Spatial early warnings of the transition to superrotation: Studying a bifurcation in the general circulation using an idealized GCM

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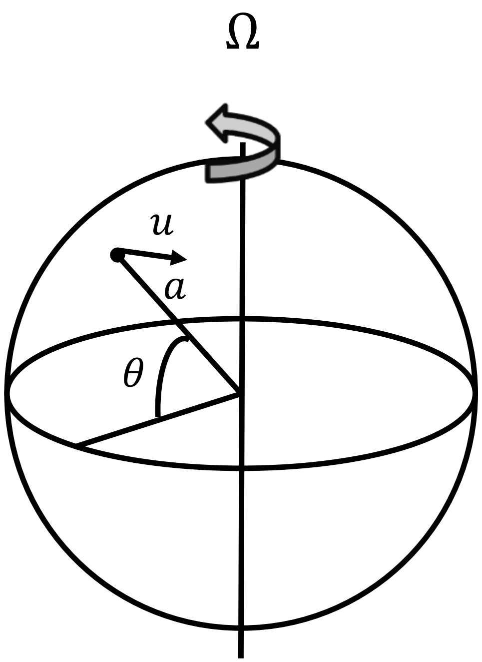
Multidimensional early warning signals of tipping points: Application to the transition to superrotation



What is superrotation?

When angular momentum of the atmosphere exceeds the solid body rotation of the planet.

$$M_E = \Omega\, a^2 cos^2\theta$$

Solid body angular momentum of Earth at latitude θ per unit mass, maximum at equator.

$$M = \left(\Omega + \frac{u}{a\cos\theta}\right) a^2 cos^2\theta$$

Angular momentum of atmosphere per unit mass

For superrotation $M > \max(M_E)$ or

$$u > \Omega\, a \frac{sin^2\theta}{\cos\theta}$$

Superrotation most likely to occur at the equator ($\boldsymbol{\theta = 0}$)

What this means for the west to east rotating Earth is that the easterlies at the equator change to westerlies following the transition to superrotation.

Superrotation occurs on Venus, Jupiter, Saturn and Titan

More background on superrotation as a tipping point

Q: Can superrotation happen on Earth?

- Possibly has already in the Early Cenozoic (Earth was much warmer than today, ~ 65 million years ago, the age of mammals)

R. Caballero, M. Huber, Spontaneous transition to superrotation in warm climates simulated by CAM3, *Geophysical Research Letters*, **37** (2010).

- Abrupt transition and bifurcation to superrotation found in 2 layer atmospheric model with asymmetric tropical heating. Transition controlled by heating strength. Multiple equilibria for the same heating strength found.

M.J. Suarez, D.G. Duffy, Terrestrial Superrotation: A Bifurcation of the General Circulation, *Journal of the Atmospheric Sciences*, **49** (1992) 1541-1554.

- Under more extreme global warming scenarios some climate models have started superrotating.

H.-P. Huang, K.M. Weickmann, C.J. Hsu, Trend in Atmospheric Angular Momentum in a Transient Climate Change Simulation with Greenhouse Gas and Aerosol Forcing, *J Climate*, **14** (2001) 1525-1534.

- Low probability but high risk potential tipping point – for example no easterlies = permanent El Nino state?

E. Tziperman, B. Farrell, Pliocene equatorial temperature: Lessons from atmospheric superrotation, *Paleoceanography*, **24** (2009).

