Transitions between blocked and zonal flows in a rotating flow with bottom topography

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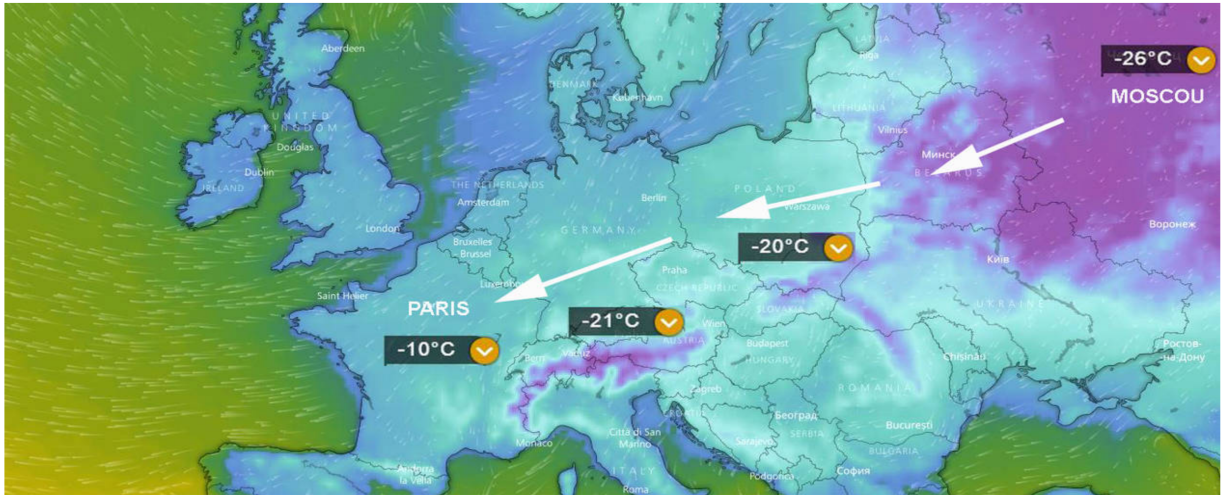
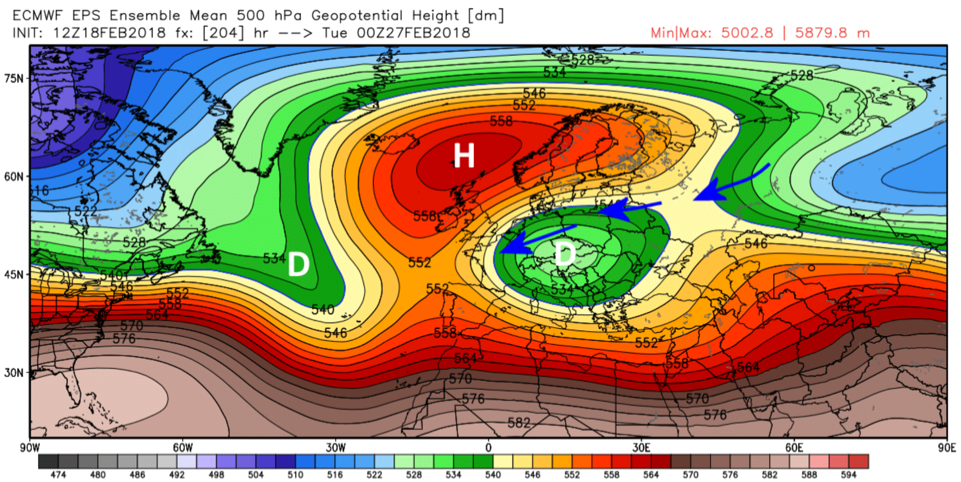
Atmospheric blocking affected us in 2018!

Météo. Vague de froid : préparez-vous à l'arrivée du « Moscou-Paris »



This was caused by a strong episode of **Scandinavian blocking**.



High pressures located over Scandinavia for extended period
⇒ bringing cold air to western Europe

Outline

1. Introduction

Atmospheric blocking

Rotating tank experiment

Numerical simulations

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QG model, method & validation

3. Results

Multiple equilibria

The effect of stochastic noise

A case of spontaneous transition

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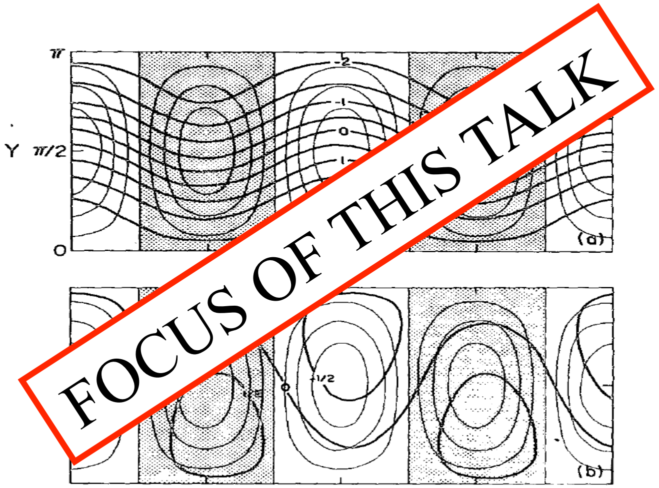
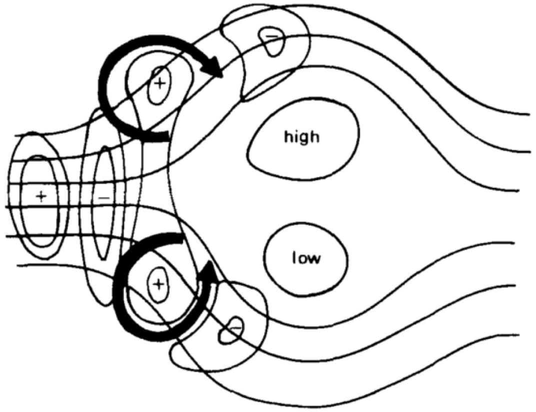
Atmospheric blocking: theoretical models

Multiple Equilibria in the presence of topography



Charney & DeVore (1979) and many follow-ups…

Interaction between eddies and the large scale flow



Schutts (1983), Nakamura et al. (1997) and many others…

+ Several alternative theories:

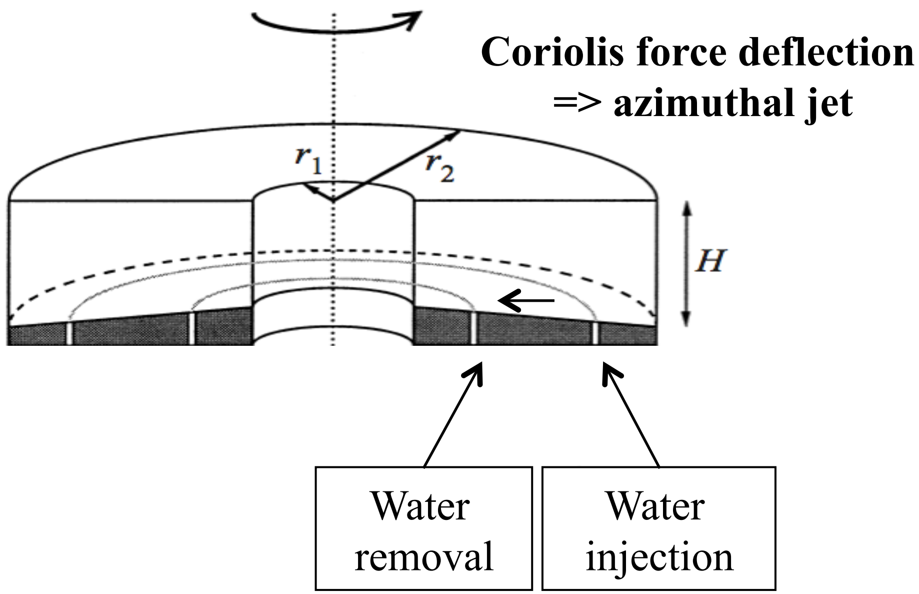
- Zonal flow instabilities *(Swanson 2001)*, role of planetary waves & tropical forcing
- Modons & solitons *(McWilliams 1980)*
- …

A rotating tank experiment

Weeks et al. (1997), Tian et al. (2001)

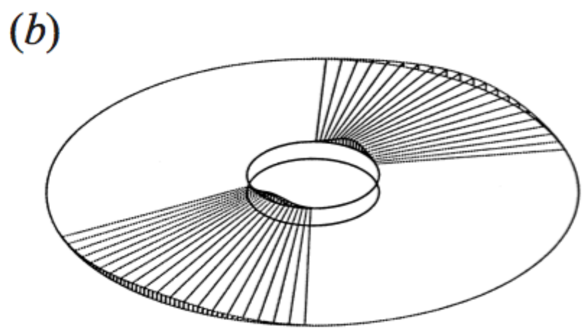
Tank properties

- Rigid top & bottom
- Inner radius: 10.8 cm
- Outer radius: 43.2 cm
- Depth: ~20 cm, increasing outward
- Filled with liquid water
- Rotation rates: up to 8π rad/s



« Mountains »

