Zonal jet formation in numerical simulations of a large rotating annulus experiment

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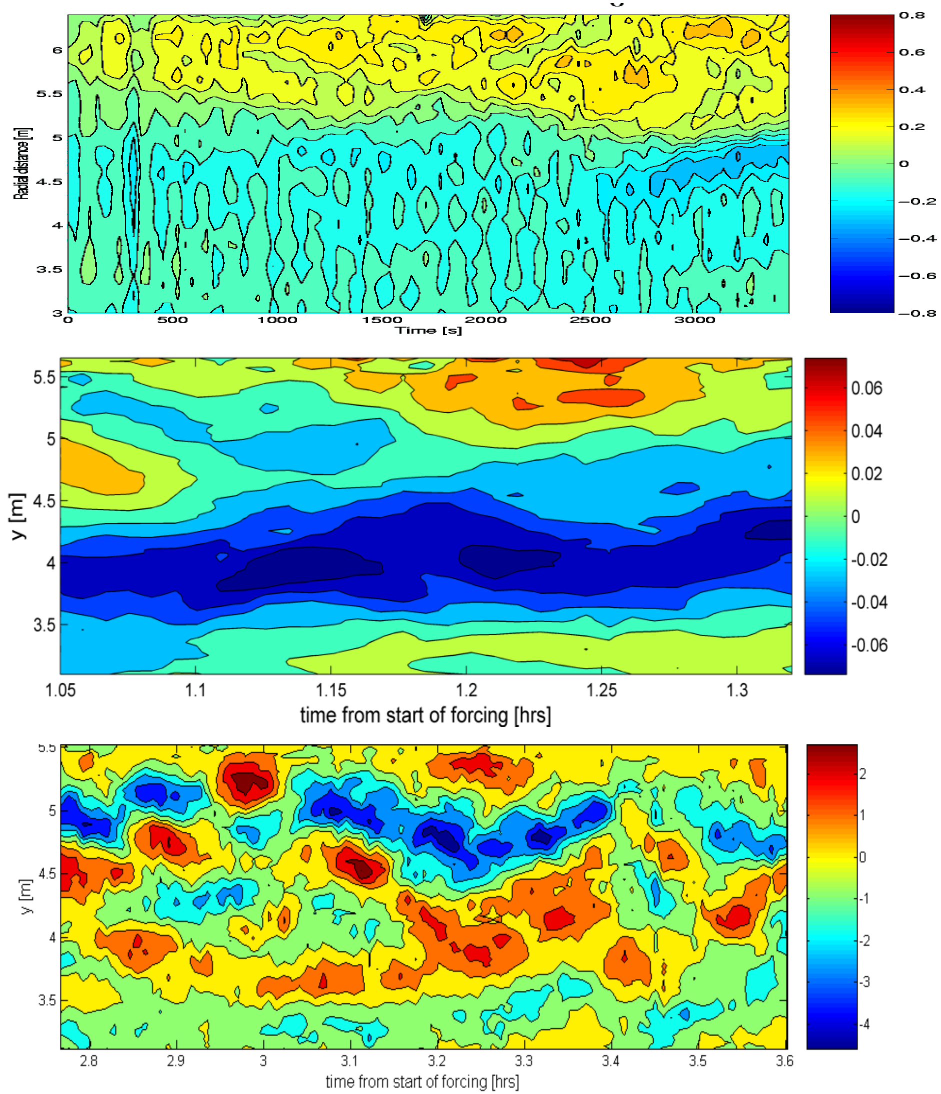
1. Lab expts in a 13 meter annulus

