Zonal Jets

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CUP [due to appear 2015?]

The answer to life, the Universe and everything?
Multiple zonal jet formation in rotating, thermally-driven convection on a topographic $\beta$-plane

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3/27/14
Motivation

• Phenomenology of anisotropic large-scale turbulence and “jets” in geophysical and planetary fluids
  – in oceans cf in gas giant planet atmospheres,

• Questions:
  – (i) Why are jets prominent on gas giant planets but weak in the oceans?
  – (ii) energetics and energy flow (esp. on gas giants)?
    • large apparent $C(K_E,K_Z)$ conversion rates?
    • Relationship to more general (upscale?) energy cascades?
    • Local or non-local?
  – (iii) Potential Vorticity and configuration of zonal jets?
    • PV mixing (‘Phillips effect’)
    • PV staircases?
  – (iv) Passive tracer transport and mixing?
    • Zonation and transport barriers?
Cascade becomes anisotropic at a scale where Rossby waves become important

\[ L \approx \frac{5}{3} \frac{l}{3}; \text{ where } L / U \]

- \( L < L_\beta \): Nonlinear effects dominate
- \( L > L_\beta \): \( \beta \)-effect dominates

[Vallis & Maltrud 1993]

Kinetic energy removed at largest scales e.g. by bottom friction

\[ L \quad L_{Rh} = \sqrt{2U_{rms} / L}; \text{ Rhines scale} \]

[Yoden et al., 1999]
`Zonation’ in the Ocean

Pacific Ocean in observations & eddy-permitting numerical models

Maximenko et al. (2005)

Thompson (2008)

Richards et al. (2006)
Planetary Zonal Jets

Cassini ISS winds for Jupiter (Porco et al. 2003)

• Robust, long-lived and ~rectilinear?
• $q_y = \beta - u_{yy} < 0$ in easterly jets
• Jets maintained by horizontal eddy momentum fluxes (Reynolds stresses)?
  – $C(K_E,K_Z) \sim 3 - 12 \times 10^{-5} \text{ W kg}^{-1}$ [??]
Zonal jets on Jupiter (Cassini)

• Unique series of Jupiter images from the Cassini fly-by in December 2000

• Closest approach has resolution ~0.05 deg/px

Credits:
Ashwin Vasavada
Cassini Orbiter
Imaging Team
(2001)
Velocity fields

Velocity field for day 2: 2000-12-12 00:03:34 to 2000-12-12 09:38:12 (c

Planetocentric latitude

Longitude

Wind speed (m s⁻¹)

0.0 23.8 47.7 71.5 95.4 119.2 143.0 166.9 190.7

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KITP Wave-zonal flows - 24-27
March 2014
Jupiter: relative vorticity
(Cassini ISS images - Galperin et al 2014)
Spectrally local vs nonlocal interactions?

- Decompose 2D KE spectrum $E(k_x, k_y) dk_x dk_y$ into
  - zonal mean
    $$E_Z(n) dn = E(k_x = 0, k_y) dk_y; \quad n = [k_x^2 + k_y^2]^{1/2}$$
  - and directionally-averaged non-zonal (residual) components
    $$E_R(n) dn = \int_0^2 E(k_x \{ 0 \}, k_y) n d k_y \; dn :$$
  such that
  $$E(k_x, k_y) dk_x dk_y = \int_0^2 [E_Z(n) + E_R(n)] d n$$

For ideal ‘zonostrophic flow’ - $E_R \sim n^{-5/3}$
[spectrally-local, isotropic inverse cascade]

$E_Z \sim n^{-5}$
[non-local “cascade”]
e.g. Sukoriansky et al. (2002) PRL....
Shallowing slope ($\sim n^{-5/3}$?)
- Upscale cascade?

\[ E_Z = C_Z b^2 \left( \frac{n}{a} \right)^5 \] (1)
\[ E_R = C_R \left( \frac{n}{a} \right)^{5/3} \] (2)

Zonostrophy index $R_\beta = \frac{L_R}{L_\beta} H^5$

Thin: Zonal spectrum
Thick: Residual (eddy) spectrum

$\sim n^{-5}$ -> non-local energy transfers

Compensated residual spectrum with $\pm \sigma$ error bars

See Galperin et al. (2014)
How to realise in Laboratory Experiments?

