Gravity Waves in the Laboratory: Mechanisms, Properties, and Impacts

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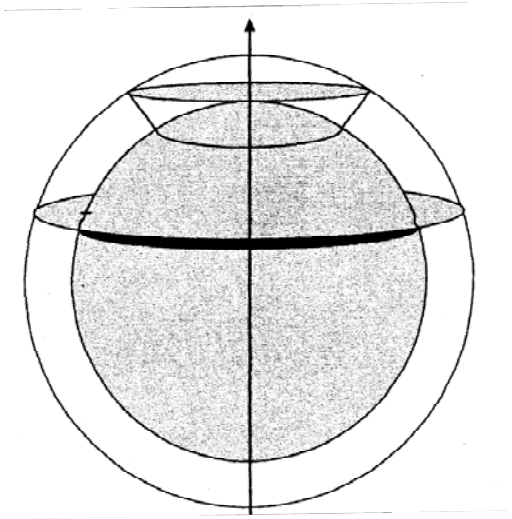
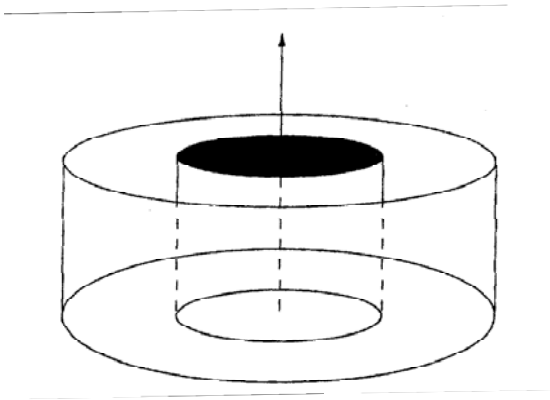
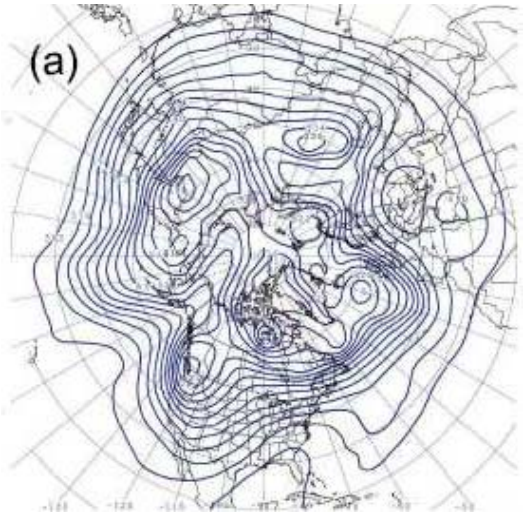
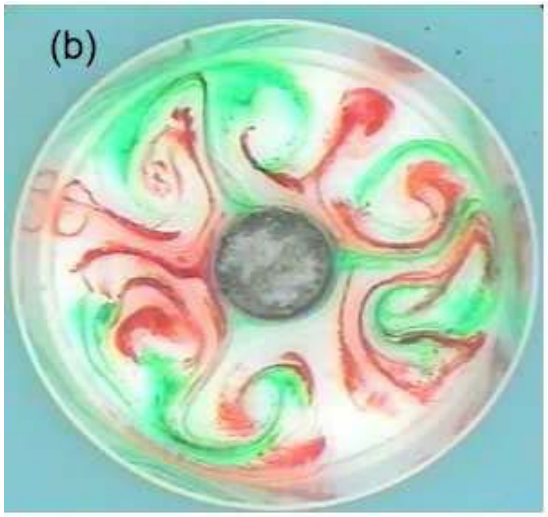
Rotating planet –v– rotating annulus



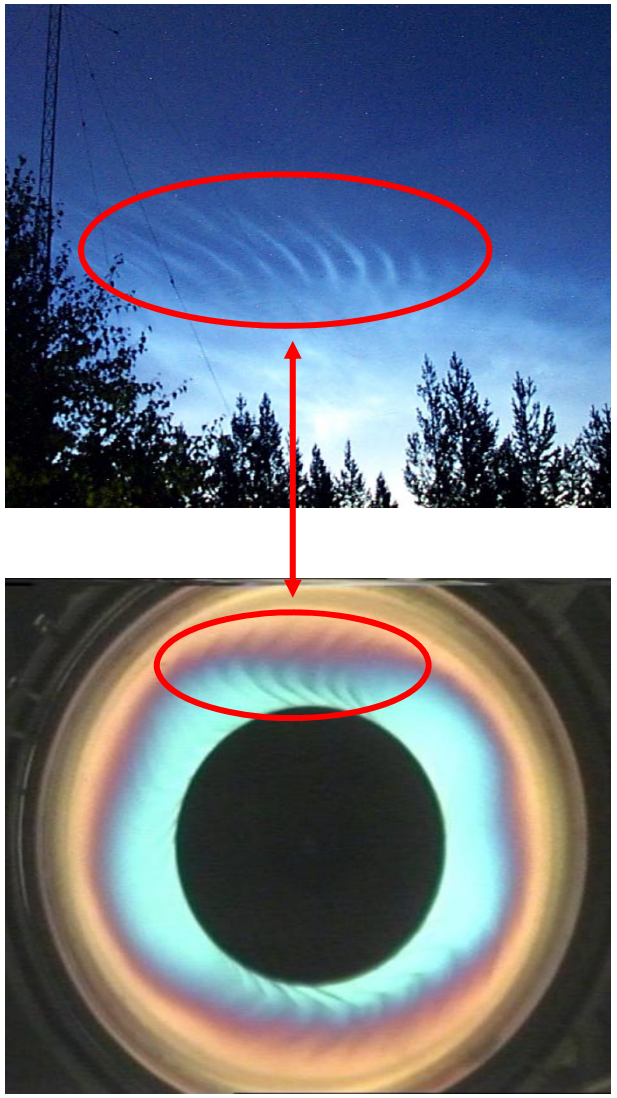


(Read et al. 1998)

