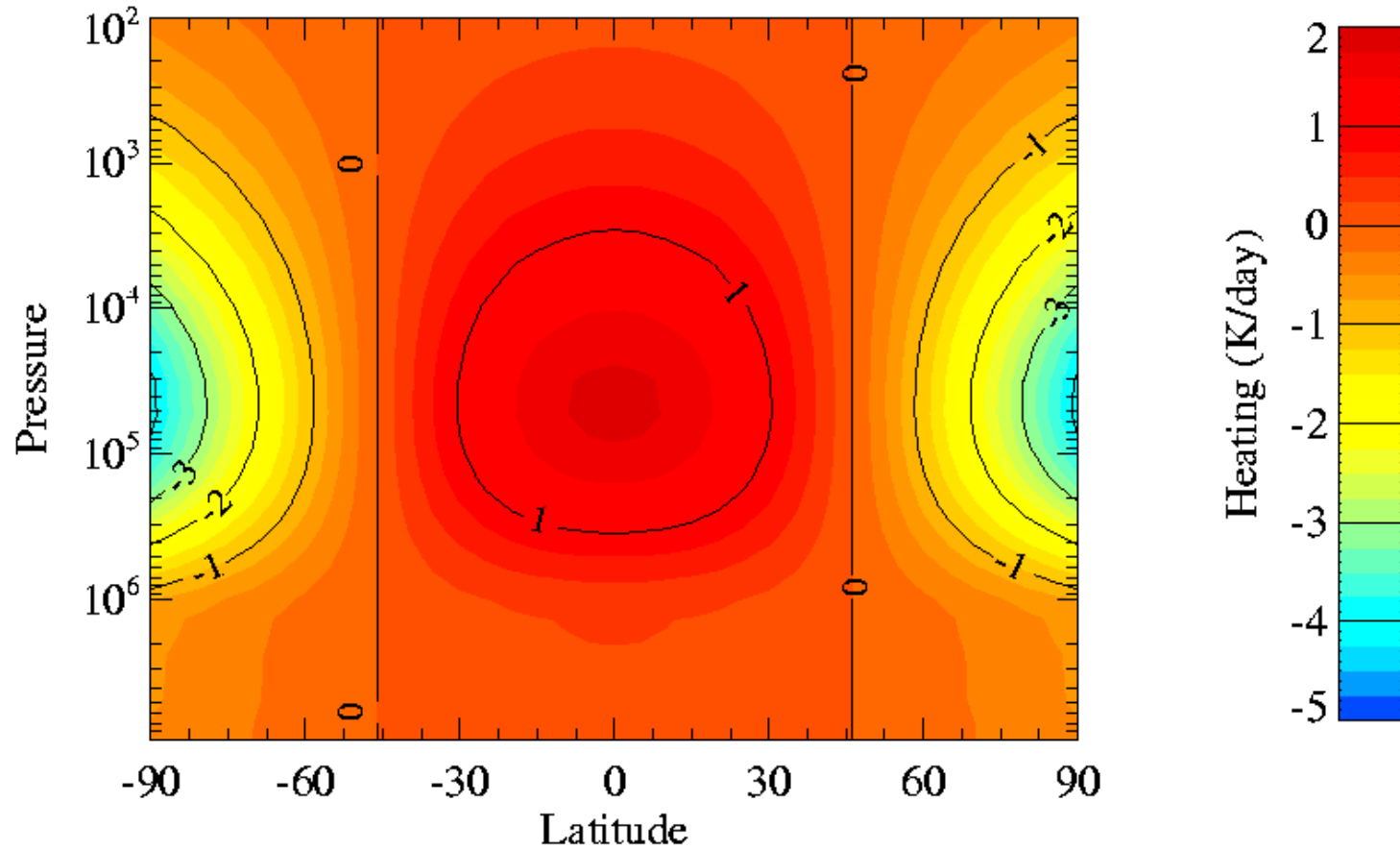
Global Mean



$$T_0 = \bar{T}(Z) + T'(Z) * \cos(\phi)$$

Linearized Cooling

Latitudinal dependence



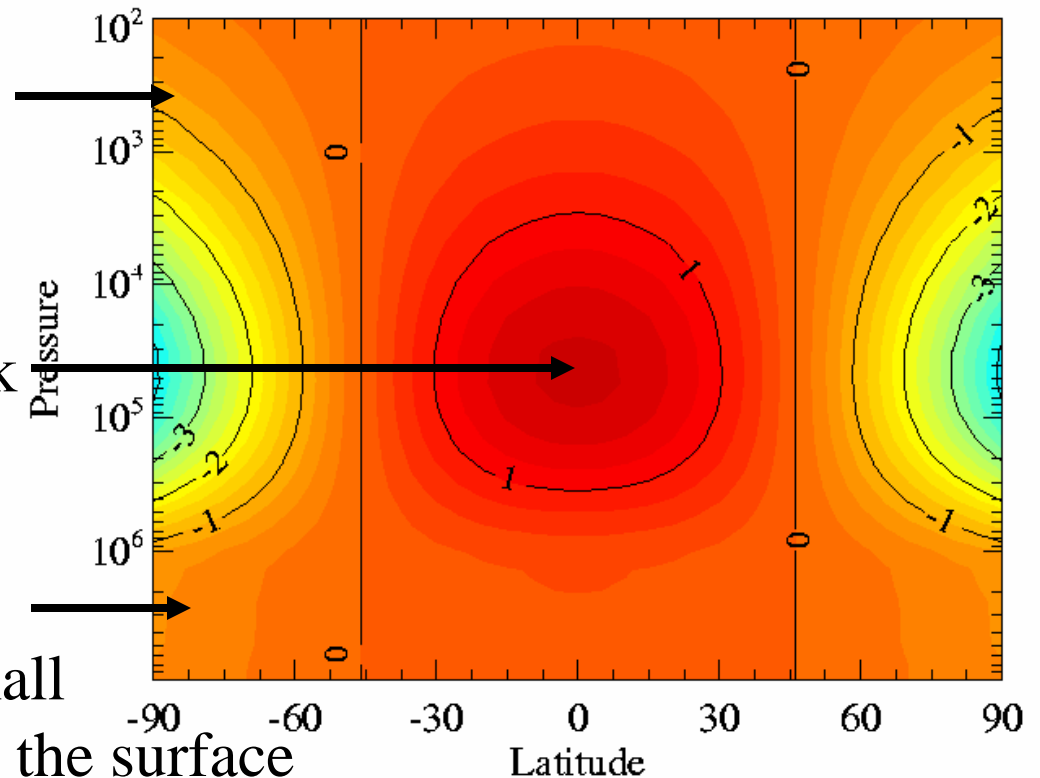
$$T_0 = \bar{T}(Z) + T'(Z) * \cos(\phi)$$

Linearized Cooling

Small gradient in the upper atmosphere because of the thinning atmosphere

Peak heating in the cloud deck

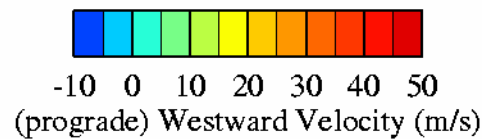
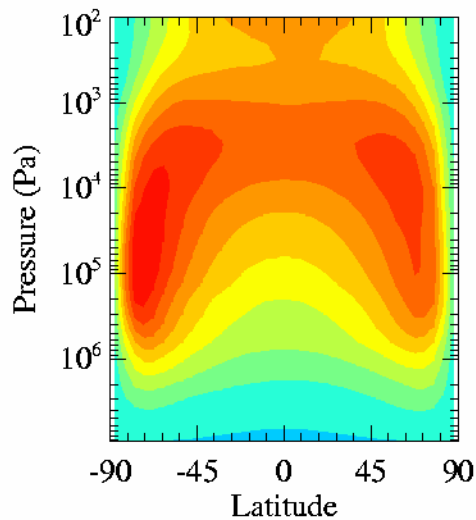
Small gradient in the lower atmosphere because of the small amount of insolation reaching the surface



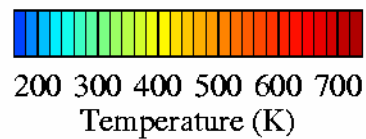
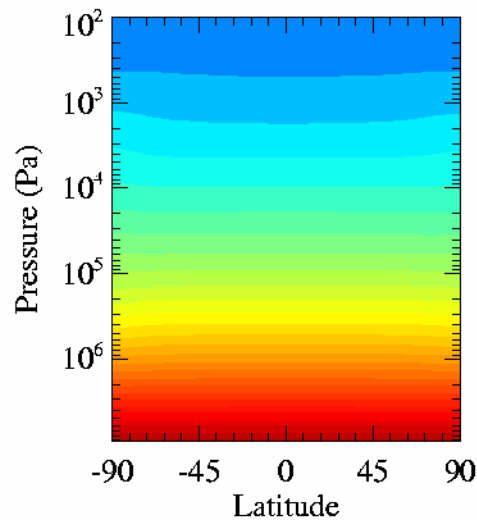
Results

- Zonal Mean State (u,v,T)
- Polar Temperature structure (Northern Hemisphere)
- Waves in the atmosphere (Kelvin, MRG)
- Super-rotation mechanisms