- Gaussian shape in azimuth
- Angular width ~70°
- Maximum height: 1.5 cm



Bottom topography exerts a drag on the jet and perturbs its dynamics

Different flow regimes

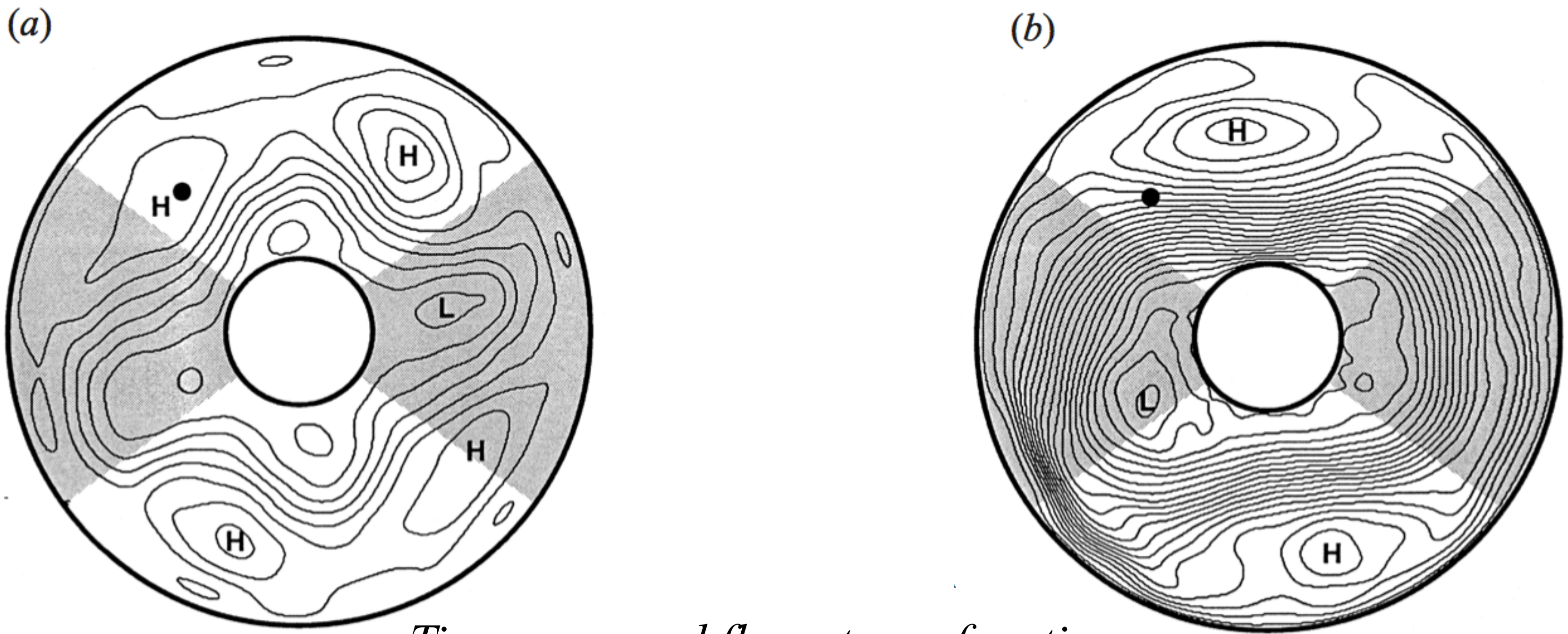
Weeks et al. (1997), Tian et al. (2001)

Blocked regime

- Slow mean zonal velocity
- Dominated by m=4 component
- Appears for weak forcing

Zonal regime

- Fast mean zonal velocity
- Dominated by m=2 component
- Appears for strong forcing

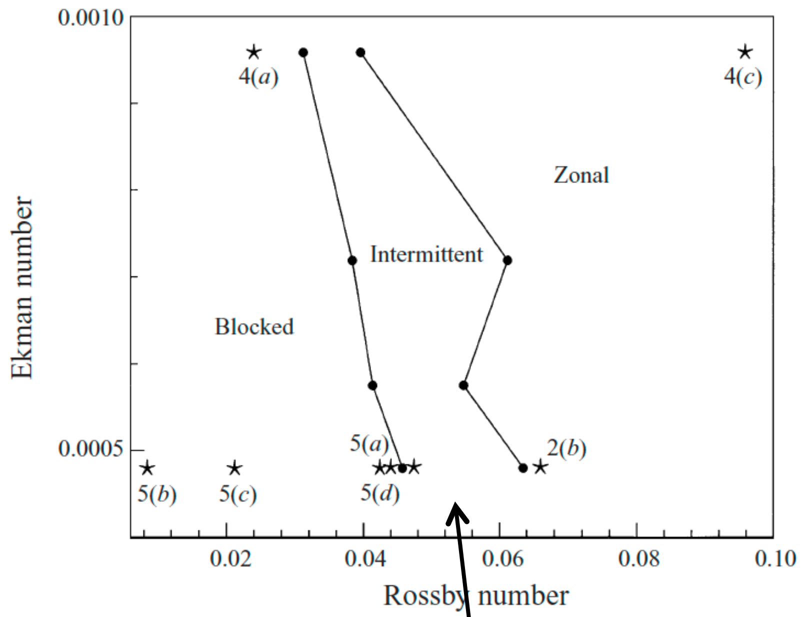


Time averaged flow streamfunction

Analoguous to the Charney & DeVore (1979) analytical results

Spontaneous transitions

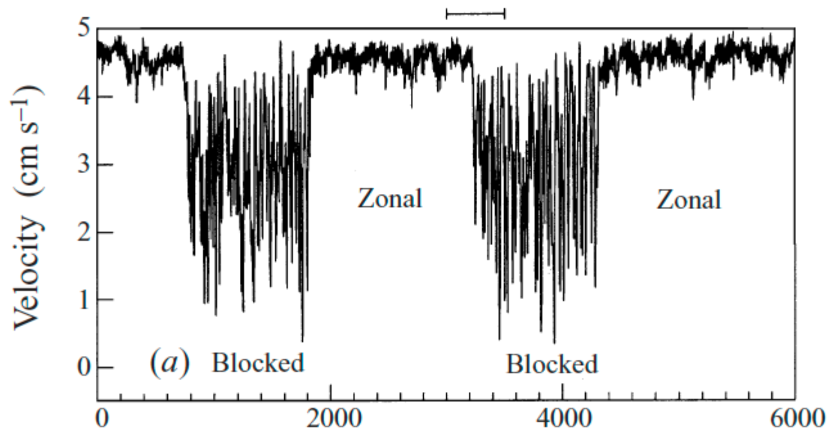
Weeks et al. (1997), Tian et al. (2001)



$$Ro = \frac{U}{fL}, \quad Ek = \left(\frac{T_{\text{annulus}}}{T_{\text{Ekman}}}\right)^2 = \left(\frac{4\pi}{H}\right)^2 \left(\frac{\nu}{\Omega}\right),$$

- Ro, Ek <<1 => flow barotropic
- Weak dependance on rotation rate

Spontaneous transitions between the two regimes found in intermediate region



A model of the experiment

Tian et al. (2001)

Use a quasi-geostrophic barotropic potential vorticity equation

$$\underbrace{\frac{\partial}{\partial t}(\nabla^2\psi)}_{\substack{\textbf{Streamfunction: }\psi\\ \textbf{Vorticity: }\Delta\psi}} + \underbrace{J(\psi, \nabla^2\psi}_{\textbf{Advection}} + \underbrace{h_m)}_{\textbf{Topography}} + \underbrace{\beta\frac{\partial\psi}{\partial x}}_{\substack{\textbf{Coriolis}\\ \textbf{term}}} = \underbrace{-a_r\kappa\nabla^2(\psi-\psi_*)}_{\textbf{Forcing}} + \underbrace{a_r\nu\nabla^4(\psi-\psi_*)}_{\substack{\textbf{Small scale}\\ \textbf{dissipation}}}.$$

Numerical method:

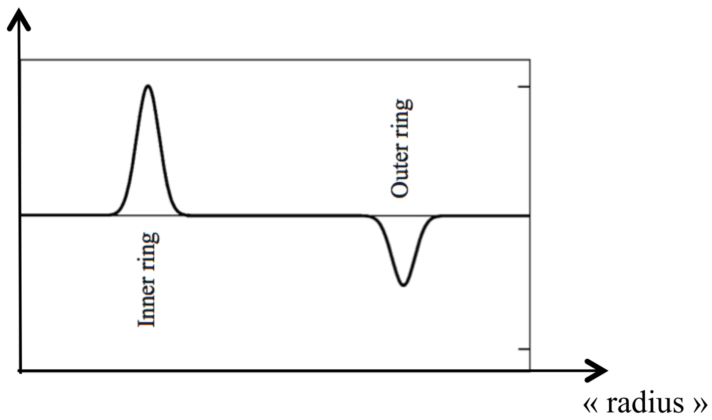
- Pseudo-spectral spatial discretization
  => *32×32 spectral modes*
- Neglect curvature terms (straight channel)
  => *no quantitative comparison*

Free parameters:

- Mountain height
  => *$0.1<h_0<0.15$*
- Dissipation
  => *$10^{-6}<\nu<10^{-4}$*

Forcing:

- Vorticity forcing $\Delta\psi^*$ (amplitude A)

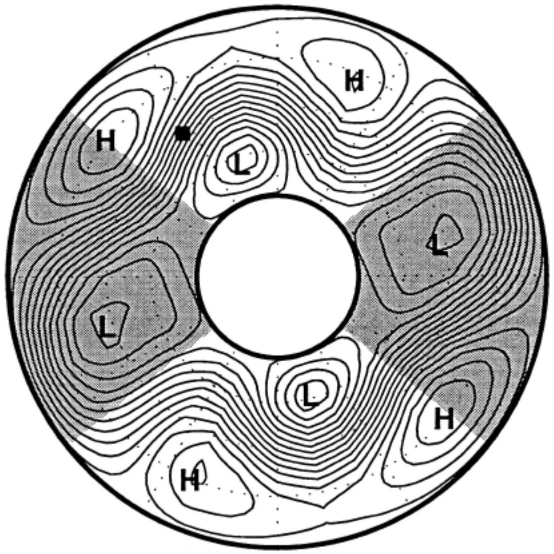


- Relaxation timescale
  => linked to the turbulent boundary layer
  => *$0.001<\kappa<0.01$*

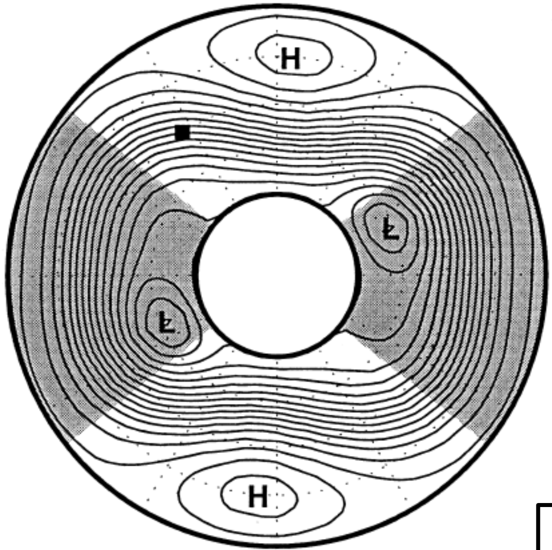
Flow regime in the simulations

Tian et al. (2001)

Main result: flow regime recovered in the simulations!