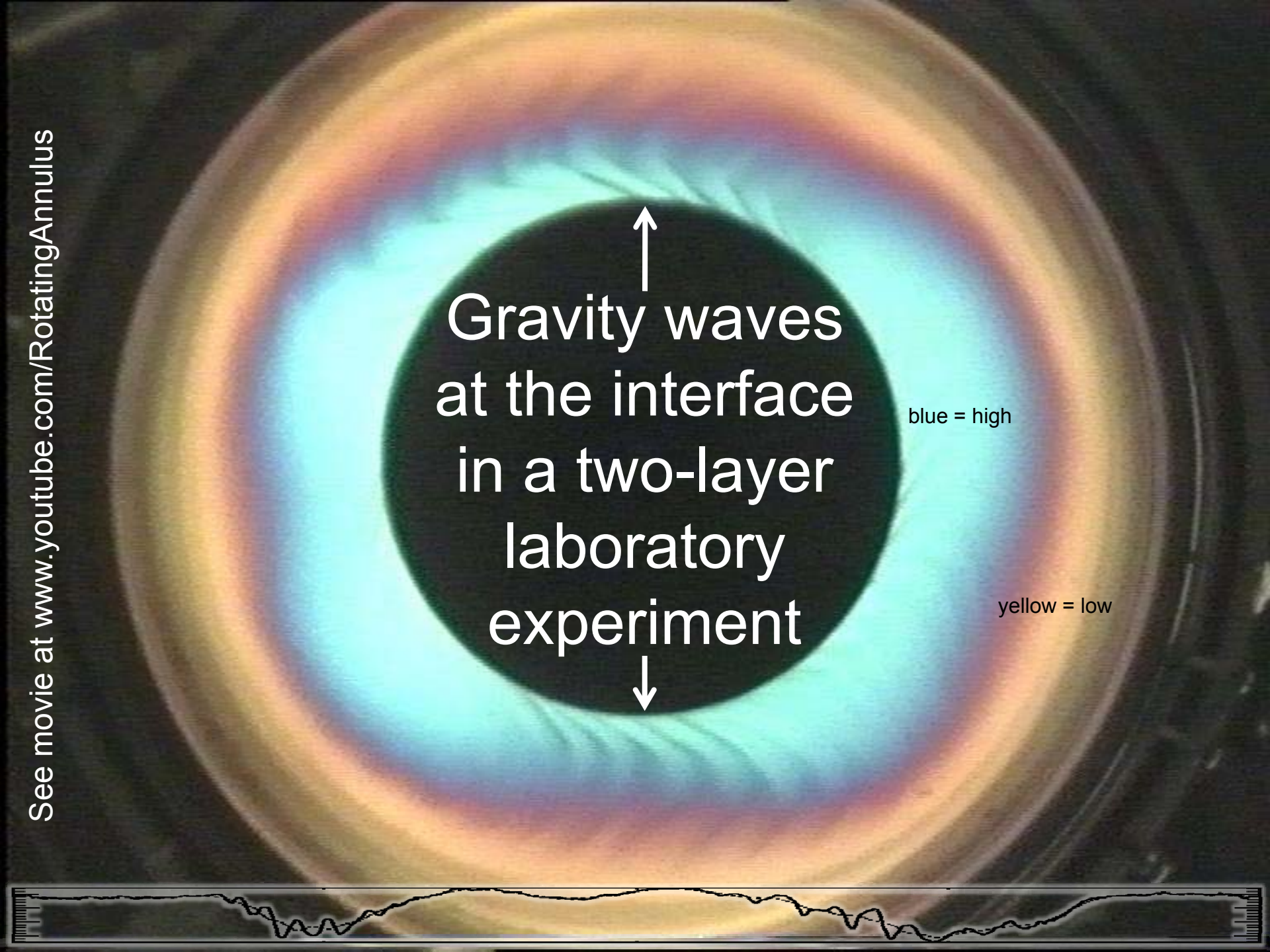




(Ravela et al. 2009)



(Williams et al. 2008)


Gravity waves
at the interface
in a two-layer
laboratory
experiment
blue = high
yellow = low
See movie at www.youtube.com/RotatingAnnulus

