Locating sources of variability in the transition to Structural Vacillation in the baroclinic annulus

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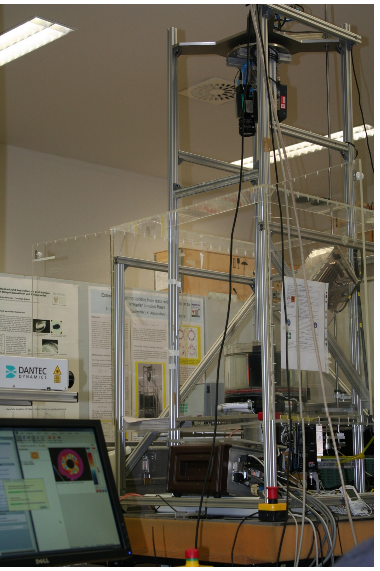
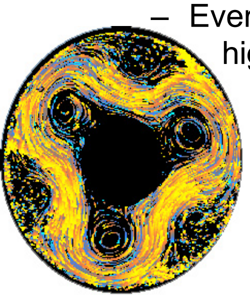
1. Transition to chaotic flow from 'Amplitude Vacillation' (AV) is well understood but the later transitions towards more turbulent flows do not seem to take place via AV.
2. Instead, 'Structural Vacillation' (SV) appears to be a frequent visitor on the route to geostrophic turbulence
   a) While AV is well described by a few global modes interacting,
   b) SV has eluded a clear modal framework
3. Higher-resolution computations suggested that the sidewalls are a serious candidate to provide small-scale vorticity and turbulence
4. Another candidate could be the breaking of internal gravity waves

—> **Can we pinpoint where the initial SV is initiated from, and how it takes the flow from highly regular to irregular?**



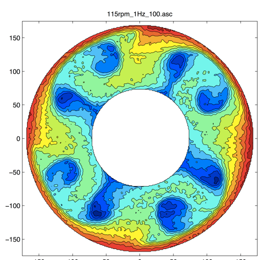
- **Annulus tank**:
  - Water-filled
  - Free surface
  - Inner radius 45 mm
  - Outer radius 120 mm
  - Fluid depth 135 mm
- Temperature differences: 6, 7.5, 9 K
- Rotation rates: 0.84 – 2.29 rad/s
- ***Taylor number***: 46×10^6 – 353×10^6
- ***Thermal Rossby number*** 0.062 – 0.63
- Measured surface temperature with co-rotating IR camera mounted on top
- Images
  - every 1 s at lower rotation rates,
    - Every 0.5 s at higher rotation rates

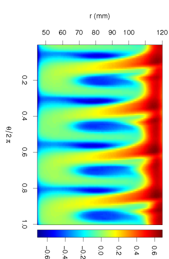


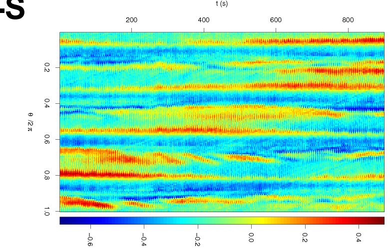
Snapshots from a timeseries lasting 15 minutes | Time mean in reference frame of main wave (r-θ plot) | Hovmøller diagram of temperature residuals (t-θ plot) taken at r= 100 mm