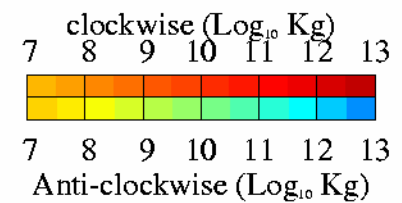
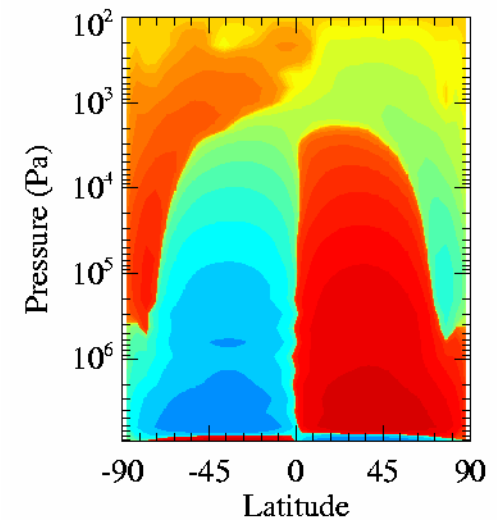
Zonal Mean Atmospheric State



U (m/s)

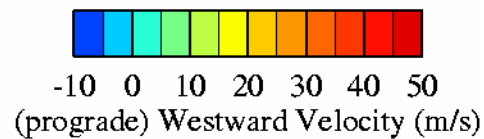
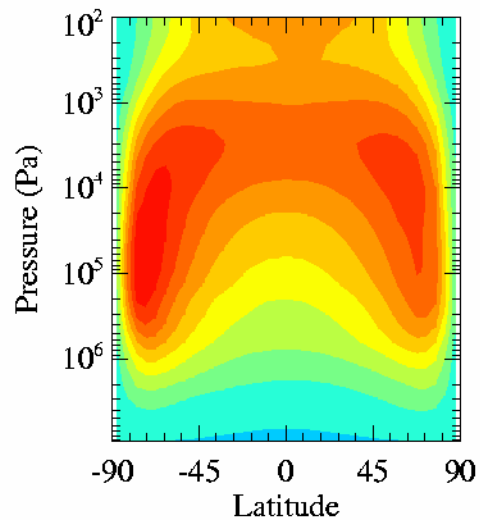


T (K)

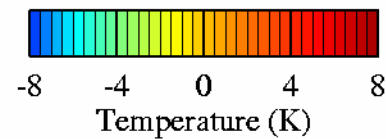
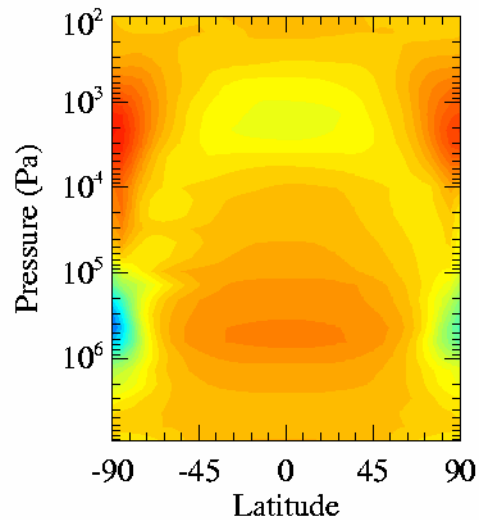


Mass circulation

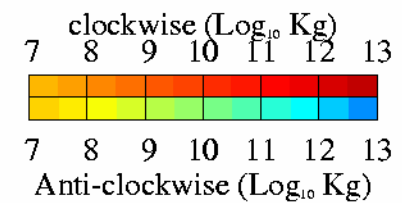
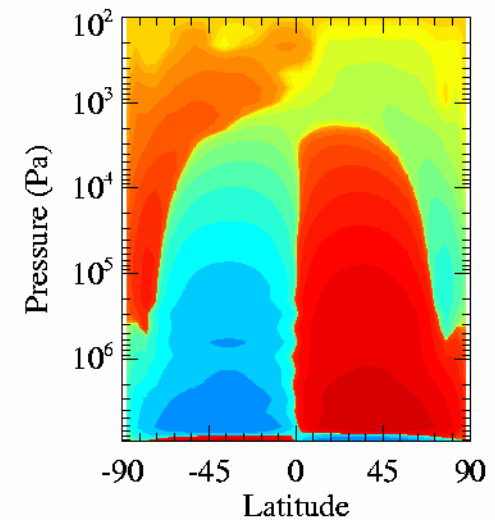
Zonal Mean Atmospheric State



U (m/s)

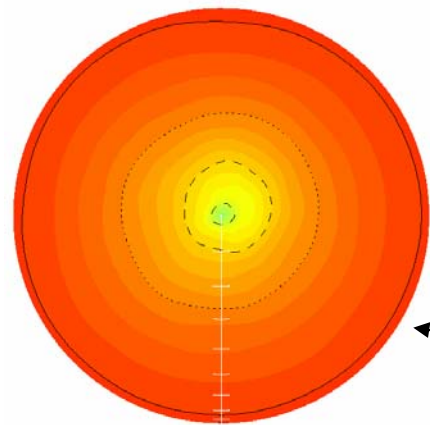


T'' (K)

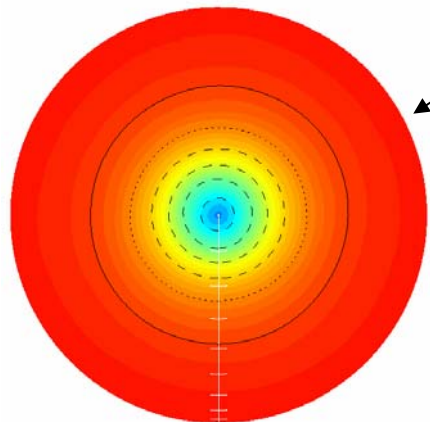


Mass circulation

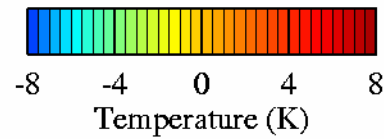
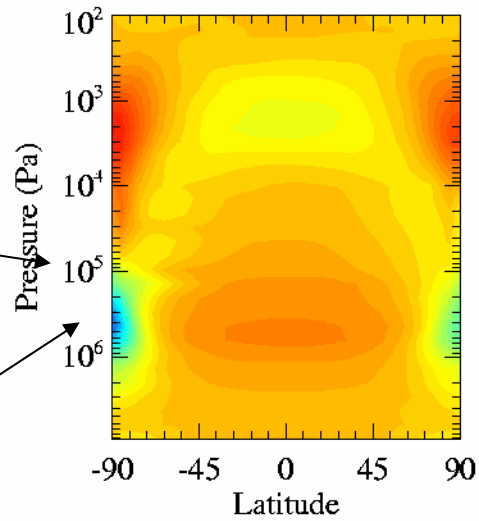
Polar Regions



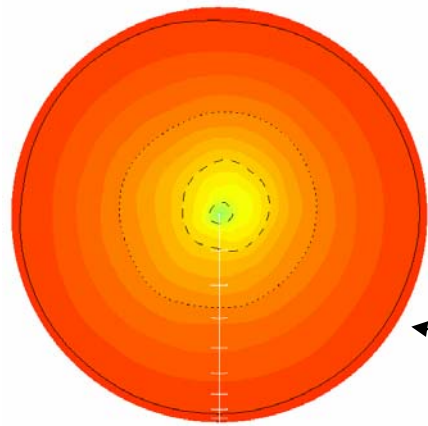
45km



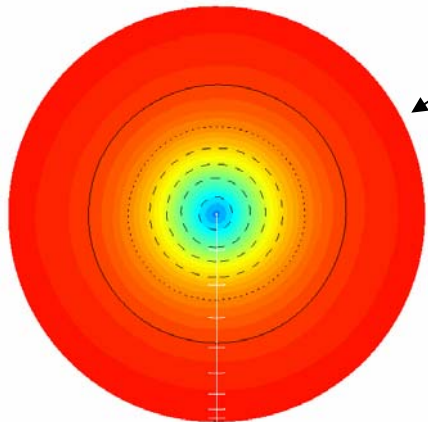
35km



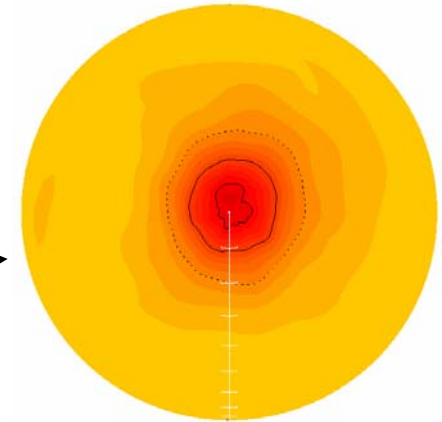
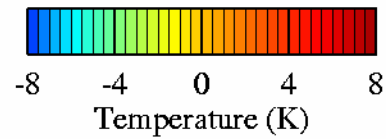
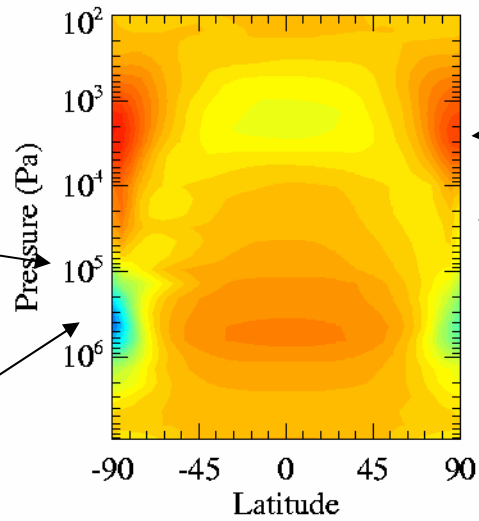
Polar Regions



