Barotropic and Super-Rotating Jet Formation in the Evolution of Very Short Mixed Rossby-Gravity Waves

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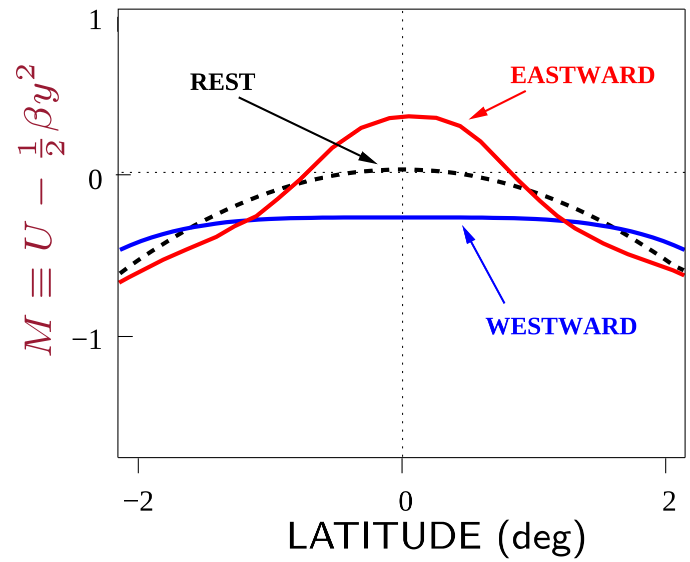
OUTLINE

1. Equatorial super-rotation
2. Super-rotation in the destabilization of a short westward MRG wave
3. Effect of non-traditional Coriolis force

1. Equatorial super-rotation

- Super-rotation refers to steady zonally symmetric eastward flow at the equator.



- Eastward flow at the equator implies absolute angular momentum greater than anywhere in the rest state.

  ⇒ cannot come about through simple 2-D (zonally symmetric) rearrangement of zonal-mean angular momentum.

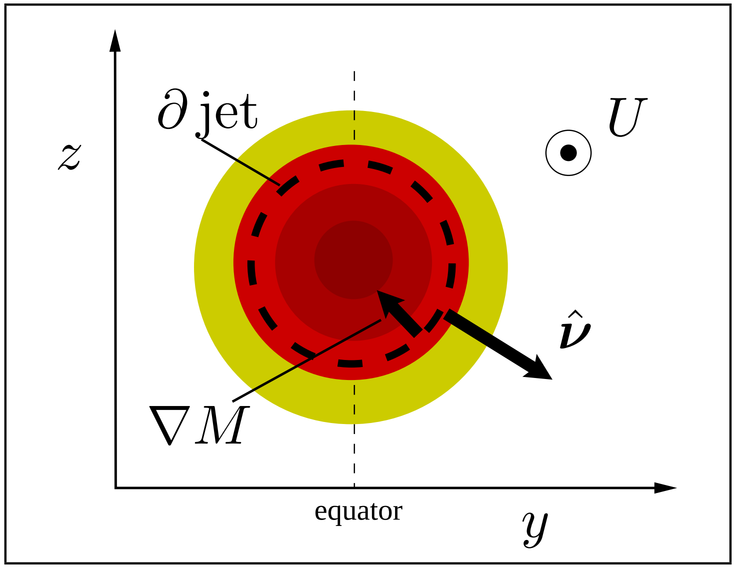
- Observed in stratosphere (QBO), other planets (global super-rotation on Venus: Gierasch, 1975), troposphere models (Suarez & Duffy, 1992; Saravanan, 1993; Williams, 2003; etc.)

