Superrotation at Earth's surface

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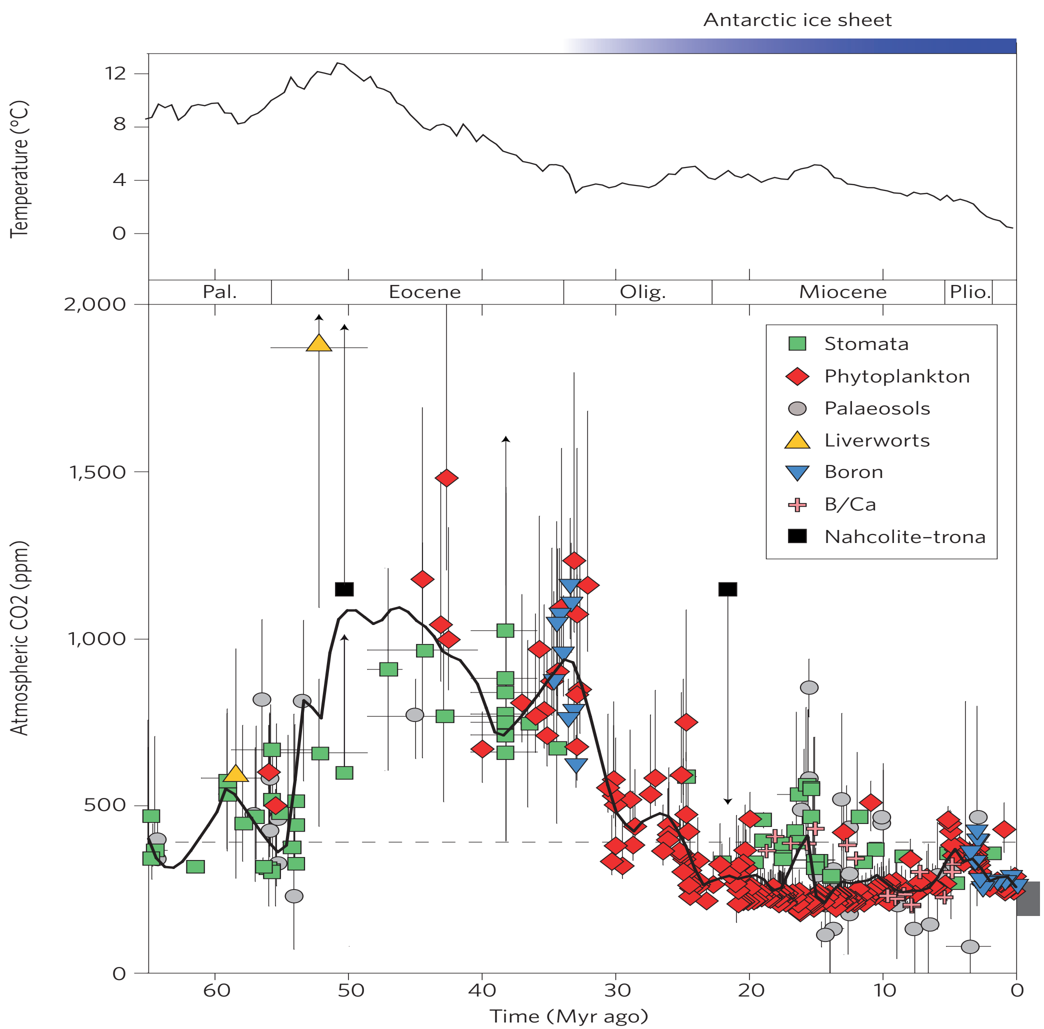
The past 50 million years on Earth



Temperature at the bottom of the ocean

Atmospheric CO2

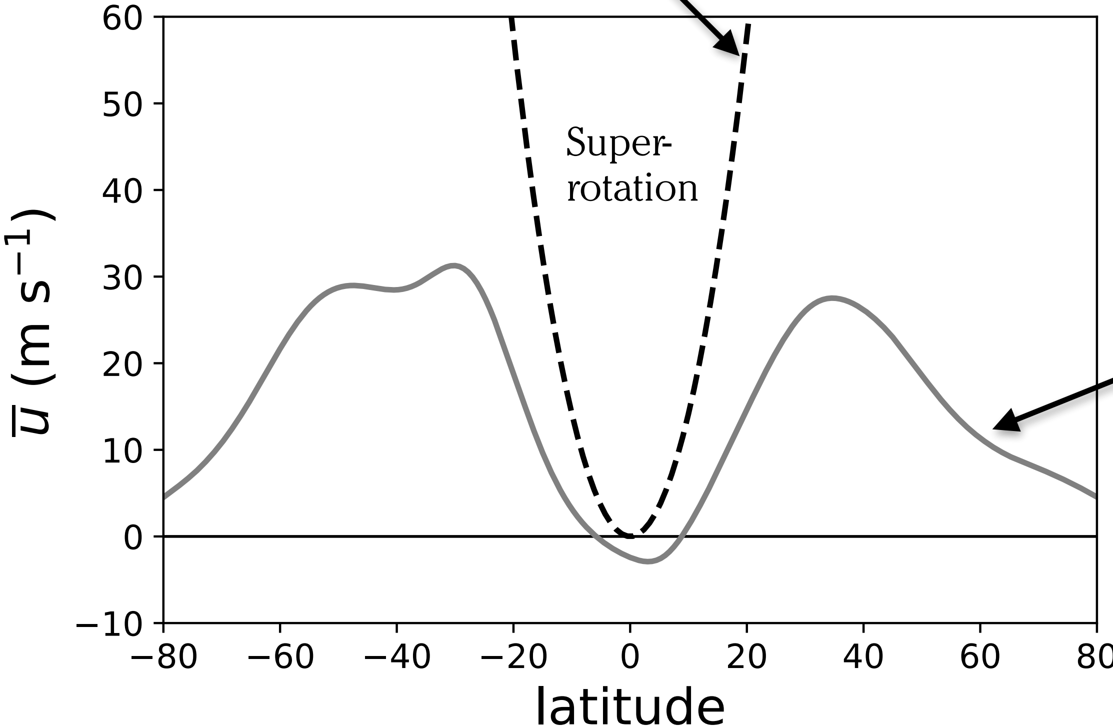
(Beerling & Royer Nat Geo 2011)

Superrotation

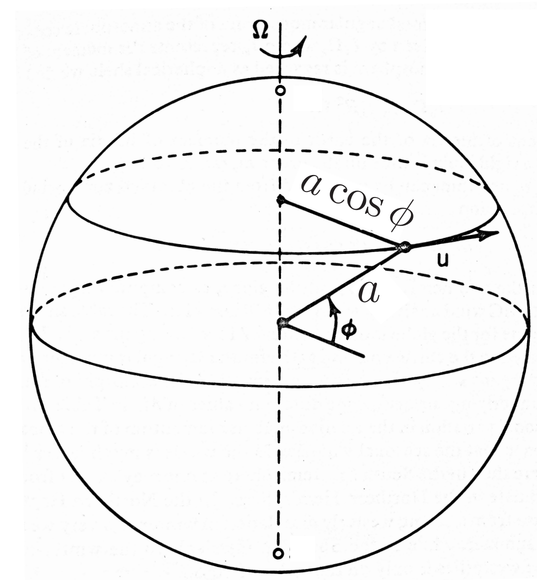
A state in which the atmosphere has greater axial angular momentum than equatorial solid-body rotation:

$$M = \Omega a^2 \cos^2 \varphi + \overline{u}\, a \cos \varphi > \Omega a^2$$

$$\overline{u} \; > \; \Omega a \frac{\sin^2 \varphi}{\cos \varphi}$$



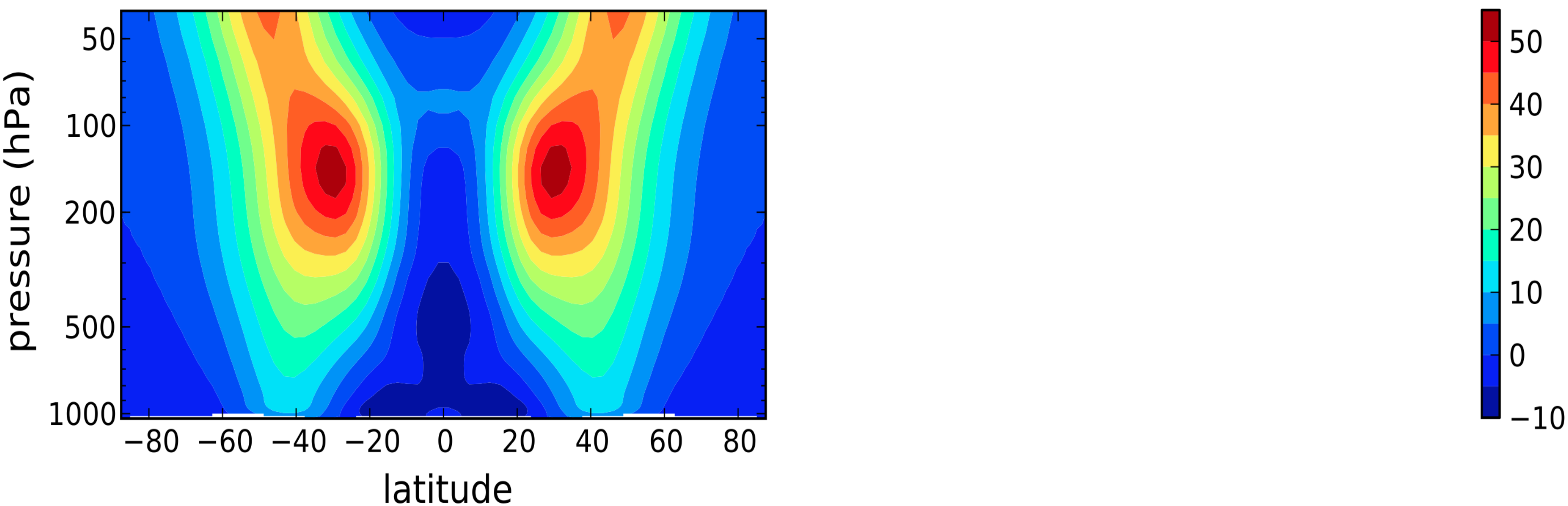
Observed 200 hPa zonal-mean wind



Superrotation in warm climates

Zonal-mean zonal wind in simulations with CAM3 coupled to aquaplanet slab ocean

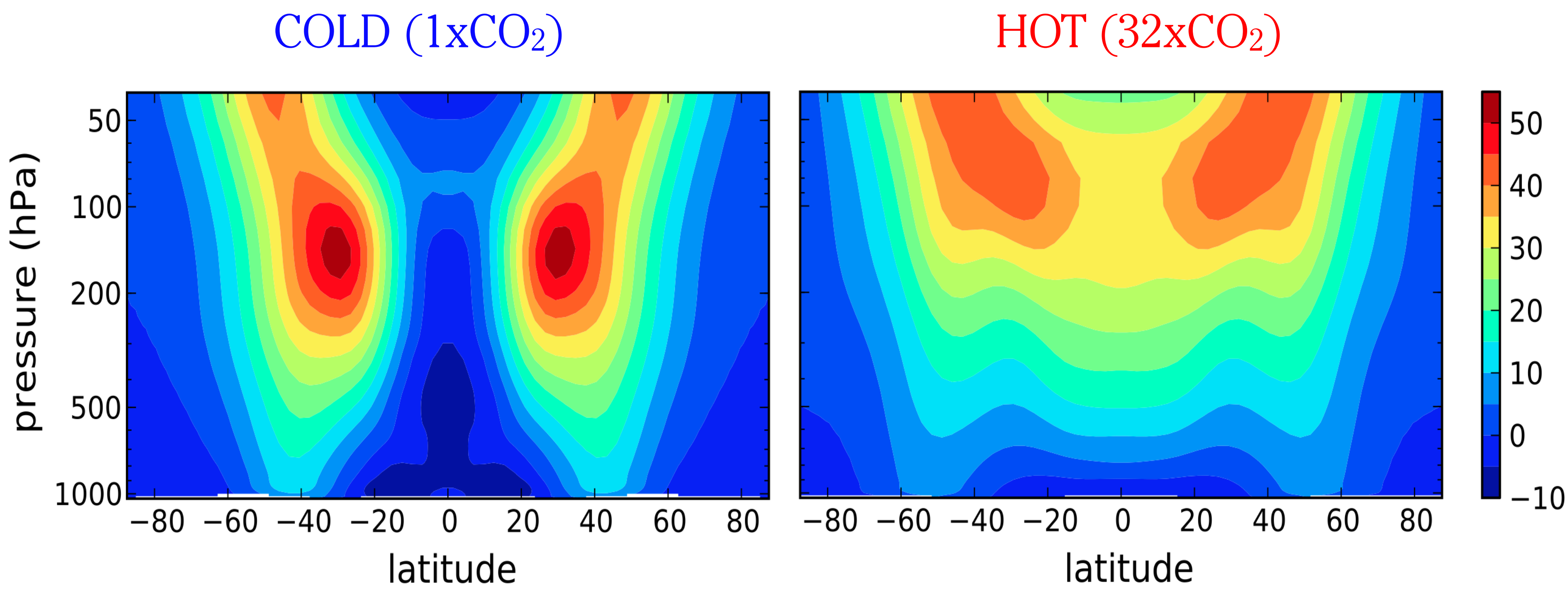
COLD ($1xCO_2$)



(Caballero & Huber GRL 2010)

Superrotation in warm climates

Zonal-mean zonal wind in simulations with CAM3 coupled to aquaplanet slab ocean



(Caballero & Huber GRL 2010)

What drives superrotation?

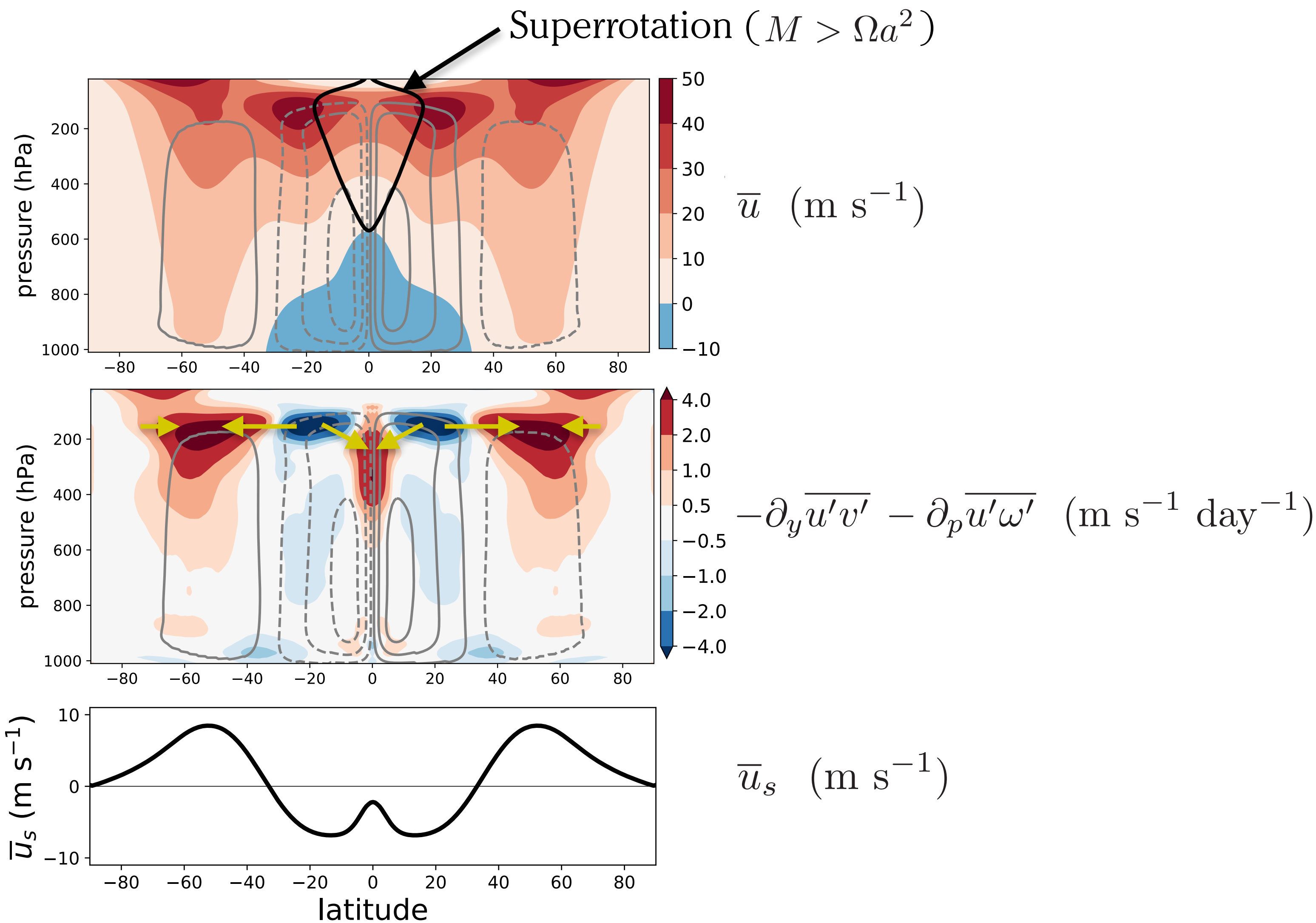
Zonal-mean momentum budget:

$$\partial_t \overline{u} = \underbrace{(f - \partial_y \overline{u})\, \overline{v} - \overline{\omega} \partial_p \overline{u}}_{\text{mean flow (conserves } M)} - \underbrace{\partial_y \overline{u'v'} - \partial_p \overline{u'\omega'}}_{\text{large-scale eddies}} - \underbrace{g\, \partial_p \overline{\tau}}_{\text{viscosity}}$$

- Mean flow conserves angular momentum
- Downgradient (diffusive) eddy momentum fluxes can only dilute *M* maxima
- Superrotation requires *countergradient* eddy momentum fluxes by large-scale eddies

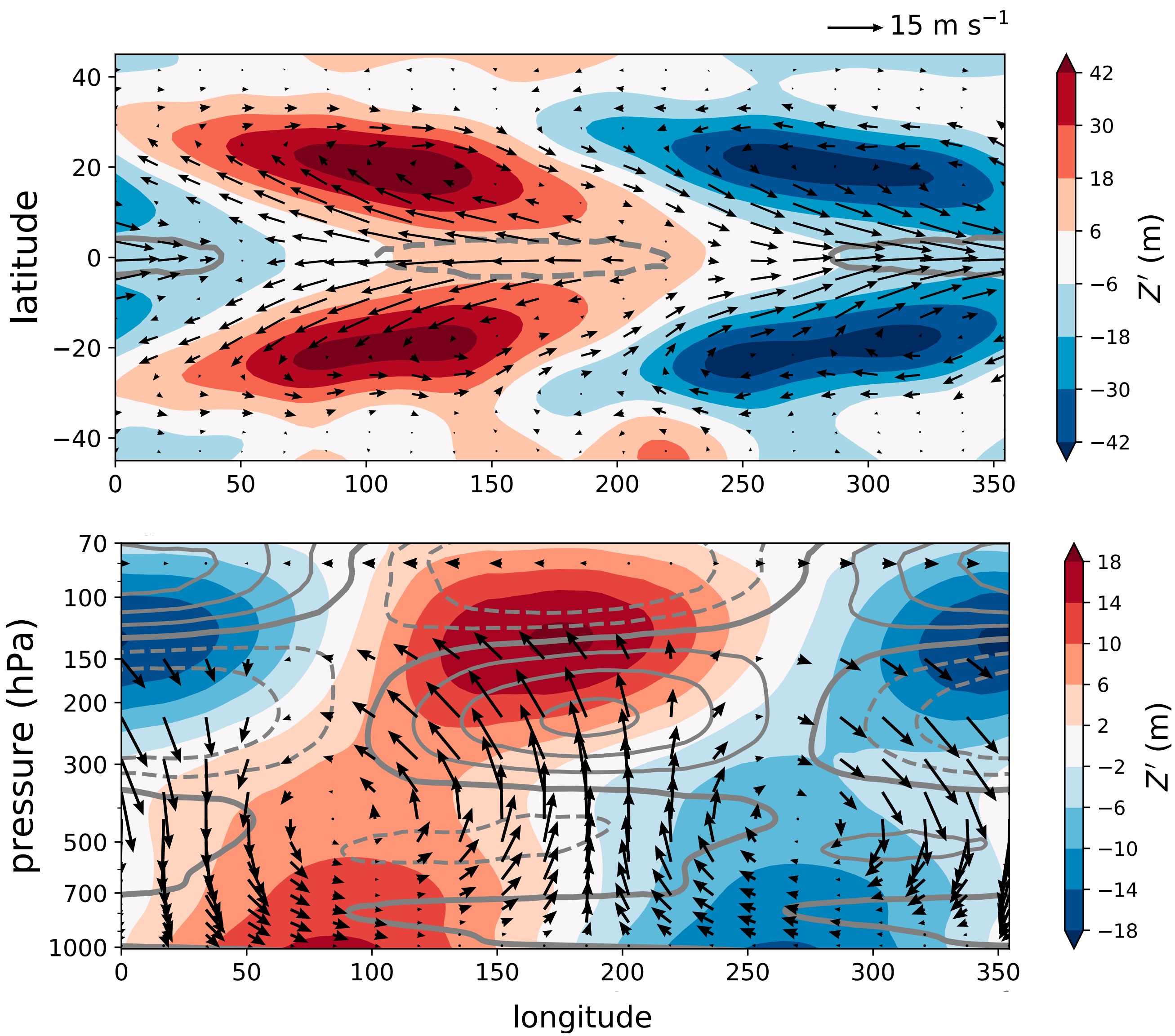
Tropical eddies drive warm-climate superrotation

Aquaplanet (CAM4) with very warm surface temperature



What are these tropical eddies?