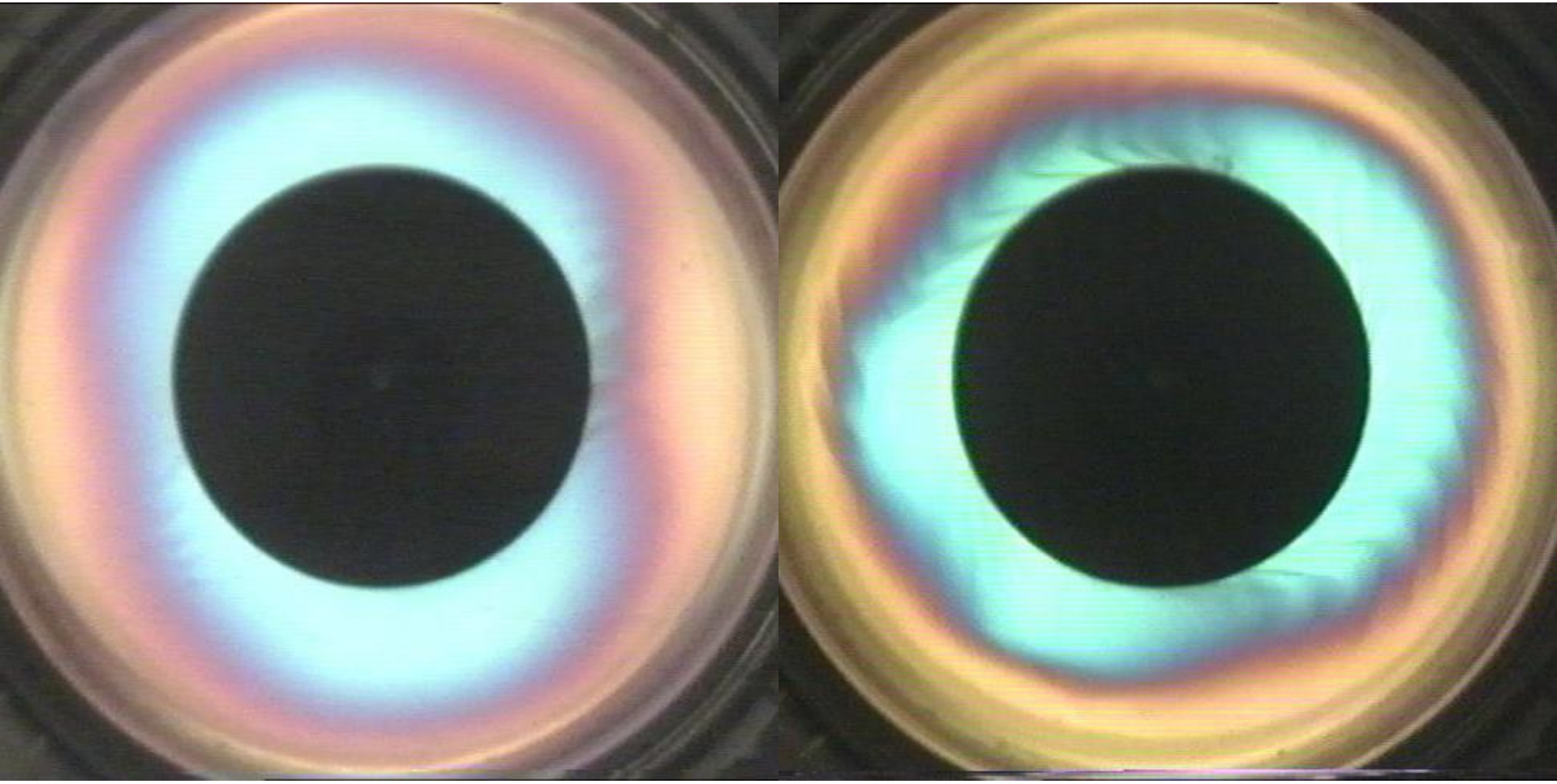
Generation mechanism

Possible generation mechanisms for the gravity waves

- Flow over topography
- Convection
- Kelvin-Helmholtz shear instability
- Surface forcing of the ocean by the atmosphere
- Lateral boundary instability
- Geostrophic-adjustment emission from an unbalanced initial state
- Spontaneous-adjustment emission