- Hide's Theorem: If departures from zonal symmetry ("eddies") can be assumed to dissipate zonal-mean angular momentum down-gradient, then an isolated jet at the equator cannot exist in the steady state.

$$\frac{\partial}{\partial t}\iint\limits_{\text{jet}} M\,\mathrm{d}y\,\mathrm{d}z = \mu \int\limits_{\partial\,\text{jet}} \nabla M\cdot\hat{\boldsymbol{\nu}}\,\mathrm{d}l = 0$$

$M \equiv U - \frac{1}{2}\beta y^2, \quad U =$ zonal velocity

$\Rightarrow$ steady state $\Leftrightarrow \nabla M = 0$, i.e. no jet

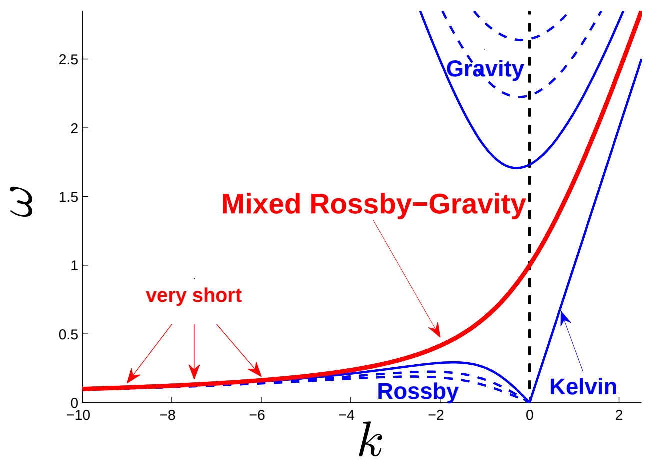


- Eddies must be tranferring angular momentum up-gradient.
- Key to maintaining super-rotation is non-local angular momentum transfer by waves (cf. QBO)

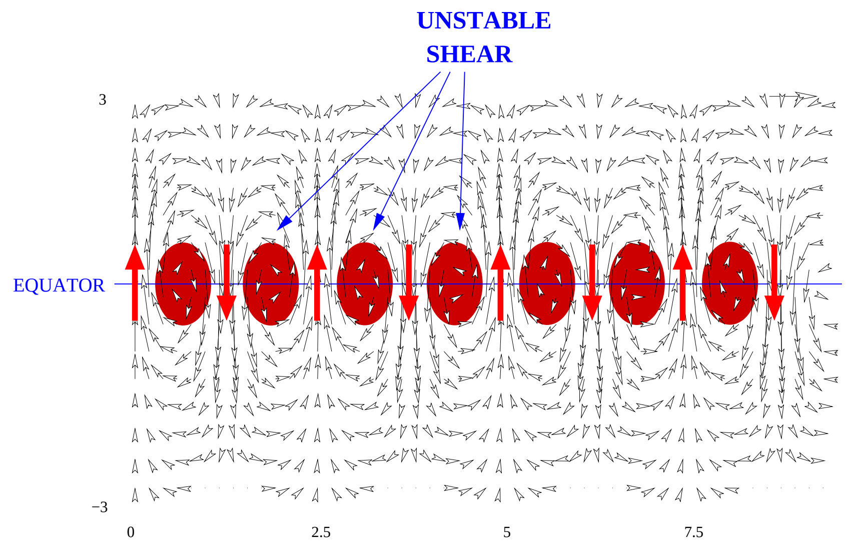
  $\Rightarrow$ Eastward jets might be sources of Rossby waves or sinks of Kelvin waves.