• Experimental requirements
  – Horizontal scale \( L > L_{\text{Rh}} \approx \pi \left( 2U_{\text{rms}}/\beta \right)^{1/2} \)
  – Reynolds number \( UL/\nu > 10^3 \)
  – Ekman number \( \left( \nu/fD^2 \right) \leq 10^{-5} \)
  – Suitable forcing on a small scale \( << L \)
    - preferably not fixed in space…
  – Rapid rotation (small Rossby number)

\[ \Downarrow \]

LARGE-SCALE EXPERIMENT
(GRENOBLE 13 m dia. Rotating table)
Experimental configuration 1: Salt-driven convection

- Overhead salt-water spray system
- Nozzles mounted on rotating, radial arm
- Spacing/orientation designed to supply uniform buoyancy flux
- Rotation, density and flow rate (buoyancy flux) controlled
Experimental configuration 2: THERMALLY-forced convection

- Coriolis Platform, Grenoble (France)
- ~3km of heating cable layed beneath hollow sloping bottom
- Smooth, rigid sloping bottom of segmented Al plates
- Upward slope with $r$ at approx. 6°
Upward-sloping bottom

Experiment running...
Measurement configuration

BUT views ~7% only of total area! – *keyhole diagnostics*

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Small-scale convection?

- 11 kW of heating $\Rightarrow F_B \sim 5.8 \times 10^{-8} \text{ m}^2 \text{ s}^{-3}$
- Intermittent convective plumes form compact, intense cyclonic vortices
  - Around 5-50 cm diameter
  - Consistent with $l_{rot} \sim (Ro^*)^{1/2}h$; $Ro^* = (F_B/f^3h^2)^{1/2} \sim 10^{-3}-10^{-2}$
    [Fernando et al. 1991]
Flow visualisation in laser sheet

- Neutrally buoyant particles
  - Measure horizontal velocity using PIV/CIV
- Jets & vortices
- Baroclinic instabilities?
Radial scale of Azimuthal mean jets

Azimuthal mean azimuthal (zonal) velocity

$\beta L^2/(2u_{rms})$

$L_{Rh}$

580

180

42

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(SW) Potential Vorticity fields

\[ E = 5 \times 10^{-6} \]
\[ \beta L^2 / (2u_{\text{rms}}) = 395 \]

- \( q = (\zeta + 2\Omega)/h(r) \)
- Complex vortex dynamics & waves
- ‘Eastward’ propagation of discrete vortices
Potential Vorticity “Staircases”:

- Band-wise PV homogenisation in retrograde jets
- PV gradient still shows sustained reversals…..instability or forcing?
Scaling of jet separation

- Determine ‘centroid’ radial wavenumber of jets ($k_{bar}$)
- ‘Pre-whiten’ zonal flow

\[ \hat{u}(r) = (\bar{u} \cdot <u>) \cdot \frac{r}{r_0}^3 \]

- FFT to get $E(k)$
- Find $k_{bar}$ vs $k_{Rhines}$

\[ k_{bar} = (1.9 \pm 0.1) k_{Rhines} \]

\[ k_{Rhines} = \left( \frac{b}{2u_{rms}} \right)^{1/2} \]
Eddy-zonal flow interactions: non-local spectral energy transfer?

- Separately compute $1/r \, \partial (ru'v')/\partial r$ and $\partial \bar{u}/\partial t$
- Correlate in time
- Significant anti-correlation ($C \sim -0.4$) across all radii:
  - Systematic KE conversion from eddies->mean flow
Eddy-zonal flow interactions: non-local spectral energy transfer?

- Compute $C(K_E, K_Z)$ as a function of time -- Strongly variable [including its sign]
- Systematic KE conversion from eddies -> zonal mean flow [averaged in time]
  - Mean conversion rate $\sim 0.5-5 \times 10^{-10}$ W/kg ($\sim 0.1-1\%$ of $F_B$)
  - Instantaneous conversion rate $\sim 10-50$ times bigger
- Hint of a characteristic timescale/period $O(10^3)$ s?
  - Cyclic decay/instability of zonal jets?

$\frac{1}{p} = \frac{1}{\sqrt{4u_{rms}}} \approx 1900$ s; or

$E = \frac{H}{\sqrt{\cdot}} \approx 2000$ s

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$$\tau_{\text{conv}} \text{ vs timescales?}$$

\[ \tau_E \sim 4.8 \tau_{\text{conv}} \]

\[ \tau_p \sim 2 \tau_{\text{conv}} \]
KE spectra

\[ \frac{L^2}{U_{rms}} = 581 \]
\[ E_Z = C_Z \left(\frac{n}{a}\right)^5 \quad (1) \]
\[ E_R = C_R \left(\frac{n}{a}\right)^{5/3} \quad (2) \]

\[ \varepsilon \approx 5 \times 10^{-10} \text{ W kg}^{-1} \]
\[ = 0.2-1 \times C(K_E,K_Z) \]
\[ \approx 1\% \times F_B \]
Eddy-zonal flow interactions: non-local spectral energy transfer?

- Spectral energy transfer function
  \[ T_\Omega = 2\pi k \text{ Re} \int_{p+q=k} dp dq / (2\pi)^2 \frac{p x q}{p^2} <\zeta(p,t)\zeta(q,t)\zeta(-k,t)>; (p,q)\geq |k_{\text{max}}| \]
  - Peaks on \( k_y \) axis with \( \beta \)-effect – NON-LOCAL transfer
  - No such peak without \( \beta \)-effect
Zonostrophy & tracer transport?

