Laboratory Modelling Of Bistability In Mid-Latitude Atmospheric Jets

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Turbulence From Angstroms to Light Years
ICTS, Bengaluru, India
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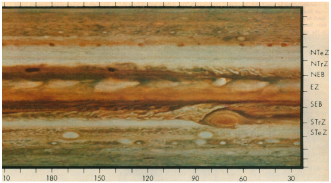
Turbulence In Geophysical Systems

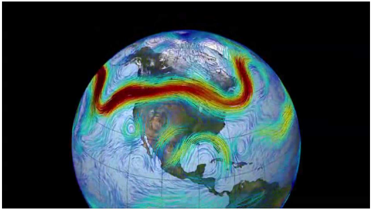
- Shallow water flows dominated by rotation; predominantly **two-dimensional**
- Inverse energy cascade
- Organization into large-scale structures like jets, vortices

Smith 1979

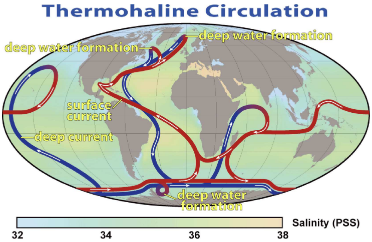


Voyager1's image of Jupiter's atmosphere

Large scale jets/currents in the atmosphere/ocean



Mid-latitude atmospheric jet

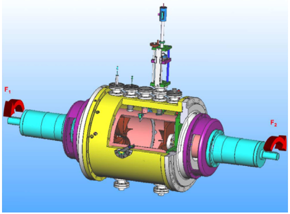


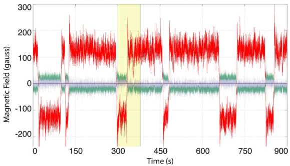
General oceanic circulation

- Abrupt qualitative changes in these large-scale structures

Abrupt qualitative changes - Examples

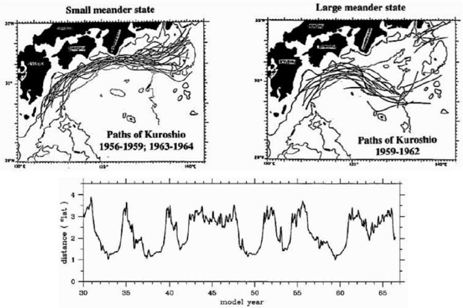
- Reversal of the Earth's magnetic field over time scale of millions of years *Cox, Doell & Dalrymple 1964*
- Turbulent flow of liquid sodium generates magnetic field - Random reversals in polarity *Berhanu et al. 2007*





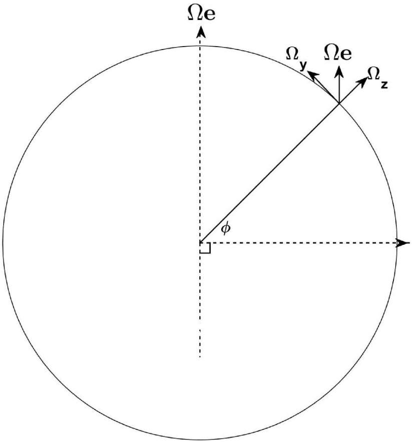
OCEAN - Kuroshio current & Gulfstream

Schmeits & Dijkstra 2001



- Random switches between small & large meander states
- Atmospheric noise can induce transitions

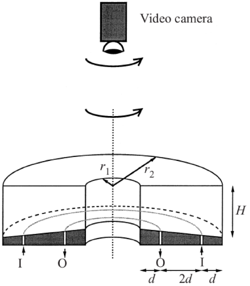
Atmospheric Jets - The $f-$ and $\beta-$ planes



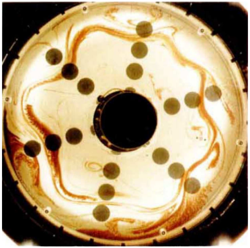
- $\Omega_z = const(f - plane)$ essential for eastward jet formation
- $\Omega_z = \Omega_0 + \beta y(\beta - plane)$ essential for Rossby waves