- Leading EOF of tropical variability looks a lot like the Madden-Julian Oscillation



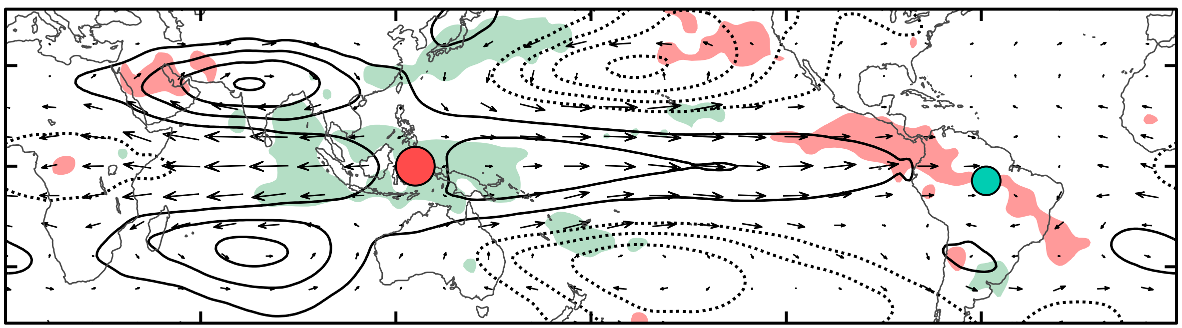
Anomalies in:

100 hPa height (shading) and wind (arrows), 500 hPa vertical wind (gray)

equatorial height (shading) wind (arrows), and temperature anomaly (gray)

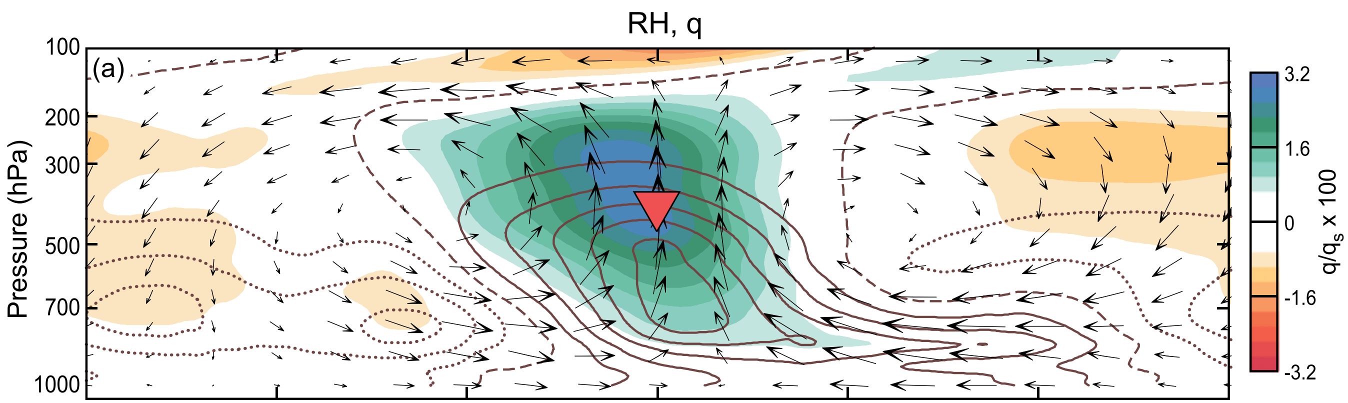
Carlson & Caballero, JAMES 2016

Observed MJO



Anomalies in:

upper troposphere height (contours) and wind (arrows), 400 hPa vertical wind (color)

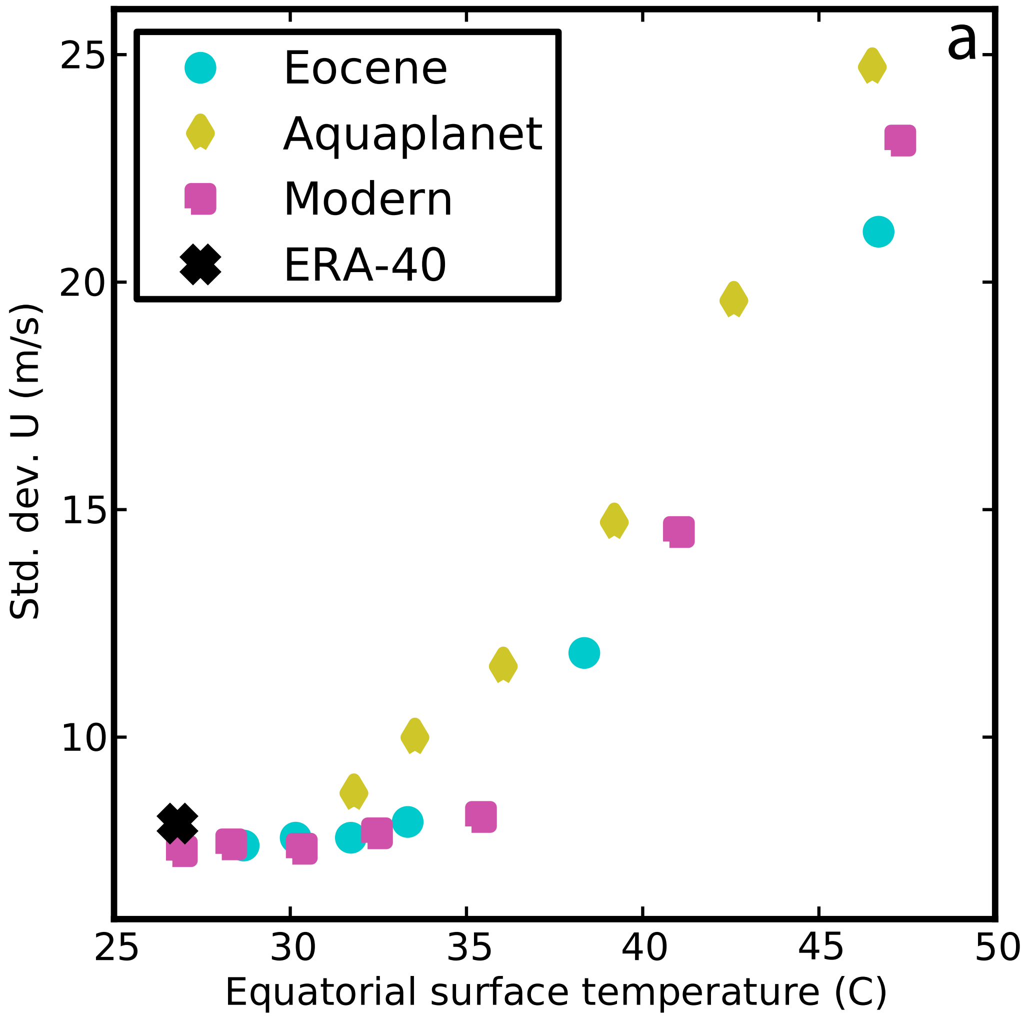


equatorial wind(arrows) and humidity (shading)

Adames et al., JAS 2015, 2016

Enhanced MJO in warm climates

Full-complexity GCM simulations (CAM3+slab ocean) with increasing CO2

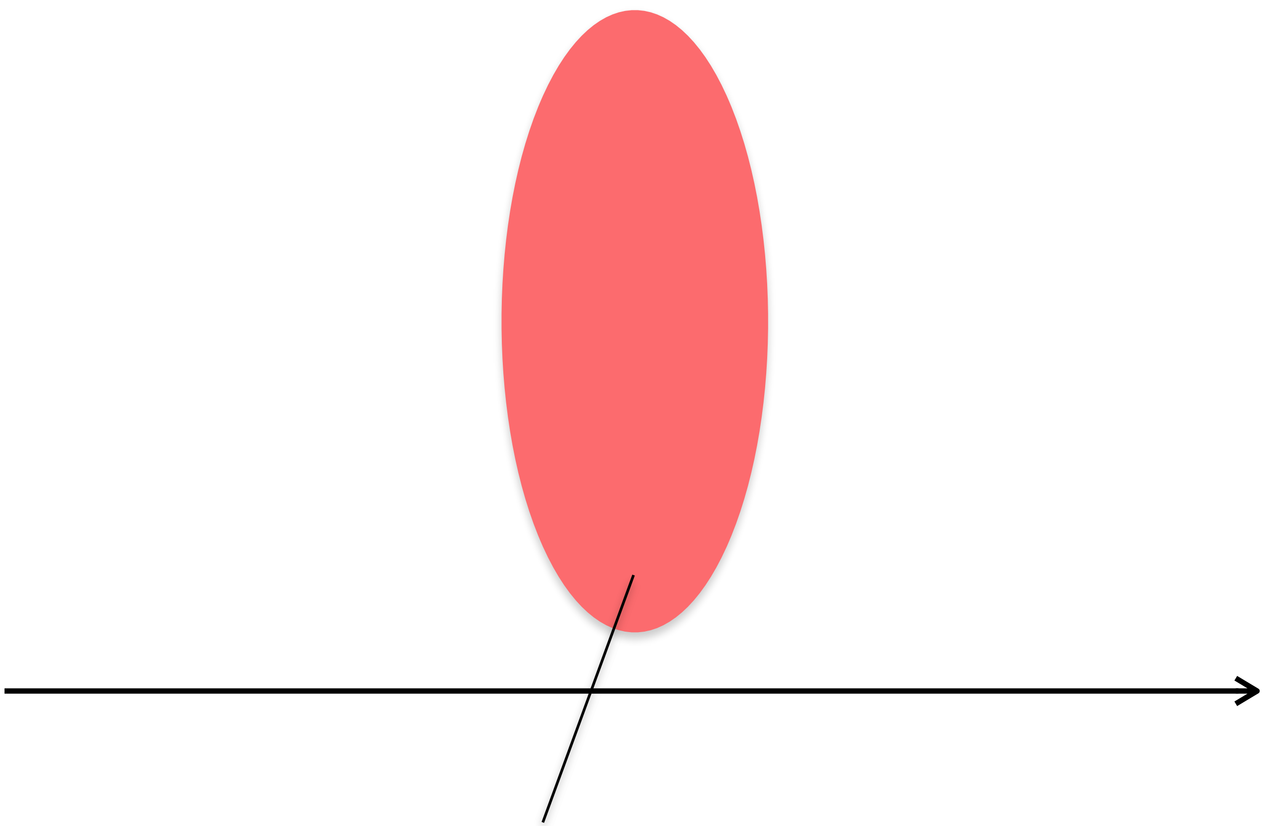


(Caballero & Huber GRL. 2010)

2 topics for the rest of this talk:

- Why does MJO amplitude increase in warm climates?
- Surface superrotation: Can equatorial winds be westerly at the surface?

