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

Mark Fruman

Lien Hua, Richard Schopp

LPO, Ifremer

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OUTLINE

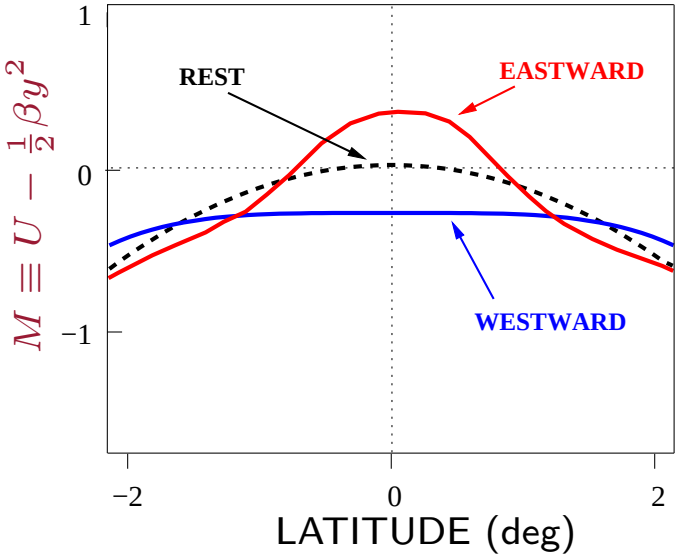
1. Equatorial super-rotation

2. Destabilization of 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, and thus a maximum of angular momentum in the interior.



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

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

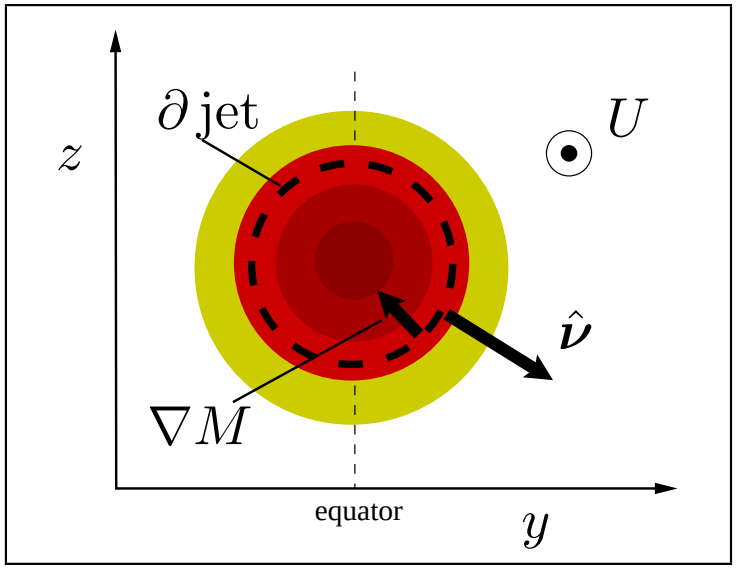
- Observed in stratosphere (QBO), other planets (global super-rotation on Venus: Gierasch, 1975), troposphere models (Suarez & Duffy, 1992; Saravanan, 1993; Williams, 2003; etc.)

- 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.

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

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

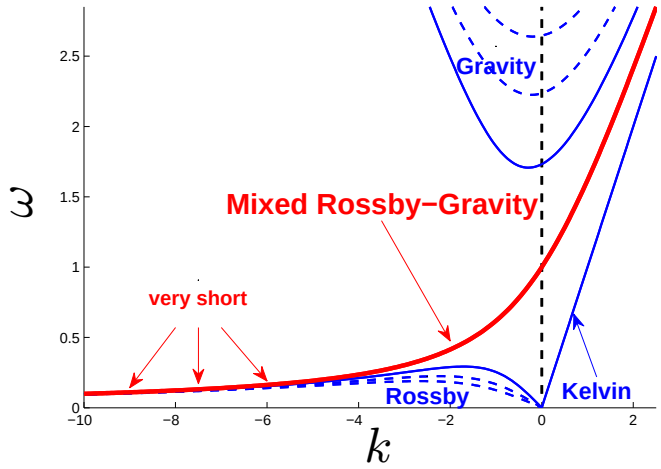
$\Rightarrow$ steady state $\Leftrightarrow \nabla M = 0$, i.e. no jet