2. Super-rotation in the destabilization of a short westward MRG wave

DISPERSION DIAGRAM FOR EQUATORIALLY TRAPPED WAVES



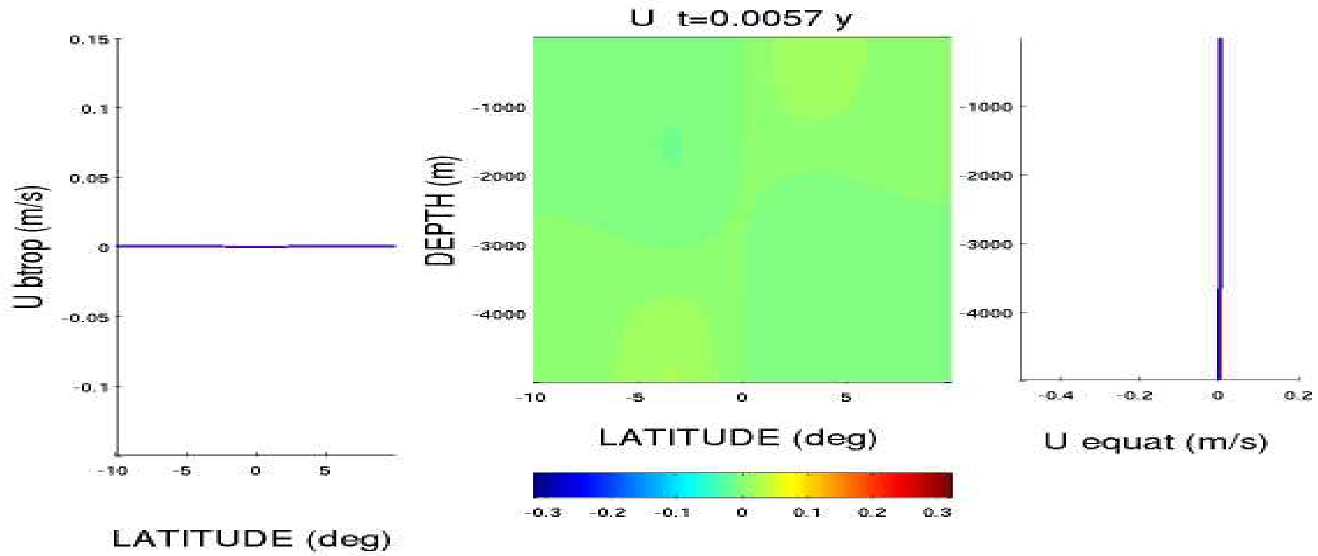
MRG WAVE VELOCITY FIELD



- Gill (1974) – short wavelength limit barotropic Rossby waves $\longrightarrow$ barotropic instability due to $\partial V/\partial x$ $\longrightarrow$ zonal jet formation.
- Hua et al. (2007) – MRG wave destabilization leads to extra-equatorial jets spaced by $\mathcal{O}(k^{-1})$ (explained by linear theory for non-divergent perturbations).

- MRG wave has same mean zonal angular momentum as rest state.
  - ⇒ Any eastward jet at equator in long time steady state implies up-gradient transfer of mean angular momentum transfer.
- We performed high-resolution (0.1° $\times$ $0.1^\circ \times$ 200 levels) simulations using ROMS for $k \lesssim -6k_R$, where k_R^{-1} is deformation radius.
- Two configurations of simulations:
  - * 10° long, 30° wide equatorial β-plane channel with periodic boundary conditions in x and lowest vertical mode MRG waves initialized over entire length.
  - * 150° long channel with MRG wave initialized over central 60°.

10° channel simulation



- Barotropic signal (left):
  - Westward flow at equator (Reason for bias – Hide's Theorem?)
  - Westward momentum flux from equator to extra-equatorial jets
- Equatorial profile (right):
  - Westward flow at depths of maximum initial wave amplitude
  - Twin eastward jets straddling depths of initial wave nodes.