$\beta = 0.002$ $m^{-1}\ s^{-1}$

$\beta = 0.02$ $m^{-1}\ s^{-1}$

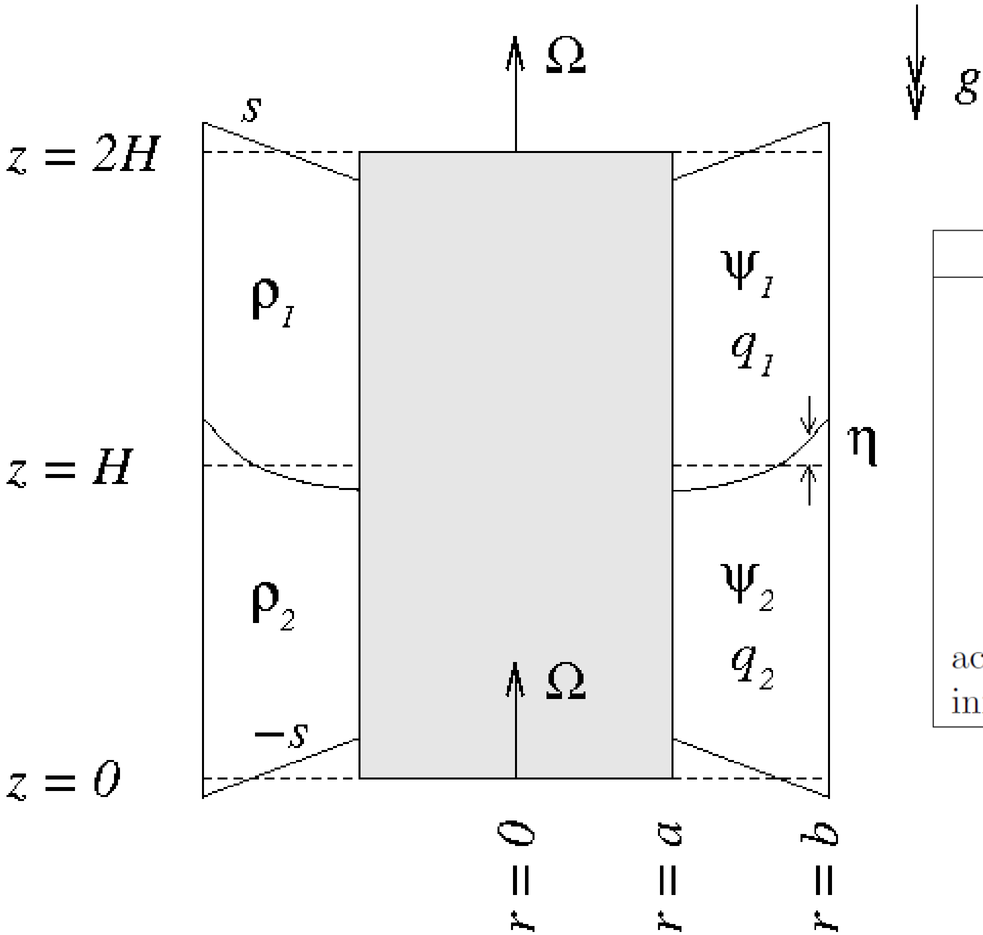
$\beta = 0.05$ $m^{-1}\ s^{-1}$



- Jet width decreases with increasing β
- Direction alternates with radius
- Time-varying meanders - transient effects?
- Wind-stress residuals?

Read et al. (2004, 2007)

2. The QG numerical model



description	parameter	value
inner radius	a	2.0 m
outer radius	b	6.5 m
layer height	H	0.275 m
average density	$\bar{\rho}$	1000.0 kg m^{-3}
density difference	$\Delta\rho$	(see Table 3)
upper boundary slope	s	0.04
lower boundary slope	$-s$	−0.04
rotation rate	Ω	0.1571 rad s^{-1}
acceleration due to gravity	g	9.81 m s^{-2}
initial condition amplitude	q_0	(see Table 3)