- Ideal study case for the spatial early warning method set out in MSW and T. M. Lenton (2015). *Chaos* **25**, 036407

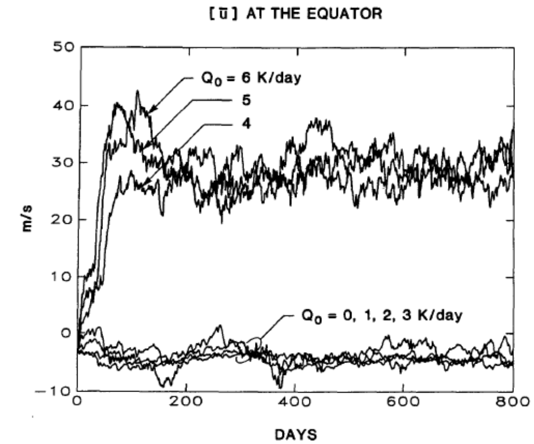


FIG. 2. Temporal evolution of the zonal average of $\bar{u}$ at the equator for various Q_0.

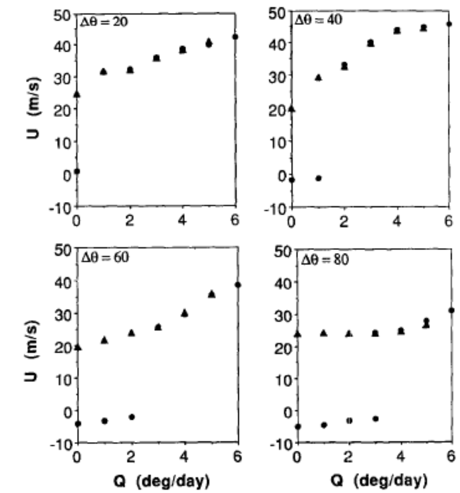
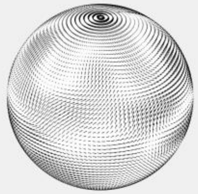
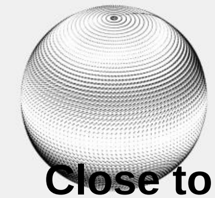


FIG. 7. The vertical mean zonal wind $[\bar{u}]$ at the equator for various values of Q_0 and $\Delta\theta$. The circles represent runs begun from a conventional circulation, and the triangles represent runs begun from a superrotating circulation.