10° channel simulation

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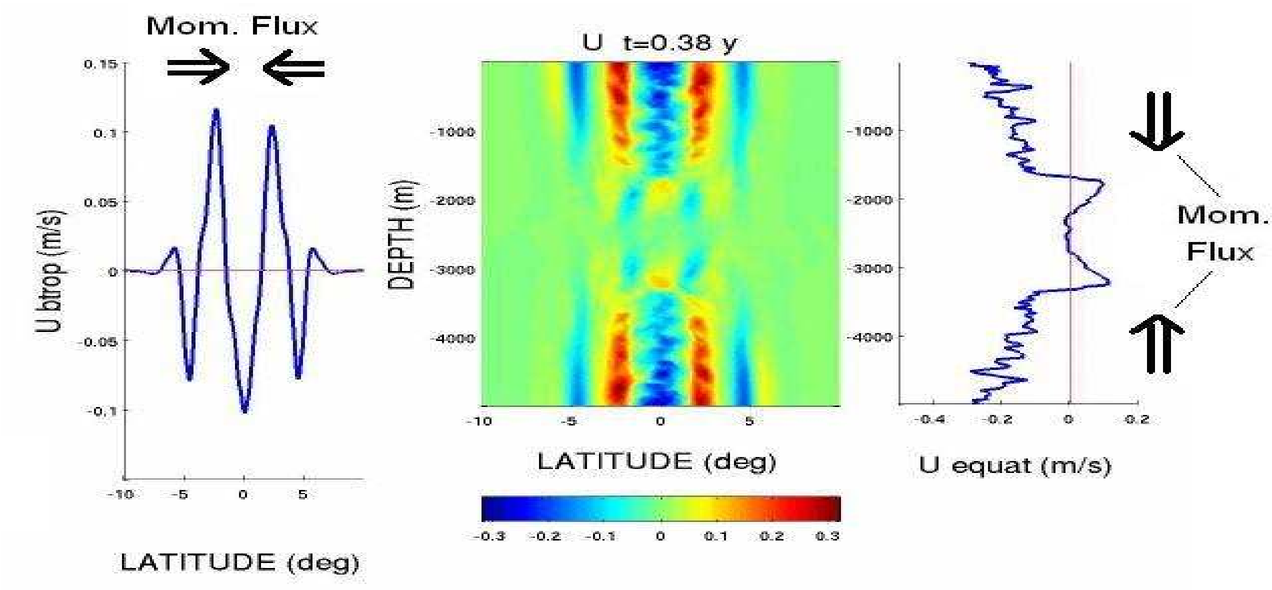

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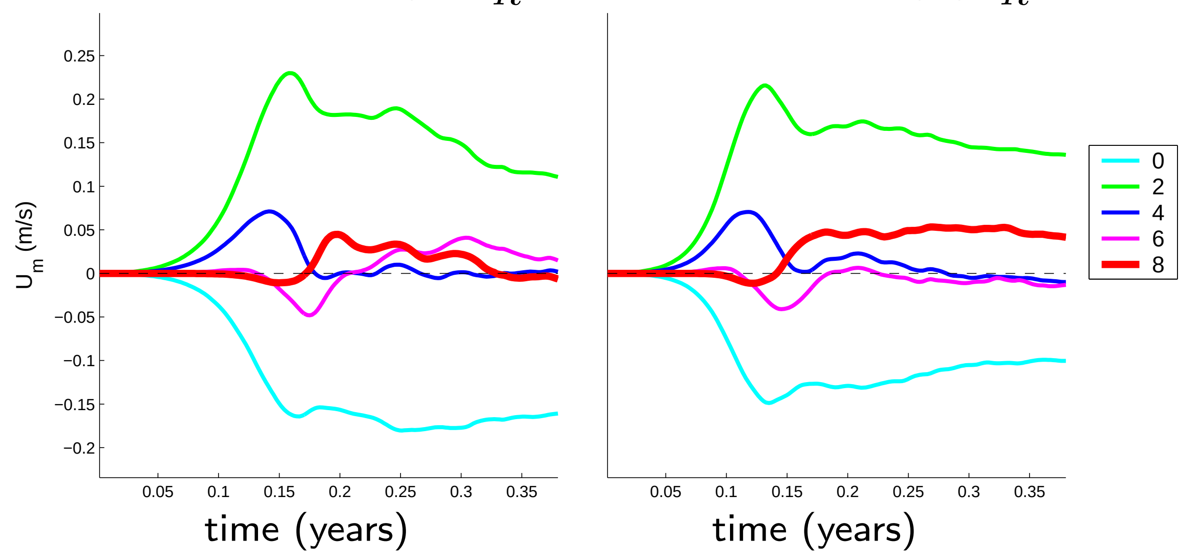
10° channel simulations

- Super-rotating jets appear for large enough $-k$ and high enough amplitude of the initial wave.