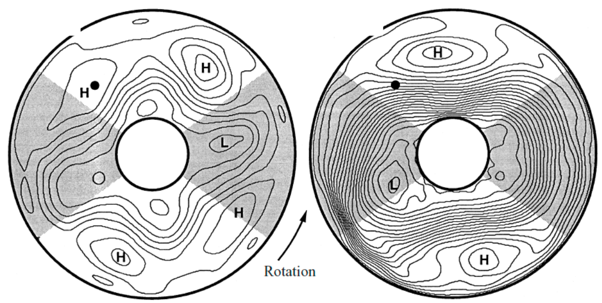
Blocked flow



Zonal flow

A=2.0, h_0=0.15, κ=0.01

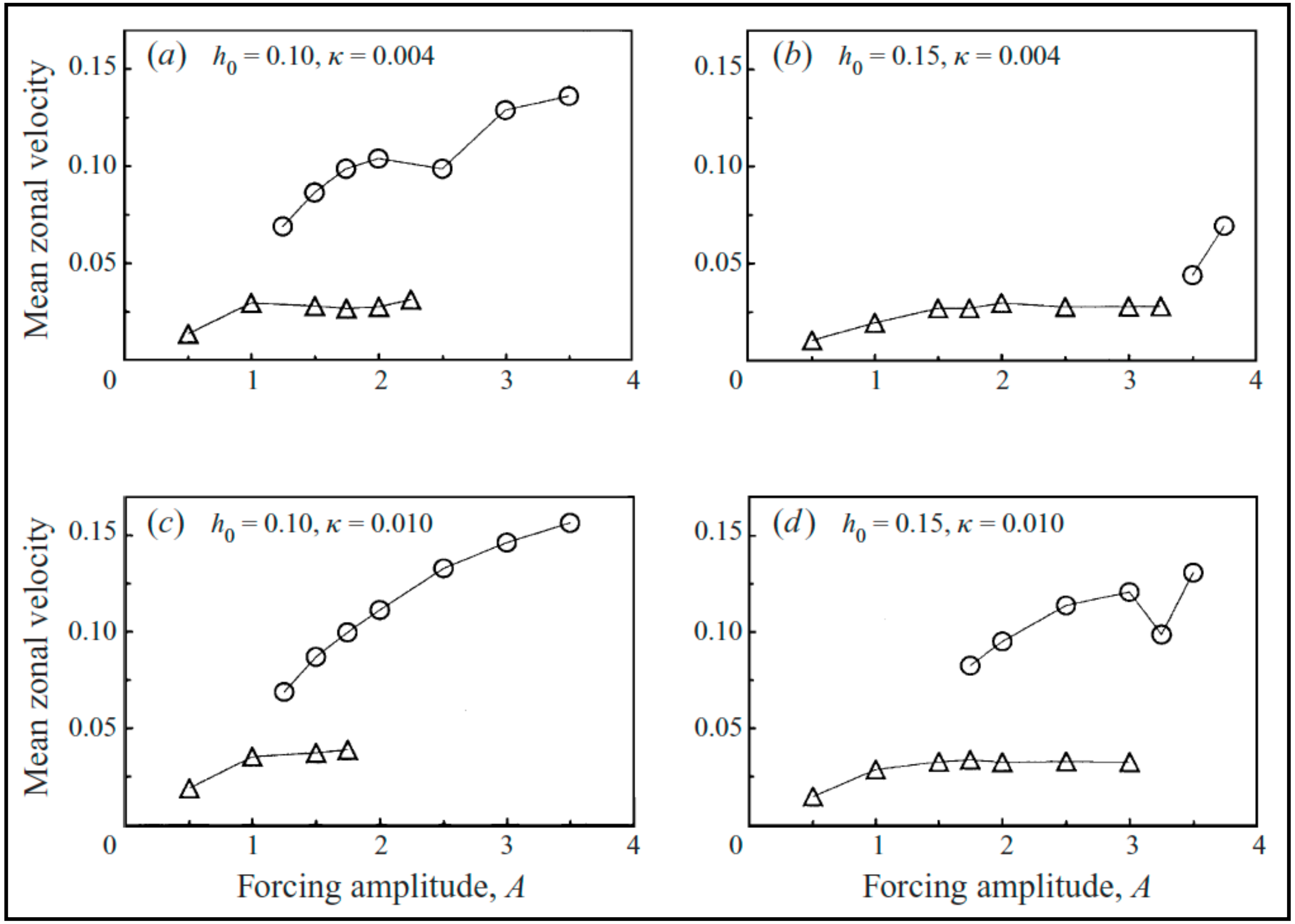
Experimental results

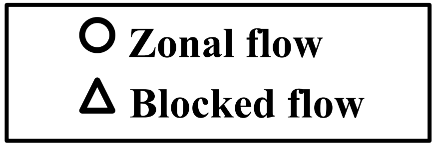


Parameter space

Tian et al. (2001)

Multiple equilibria obtained for a wide range of parameters





Motivation for this work

From Tian et al. (2001) discussion section:

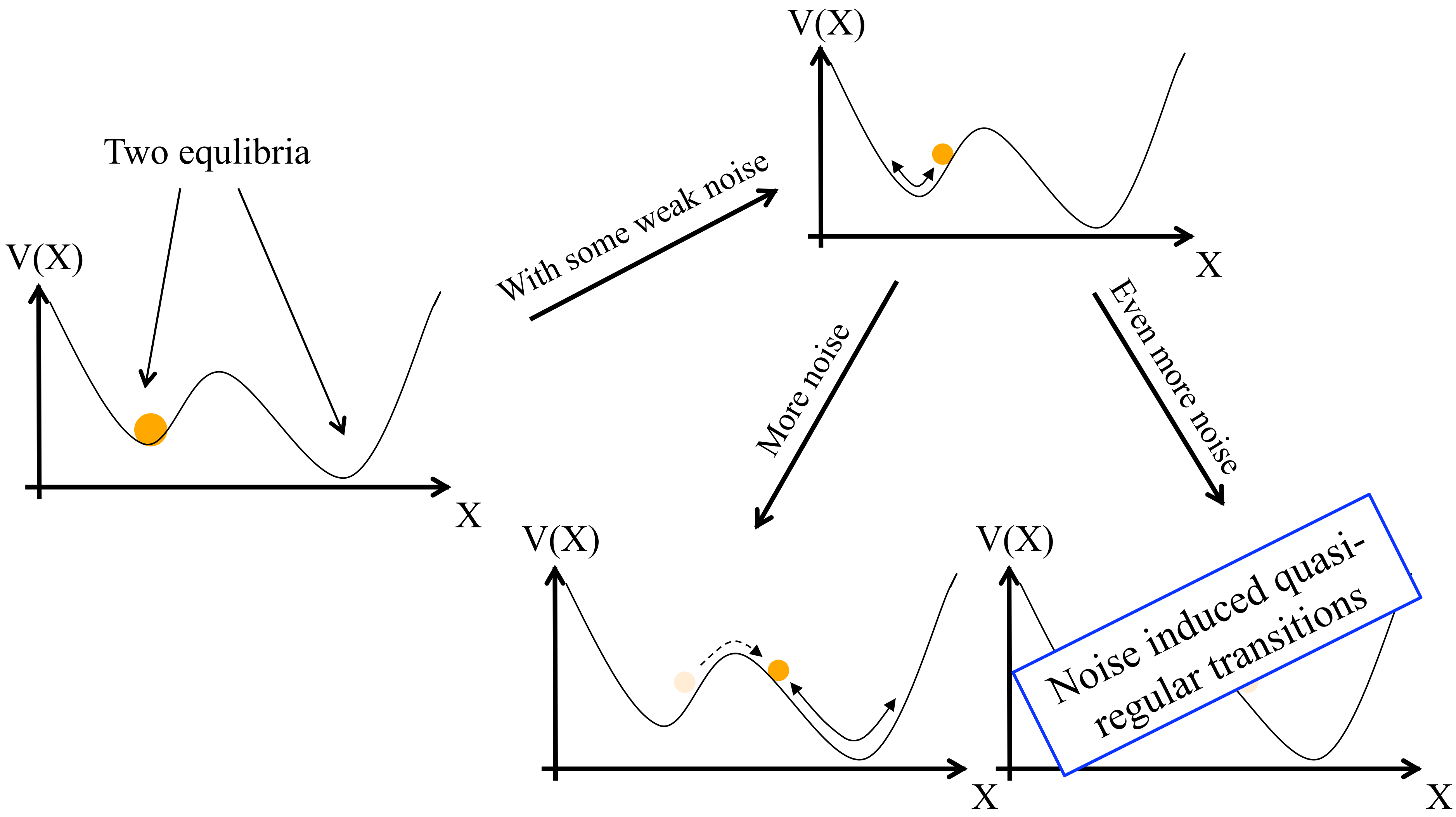
(see figure 12*d*). This is in contrast to the laboratory experiments, where no multiple equilibria were observed. Instead, at moderate *Ro* both flows in the rotating annulus are metastable, and spontaneous transitions between the two take place abruptly and at irregular intervals.

Two-way spontaneous transitions between the zonal and blocked flows have not been found in the numerical model. Since there is a certain amount of noise in the tank's forcing, $O(1\,\mathrm{cm}^3\,\mathrm{s}^{-1})$, we tried adding white noise to the forcing in the numerical model; even when the noise was fairly strong, however, no transitions were observed. Furthermore, as the Ekman friction is a function of the flow instead of the

Can we reproduce and confirm that result?
What triggers the transition in the experiment?