“Moisture-mode” instability

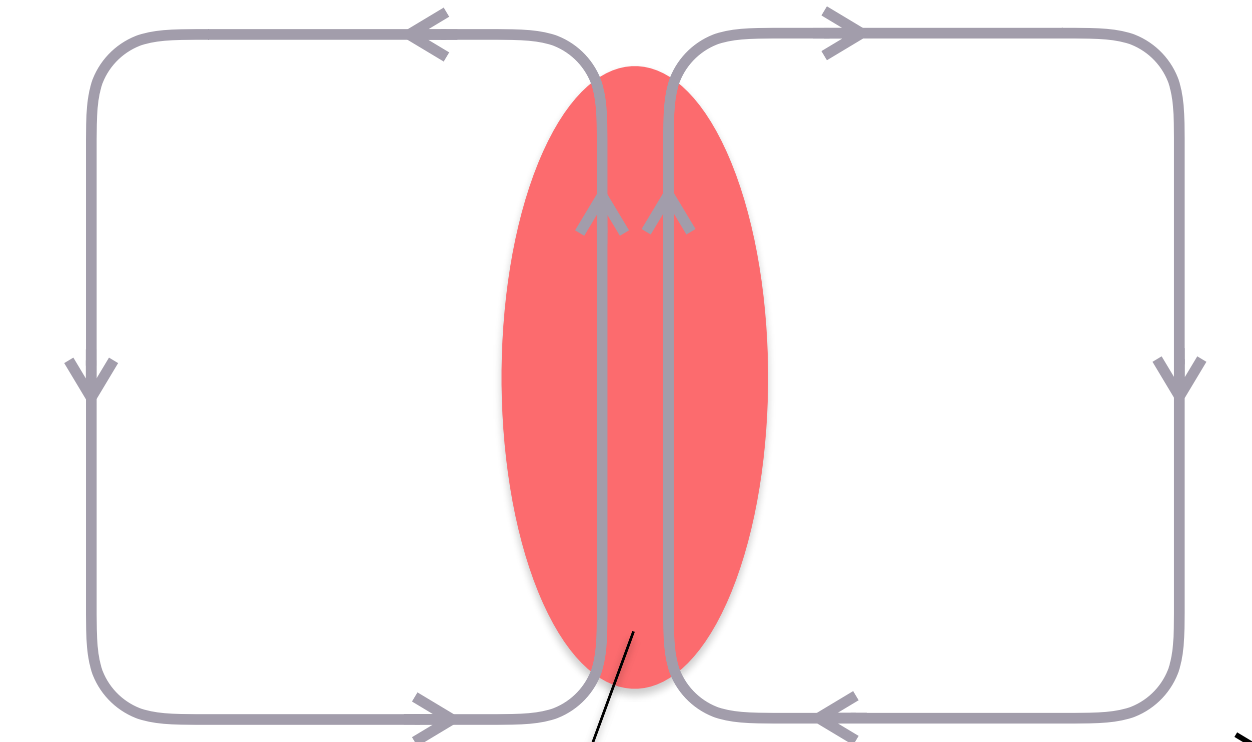


Moist static energy anomaly

$$h = C_p T + gz + Lq$$

(Raymond & Fuchs JAS 2009)

“Moisture-mode” instability



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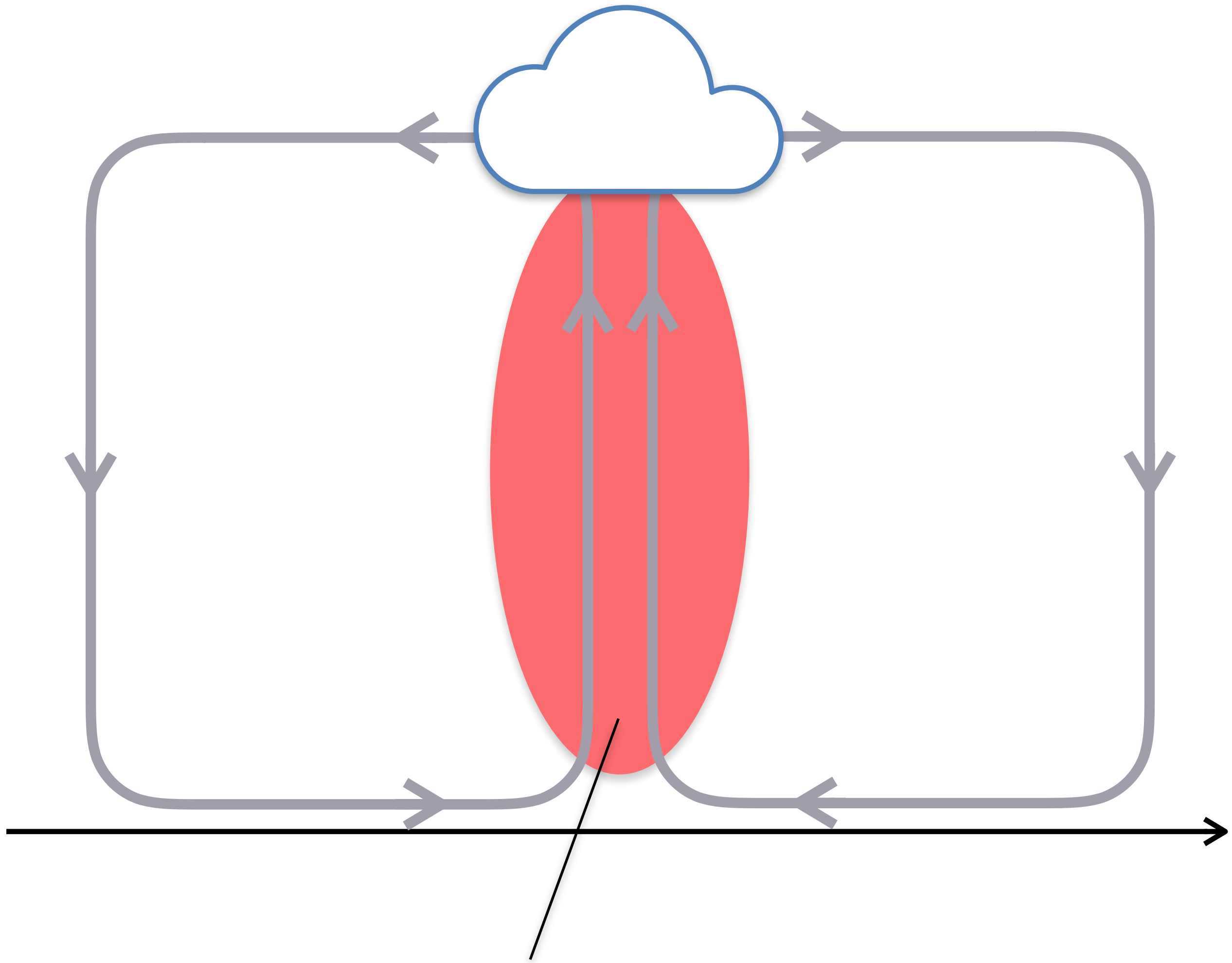

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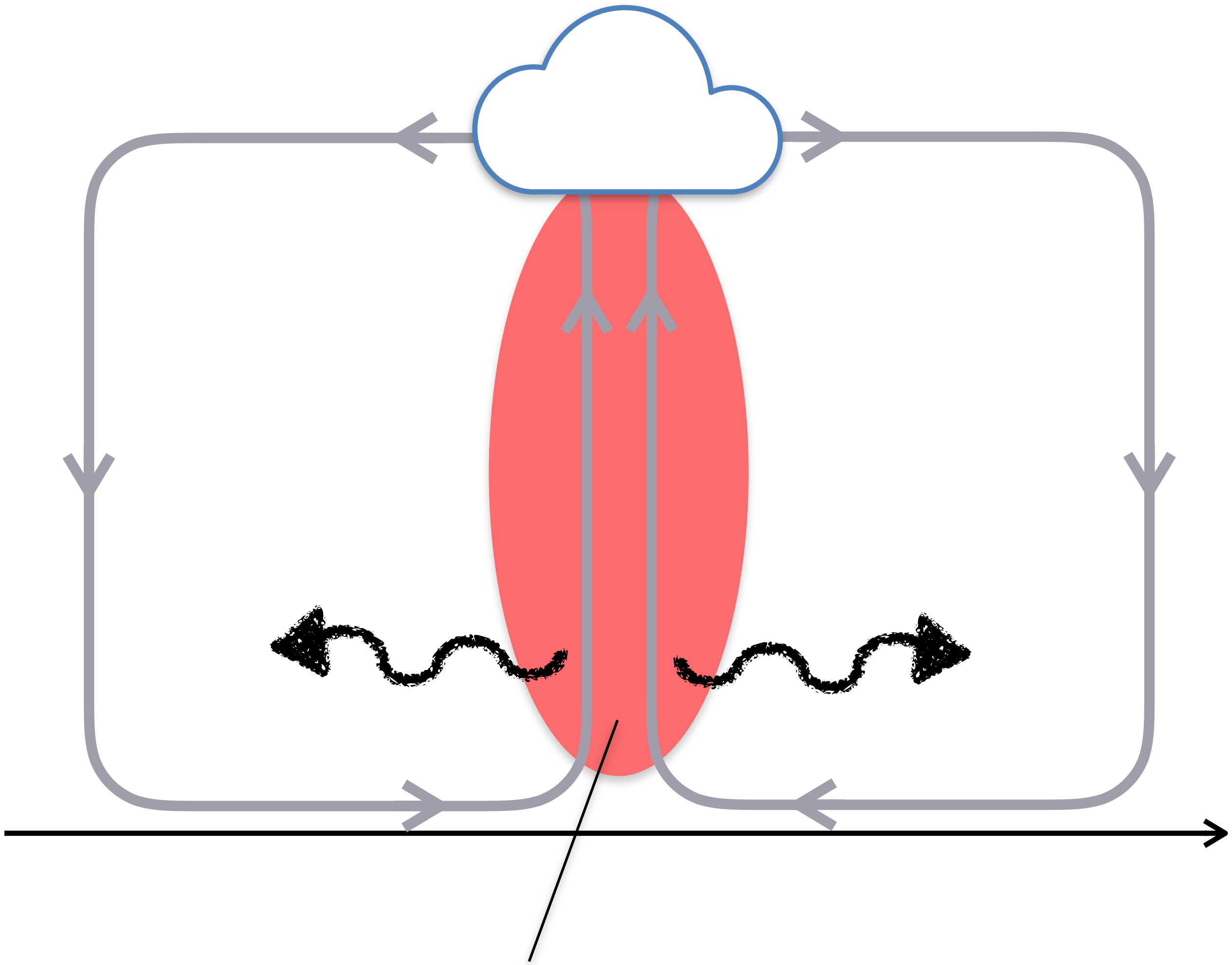
"Moisture-mode" instability