VERTICAL MODE AMPLITUDES

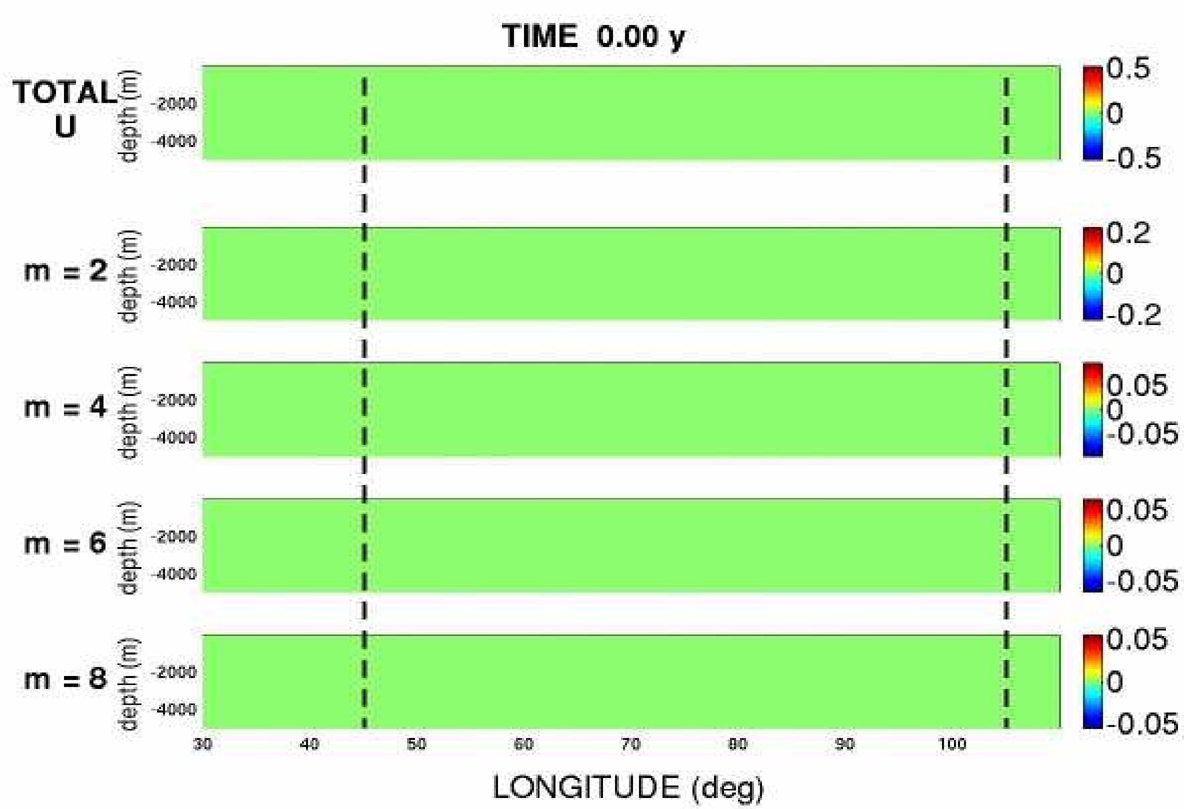
$k = -6.4k_R$ $\qquad$ $k = -8.6k_R$



LEFT: No super-rotation $\qquad$ RIGHT: Super-rotation

- Super-rotating state distinguished by strong **vertical mode 8**
- **Modes 8 and 6** amplify at expense of **modes 2 and 4**.