Laboratory realization of a nonlinear, wavy eastward jet

Sommeria, Meyers & Swinney 1989

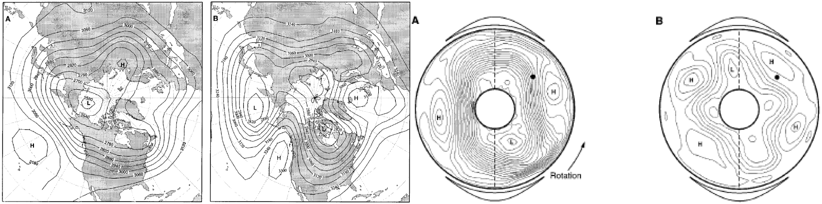


Schematic of experimental set-up



Dye visualization - Top view

Atmospheric Blocking



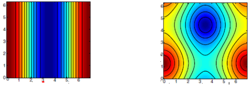
Weeks et al. 1997

- Zonal & blocked states observed using 10-day averaged isobars in the Northern hemisphere
- Blocked state - anti-cyclones - deflect the jet poleward.
- Bi-stable behaviour in experiments with azimuthal topography
- Spontaneous transitions (with no external noise) observed only in experiments

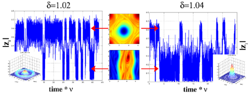
2D Navier Stokes Equations (Bouchet & Simmonet 2009)

- 2D Euler equations on a doubly periodic domain

Equilibrium statistical mechanics predicts a 2nd order phase transition between unidirectional and dipole flows

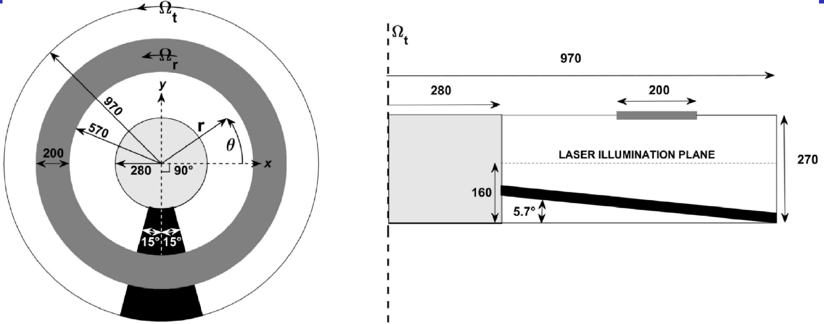


- Adding stochastic forcing and dissipation takes the system away from equilibrium - 1st order phase transition - Bistability



- 2D NS equations are structurally similar to more realistic models (quasi-geostrophic) of geophysical flows

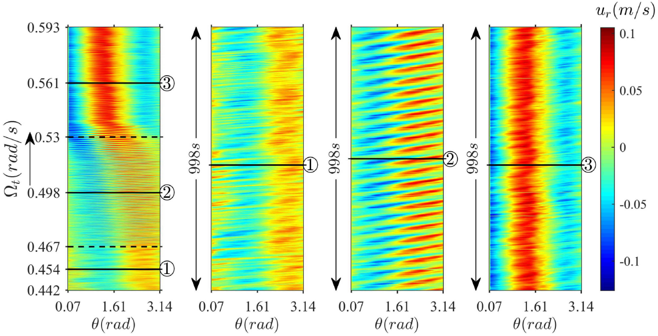
Experimental Setup



- Operating Parameters:
  $\Omega_t \approx 0.4 - 0.6 rad/s,\ \Omega_r \approx 0.78 rad/s,\ \beta = 0.37\text{rad/s/m}$
  $Ro = U/(2\Omega_t L) \approx 2.6,\ Ek = (4\pi/H)^2(\nu/\Omega_t) \approx 0.0043$

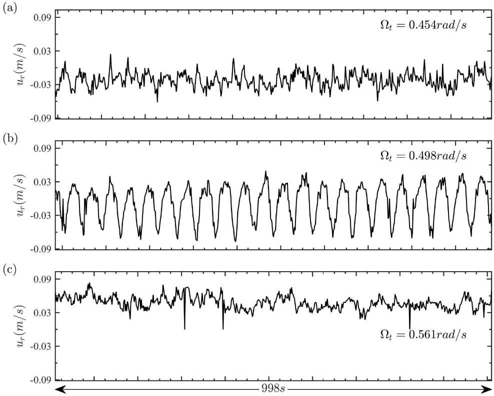
A Typical Experiment

Ω_t ramp up experiment (fixed Ω_r)



- Plots of $u_r(r = 0.5)$ vs Ω_t at different azimuthal locations
- Three qualitatively different states observed. States 2 & 3 resemble the zonal & blocked states