Moist static energy anomaly

$$h = C_pT + gz + Lq$$

(Raymond & Fuchs JAS 2009)

Moist static energy budget

Local evolution of moist static energy $h = C_p T + gz + Lq$

$$\partial_t h = -\mathbf{u} \cdot \nabla h - \omega \partial_p h + R + F_s$$

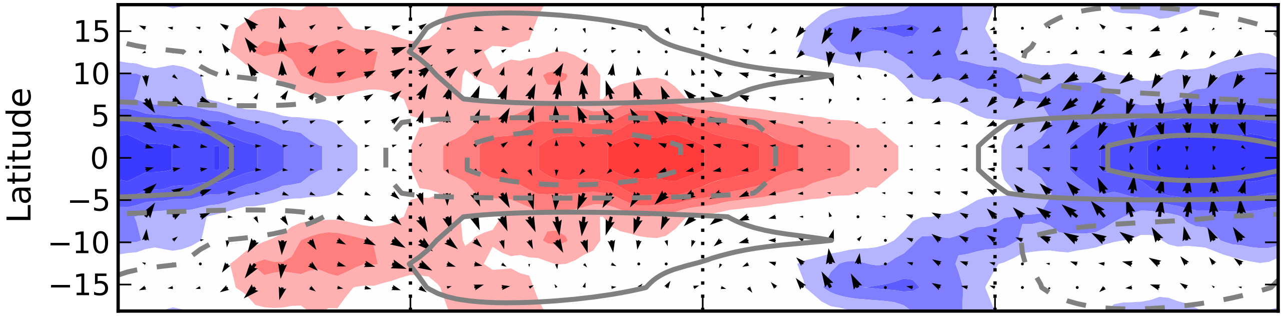
Partition into zonal mean, MJO mode and residual:

$$h = \overline{h} + h_{MJO} + h'$$

Substitute into evolution equation, project onto MJO mode; turns out that

$$\partial_t h_{MJO} \approx -\omega_{MJO} \partial_p \overline{h} - \nabla \cdot \mathbf{u}' h' + R_{MJO}$$

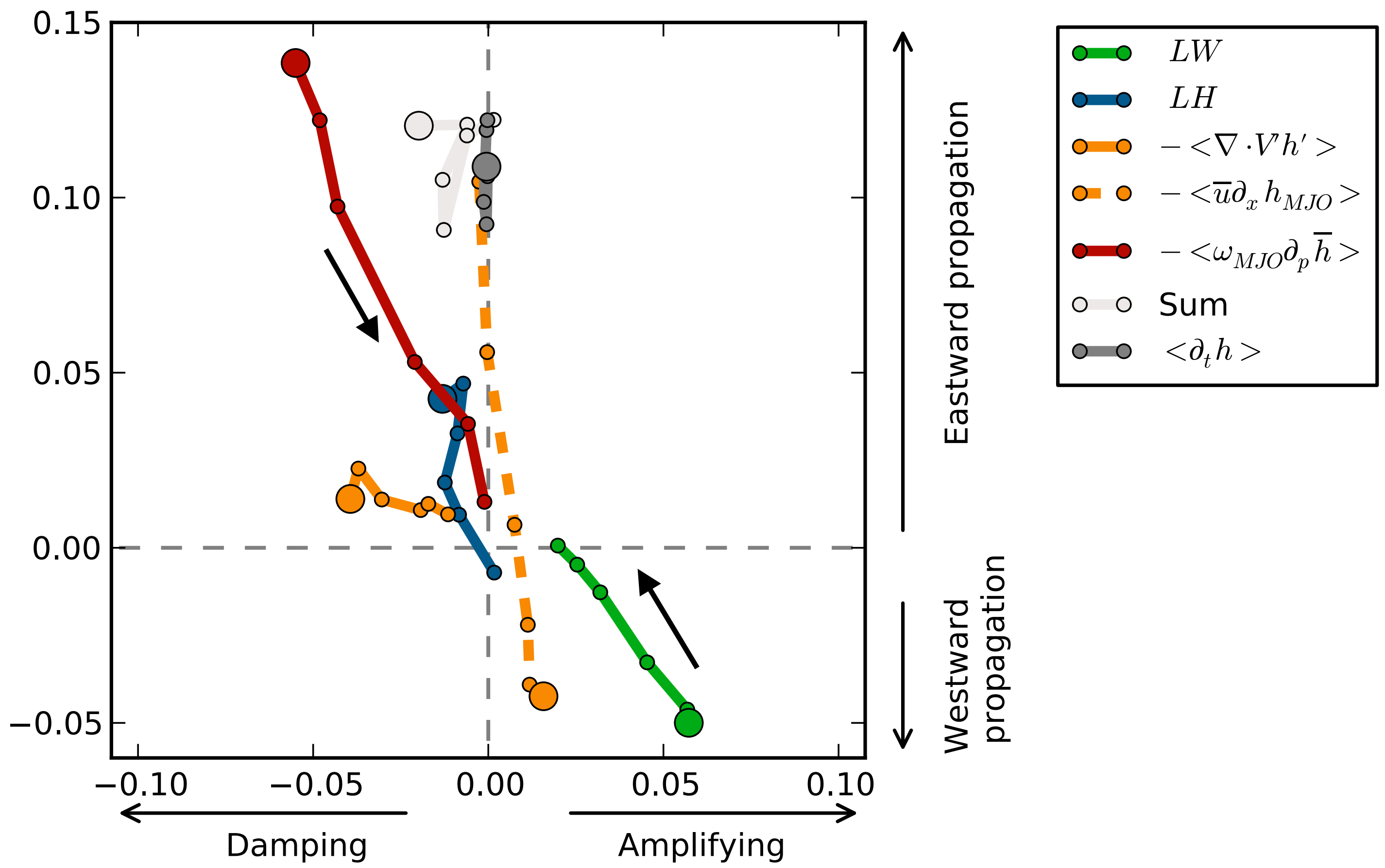
Negative (damping) Positive (amplifying)



h_{MJO} (shading)

$\nabla \cdot \mathbf{u}' h'$ (gray contours)

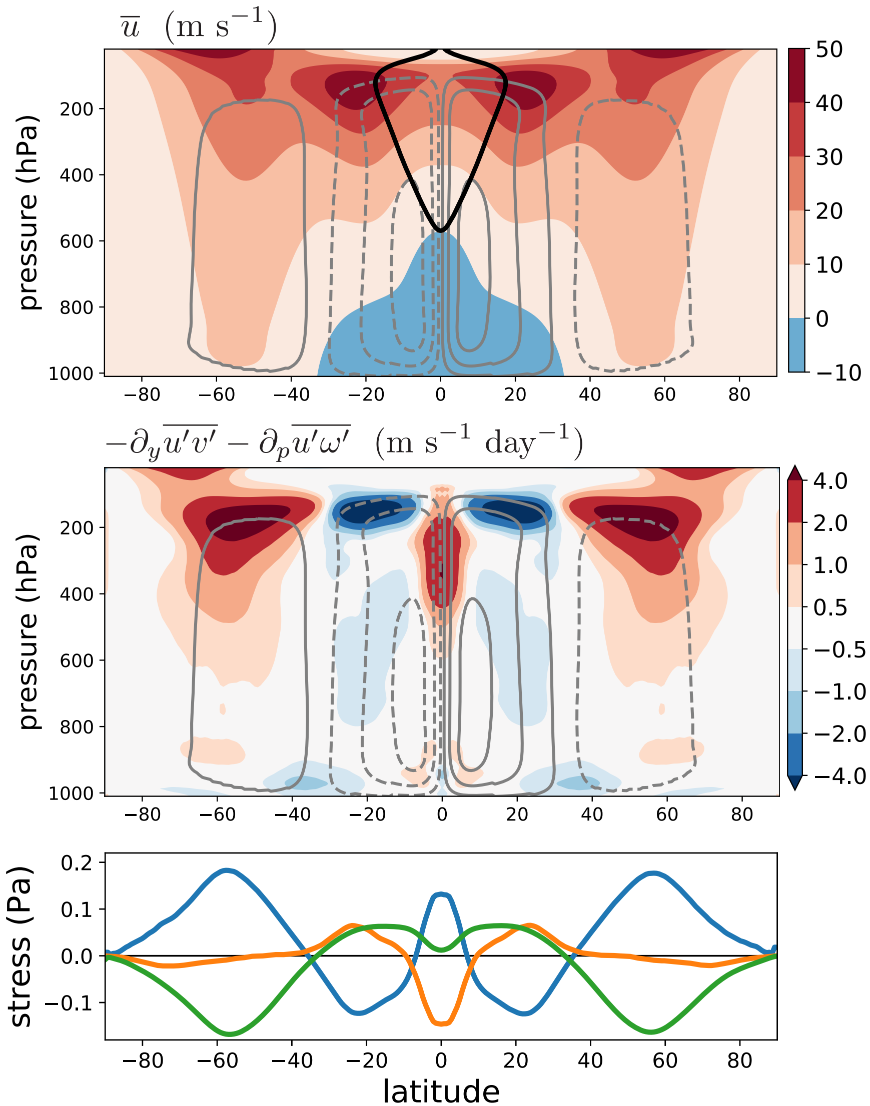
Response of MSE budget terms to warming



Damping gets weaker as climate warms => MJO amplitude grows

(Carlson & Caballero, JAMES 2016)