150° channel simulation



- Mostly westward (group) propagation of low vertical modes (Rossby waves?)
- Spatial correspondence of weakened **modes 2 and 4** and intensified **modes 6 and 8**, with **mode 8** predominating.

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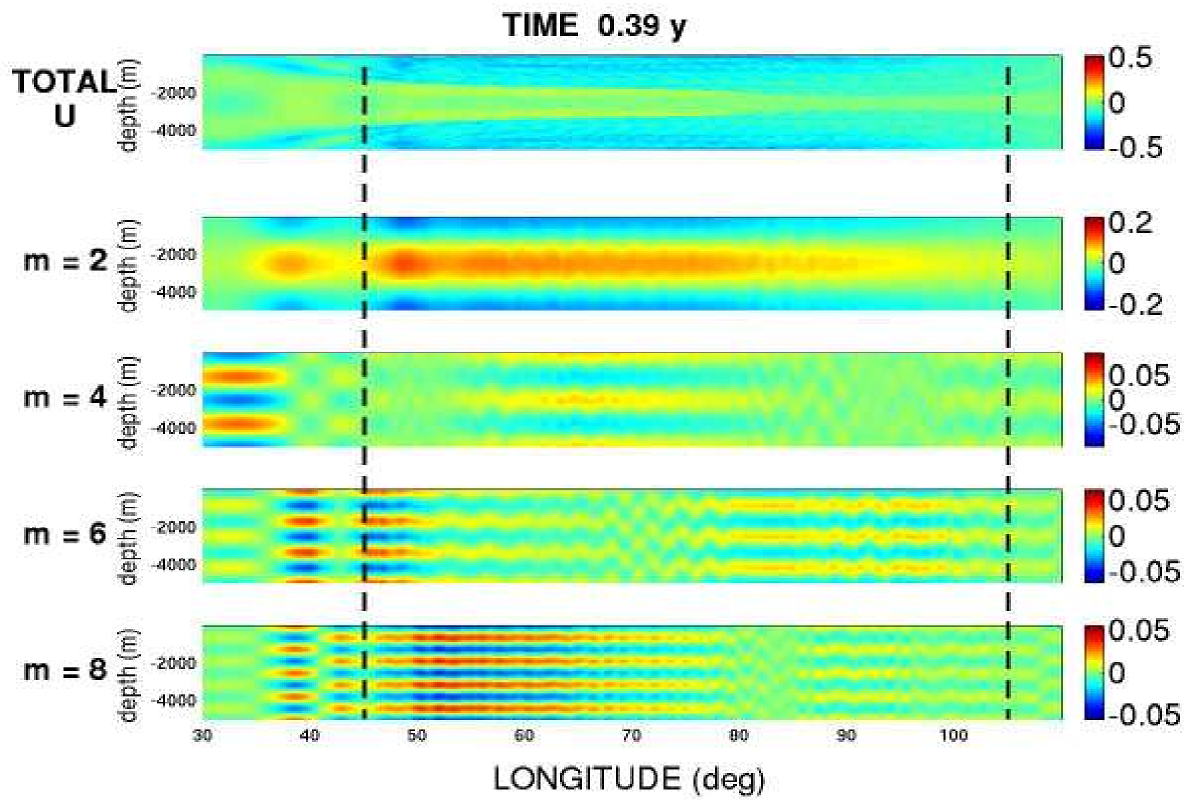

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3. Effect of non-traditional Coriolis force