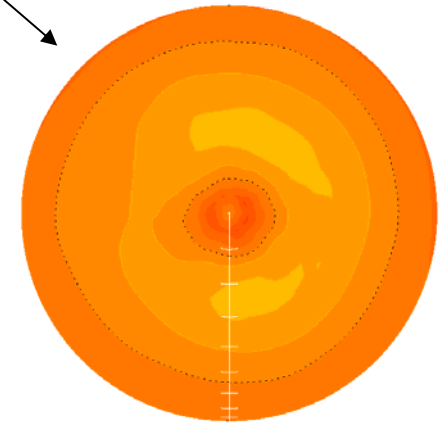
45km



35km



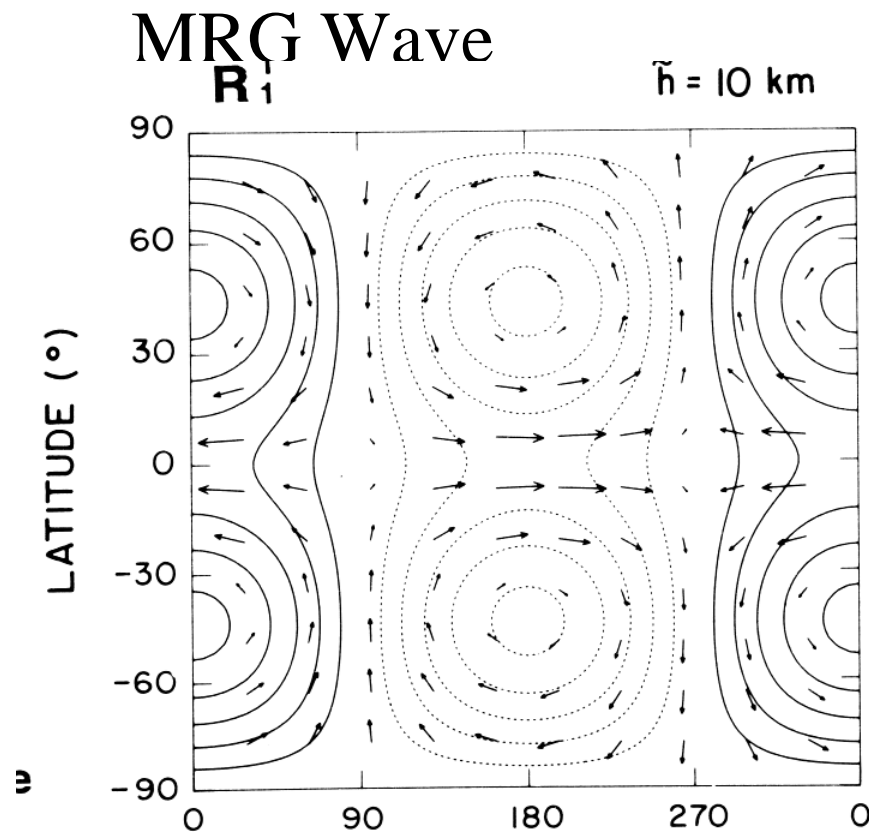
65km



55km

Oxford

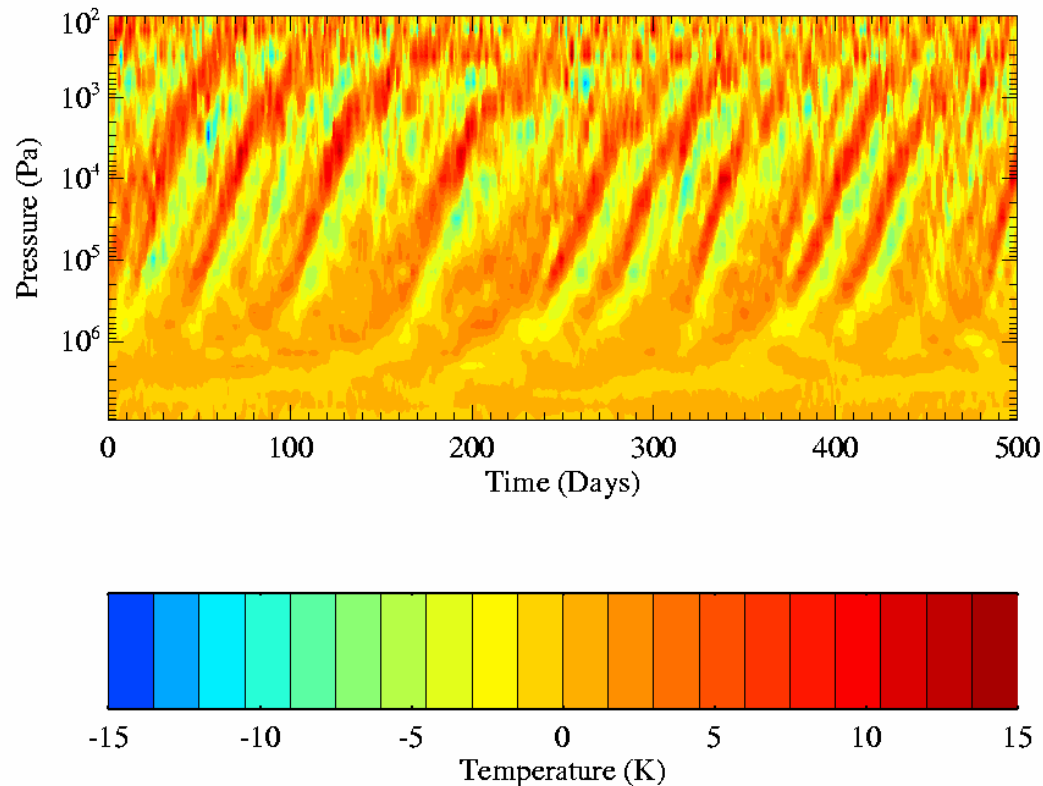
Principal Wave Modes in the Model Atmosphere



- Mid-latitude and Poles
- Slower than the mean flow (retrograde)
- Minimum amplitude at the equator

Mixed Rossby Gravity Wave

(in temperature)

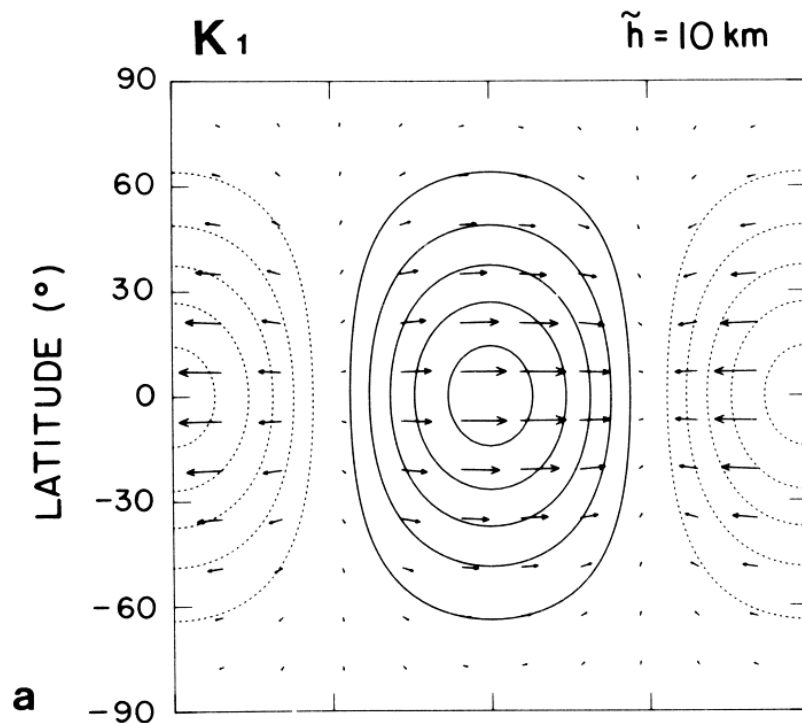


Period: 30 ± 2 days
Amp: 7K
(at 50kPa)

(Observed period
of 5-6 days at the
cloud decks)