The initial condition is noise in *q*
on scales 5-10 times the grid spacing

3. Suite of 15 numerical experiments

control parameters ↓ ↓

experiment number	$\Delta\rho$ (kg m^{-3})	q_0 (s^{-1})	Urms (mm s^{-1})	baroclinic Rossby radius (m)	baroclinic Rhines scale (m)	jet spacing (m)
1	1.0	0.2	0.24	0.12	0.41	0.88 ± 0.47
2	1.0	0.4	0.56	0.12	1.53	1.08 ± 0.68
3	1.0	0.6	0.83	0.12	–	–
4	1.0	0.8	1.17	0.12	–	–
5	1.0	1.0	1.42	0.12	–	–
6	10.0	0.2	0.25	0.37	0.34	0.90 ± 0.26
7	10.0	0.4	0.55	0.37	0.51	1.66 ± 0.63
8	10.0	0.6	0.85	0.37	0.65	1.85 ± 0.63
9	10.0	0.8	1.14	0.37	0.78	1.65 ± 0.62
10	10.0	1.0	1.45	0.37	0.90	1.76 ± 0.84
11	100.0	0.2	0.26	1.17	0.34	0.70 ± 0.08
12	100.0	0.4	0.56	1.17	0.49	1.03 ± 0.14
13	100.0	0.6	0.87	1.17	0.62	1.30 ± 0.42
14	100.0	0.8	1.17	1.17	0.72	1.66 ± 0.38
15	100.0	1.0	1.45	1.17	0.80	1.90 ± 0.52

Experiments 1–5: $u_{rms} > \beta L_{Ro}^2$ → isotropy?

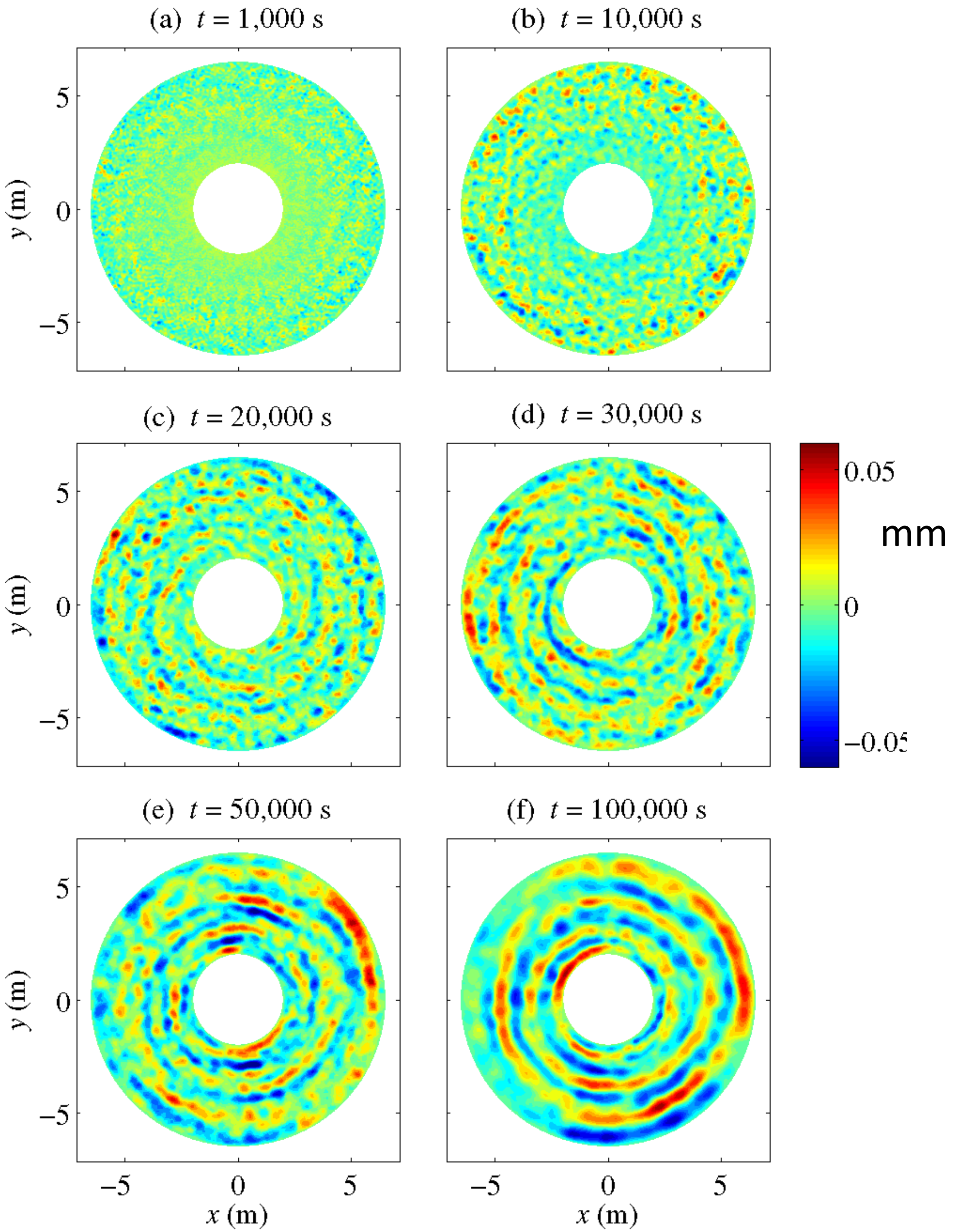
Experiments 6–10: $u_{rms} \approx \beta L_{Ro}^2$ → undulation?