What should we expect?

System dynamics analoguous to a particle evolving in a potential that features two local minima



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A two layers QG model

Advection of Potential Vorticity q

$$\begin{cases} q_1(x,y) = \dfrac{\partial^2 \Psi_1}{\partial x^2} + \dfrac{\partial^2 \Psi_1}{\partial y^2} - \dfrac{\Psi_1 - \Psi_2}{\lambda^2} \\ q_2(x,y) = \dfrac{\partial^2 \Psi_1}{\partial x^2} + \dfrac{\partial^2 \Psi_1}{\partial y^2} + \dfrac{\Psi_1 - \Psi_2}{\lambda^2} \end{cases}$$

$$\frac{\partial q}{\partial t} + \frac{\partial uq}{\partial x} + \frac{\partial vq}{\partial y} + \beta v = \text{F(x,y,z)}$$

Forcing, topography, dissipation…

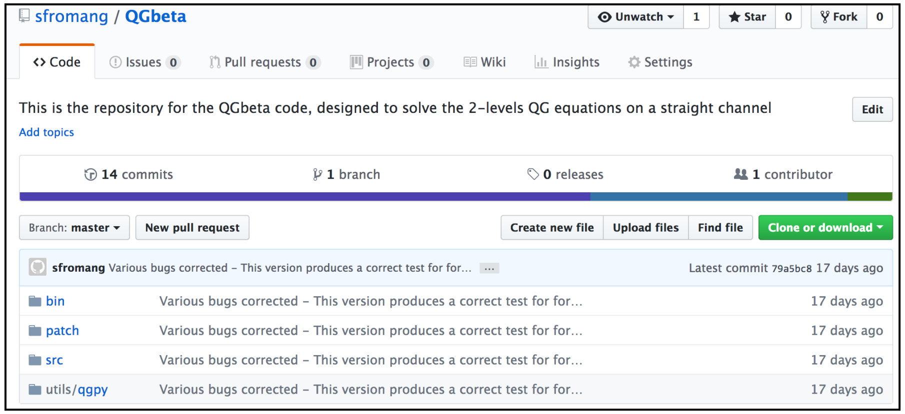
$$\begin{cases} u(x,y) = -\dfrac{\partial \Psi}{\partial y} \\ v(x,y) = \dfrac{\partial \Psi}{\partial x} \end{cases}$$

Fluid velocities

Numerical method:

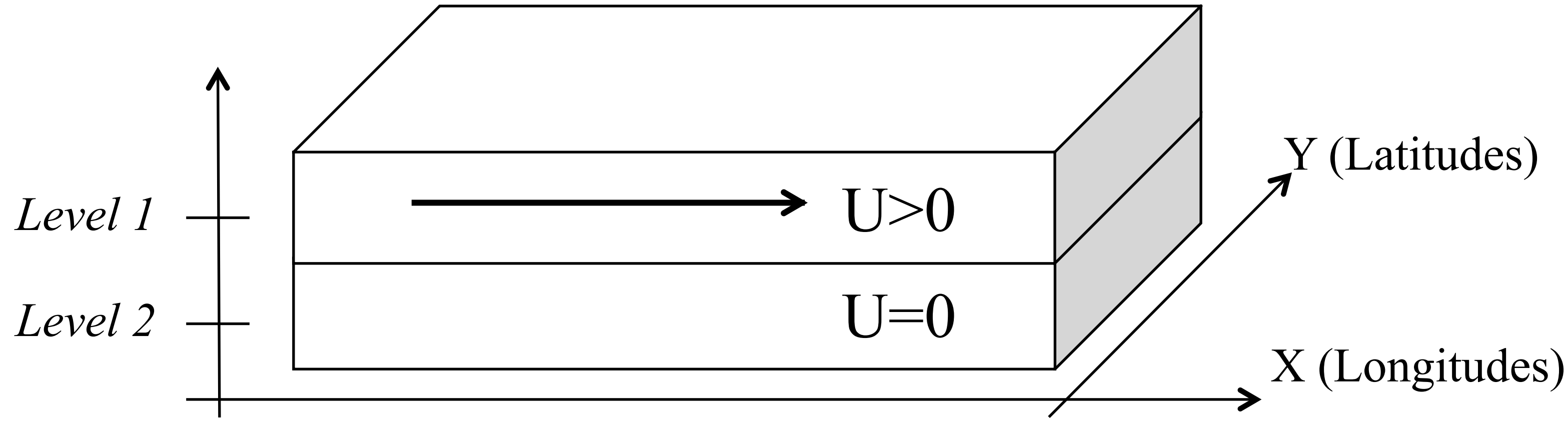
- Finite difference
- Leapfrog time integration (RAW filter)
- Poisson equation solved spectrally
- Various lateral boundary conditions

- Spectral version under development
- Publically available on Github



https://github.com/sfromang/QGbeta

Test 1: the Eady problem

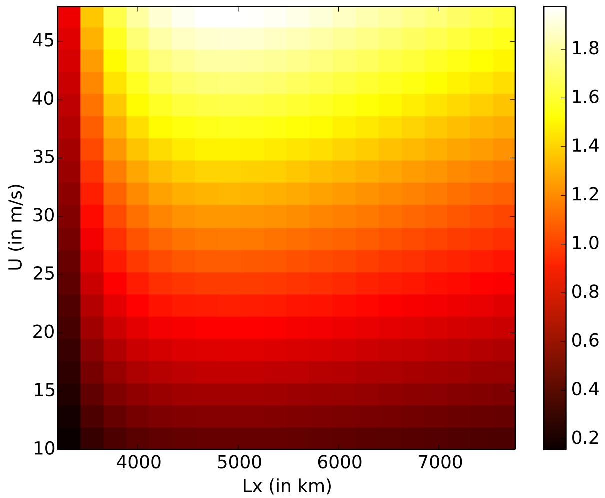


Unstable to the baroclinic instability (with analytical eigenmodes)

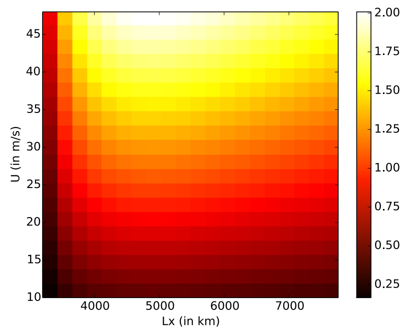
Add a sinusoidal perturbation of given wavelength Lx and let the instability grow…

400 simulations
3200 km < Lx < 8000 km
10 m/s < U < 50 m/s

Numerical growth rate

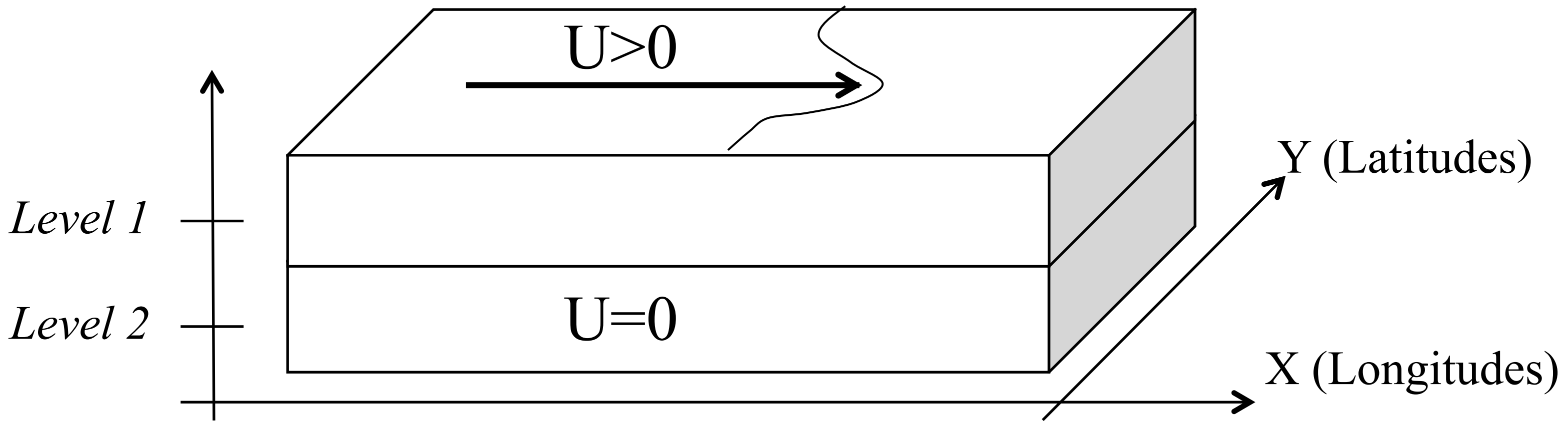


Theoretical growth rate



Test 2: baroclinic jet

Zurita-Gotor (2014, JAS, 71, 410)



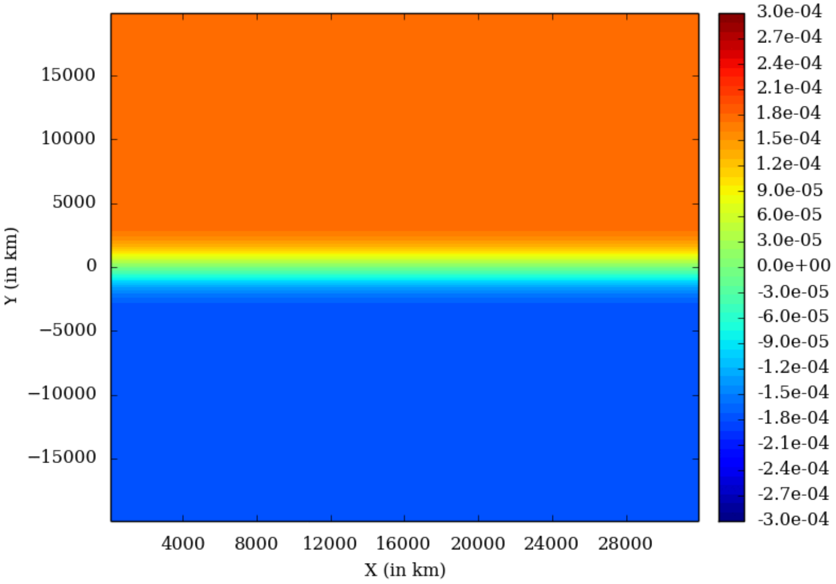
Forcing added to relax the flow to a zonally uniform jet
Small scale hyperdiffusion – bottom friction