Properties

Variation of gravity wave amplitude with Ro

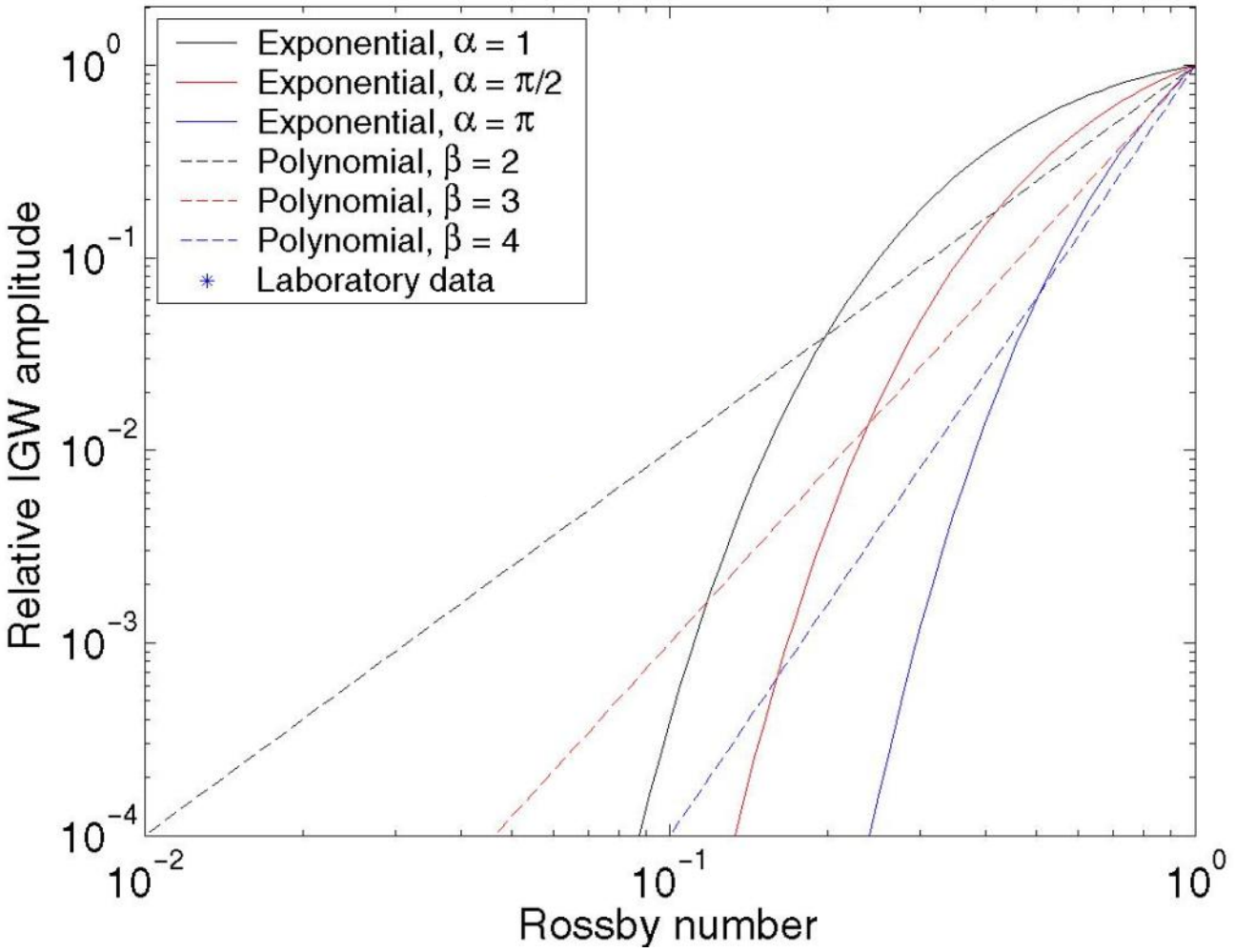


Ro = 0.05

Ro = 0.14

(Williams et al. 2008)

Variation of gravity wave amplitude with Ro



- non-asymptotic theories suggest $\sim Ro^{-1/2} \exp(-\alpha/Ro)$ (e.g. Vanneste & Yavneh 2004; Plougonven et al. 2005 find that $\alpha >= \pi/2$)
- standard asymptotic analysis suggests $\sim Ro^{\beta}$, where $\beta >= 2$
- but the laboratory data suggest $\sim Ro^{1}$, **apparently in contradiction to theory**

(Williams et al. 2008)

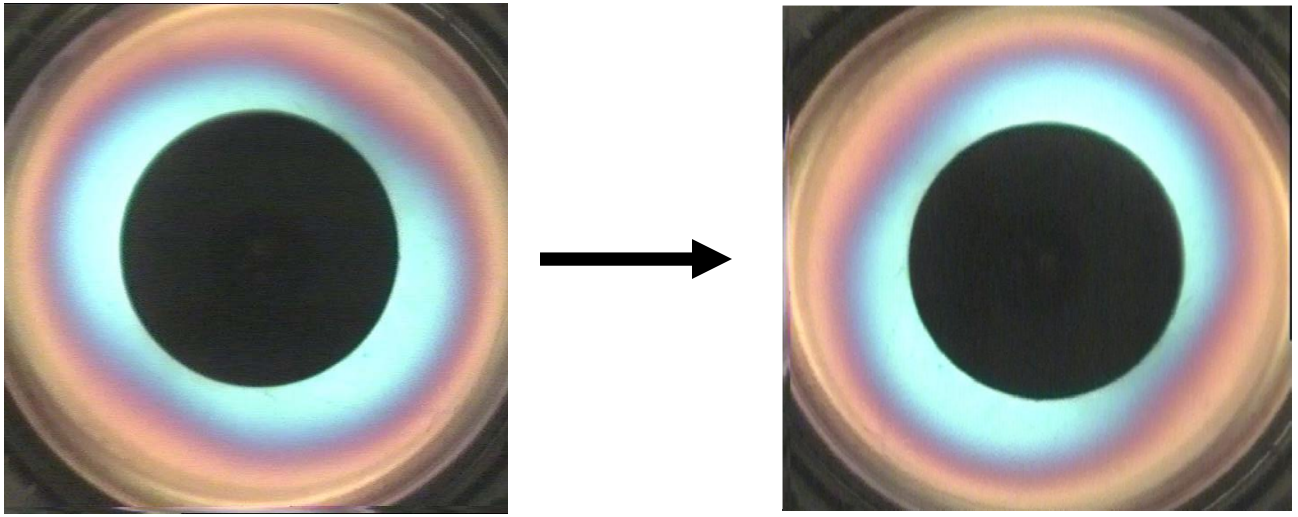
Wave energetics

- The total energy (i.e. kinetic plus potential) of the fluid has contributions from the waves and the zonal-mean zonal flow.
- For Rossby numbers ~0.1, we find that 91% of the wave energy is in the large-scale rotational wave, and the remaining 9% is in the short-scale inertia-gravity waves (Williams et al. 2008).
- These numbers compare well with those from atmospheric reanalysis data (90% and 10%, respectively; Žagar et al. 2009).
- Of the energy in the large-scale wave, we find that ~1% per 'day' is fed into the inertia-gravity waves.