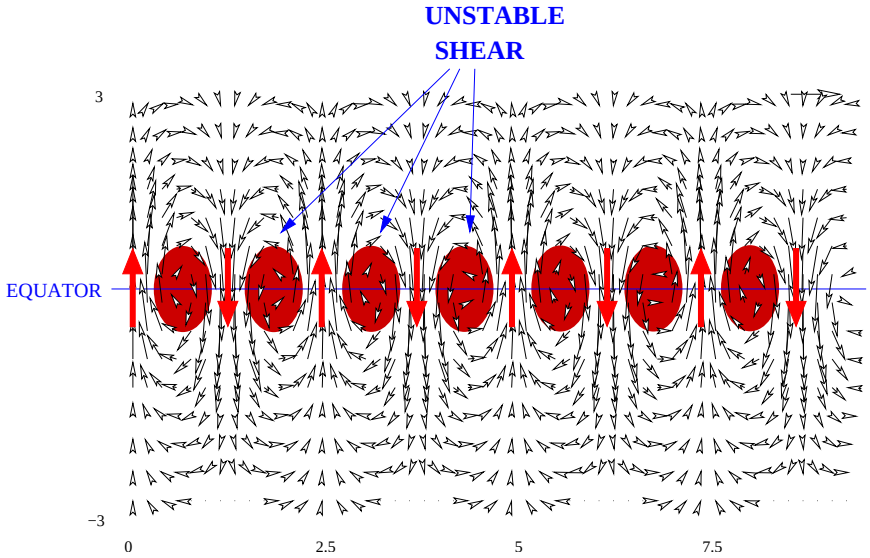


- Eddies must be tranferring angular momentum up-gradient.
- Key to maintaining super-rotation is non-local angular momentum transfer by waves

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

2. Destabilization of short westward MRG wave



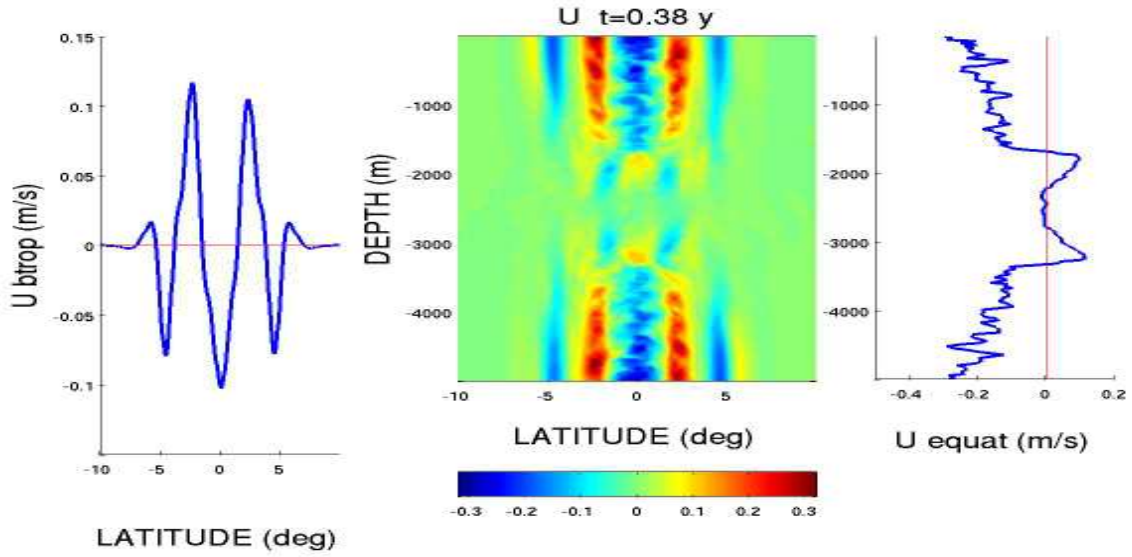


- Gill (1974) – short wavelength limit Rossby waves $\longrightarrow$ barotropic instability due to $\partial V/\partial x \longrightarrow$ zonal jet formation.
- Hua et al. (2007) – MRG wave destabilization leads to Extra-equatorial jets spaced by $\mathcal{O}(k^{-1})$ predicted by linear theory for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

10° channel simulation

- Barotropic signal:
  - westward flow at equator (reason for bias? Hide's Theorem?)
  - westward momentum flux from equator to extra-equatorial jets
- Equatorial profile:
  - westward flow at depths of maximum initial wave amplitude
  - narrow twin eastward jets stradling depths of initial wave nodes