Principal Wave Modes in the Model Atmosphere

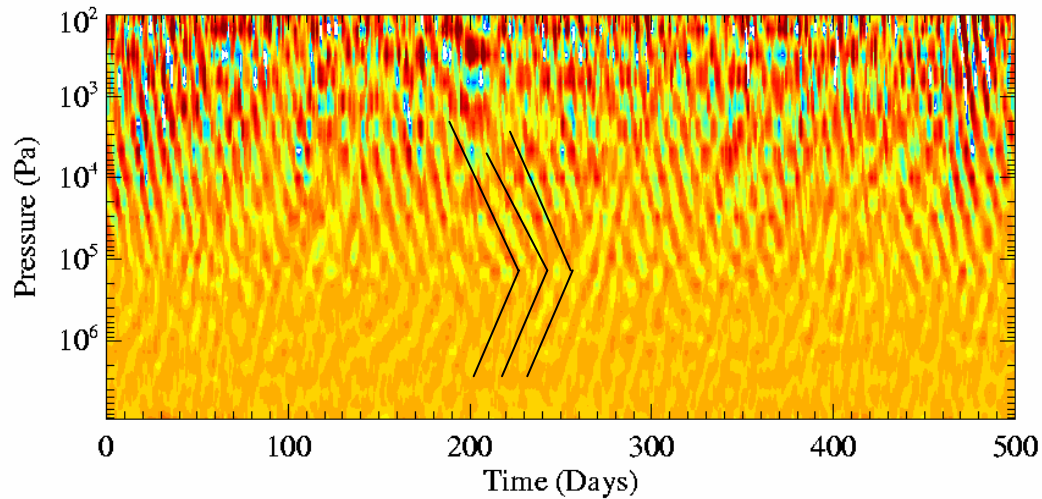
Kelvin Wave



- Maximum at the equator
- Faster than the mean flow
- No meridional winds at the equator

Kelvin Wave

(in temperature)

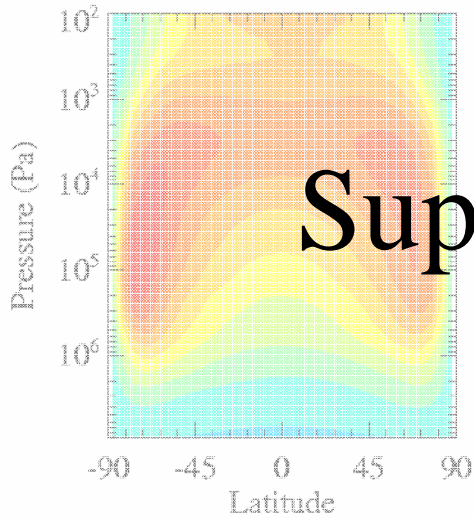


Period: 9.5 ± 0.5 days
Amp: 2K
(at 50kPa)

Propagating away
from peak forcing
at 100kPa

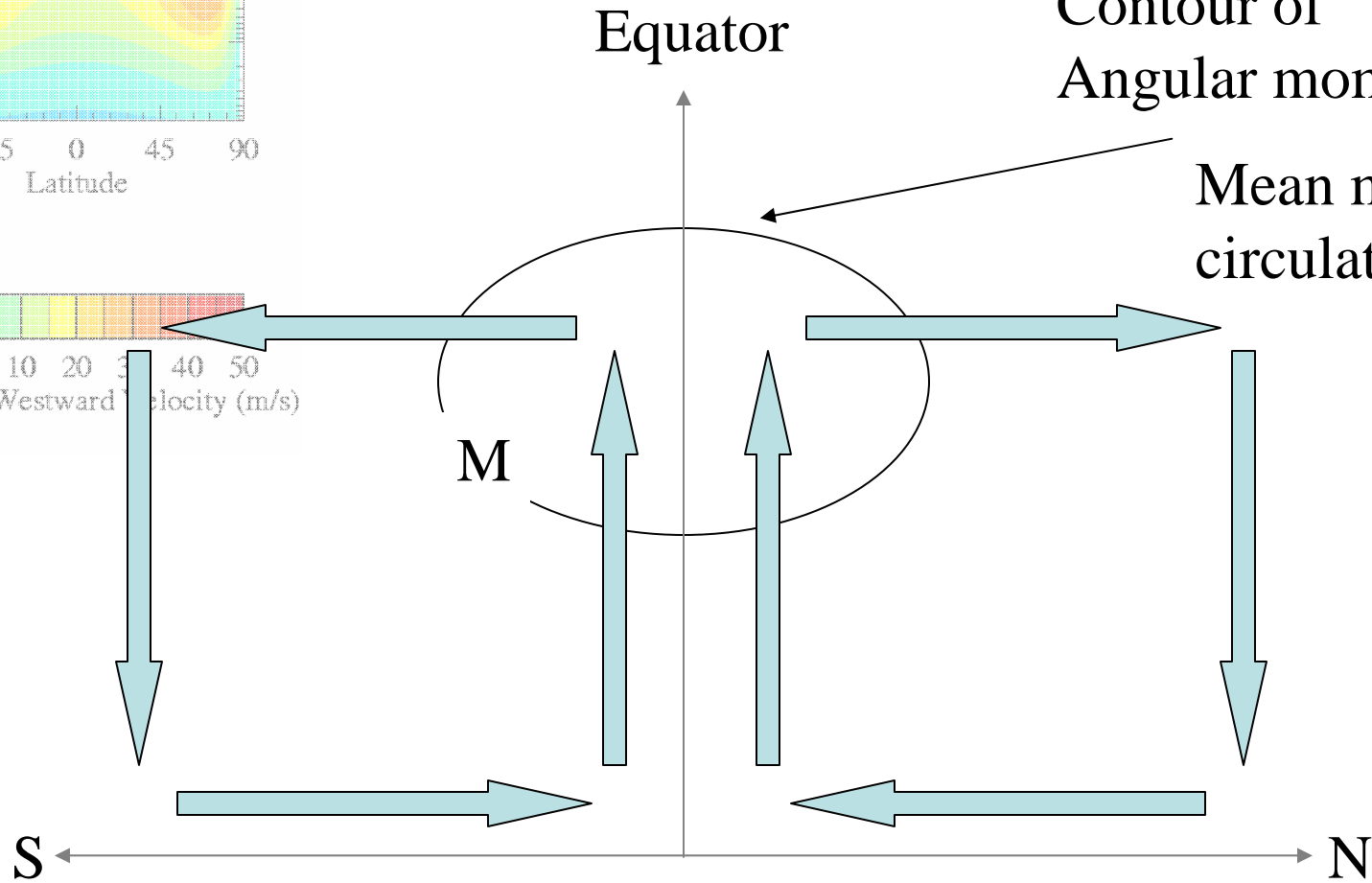
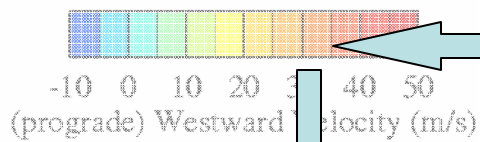
(Observed period
of 4-5 days at the
cloud decks)

Super-rotation Mechanisms

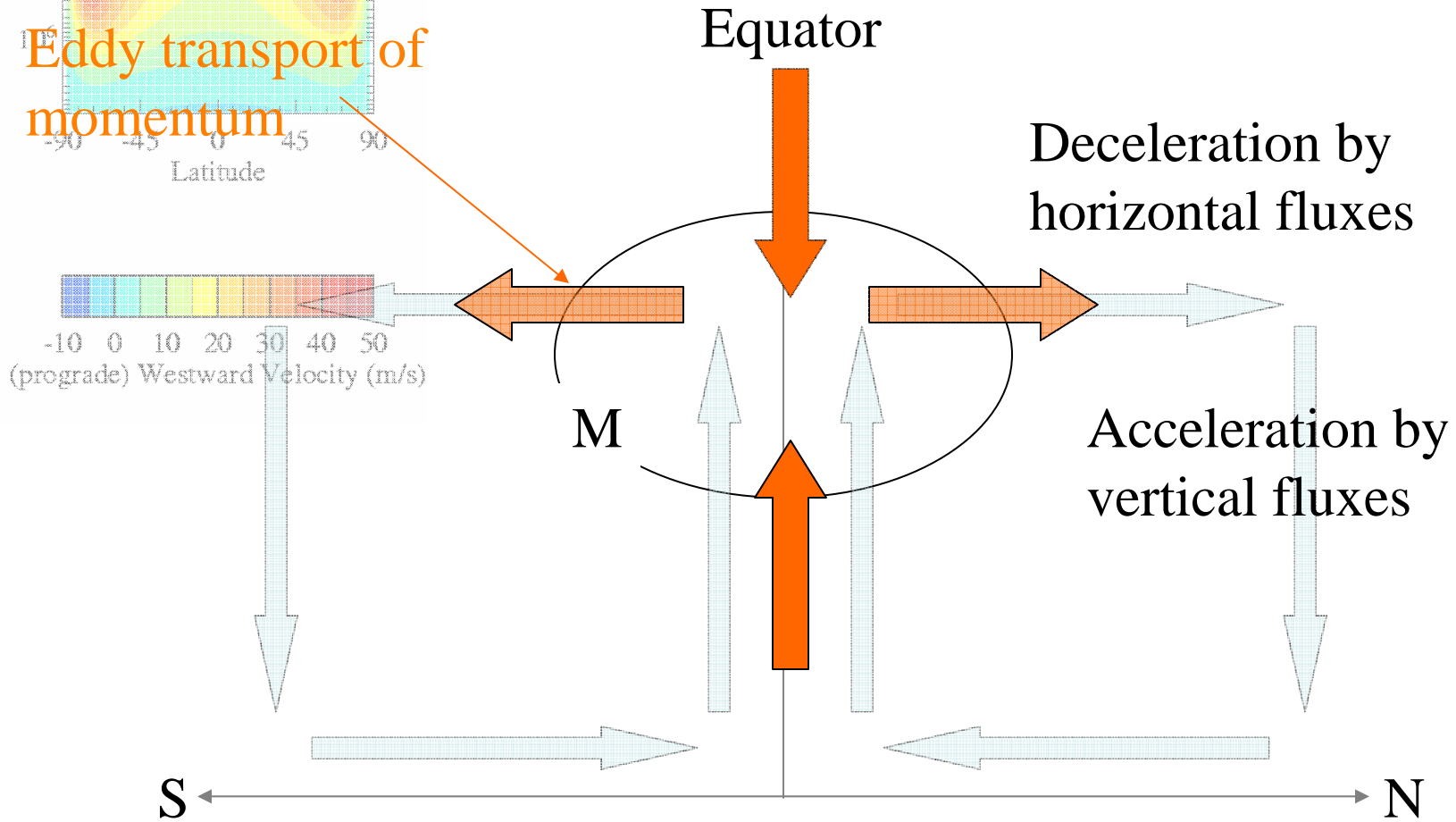
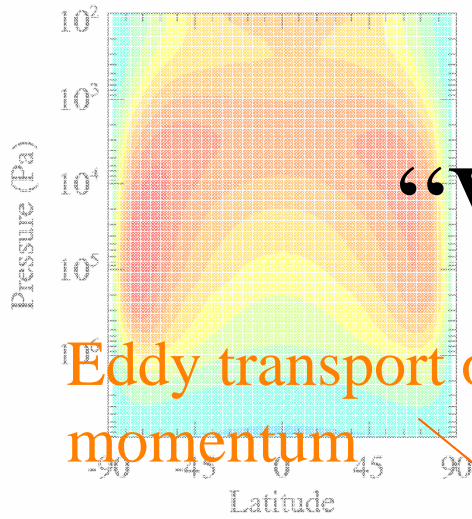