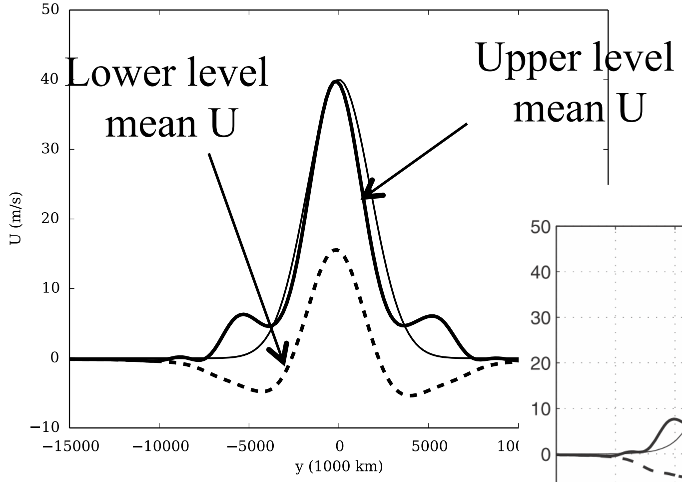
Unstable to the baroclinic instability again…

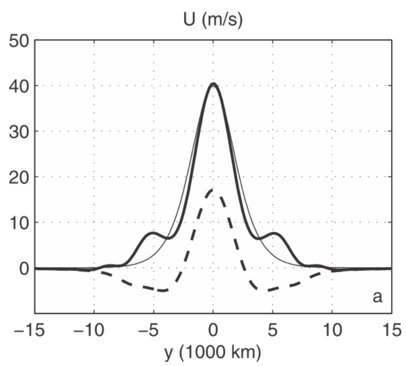
Test 2: baroclinic jet

Zurita-Gotor (2014, JAS, 71, 410)

PV time evolution

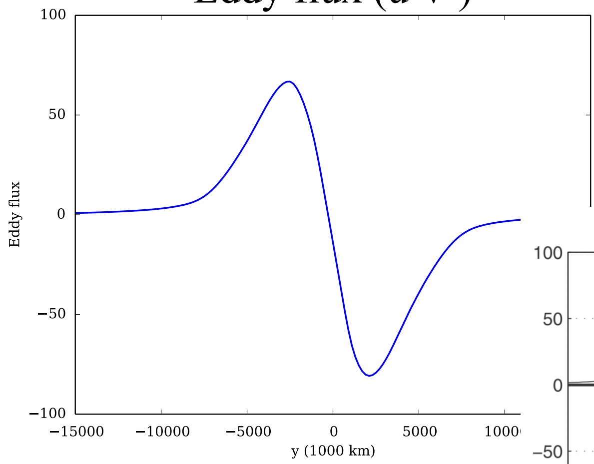


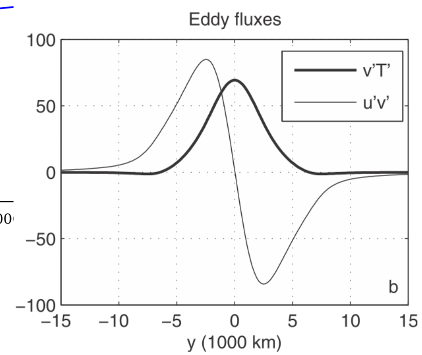




Zurita-Gotor (2014)

Eddy flux (u'v')





Zurita-Gotor (2014)

Reproducing the experiment

RECIPE

1/ Take one layer only

2/ Adapt the lateral boundary conditions

(*free slip boundary conditions*)

3/ Same forcing & channel size as in Tian et al. (2001)

4/ Resolution: Nx=100, Ny=50

Word of caution: curvature terms neglected as Tian et al. (2001) – Straight channel but *visualization projected on a polar grid*

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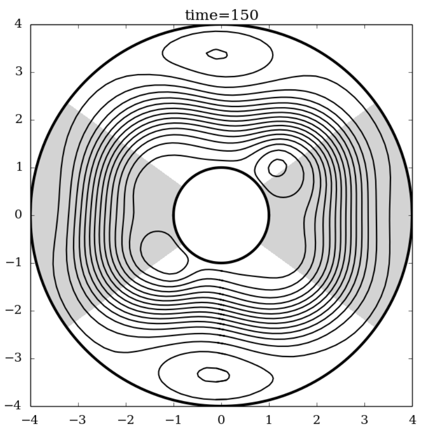
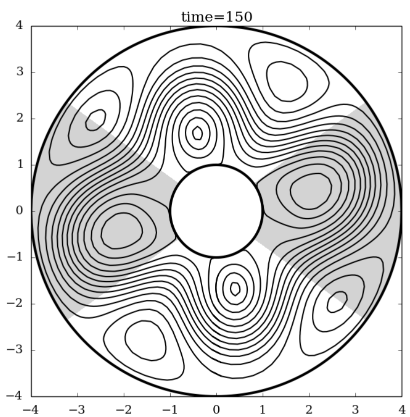
Multiple equilibria

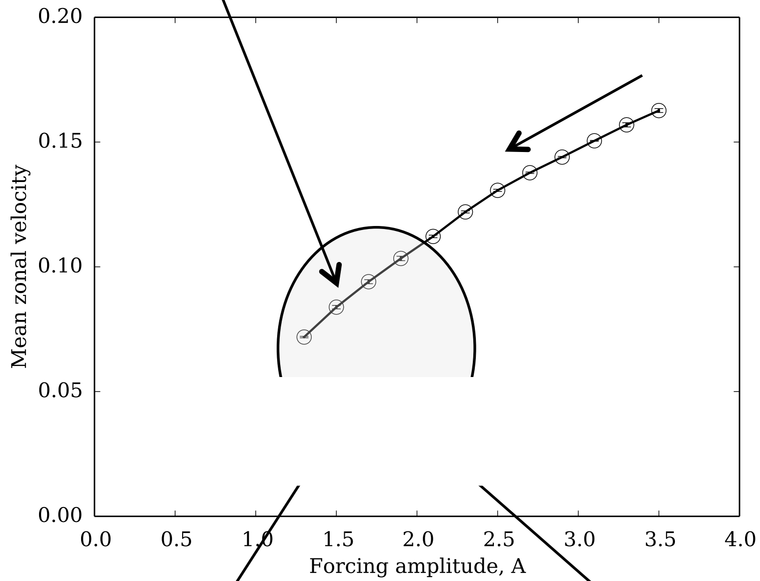
h_0=0.1 & κ=0.01

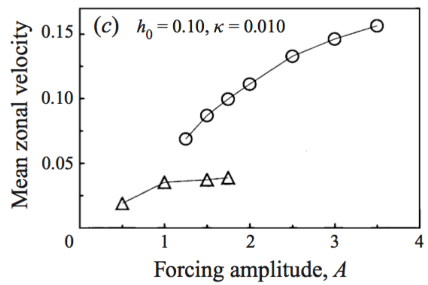
1. Start @ high forcing and gradually decrease A…
2. Start @ low forcing and gradually increase A…



A=1.5







Recover bistable region and phase diagram as in Tian et al. (2001)

Adding stochastic white noise

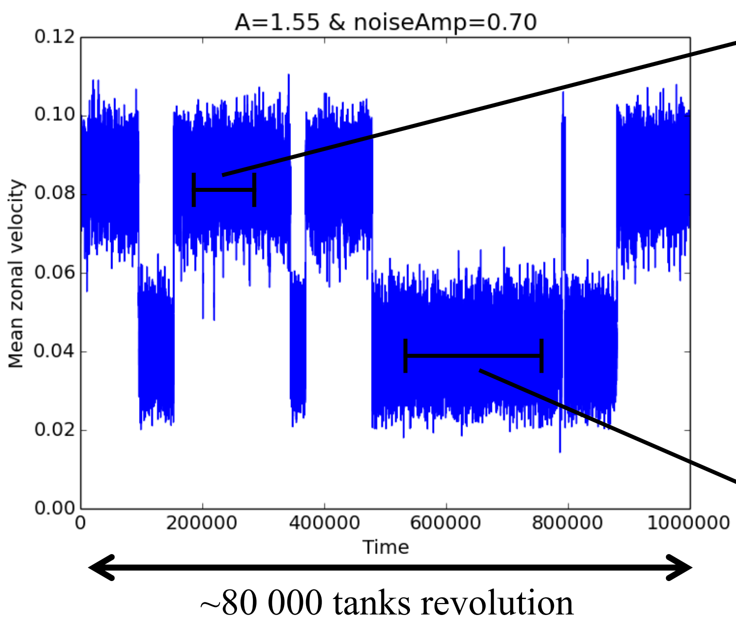
Add simplest random forcing: $$\frac{\partial q}{\partial t} = \epsilon(x, y, z, t)\,,$$