10° channel simulation



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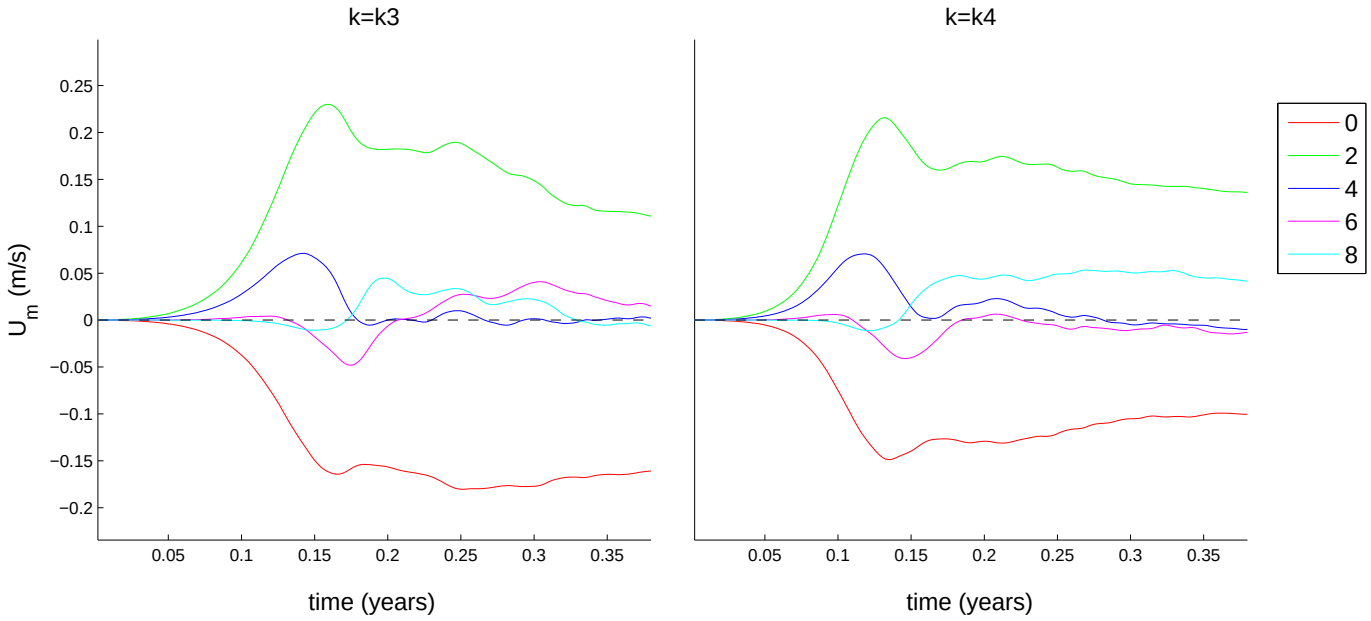
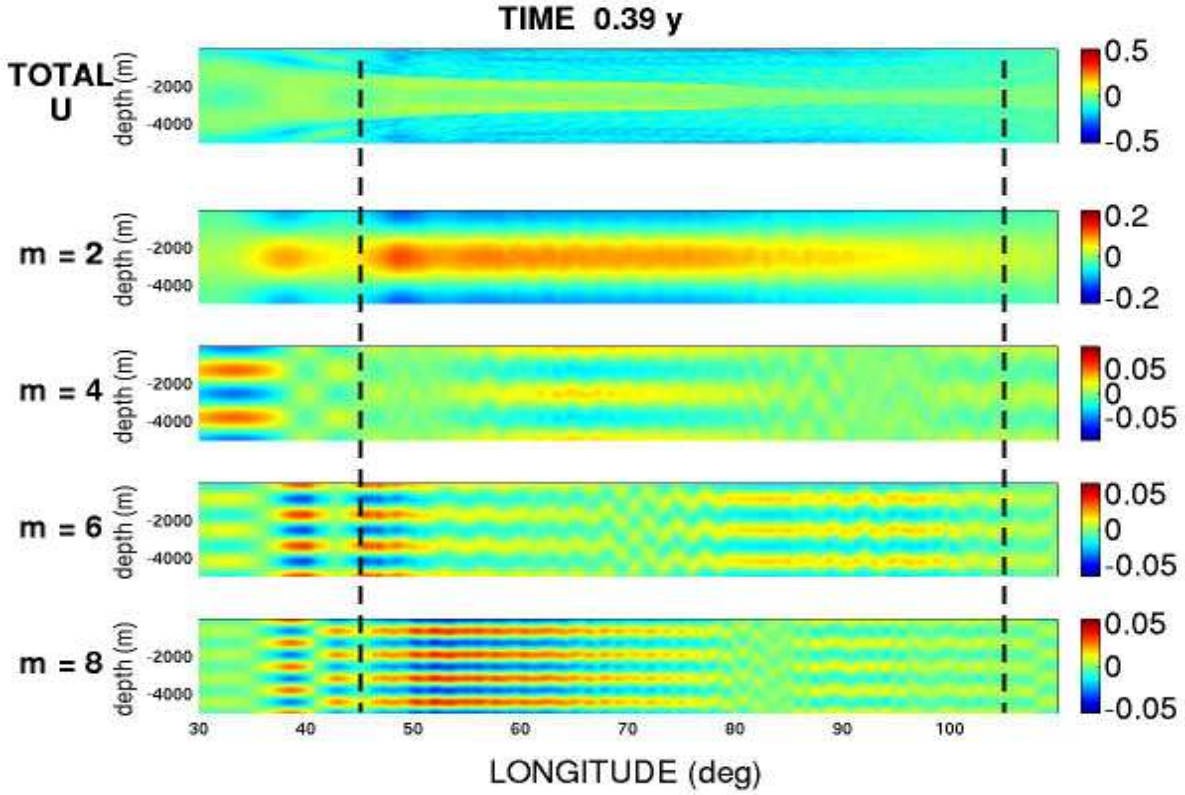