Contour of
Angular momentum

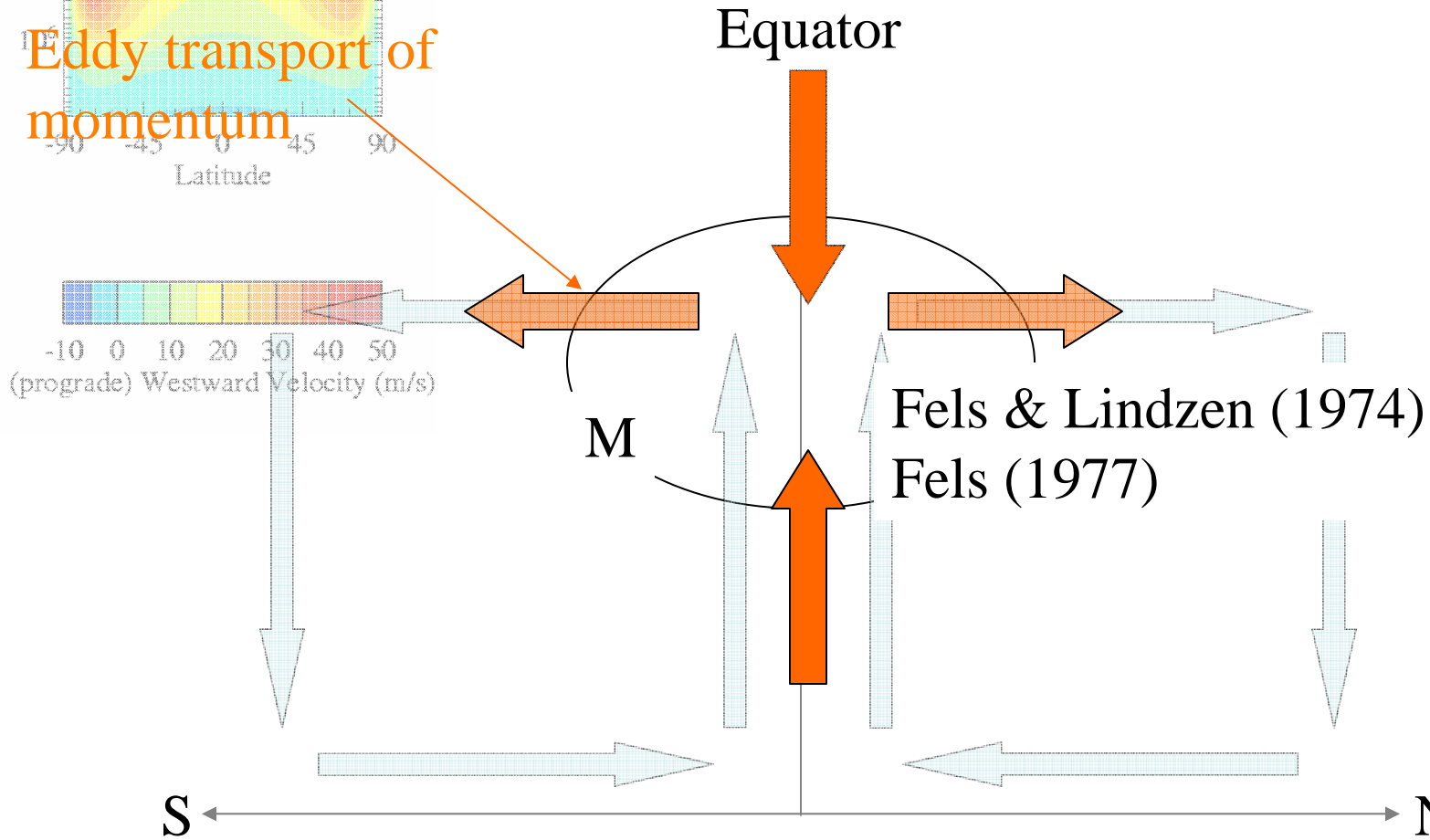
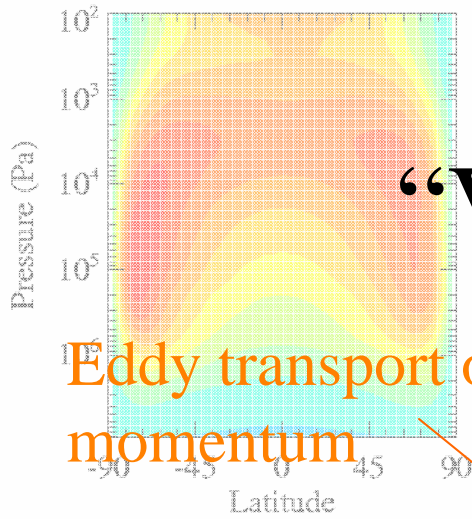
Mean meridional
circulation