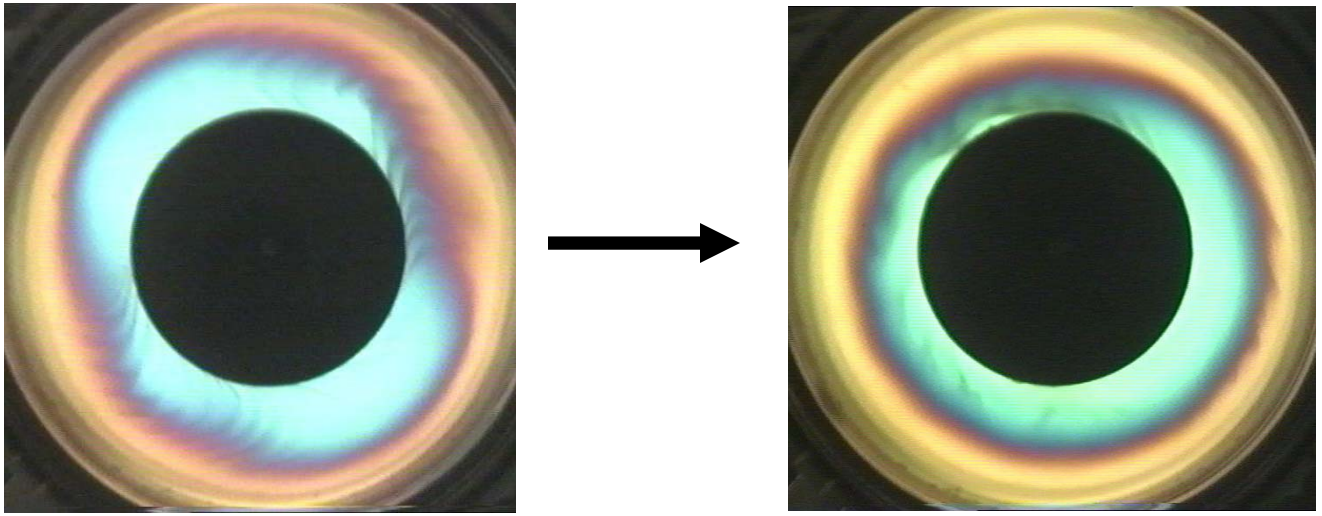
Impacts on the large-scale flow

Gravity wave-induced flow transitions

without gravity waves



with gravity waves ('noise'-induced transition)



Crude stochastic gravity-wave parameterisation in QG equations:

$$\frac{\partial q_1}{\partial t} = \frac{1}{r}\frac{\partial \psi_1}{\partial \theta}\frac{\partial q_1}{\partial r} - \frac{1}{r}\frac{\partial \psi_1}{\partial r}\frac{\partial q_1}{\partial \theta} - \frac{\sqrt{\Omega\nu_1}}{H}\left[\nabla^2\psi_1 + \chi_2\nabla^2(\psi_1 - \psi_2)\right] + \frac{2\Delta\Omega\sqrt{\Omega\nu_1}}{H} + \eta$$

$$\frac{\partial q_2}{\partial t} = \frac{1}{r}\frac{\partial \psi_2}{\partial \theta}\frac{\partial q_2}{\partial r} - \frac{1}{r}\frac{\partial \psi_2}{\partial r}\frac{\partial q_2}{\partial \theta} - \frac{\sqrt{\Omega\nu_2}}{H}\left[\nabla^2\psi_2 + \chi_1\nabla^2(\psi_2 - \psi_1)\right] - \eta$$

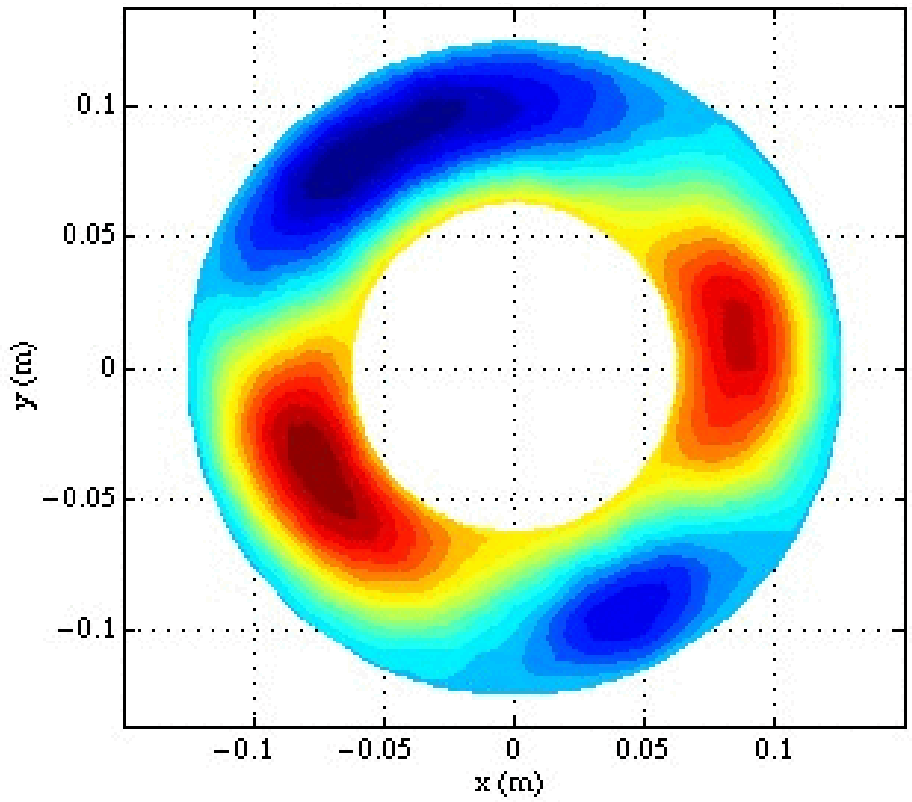
advection | Ekman layer dissipation | lid | additive, uniformly-distributed white noise (purely baroclinic)

where:

$$q_1 = \nabla^2\psi_1 + \frac{f^2}{g'H}(\psi_2 - \psi_1) + \frac{f}{H}\frac{r^2\Omega^2}{2g}$$