- Super-rotating state dominated by **vertical modes 2 and 8**.
- For large enough $-k$ and high enough amplitude, see twin eastward jets in long time equilibrated state.

150° channel simulation

- Westward (group) propagation of low vertical modes (Rossby waves?).
- Spatial correspondence of weakened **modes 2 and 4** and intensified **modes 6 and 8**.

150° channel simulation



- Westward (group) propagation of low vertical modes (Rossby waves?).
- Spatial correspondence of weakened **modes 2 and 4** and intensified **modes 6 and 8**.

3. Effect of non-traditional Coriolis force

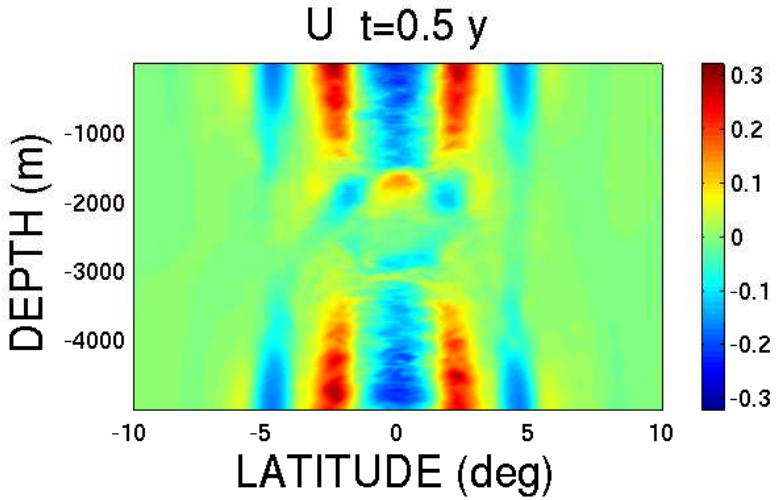
- Coriolis force terms associated with $\gamma \equiv 2\Omega \cos\theta$ neglected in traditional approximation (Eckhart, 1960):

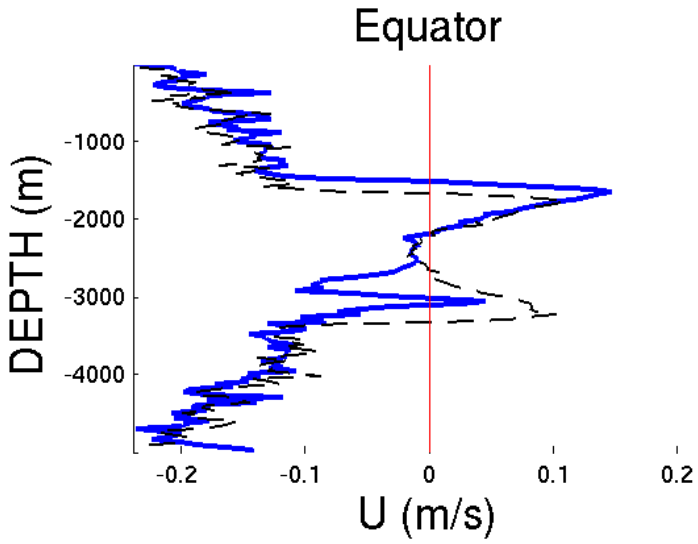
$$Du/Dt = \beta y v - \gamma w - p_x$$

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

- Significant for small aspect ratio (large w, 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: strong upper jet, weaker lower
- Perhaps due to interaction of lower boundary condition $w = 0$ with zonal velocity through term $2\Omega \cos\theta w$ in zonal momentum equation?





Summary

- Short westward propagating MRG wave destabilization can lead to sustained 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, perhaps through lower boundary and coupling of u and w, strengthening upper branch of super-rotating jet.

Continuing Work

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