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

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1. Lab expts in a 13 meter annulus

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

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

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

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

Read et al. (2004, 2007)
2. The QG numerical model

The initial condition is noise in \( q \) on scales 5-10 times the grid spacing.
3. Suite of 15 numerical experiments

<table>
<thead>
<tr>
<th>experiment number</th>
<th>$\Delta \rho$ (kg m$^{-3}$)</th>
<th>$q_0$ (s$^{-1}$)</th>
<th>$U_{rms}$ (mm s$^{-1}$)</th>
<th>baroclinic Rossby radius (m)</th>
<th>baroclinic Rhines scale (m)</th>
<th>jet spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>0.2</td>
<td>0.24</td>
<td>0.12</td>
<td>0.41</td>
<td>0.88 ± 0.47</td>
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<td>2</td>
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<td>0.4</td>
<td>0.56</td>
<td>0.12</td>
<td>1.53</td>
<td>1.08 ± 0.68</td>
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<td>0.6</td>
<td>0.83</td>
<td>0.12</td>
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<tr>
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<td>1.17</td>
<td>0.12</td>
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<tr>
<td>5</td>
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<td>1.0</td>
<td>1.42</td>
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<td>0.2</td>
<td>0.25</td>
<td>0.37</td>
<td>0.34</td>
<td>0.90 ± 0.26</td>
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<tr>
<td>7</td>
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<td>0.4</td>
<td>0.55</td>
<td>0.37</td>
<td>0.51</td>
<td>1.66 ± 0.63</td>
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<tr>
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<td>0.37</td>
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<td>1.85 ± 0.63</td>
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<td>0.37</td>
<td>0.78</td>
<td>1.65 ± 0.62</td>
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<td>1.45</td>
<td>0.37</td>
<td>0.90</td>
<td>1.76 ± 0.84</td>
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<td>0.2</td>
<td>0.26</td>
<td>1.17</td>
<td>0.34</td>
<td>0.70 ± 0.08</td>
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<tr>
<td>12</td>
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<td>0.4</td>
<td>0.56</td>
<td>1.17</td>
<td>0.49</td>
<td>1.03 ± 0.14</td>
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<tr>
<td>13</td>
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<td>0.6</td>
<td>0.87</td>
<td>1.17</td>
<td>0.62</td>
<td>1.30 ± 0.42</td>
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<td>0.72</td>
<td>1.66 ± 0.38</td>
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<td>1.45</td>
<td>1.17</td>
<td>0.80</td>
<td>1.90 ± 0.52</td>
</tr>
</tbody>
</table>

$u_{rms} > \beta L_{Ro}^2 \rightarrow$ isotropy?

$u_{rms} \approx \beta L_{Ro}^2 \rightarrow$ undulation?

$u_{rms} < \beta L_{Ro}^2 \rightarrow$ zonation?
4. Snapshots of $\eta$

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

(deviation from the parabolic equilibrium shape)
5. Hovmöller diagram of mid-radius $\eta$

→ acceleration of baroclinic Rossby waves according to:

$$c_{\text{baroclinic}} = \frac{\beta}{k^2 + l^2 + 1/L_{Ro}^2}$$
6. Snapshots of final states

- Isotropy?
- Undulation?
- Zonation?

closest to laboratory conditions
7. Objectively diagnosing the jet width

$\theta = 90^\circ$

$\theta = 180^\circ$

$\theta = 270^\circ$

$\theta = 0^\circ$

(a) perturbation interface height (mm) at $\theta = 180^\circ$

(b) autocorrelation function at $\theta = 180^\circ$

half the jet width

(c) jet width (m)

0.70 ± 0.08 m
8. Comparison with theoretical scaling

\[ \Delta \rho = 100 \text{ kg m}^{-3} \]

\[ y = 2.6x - 0.2 \]

\[ L_{Rh,\text{baroclinic}} = \pi \sqrt{\frac{2\upsilon_{\text{rms}}}{\beta - \upsilon_{\text{rms}}/L_{Ro}^2}} \]
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