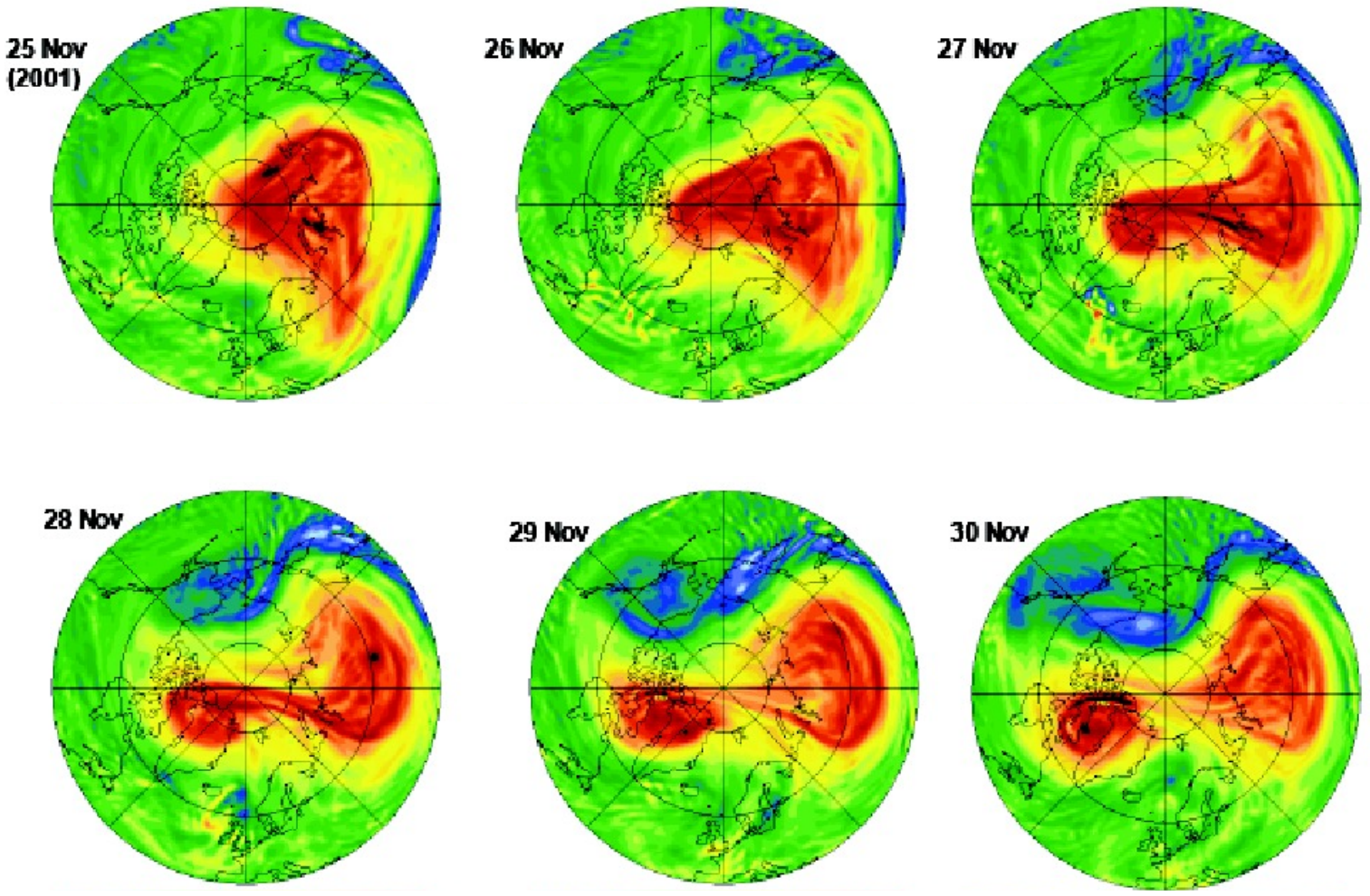
$$q_2 = \nabla^2\psi_2 - \frac{f^2}{g'H}(\psi_2 - \psi_1) - \frac{f}{H}\frac{r^2\Omega^2}{2g}$$

Noise-induced transition in the *QUAGMIRE* quasi-geostrophic model



(Williams et al. 2004)

Polar vortex splits as gravity wave noise-induced transitions



Birner and Williams (JAS; 2008)

Summary

- We appear to have observed the spontaneous generation of gravity waves by balanced flow in the laboratory
- The gravity wave amplitude varies linearly with Ro… does anyone have an explanation for this?!
- About 1% of the balanced flow energy is lost to gravity waves each ‘day’
- The gravity waves influence large-scale flow transitions and may be modelled as random stochastic noise