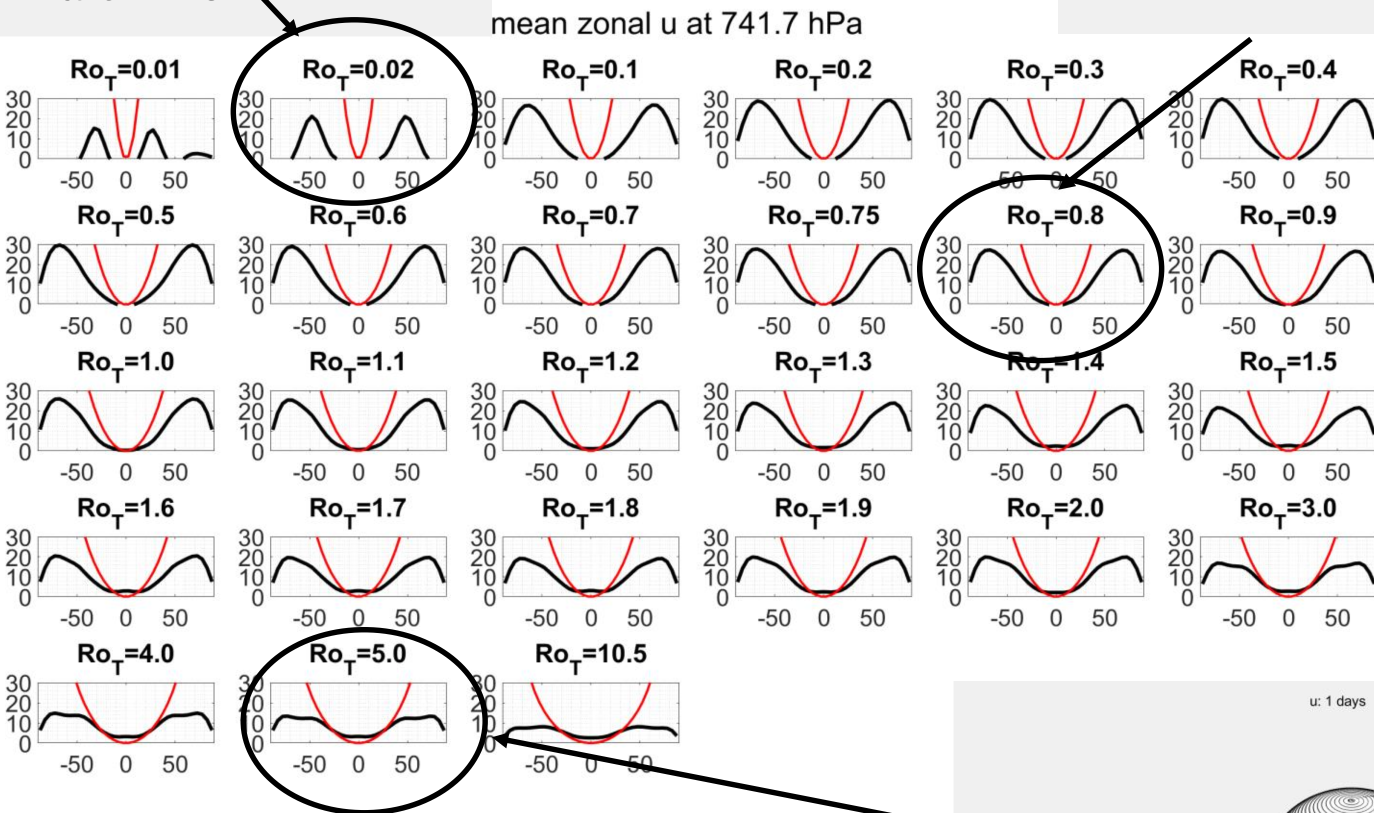
Mean state in simulations

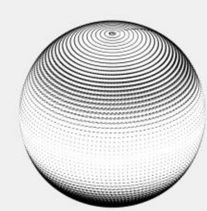


Earth like



Close to superrotation transition





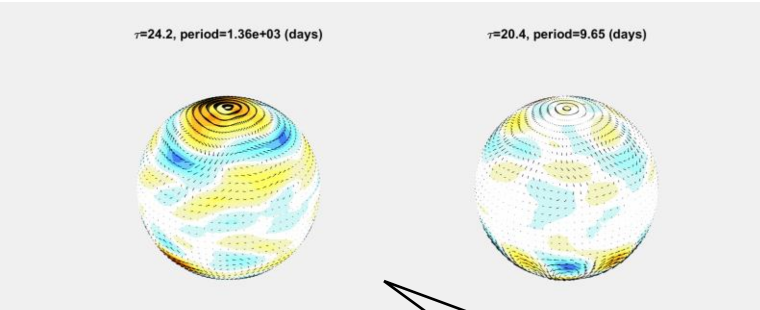
Fully superrotating

Control parameter thermal Rossby number $Ro_T = \frac{RT_0\Delta_H}{(2\Omega a)^2}$

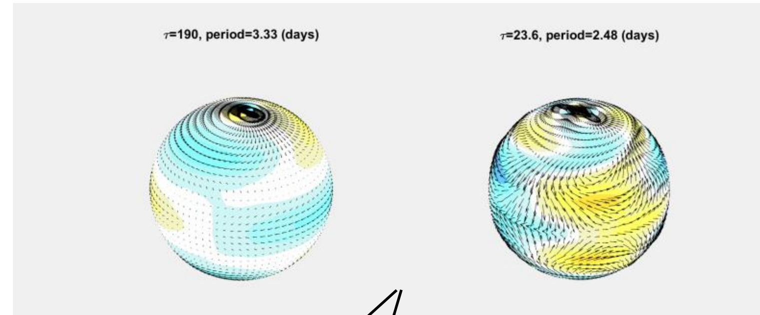
(via the planetary radius *a*)