Experiments 11–15: $u_{rms} < \beta L_{Ro}^2$ → zonation?

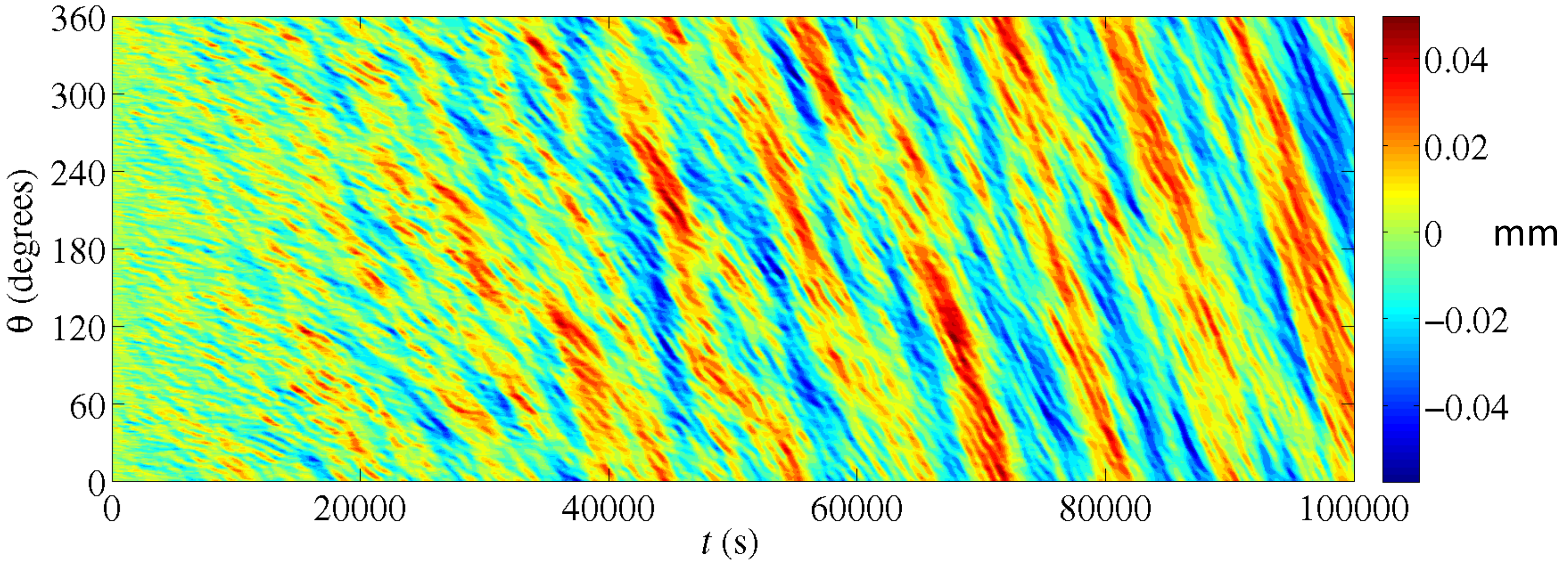
4. Snapshots of η

$$\eta = \frac{f}{g'}(\psi_2 - \psi_1)$$

(deviation from the parabolic equilibrium shape)



5. Hovmöller diagram of mid-radius η



→ acceleration of baroclinic Rossby waves according to: $c_{\mathrm{baroclinic}} = \dfrac{\beta}{k^2 + l^2 + 1/L_{\mathrm{Ro}}^2}$