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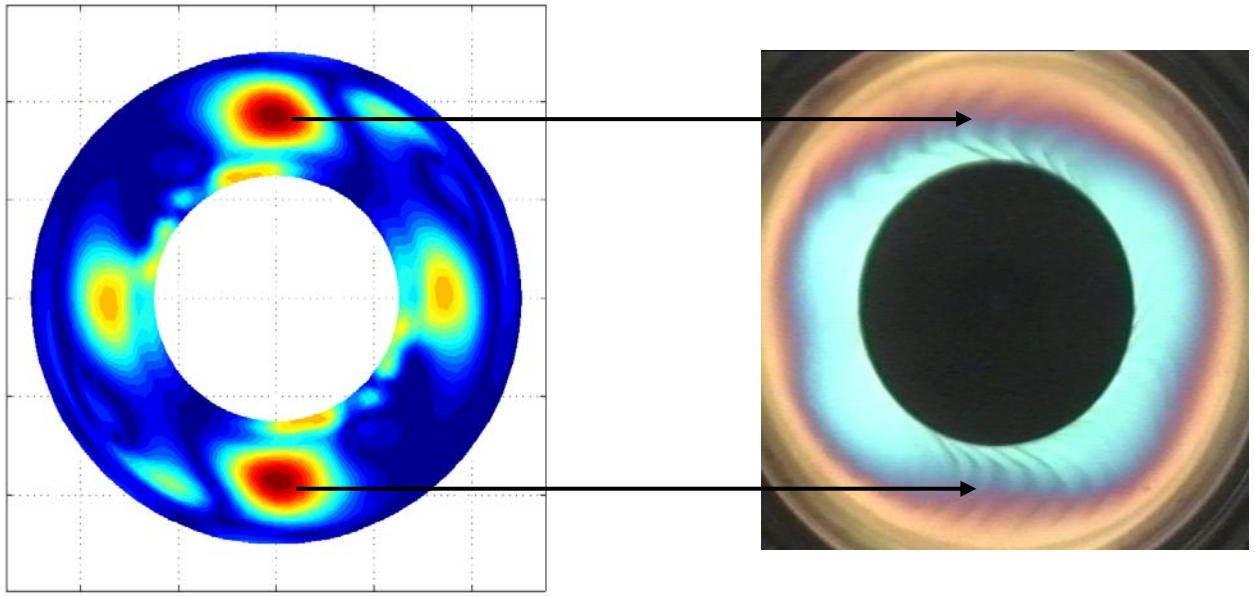
Spontaneous-adjustment emission?

RSWEs (Ford, 1994): $$\left(\frac{\partial^2}{\partial t^2} + f^2 - gH\nabla^2\right)\frac{\partial h}{\partial t} = \frac{\partial}{\partial t}\nabla\cdot\boldsymbol{G} + f\boldsymbol{k}\cdot\nabla\times\boldsymbol{G} + \frac{g}{2}\frac{\partial}{\partial t}\nabla^2 h^2$$

eigenmodes are GWs: $\omega^2 = f^2 + gHK^2$

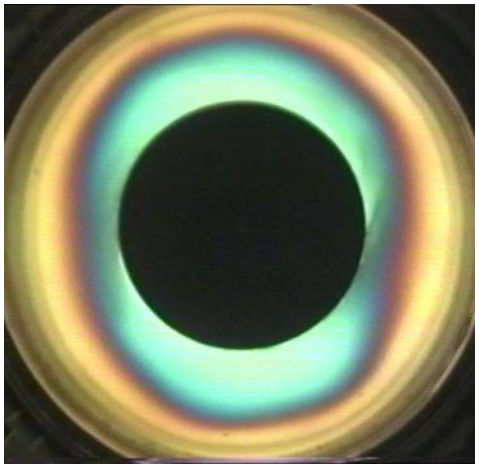
GW source term, where $\boldsymbol{G} = \boldsymbol{u}\nabla\cdot(h\boldsymbol{u}) + (h\boldsymbol{u}\cdot\nabla)\boldsymbol{u}$



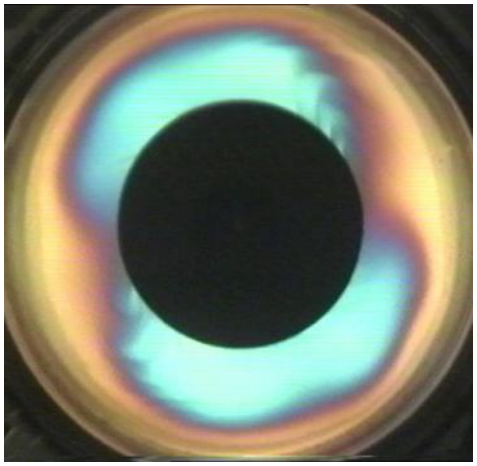
GW source term

Williams, Haine & Read (JFM; 2005)

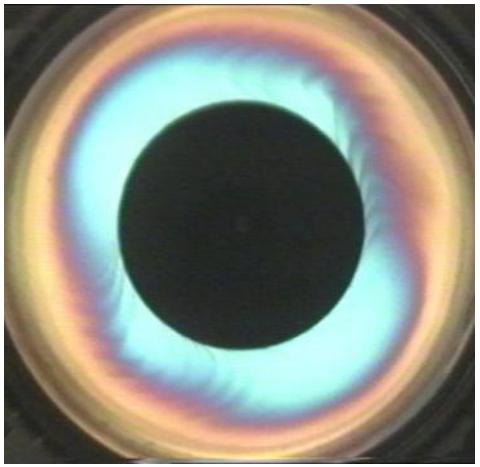
Baroclinic lifecycle (Δt = 22 s):