Superrotation threshold $u > \Omega\, a \frac{sin^2\theta}{\cos\theta}$

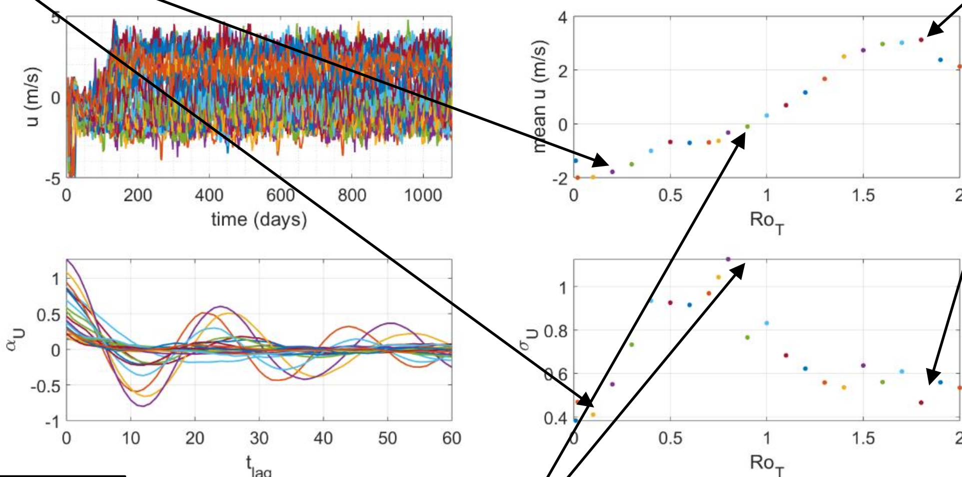
Development and theory of early warning signals of tipping points: Application to the transition to superrotation



$$\underline{\dot{\delta x}} - J\underline{\delta x} = \underline{\zeta}\,(t)$$



J mode space extremely degenerate at Earth like values

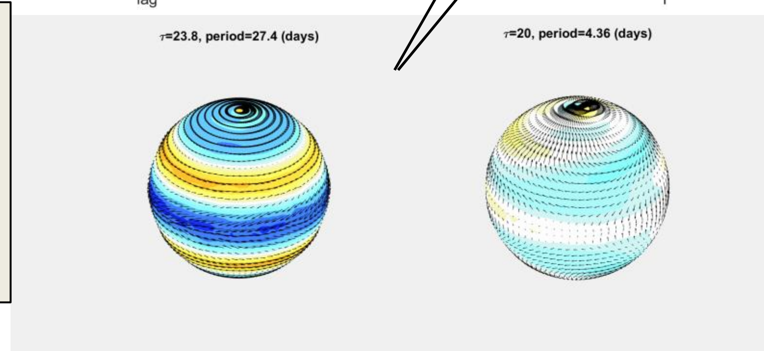


Overwhelmingly dominant J mode when superrotating

J goes through a series of broken symmetries

$$Z_2 \times SO(n) \rightarrow Z_2 \times SO(n-1)$$

Looks like a second order phase transition



Zonally symmetric 30 day oscillatory mode becomes dominant just before the superrotation transition

Summary

- Lots of interesting things going on in the spectrum and mode structure (plateaus, crossings, broken degeneracies/symmetries of subspaces of J) going through the transition to superrotation – work in progress.
- Prior to the transition a long period, lightly damped zonal mode appears and dominates the dynamics.
- Are there any generic properties in the precursors to this transition? Can you use any of the phase transition literature in statistical physics?
- Is it a bifurcation? Is it a second order phase transition? Is it something else?
- Under future global warming scenarios the Earth probably would not transition to superrotation in this way (radius of the planet unlikely to decrease under global warming). Could simulate this transition using a more plausible control parameter.
- Main reason to use this method was to get something working quickly to test the spatial early warning methods and build intuition.