Momentum transport and surface wind



Momentum budget:

$$\partial_t \overline{u} = (f - \partial_y \overline{u})\, \overline{v} - \overline{\omega} \partial_p \overline{u} - \partial_y \overline{u'v'} - \partial_p \overline{u'\omega'} - g\, \partial_p \overline{\tau}$$

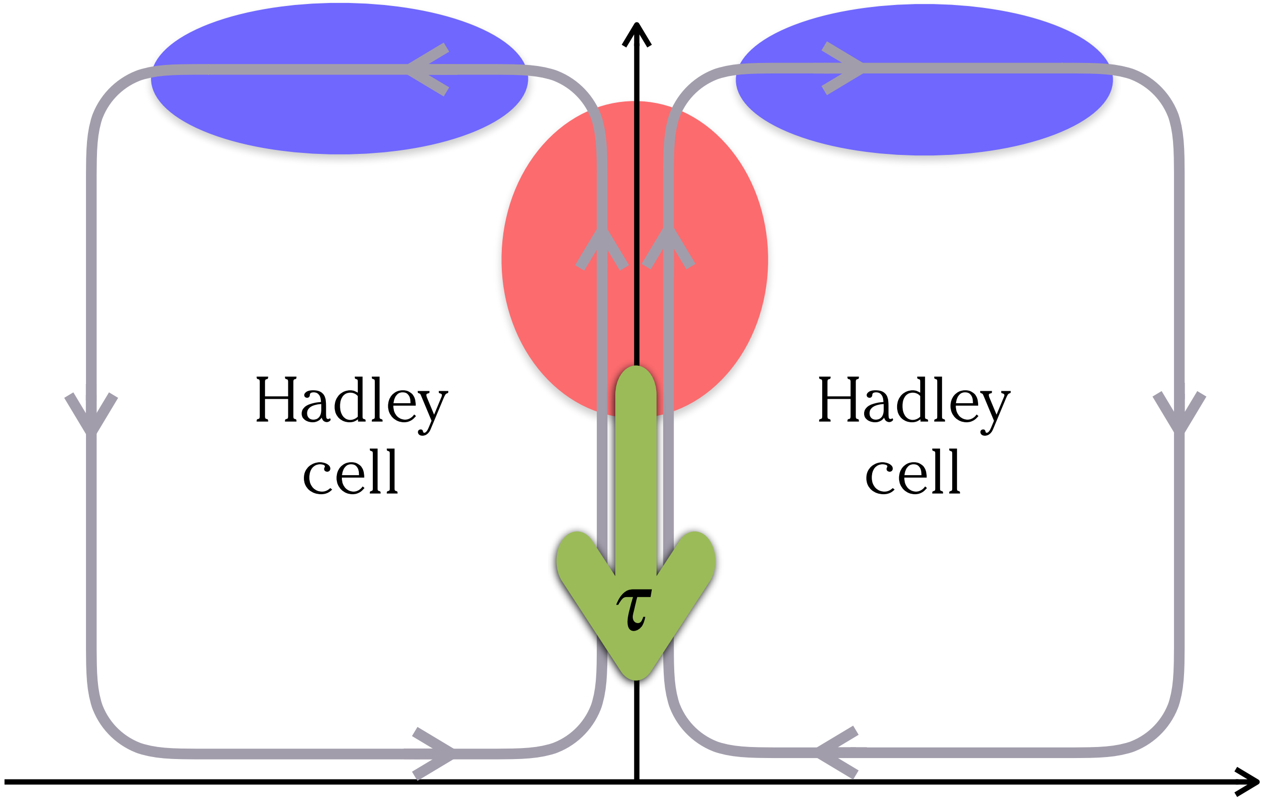
Take vertical integral $\langle \cdot \rangle = g^{-1} \int_0^{p_s} (\cdot)\, dp$:

$$-\langle \overline{v} \partial_y \overline{u} \rangle - \langle \overline{\omega} \partial_p \overline{u} \rangle - \partial_y \langle \overline{u'v'} \rangle - \overline{\tau}_s = 0$$

mean flow | large-scale eddies | surface stress

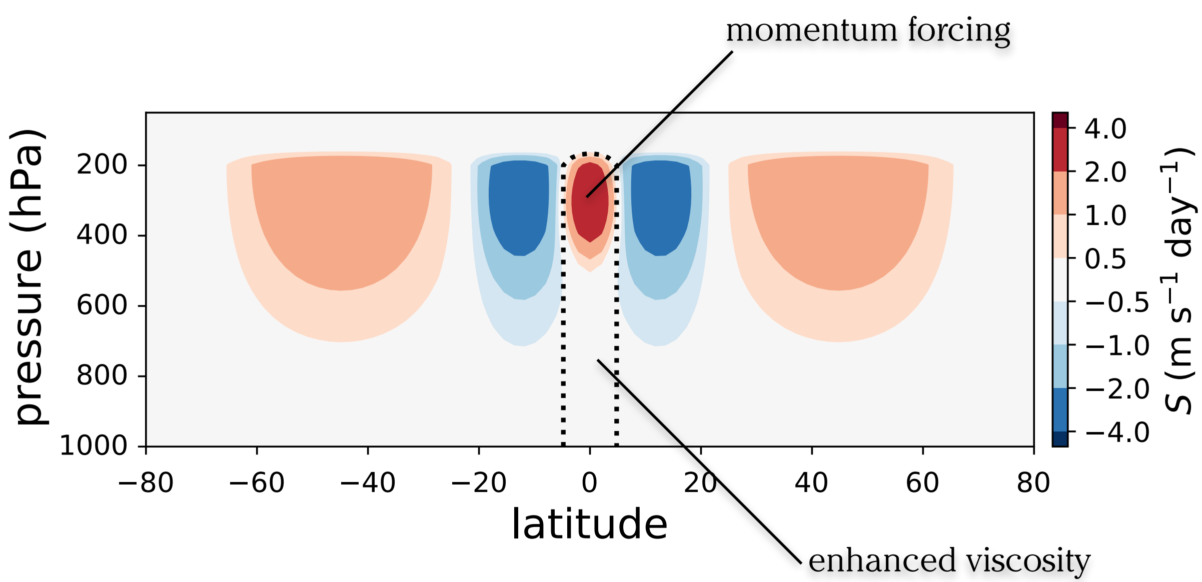
- Midlatitudes:
  eddy mom. convergence balanced by surface westerlies
- Equator:
  eddy mom. convergence balanced by surface westerlies

A pathway to surface superrotation

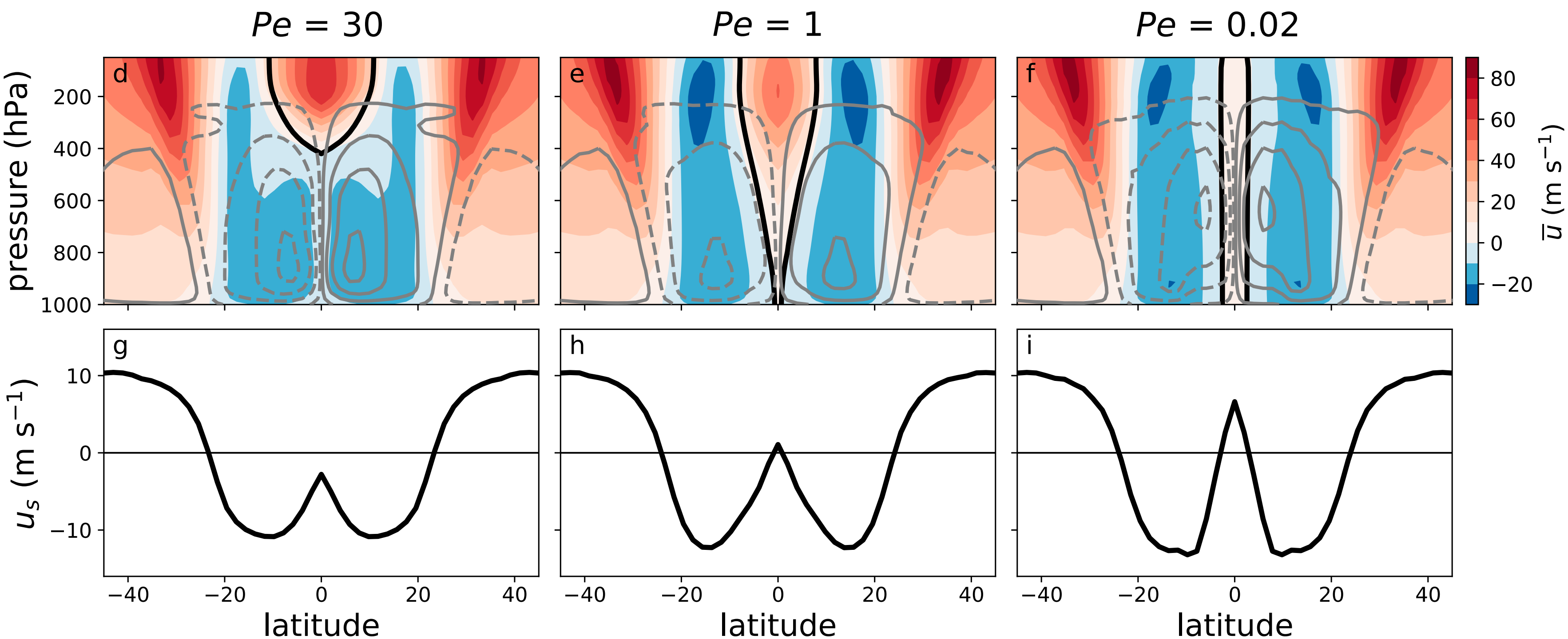


Axisymmetric simulations

- 2D axisymmetric model, similar to Held & Hou (1980)
- Momentum forcing by prescribed distribution of zonal torque
- Diffusive vertical viscosity enhanced near equator



Increased equatorial viscosity leads to surface superrotation



Péclet number: $$Pe = \frac{\text{advective timescale}}{\text{diffusive timescale}} = \frac{\omega / p_s}{\nu / H^2}$$