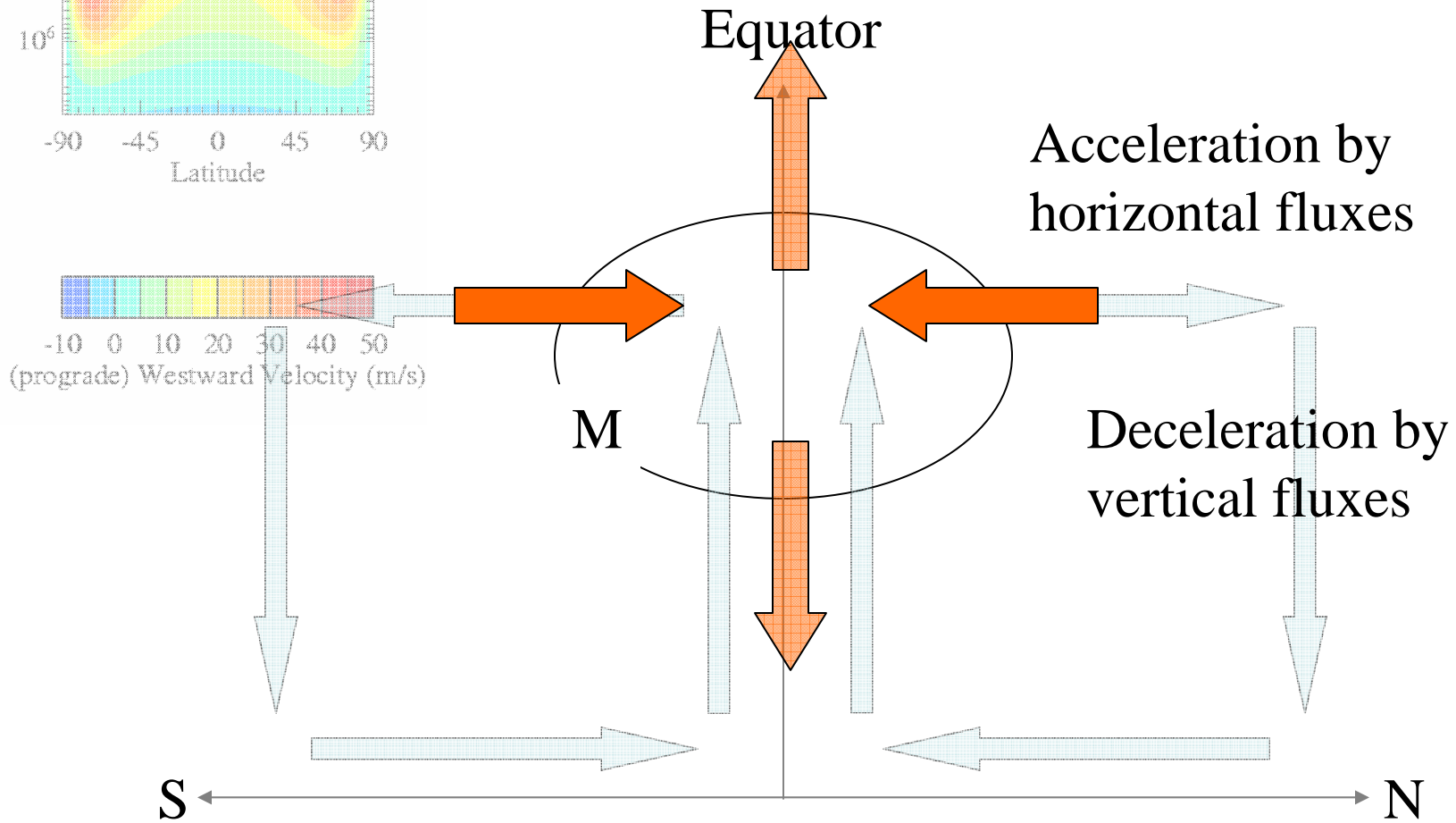
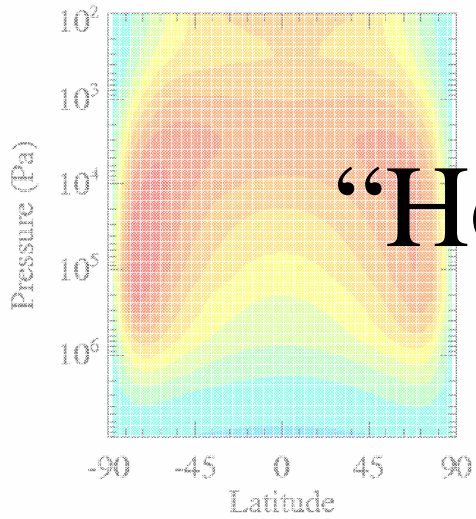
“Vertical” Mechanisms



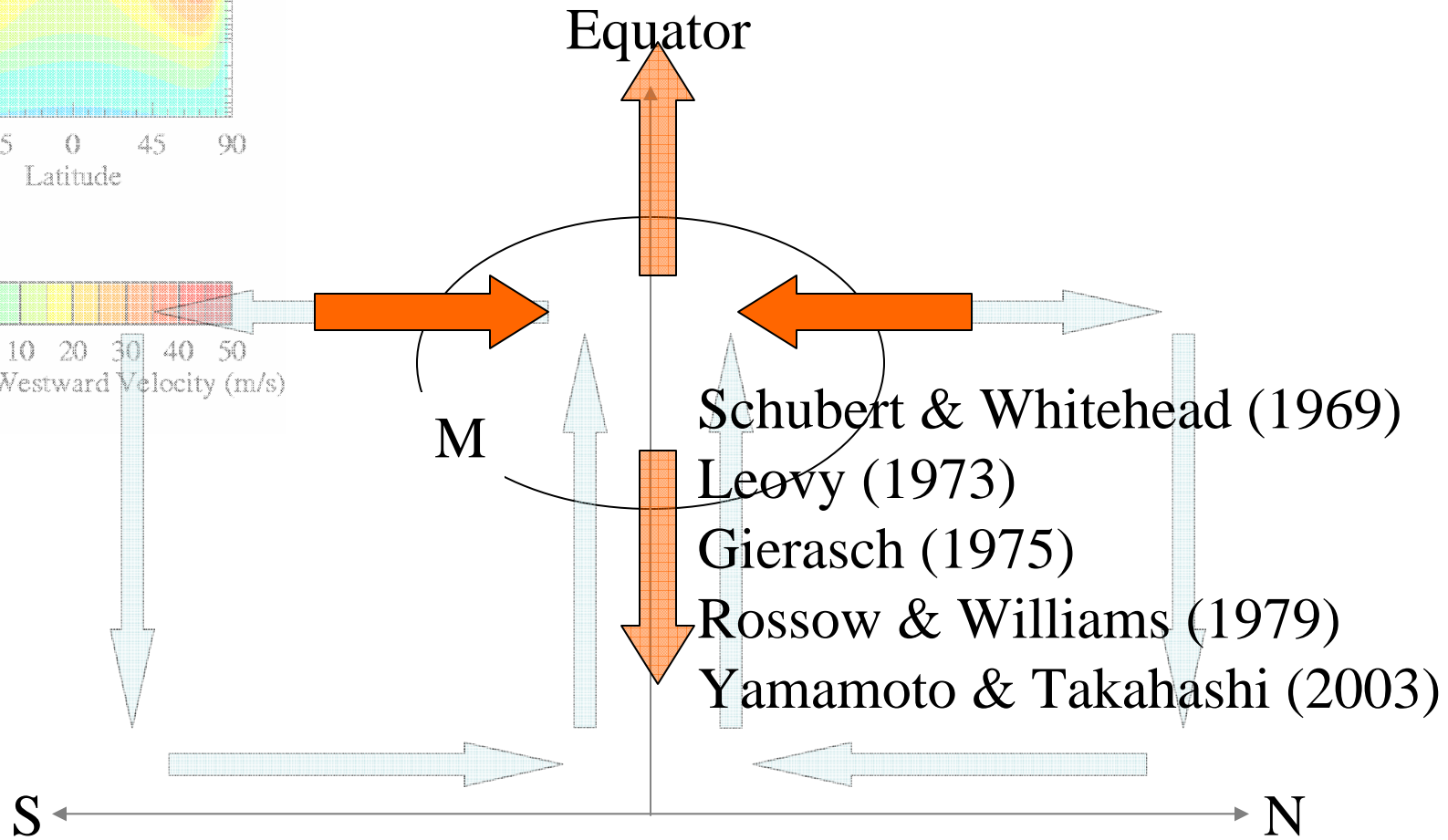
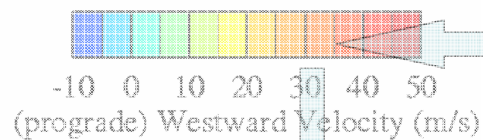
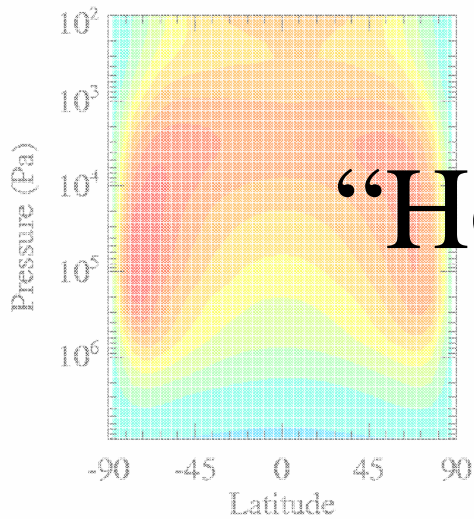
“Vertical” Mechanisms



“Horizontal” Mechanisms



“Horizontal” Mechanisms



Eliassen Palm Flux Divergence

Acceleration of zonal flow

Eddy fluxes

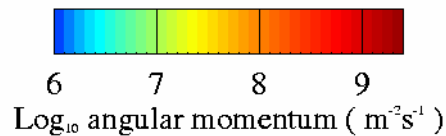
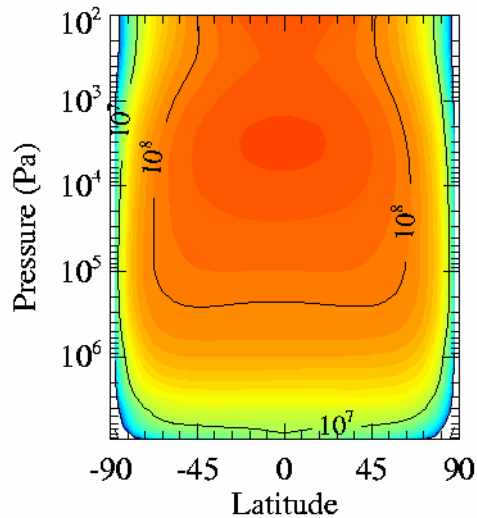
$$\overline{m}_t + \overline{\mathbf{u}}_{\star} \cdot \nabla \overline{m} = -\nabla \cdot \mathbf{E} + \mathbf{F}/\rho$$