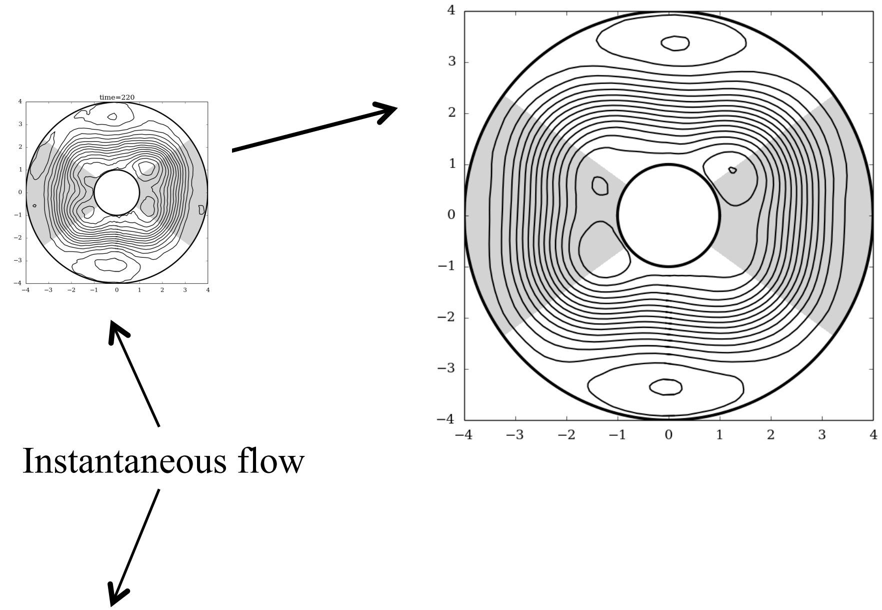
Random number generated from a white noise with amplitude ε_0

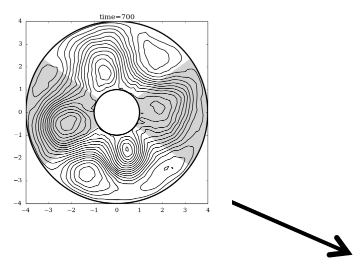
The effect of stochastic noise

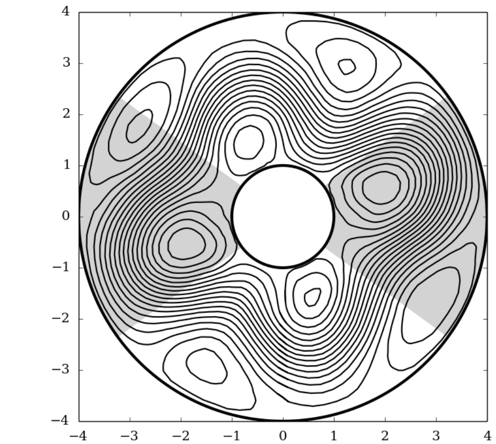
h_0=0.1 & κ=0.01 – The case A=1.55

ε_0=0.7







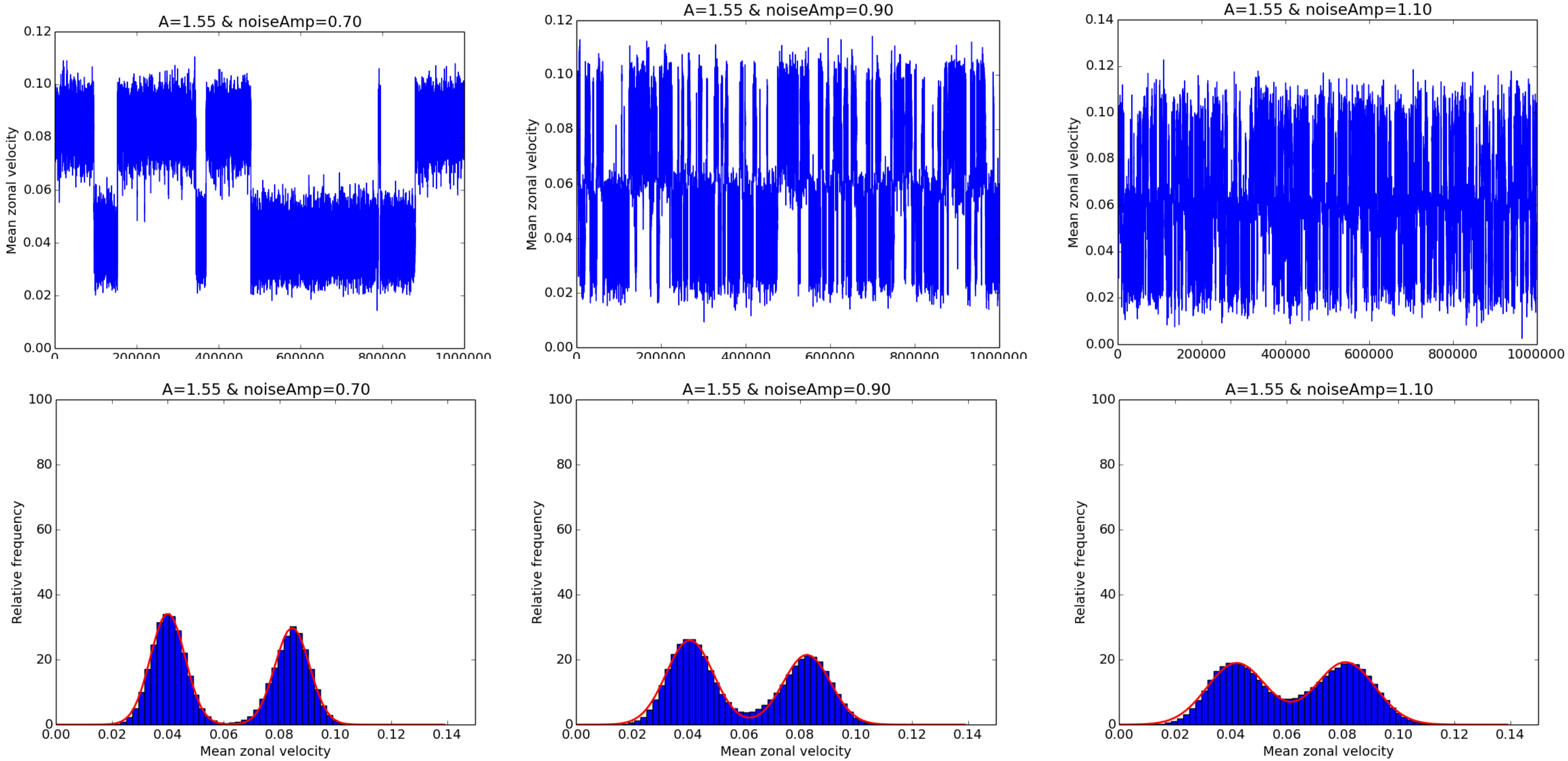


- Regime transition triggered by stochastic noise
- Typical regime lifetime: ~few thousands tank period

The influence of the noise amplitude

h_0=0.1 & κ=0.01 – The case A=1.55

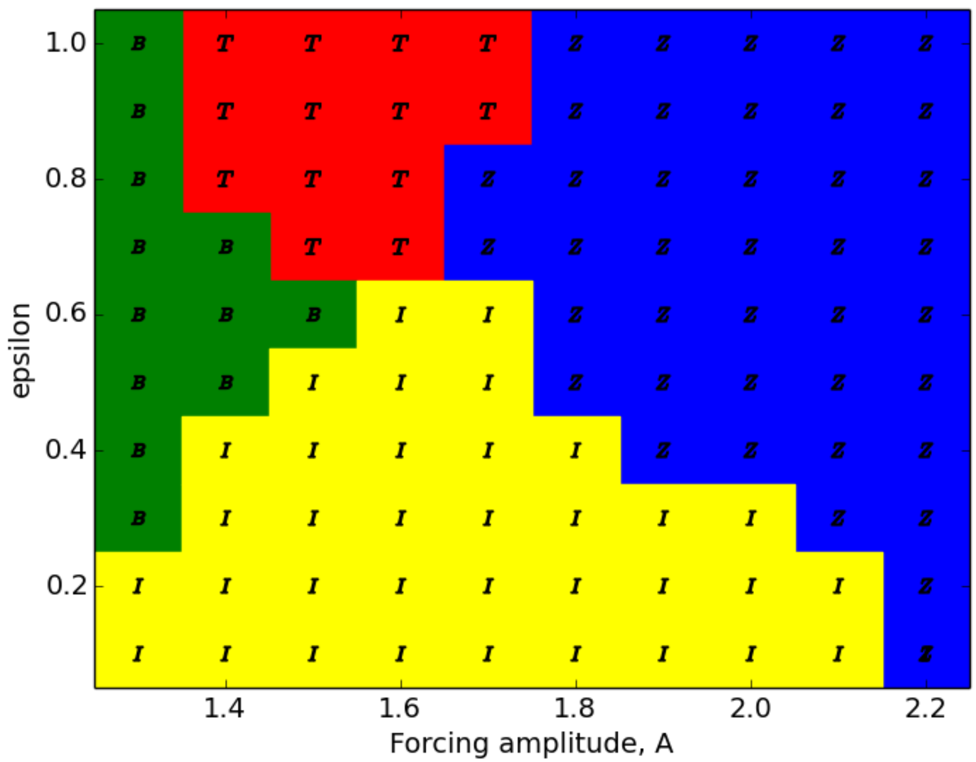
ε_0=0.7 **ε_0=0.9** **ε_0=1.1**



- Broader PDF and smaller regime lifetime when A ↗↗
- Regime occurrence probability only weakly dependent of noise