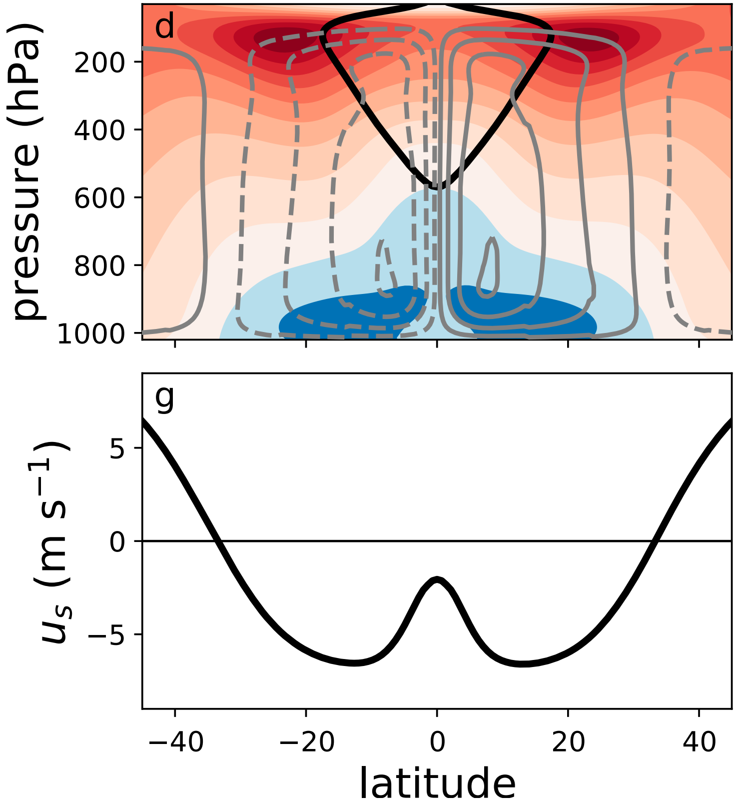
Surface superrotation in full GCM

Reduce Péclet number in GCM by:

- reducing equator-pole temperature gradient (=> reduced Hadley cell strength)
- artificially increasing convective momentum transport (CMT)

Control case

$\nu \sim 1\ \mathrm{m}^2\ \mathrm{s}^{-1} \quad Pe \sim 16$



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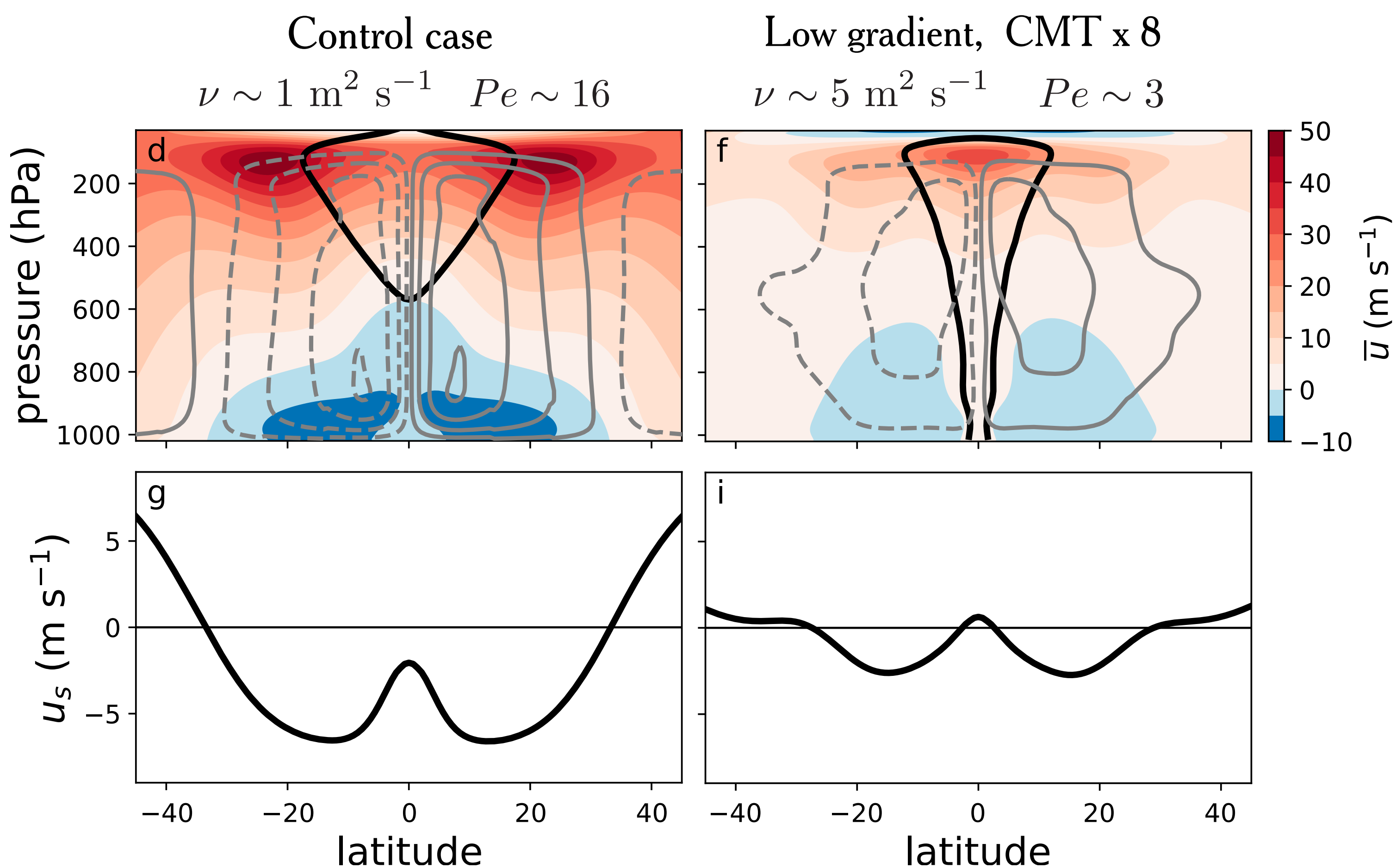
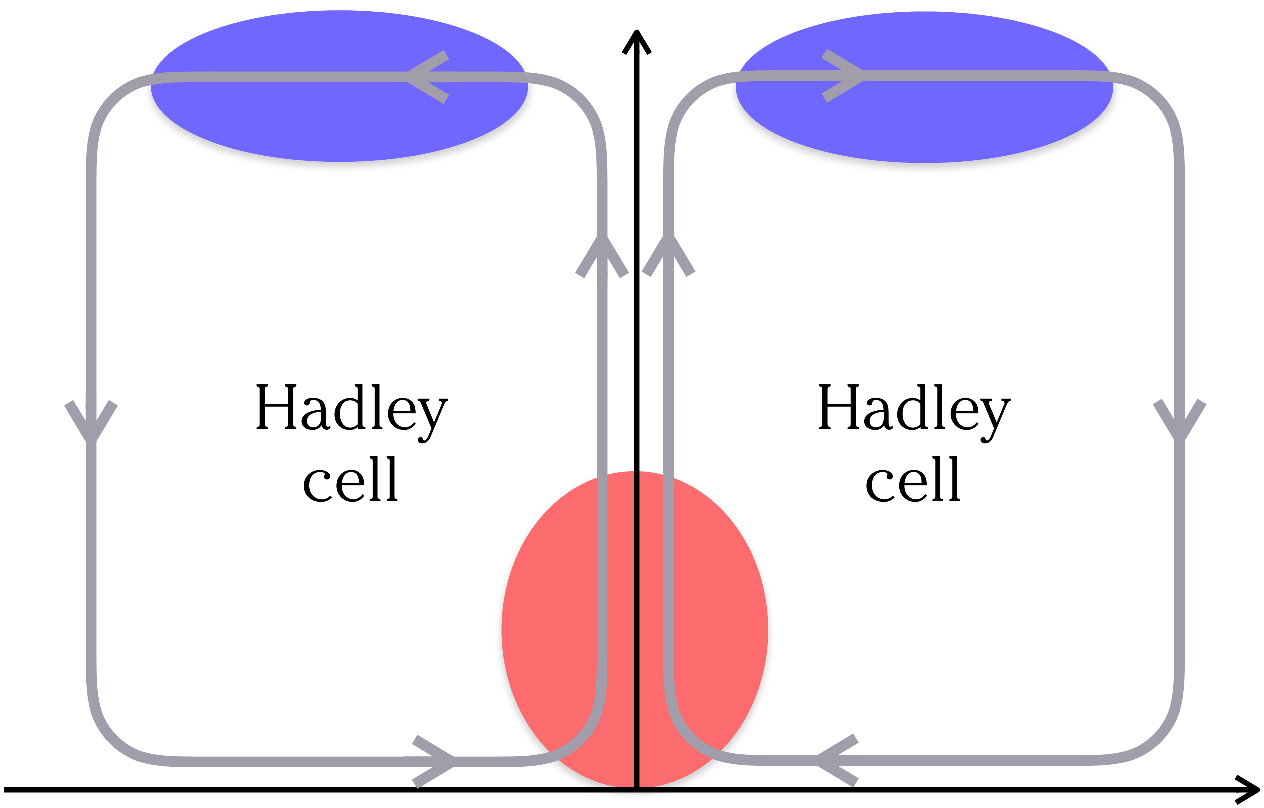
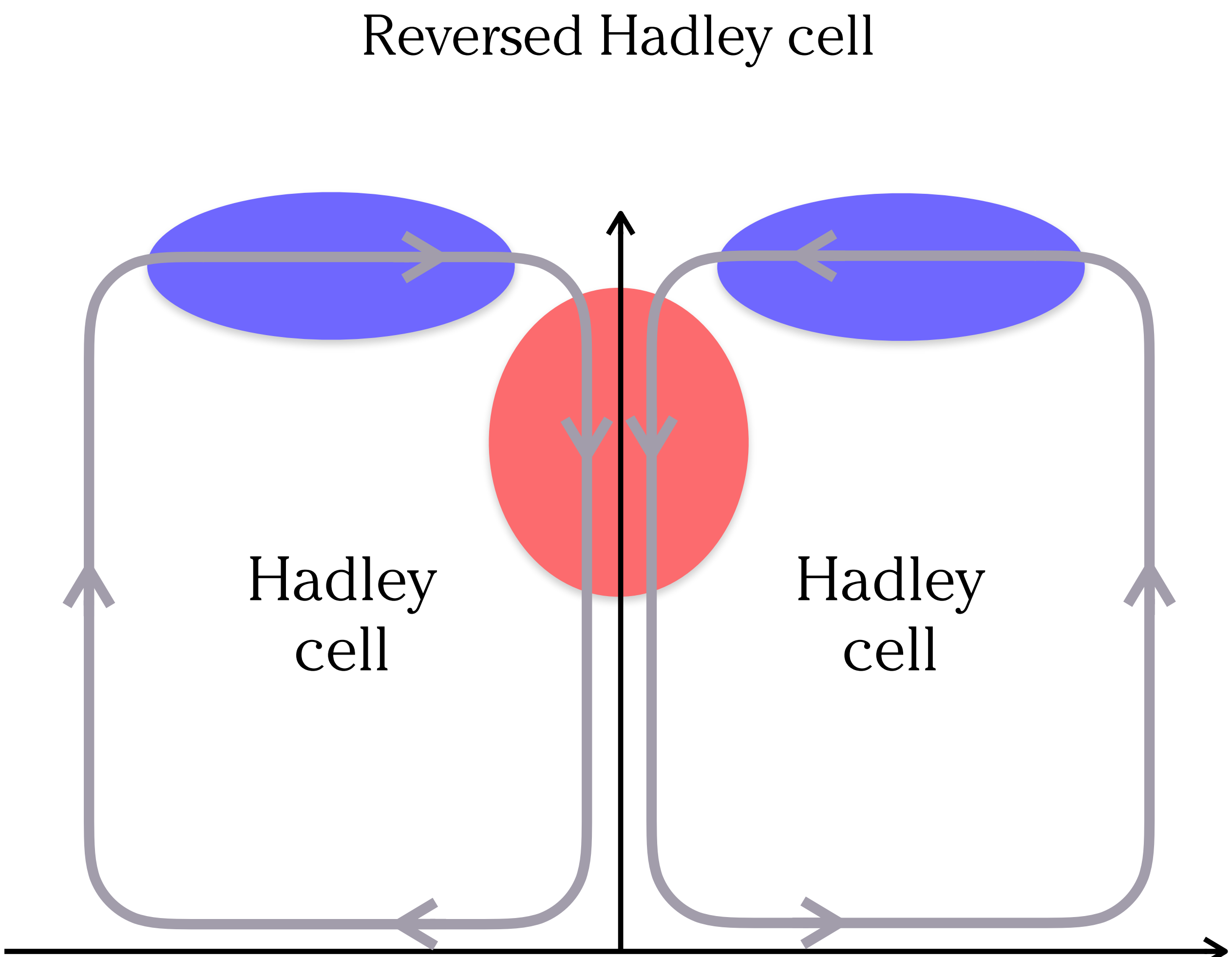