Mean meridional circulation

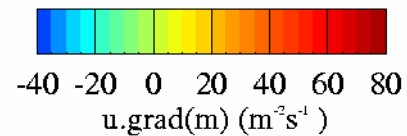
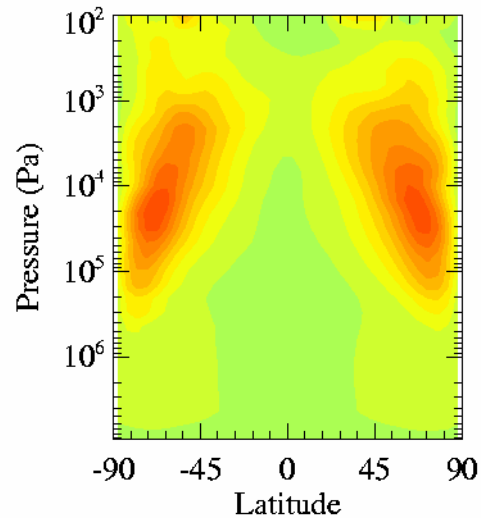
Parameterized forces
(e.g. diffusion)

$$\overline{m}_t + \overline{\mathbf{u}}_* \cdot \nabla \overline{m} = -\nabla \cdot \mathbf{E} + \mathbf{F}/\rho$$

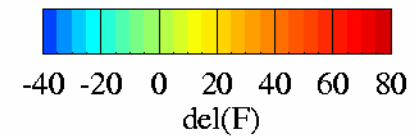
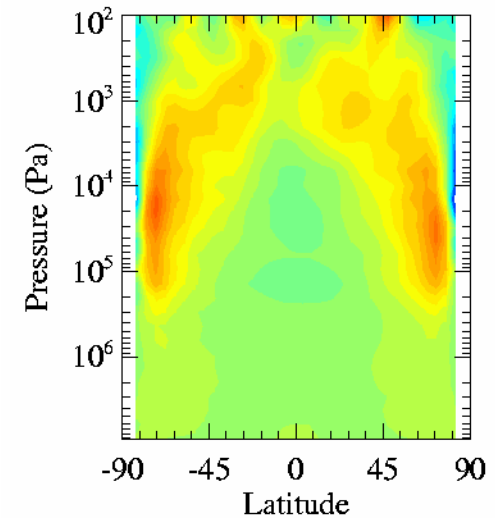
Eliassen Palm Fluxes



Angular Momentum



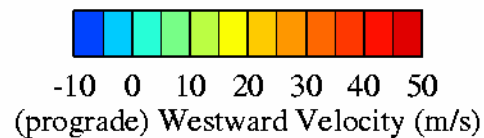
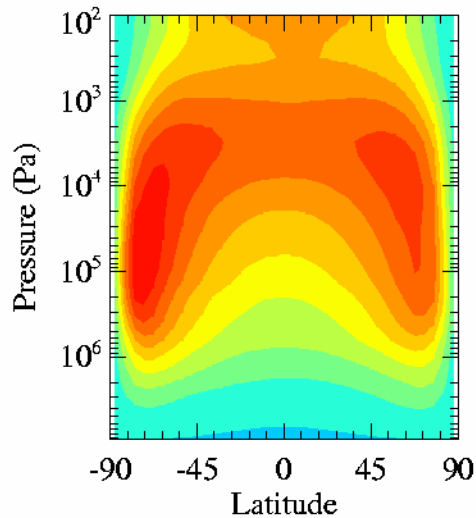
Mean circulation
(acceleration)



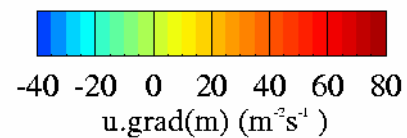
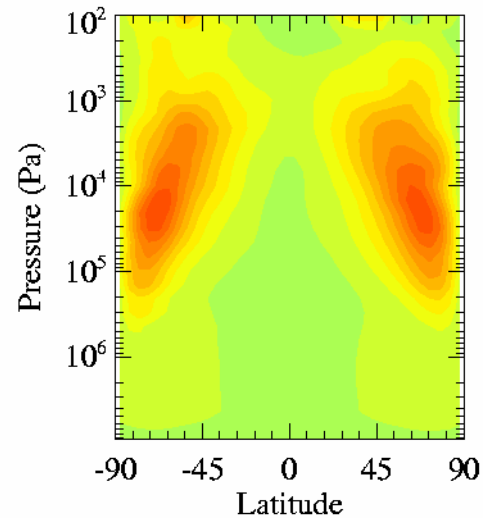
EP flux divergence
(deceleration)

$$\overline{m}_t + \overline{\mathbf{u}}_* \cdot \nabla \overline{m} = -\nabla \cdot \mathbf{E} + \mathbf{F}/\rho$$

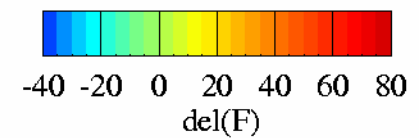
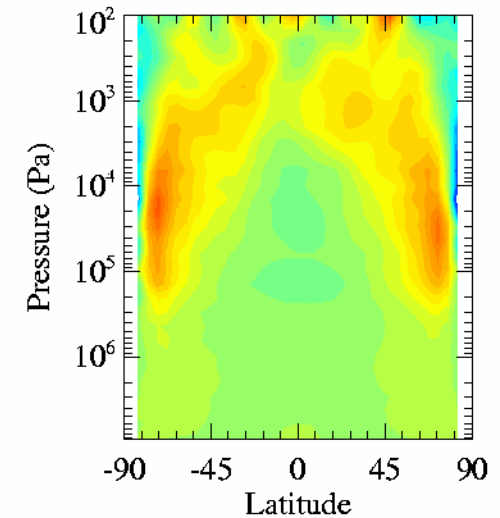
Eliassen Palm Fluxes



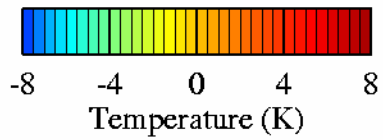
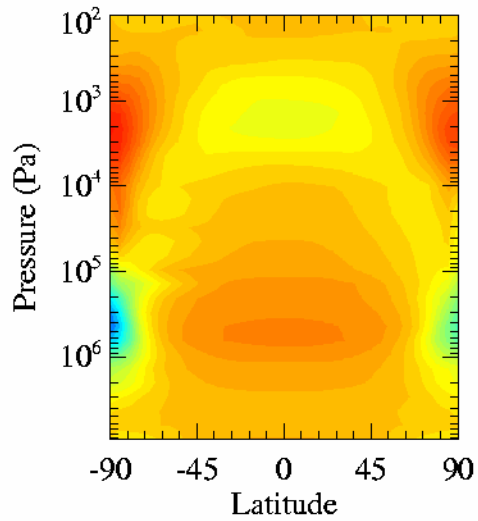
Westward wind



Mean circulation
(acceleration)



EP flux divergence
(deceleration)

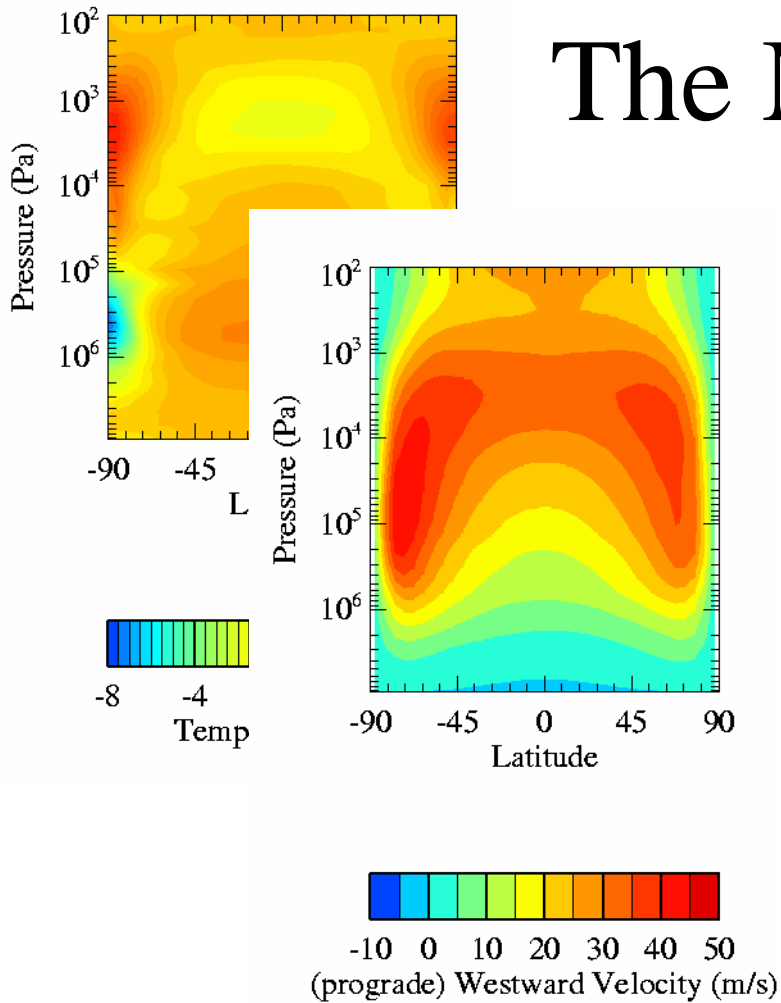


The Mechanism?

Latitudinal gradient in insolation/heating drives a latitudinal temperature gradient.