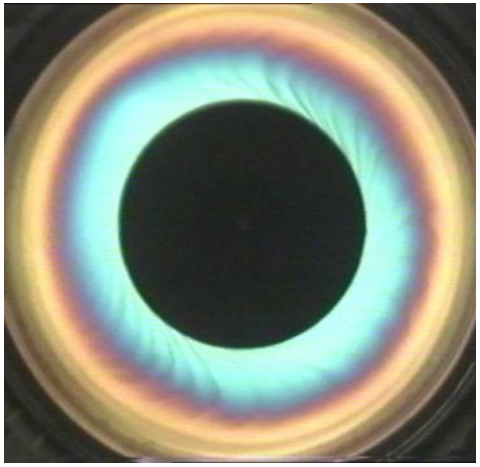
φ = 0°



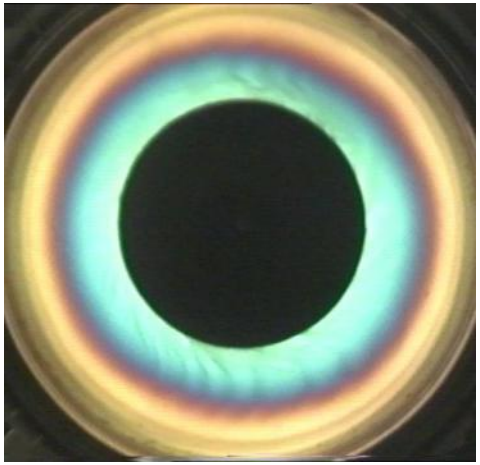
φ = 60°



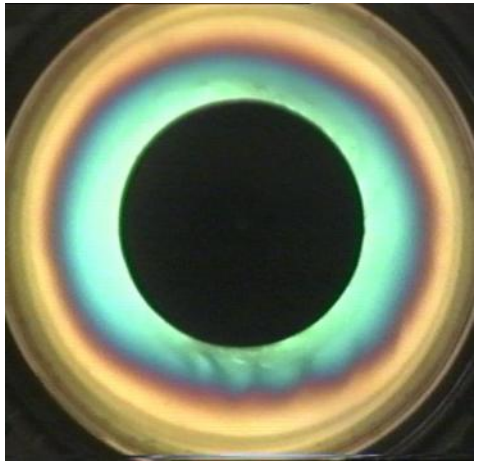
φ = 120°



φ = 180°



φ = 240°

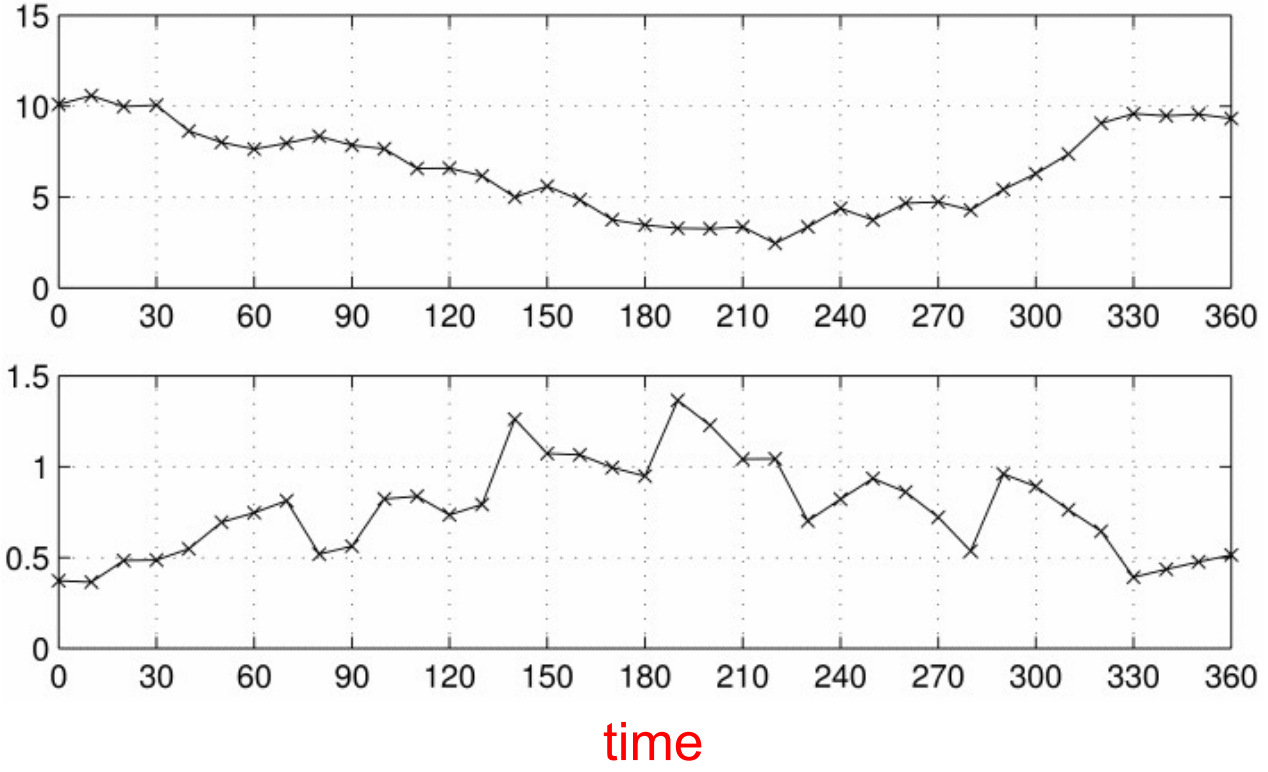


φ = 300°

(Williams et al. 2008)

large-scale flow amplitude (mm)

gravity wave amplitude (mm)



→ rate of energy growth in the gravity waves, as a fraction of the large-scale wave energy, is ~1% per turntable rotation period

(Williams et al. 2008)