Surface superrotation — pathway 2

Momentum convergence at surface

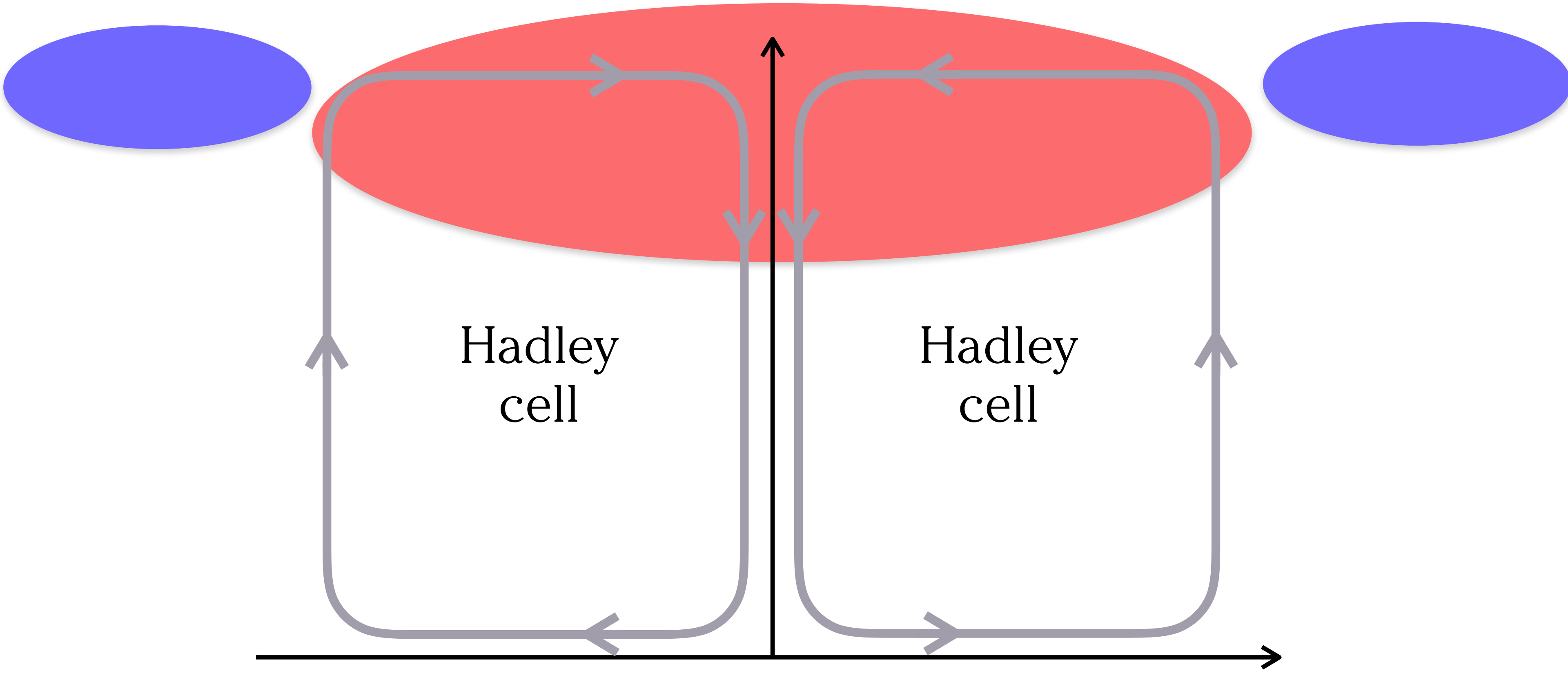


Surface superrotation — pathway 3

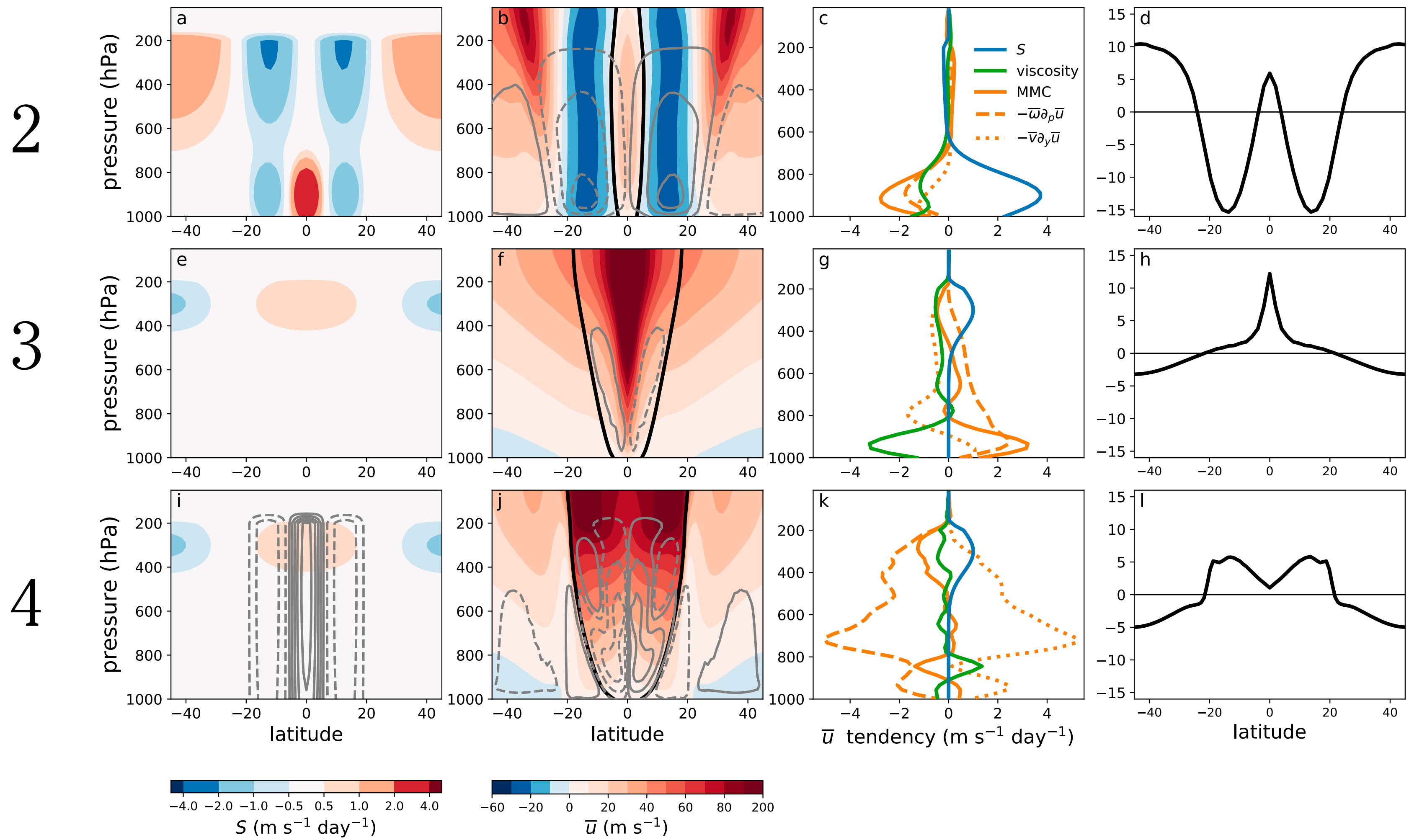


Surface superrotation — pathway 4

Momentum convergence
throughout Hadley cell region



Can realise all pathways in axisymmetric model



Conclusions

- Elevated tropical temperatures lead to enhanced MJO-like variability
- MJO-like mode is trapped within the upper-level subtropical jets
- Momentum convergence is confined to upper troposphere and drives superrotation
- Sufficiently high vertical viscosity can bring superrotation down to the surface, but in GCM requires order-of-magnitude increase in CMT
- Transition to surface superrotation in past or future warm climate seems unlikely; on the other hand, understanding of CMT remains crude and surprises could be in store.

Péclet number over broad range

$$Pe = \frac{\text{advective timescale}}{\text{diffusive timescale}} = \frac{\omega/p_s}{\nu/H^2}$$