(Almost) steady wave

4-S

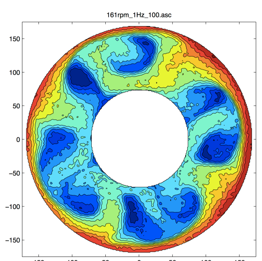


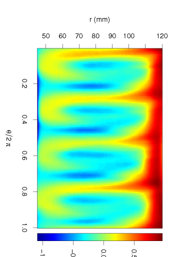


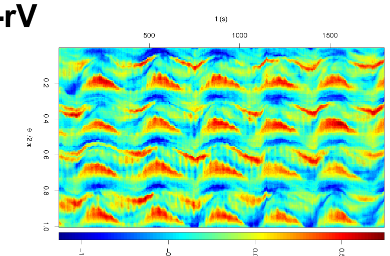


Periodic Vacillation

4-rV

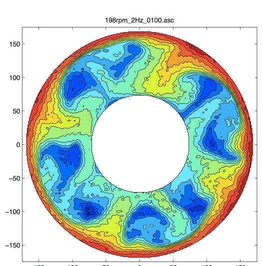


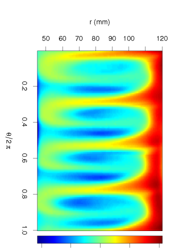


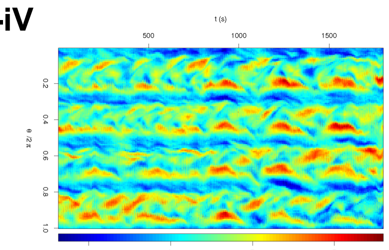


Irregular Vacillation

4-iV





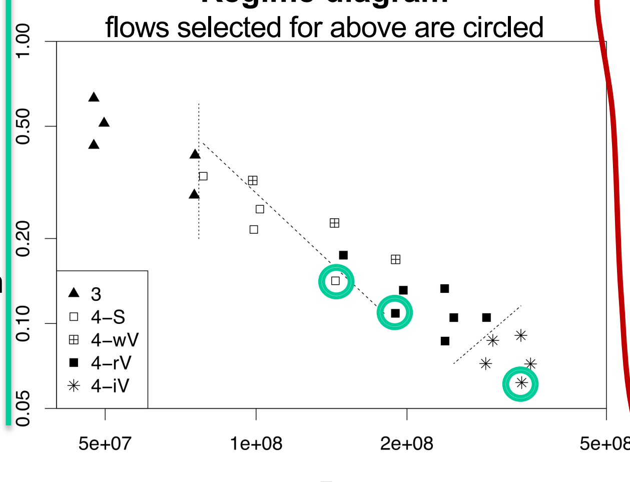


Analysis steps:

1. Normalise the temperatures for each image
   Use spatial mean and standard deviation of each image
2. Identify phase of dominant mode
3. Rotate images to create a stationary wave
4. Calculate the time mean field
5. And the time series of the fields of residuals

Regime diagram

flows selected for above are circled



Results so far:

4-S: Leading to up onset of vacillation
   a) Fairly featureless spectrum over bulk
   b) High-frequency signal (2- 4 tank rotations) at inner boundary and in regions of high temperature gradient

4-rV: spatial pattern of clusters extended and refined into 3 clusters
   a) Much less high-frequency signal
   b) Enhanced mid-frequency variability in 'rim' between high temperature gradient and bulk

4-iV: spatial pattern of clusters still traces mean flow structure but
   a) clustering no longer reflects the (4-fold) symmetry but associates with individual wave lobes -> ***localised response***

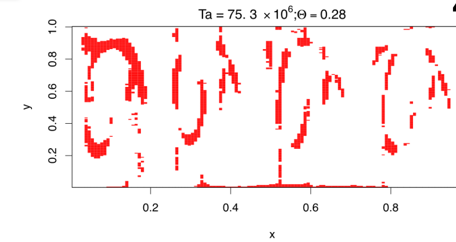
Classification steps:

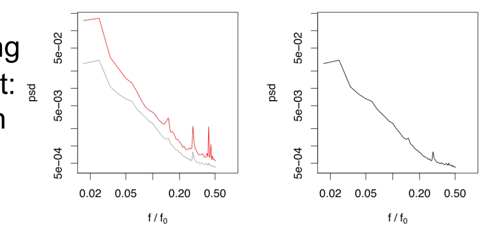
6. Calculate power spectra at each location in r-θ grid
7. To focus on differences among spectra within one experiment: Calculate the ensemble mean of all spectra for that experiment
8. Calculate the ratio of spectral amplitude at each location to the ensemble mean
9. Restrict analysis to frequencies lower than half the turntable rotation
10. Carry out k-means Cluster Analysis on set of low-frequency spectral ratios number of clusters chosen for each experiment by judgment of discrimination
11. Identify to which cluster each location in fluid is associated with, and create **map of cluster membership**
12. Obtain a set of **'representative spectra'** by ensemble average across spectra belonging to cluster

-> Interpret representative spectra and their location with reference to mean field

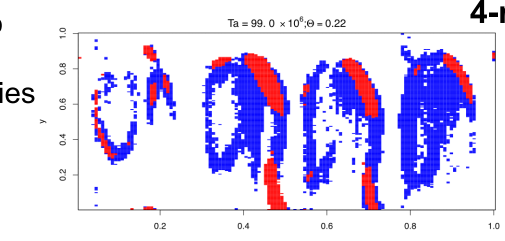
Cluster maps And Representative spectra

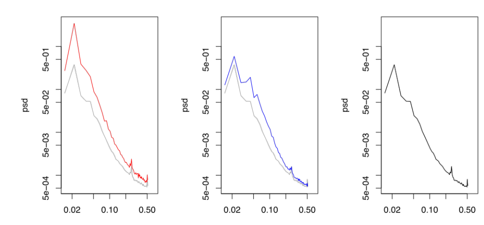
4-S





4-rV





4-iV