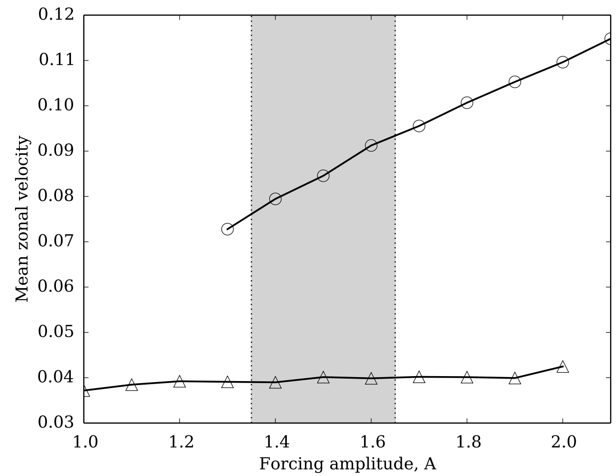
Stochastic noise - summary

h_0=0.1 & κ=0.01



Systematic exploration

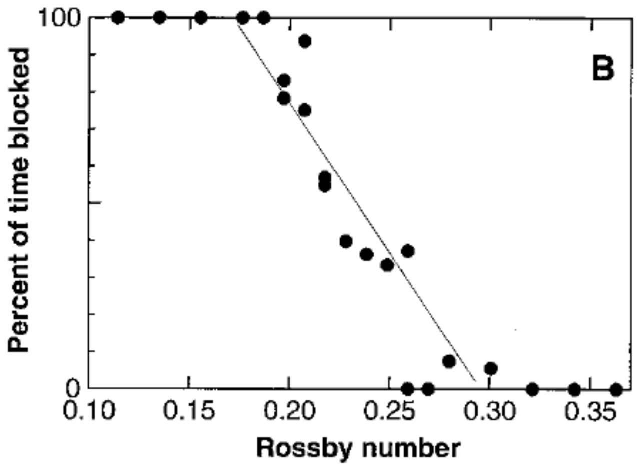
$0.1<\varepsilon_0<1.0$ $1.3<A<2.2$



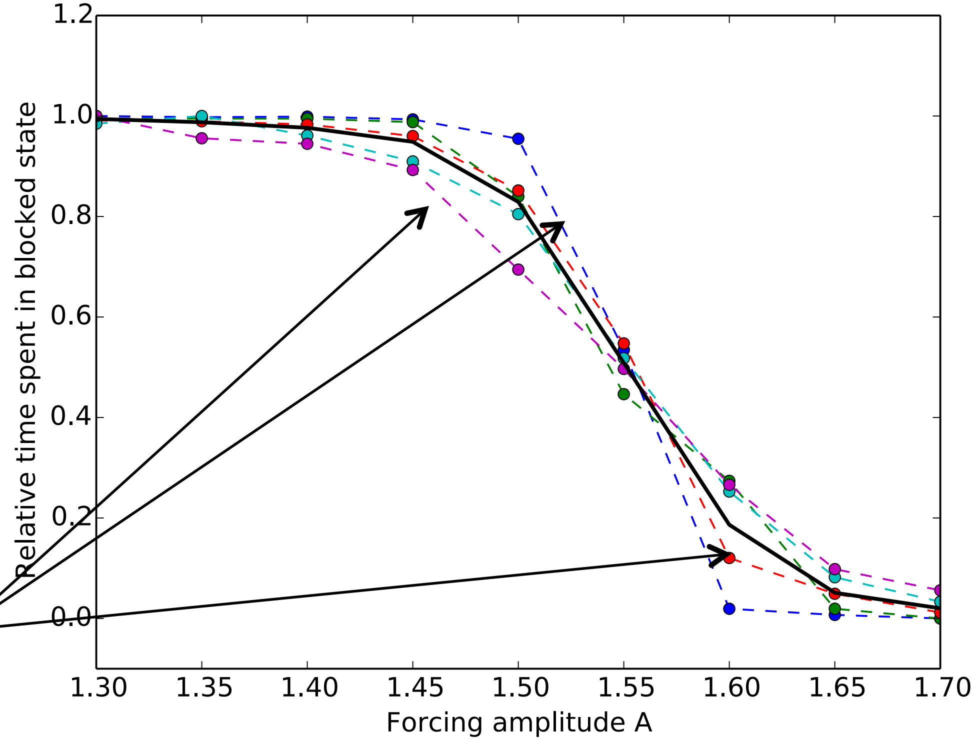
B	Flow stays in blocked regime	I	Flow remains in initial state forever
Z	Flow stays in zonal regime	T	Multiple transitions between both regimes

Regime occurrence probability

Weeks et al. (1997)



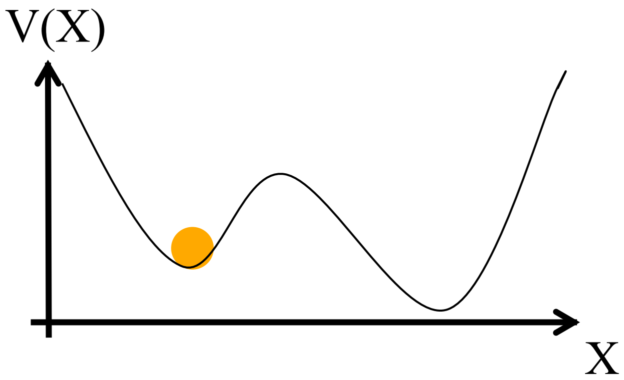
Numerical results



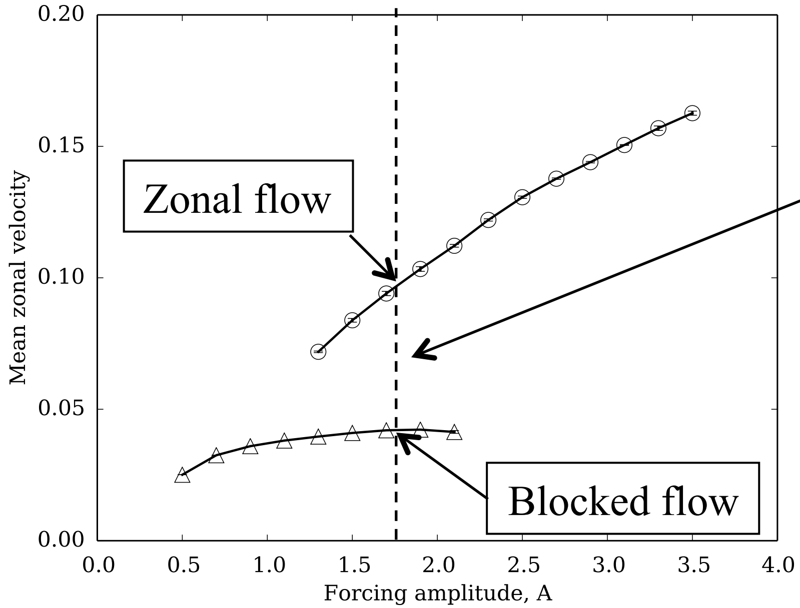
Various dashed curves ⇔ various noise amplitudes ⇔ little effect on regime prevalence

Blocked (zonal) regime favored for weak (strong) forcing ⇔ Qualitative agreement with the experiment

A simple interpretation



Can we understand (or get a feel) for this result in term of the potential discussed before ?

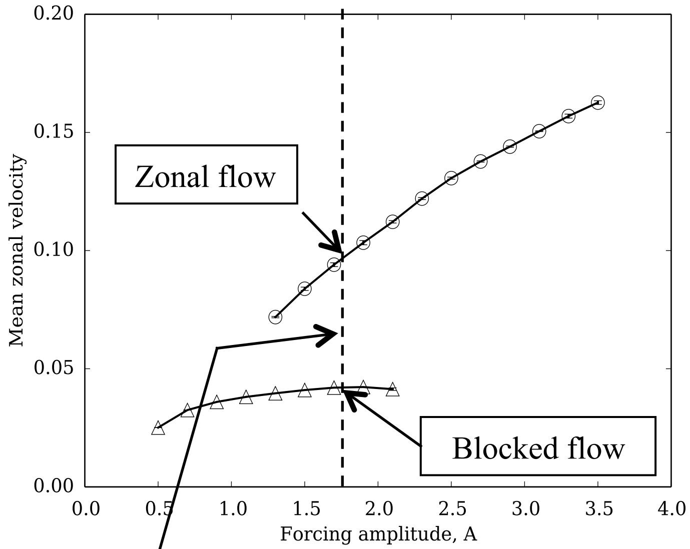


Consider a given A

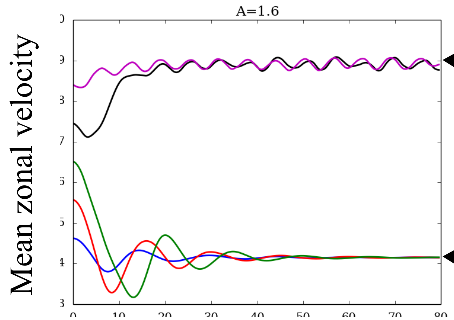
What happen to a flow that would start « in between »?

Additional simulations with initial vorticity: $\xi_{init} = \alpha \xi_Z + (1-\alpha)\xi_{BL}$ with $0<\alpha<1$ and w/o noise…

A simple interpretation



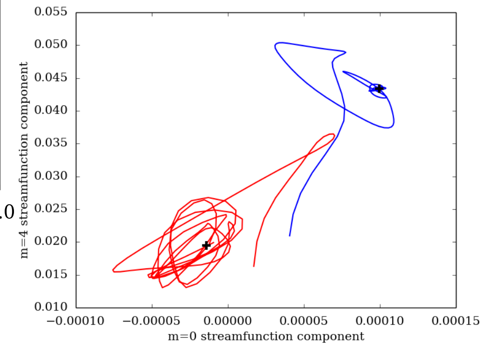
$$\xi_{init} = \alpha\xi_Z + (1-\alpha)\xi_{BL}$$