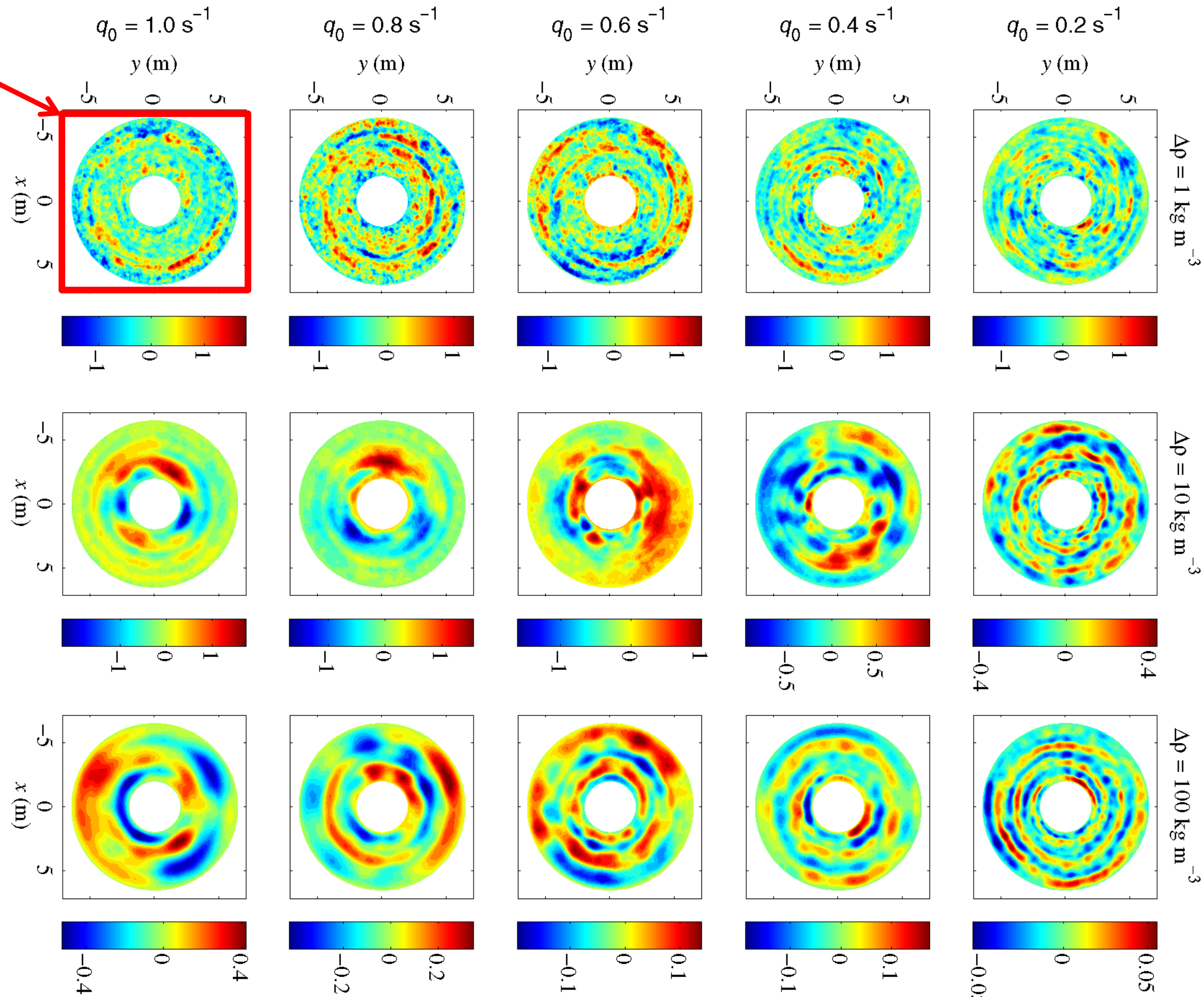
6. Snapshots of final states

closest to