- Coriolis force terms associated with $\gamma \equiv 2\Omega \cos\theta$ neglected in "traditional approximation" (Eckhart, 1960):

$$Du/Dt = \beta y v - \gamma w - p_x$$

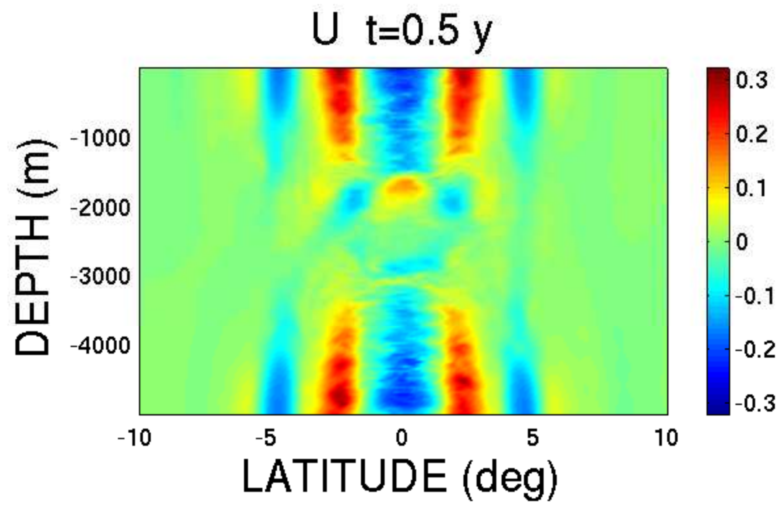
$$(\, Dw/Dt \,) = \gamma u - g\rho' - p_z$$

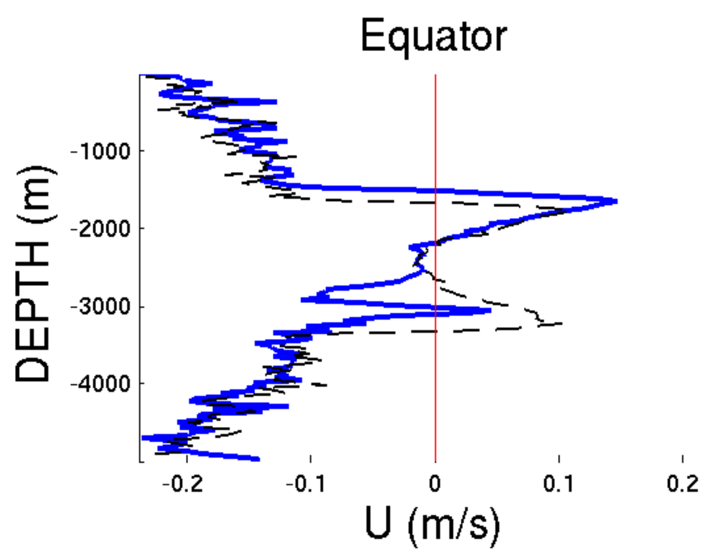
- Non-traditional terms couple zonal and vertical velocities and complicate interactions with bottom boundary (where $w = 0$).

- Significant for small aspect ratio (deep atmosphere - e.g. Jupiter), and near equator (White & Bromley, 1995; de Verdière & Schopp, 1994)

- Effect on equatorial wave solutions is $\mathcal{O}(2\Omega/N)$ (which is 10% in our simulations) in magnitude of velocity components.

- Effect on super-rotating jet much greater than 10%.
- Symmetry breaking in vertical: stronger upper jet, weaker lower
- What is reason for asymmetric vertical redistribution of angular momentum $M_\gamma \equiv U - \frac{1}{2}\beta y^2 + \gamma z$?
- For higher vertical mode initial states, symmetry is broken for each pair of eastward jets.





Summary

- Short westward propagating MRG wave destabilization can lead to sustained low vertical mode super-rotating jets, implying up-gradient angular momentum transfer.
- Eastward "super-rotating" jets appear to be associated with westward propagating modes of the instability (long Rossby waves?)
- Non-traditional Coriolis force acts to break vertical symmetry through coupling of u and w, strengthening upper branches of super-rotating jets.

Continuing Work

- Analysis of vertical and meridional momentum fluxes, diagnosis of momentum source for eastward jets.
- Quantification of effect of non-traditional Coriolis force terms and assessment of relevance to equatorial ocean dynamics.