Zonal flow

α=0.1,0.3,0.5,0.7,0.9

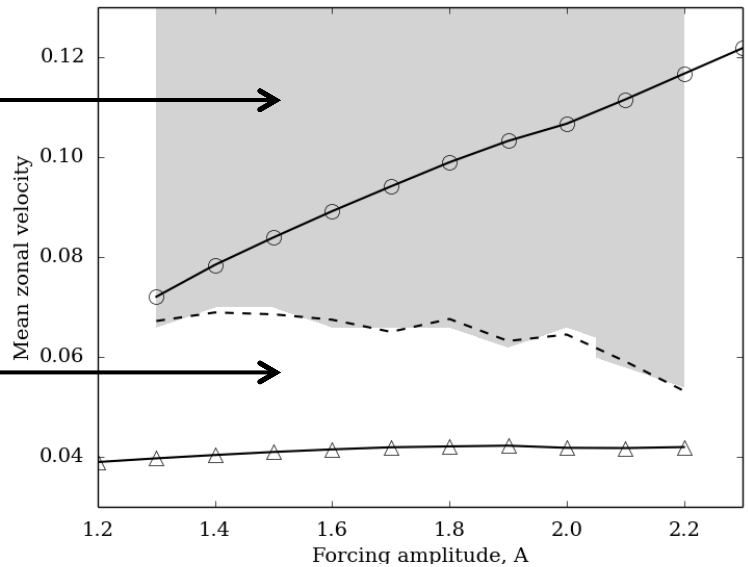
Blocked flow

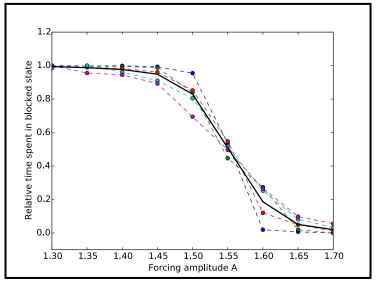


$\Rightarrow$ **but complex dynamics when looking at system trajectories in m=4 vs m=0 plane!**

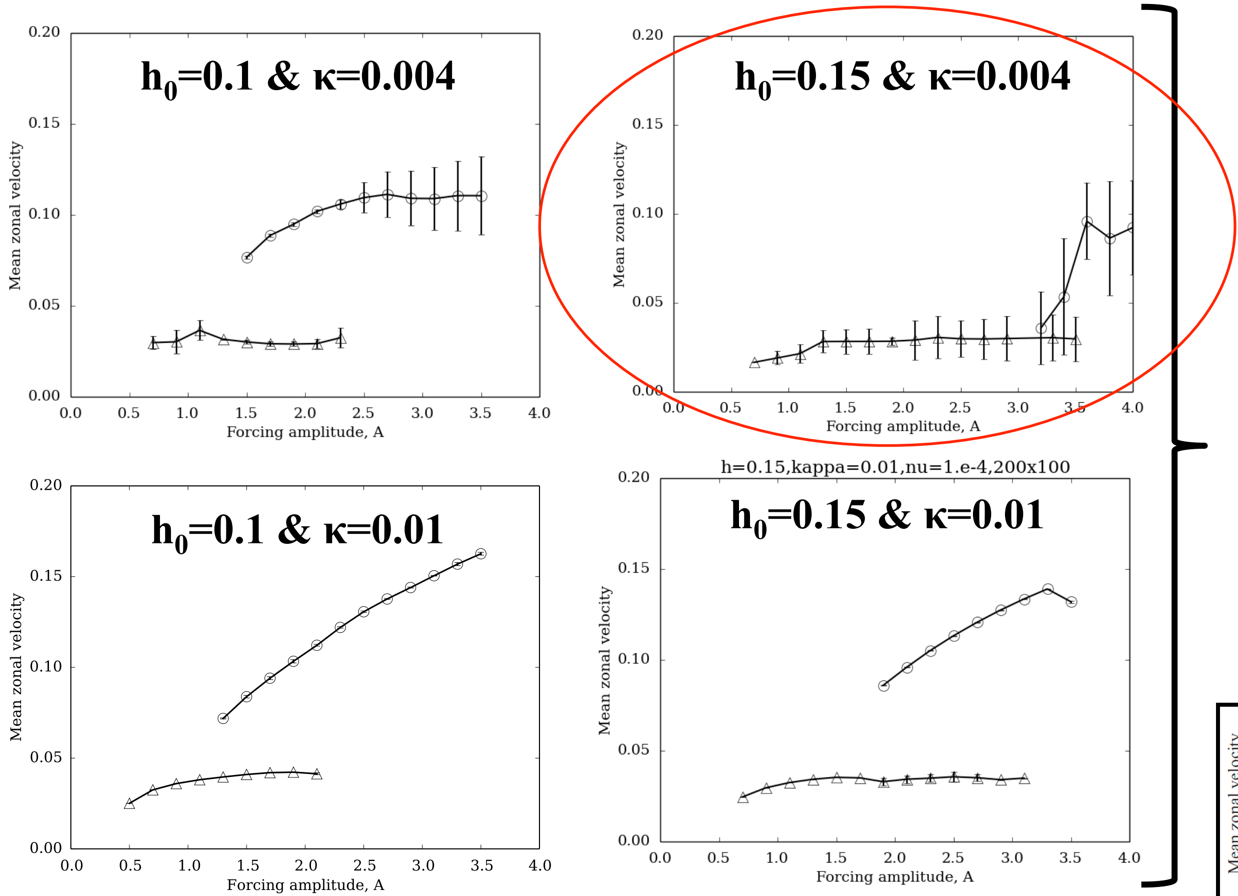
Basin of attraction for the zonal regime

Basin of attraction for the blocked regime

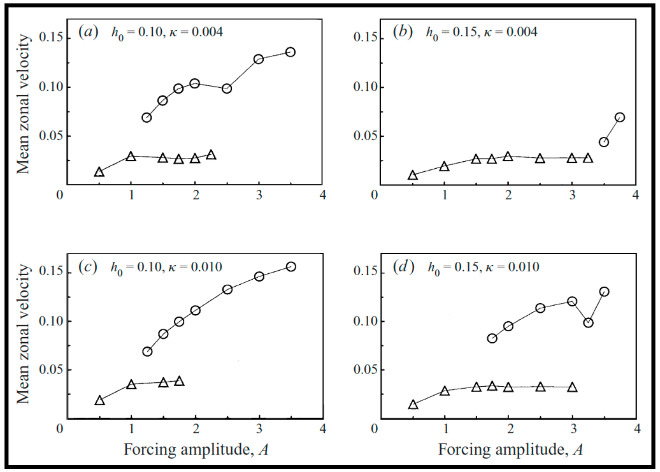




Multiple regime for other parameters



Good agreement with Tian et al. (2001), except for the case of high mountain and long relaxation timescales



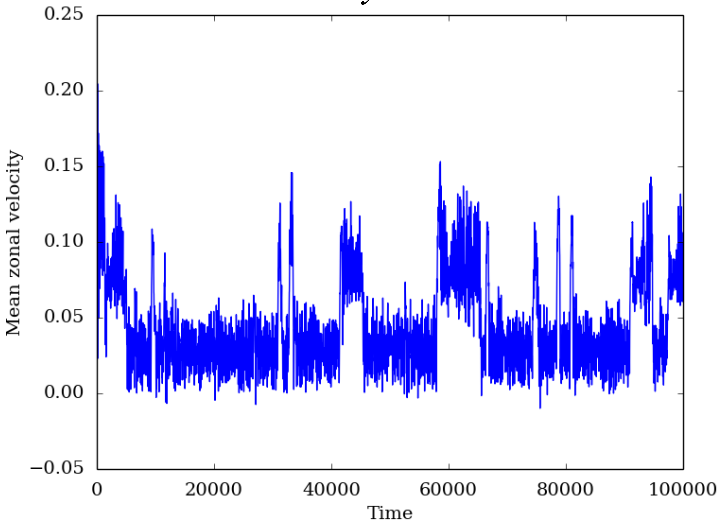
Tian et al. (2001)

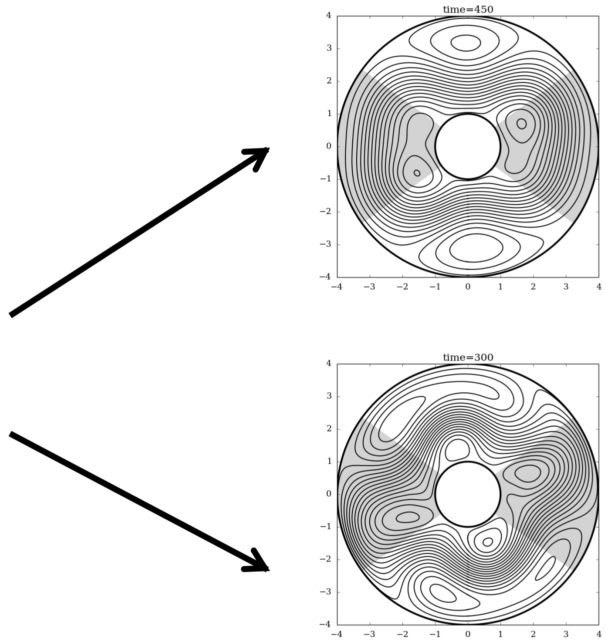
Spontaneous transition (NO NOISE!)

h_0=0.15 & κ=0.004 – A=3.30 (large forcing)

κ=0.004 ⇔ Relaxation timescale ~20 tank rotation period

Zonal velocity time evolution





Zonal regime

Blocked regime

Increased spatial resolution: 200x100

<u>Clear up & down transitions between the two states</u>, but some sensitivity to numerical details (dissipation & spatial resolution). More work needed…

Conclusions

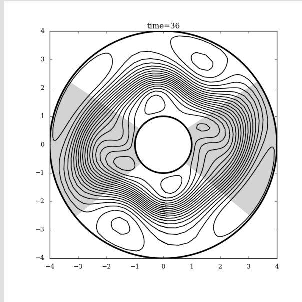
- **Results of Tian et al. (2001) confirmed with a single layer QG code**

  => Multiple equilibria found for a wide range of parameters – but still ignoring curvature effects
- **Transition between the equilibria in the presence of stochastic forcing**
- **Regime prevalence in qualitative agreement with the results of Weeks et al. (1997)**
- **Indication of spontaneous transitions for long relaxation timescales**

Perspectives

- **Robustness of the spontaneous transitions?**

  ⇒ Extension of the code to a spectral algorithm



  ⇒ Bifurcation diagram - use of the AUTO software - Doedel et al. 1997)

- **Rare transitions in the weak noise regime?**

  ⇒ Quantifying the return time using a large deviation algorithm *(Ragone, Wouters & Bouchet 2017)?*