- Turbulence becomes anisotropic for $L > L_\beta$
- Tracer diffusivity (e.g. obtained from FSLEs) scale-dependent (Richardson law) for $L < L_\beta (k > k_\beta)$
  $$D_y = C_D^{1/3} k^{4/3}$$
- For $L > L_\beta$, however, $D_y$ becomes scale-independent (Taylor law)
  $$D_y = C_D^+ {1/3} k^{4/3} = C_D^* {3/5} k^{4/5}$$

(Laboratory experiments by Stefani Espa
In Rome:
- Galperin et al. 2014 submitted)
- Break in gradient at $\sim 2L_\beta$
Zonostrophy & tracer transport?

- For $L > L_\beta$, however, $D_y$ becomes scale-independent (Taylor law)
  \[ D_y = C_D^{+} \frac{1}{3} k^{4/3} = C_D^* \frac{3}{5} \frac{4}{5} \]
- Large scale (Taylor) diffusivity a strong function of $R_\beta$
  - Much weaker in transitional/zonostrophic regimes
  \[ D_y \approx 0.5 \frac{3}{5} \frac{4}{5} \]
  - Consistent with spread of debris on Jupiter from comet Shoemaker-Levy?
- Jet-scale meridional barriers...?

Sukoriansky et al. GRL (2009)
- Uses barotropic vorticity equn on a sphere
Belts & Zones as transport barriers?

- Zones regions of enhanced NH$_3$ & PH$_3$ (from deep levels)
- Belts regions of weaker tracer conc.
  - (Irwin et al. 2004)
Belts & Zones as transport barriers?

- Zones regions of enhanced NH$_3$ & PH$_3$ (from deep levels)
- Belts regions of weaker tracer conc.
- (Fletcher et al. 2009)
Laboratory Experiments:
the challenge of producing zonostrophic conditions?

- Experimental requirements
  - Horizontal scale \( L > L_{Rh} \sim \pi(2u_{rms}/|\beta|)^{1/2} \) i.e. \( L^2/u_{rms} \geq 100 \)
  - AND Zonostrophy parameter \( k_{\beta}(\sim[\beta^3/\varepsilon]^{1/5})/k_R \)

\[
R = \frac{k}{k_{Rh}} \quad u_{rms}^2 \frac{2^{1/10}}{E} = [ \ast .Ro^2.E^{-1}]^{1/10} 2
\]

- Translates to

\[
\frac{u_{rms}H \tan{\theta}}{10^3} \quad \text{AND} \quad \frac{L^2}{u_{rms}} \geq 100
\]

- Or

\[
\frac{L^2 \tan^2}{u_{rms}} \ll 10^5 \quad \text{setting} \quad \frac{L^2}{u_{rms}} = 100
\]

Approximating \( \varepsilon \sim u_{rms}^2/(2\tau_E) \)
**Zonostrophic expts?**

<table>
<thead>
<tr>
<th></th>
<th>Coriolis (Grenoble)</th>
<th>New Coriolis (Grenoble)</th>
<th>10Hz (Oxford)</th>
<th>100Hz (Grenoble)</th>
<th>Torino</th>
<th>Cryo He</th>
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<tbody>
<tr>
<td>$\nu \times 10^{-6}$ (m$^2$ s$^{-1}$)</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>$\Omega$ (rad/s)</td>
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<td>600</td>
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<td>3</td>
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<td>$L$ (m)</td>
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<td>0.3</td>
<td>0.25</td>
<td>2.5</td>
<td>1.0</td>
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<tr>
<td>$\Theta$ ($^\circ$)</td>
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<td>10</td>
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<td>$E_{k_z}$</td>
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<td>2.488</td>
<td>3.370</td>
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<td>3.323</td>
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</table>

$R \left( U_{rms}^2 \frac{2}{E} \right)^{1/10}$; but $U_{rms}^2 \mu \frac{F_B}{H}$ so $R \mu \left[ F_B H \right]^{1/2} \tan^{1/10}$

Larger $R_\beta$ ⇒ deeper tank, steeper slope and/or stronger forcing(!!)
Conclusions

- Multiple-jet formation by nonlinear eddy-zonal flow processes in forced-dissipative geostrophic turbulence
  - Shows clear Rhines scaling in jet separation
  - Eddy->zonal flow energy exchanges dominate
  - Vorticity dynamics and jet stability?
    - Determines strength of jets?
    - Jets meander unless $R_\beta \leq k_\beta/k_{Rhines} \leq 2$
  - Mixing and transport barriers?
    - Reduced lateral dispersion in ~zonostrophic flow?

- We have [real experimental/observational] data!
  - Lab experiments [PIV velocities…]
  - Jupiter cloud winds, PV….
Thanks for your attention!

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