laboratory conditions

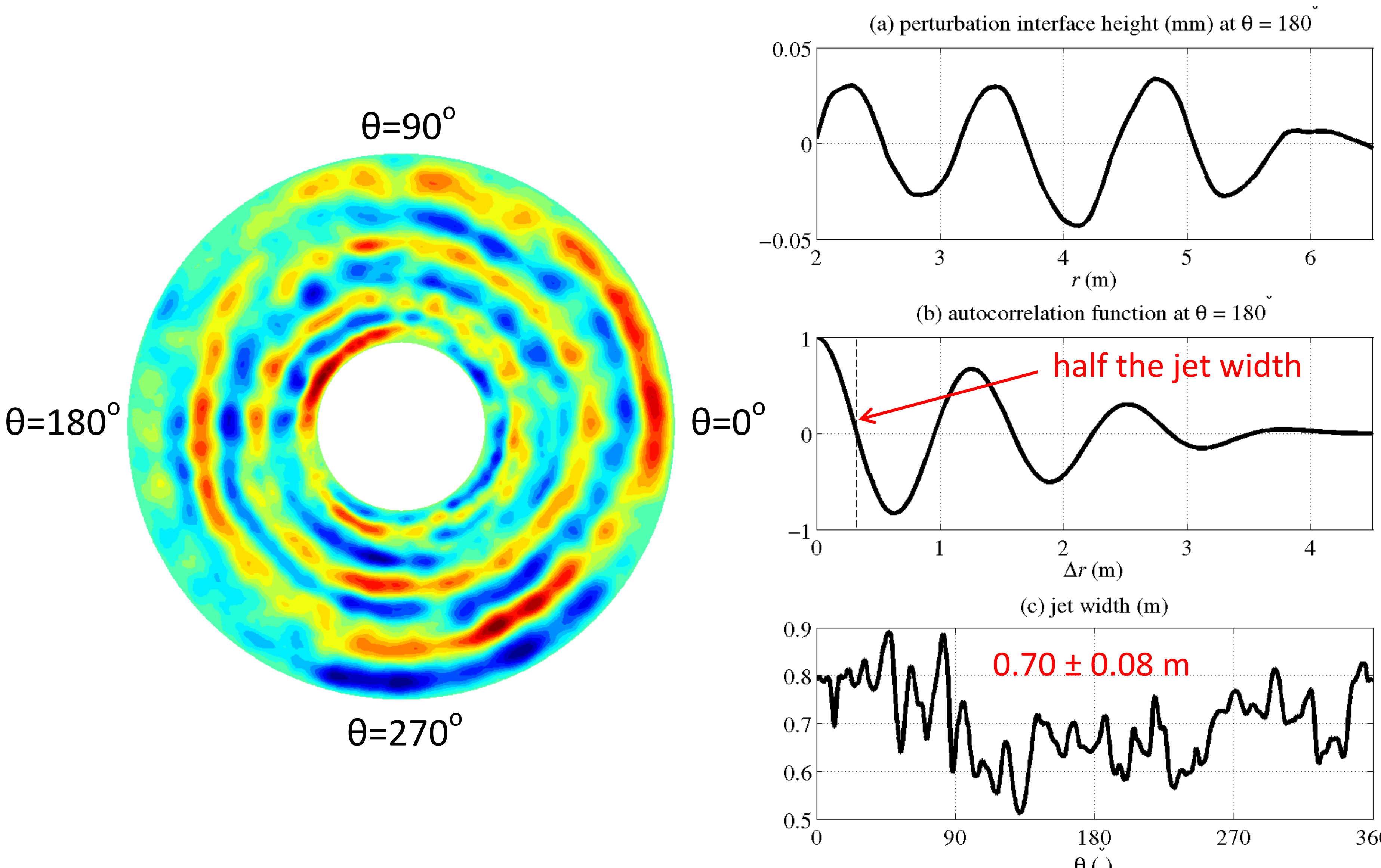
isotropy?

undulation?