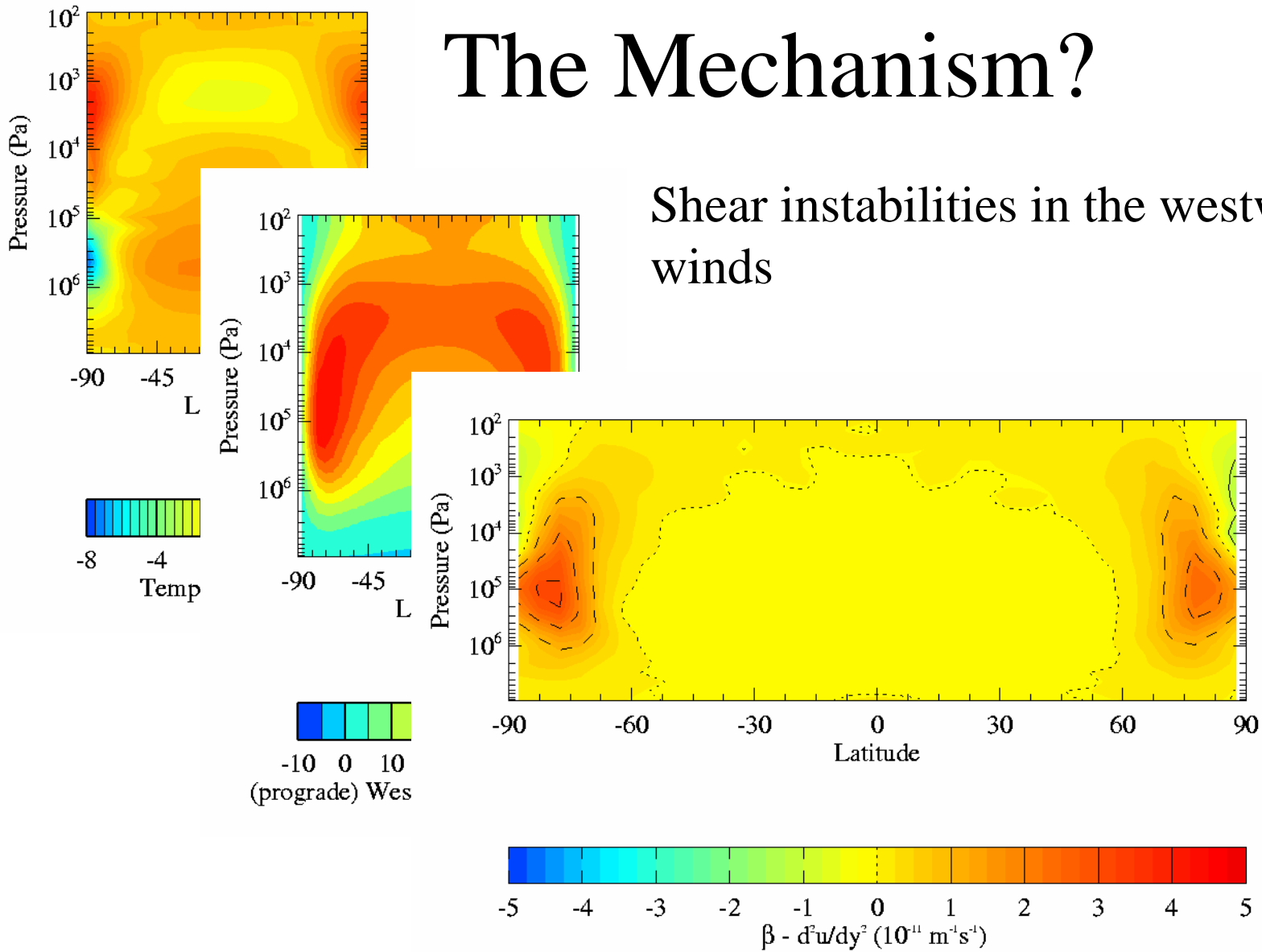
The Mechanism?

Temperature gradient drives a meridional circulation, leading to the formation of a mid-latitude jet



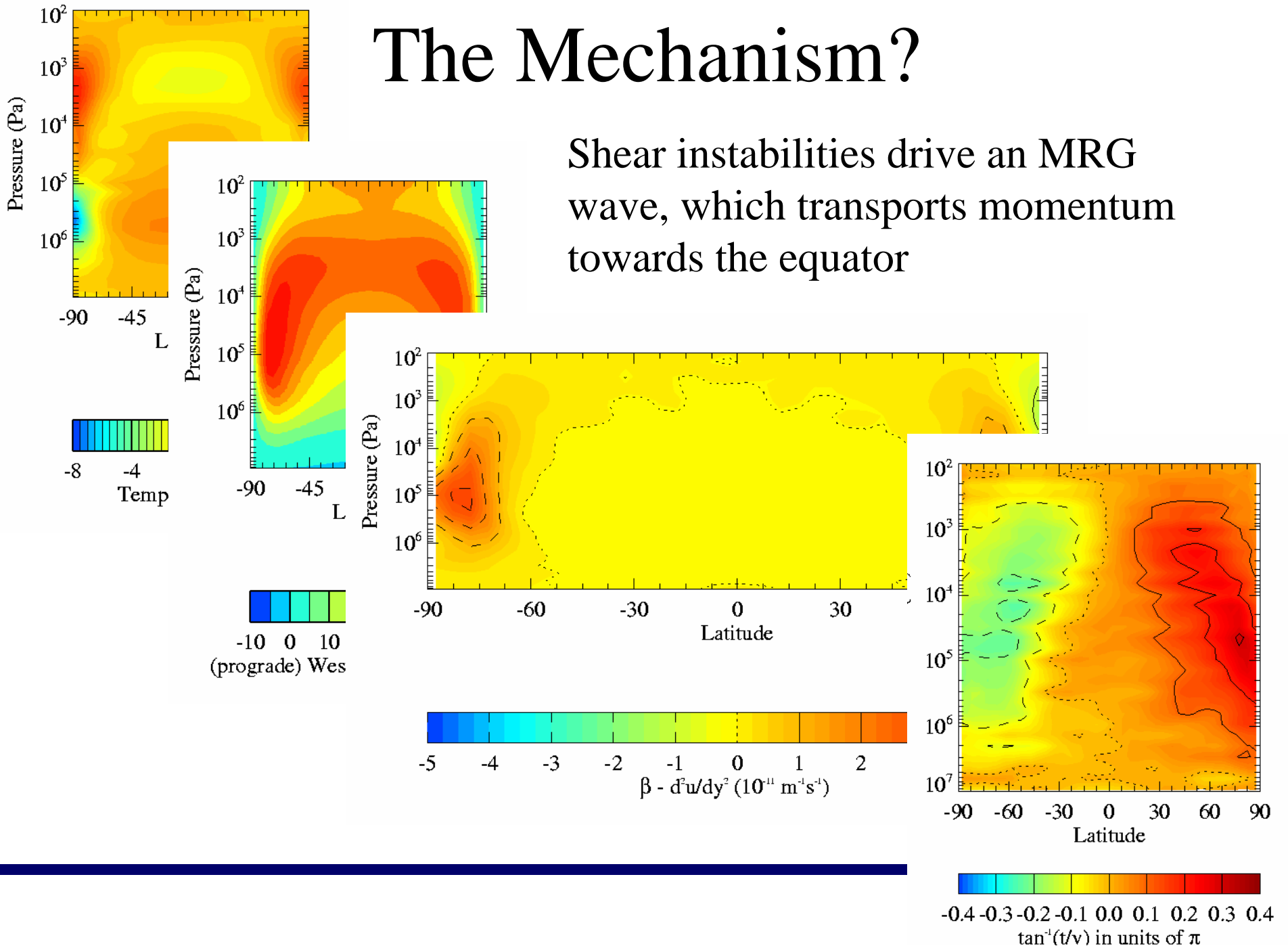
The Mechanism?

Shear instabilities in the westward winds



The Mechanism?

Shear instabilities drive an MRG wave, which transports momentum towards the equator



Summary & Conclusions

- Westward jets, MRG and Kelvin waves are present in the model atmosphere.
- Super-rotation is maintained by horizontal transport of momentum.
- Mean wind speeds and wave periods in the model don't yet match observed values.

Eliassen Palm Fluxes

- Use E_ϕ and E_P to diagnose eddy momentum transport

$$E_\phi = R \cos \phi \left((\overline{u'v'}) - (\overline{u}_P (\overline{v'\theta'}) \overline{\theta}_P) \right)$$

$$E_P = R \cos \phi \left((\overline{w'u'}) + \right.$$

$$\left. ((\overline{u} \cos \phi)_P / (R \cos \phi) - 2\Omega \sin \phi) (\overline{v'\theta'}) / \theta_P \right)$$

Residual Circulation

$$\bar{\mathbf{u}}_{\star} = (\bar{v}_{\star}, \bar{\omega}_{\star})$$

$$\bar{v}_{\star} = \bar{v} - \left\{ \frac{\overline{v'\theta'}}{\theta_p} \right\}_p$$

$$\bar{\omega}_{\star} = \bar{\omega} - \frac{1}{a \cos \phi} \left\{ \frac{\overline{v'\theta' \cos \phi}}{\bar{\theta}_p} \right\}_{\phi}$$