Time series of the three flow states

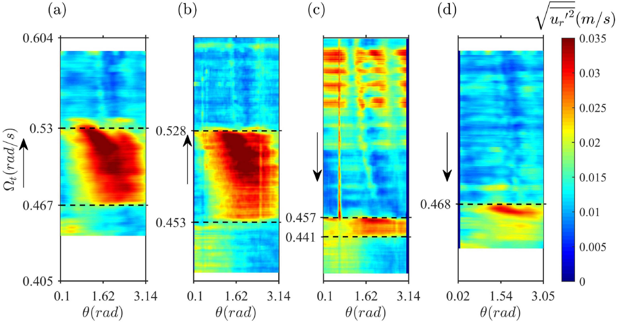


- Plots of $u_r(r = 0.5, \theta = \pi/2)$ vs time, t

Ramping up Experiment

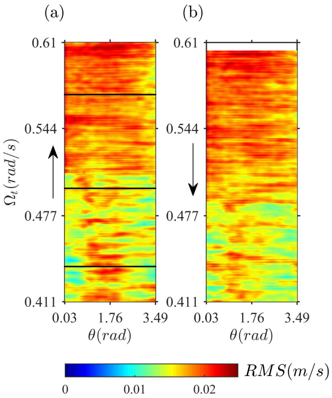
- State 3 contains a distinct vortex, absent in state 2.

Hysteresis - Evidence for bistability



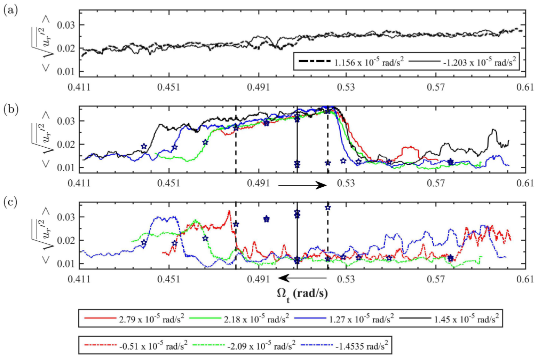
- RMS of radial velocity fluctuations vs Ω_t at $r = 0.5$ at various azimuthal locations

Without azimuthal topography - No hysteresis



- RMS of radial velocity fluctuations

In Summary...



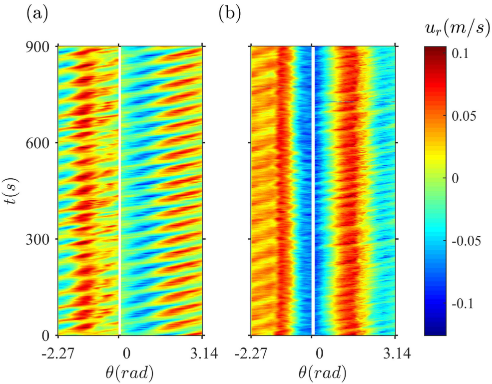
- Hysterisis indicates bistability

Bistable regime at $\Omega_t = 0.51$ rad/s

Blocked

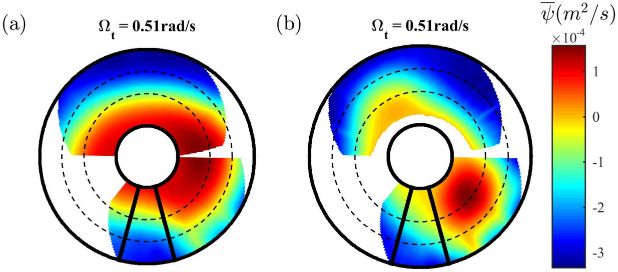
Propagating

The bistable regime at $\Omega_t = 0.51$ rad/s



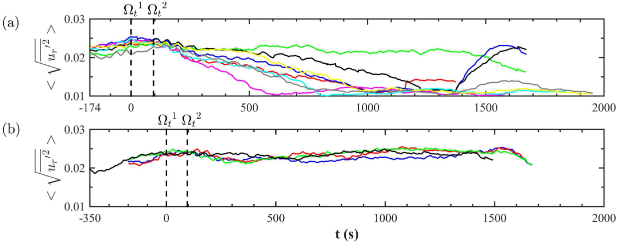
- $u_r(r = 0.5)$ vs t at $r = 0.5$

The bistable regime at $\Omega_t = 0.51$ rad/s



- Stream function of the time-averaged flow for the propagating (left) and blocked (right) states
- No spontaneous transitions!

Sudden noise in Ω_t



- $<\sqrt{u_r'^2}>$ vs t; noise given from $|\Omega_t|^1$ and $|\Omega_t|^2$, at constant $\Omega_r = 0.8$ rad/s
- Transitions seemingly random

Ongoing studies

- Role of amplitude, spatial & temporal scales in the noise - External forcing and/or turbulence
- Perspectives from the large deviation theory (Freddy Bouchet, ENS Lyon)