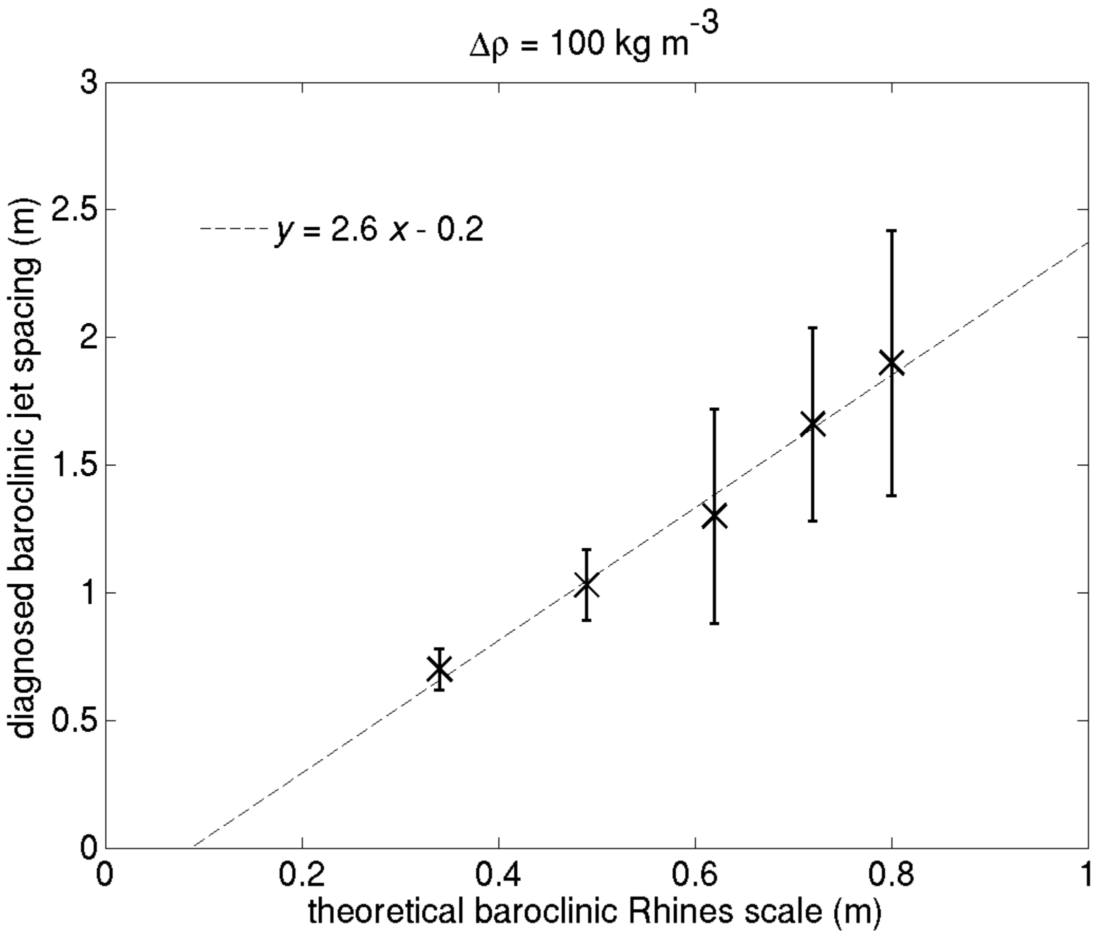
zonation?



7. Objectively diagnosing the jet width



8. Comparison with theoretical scaling



$$L_{\mathrm{Rh,baroclinic}} = \overset{\mathbf{2.6}}{\wedge}\,\pi\sqrt{\frac{2u_{\mathrm{rms}}}{\beta - u_{\mathrm{rms}}/L_{\mathrm{Ro}}^2}}$$

Summary

- Laboratory experiments
  - Read et al. (2004, 2007) observed zonal jet formation in a large, convectively forced rotating annulus laboratory experiment with sloping topography
  - But the jets were not very persistent and meandered significantly in time… why?
- Numerical experiments
  - We have used a quasi-geostrophic numerical model to simulate the laboratory experiments
  - Possible reasons for the jet meandering:
    - the effects of the finite baroclinic deformation radius mean the jet existence condition is only marginally satisfied
    - fully developed jets take a long time (>3-6 h) to emerge

Related manuscript submitted to *Journal of the Atmospheric Sciences*