Equilibrating baroclinic instability and zonal jets on the polar beta-plane: experiments with altimetry

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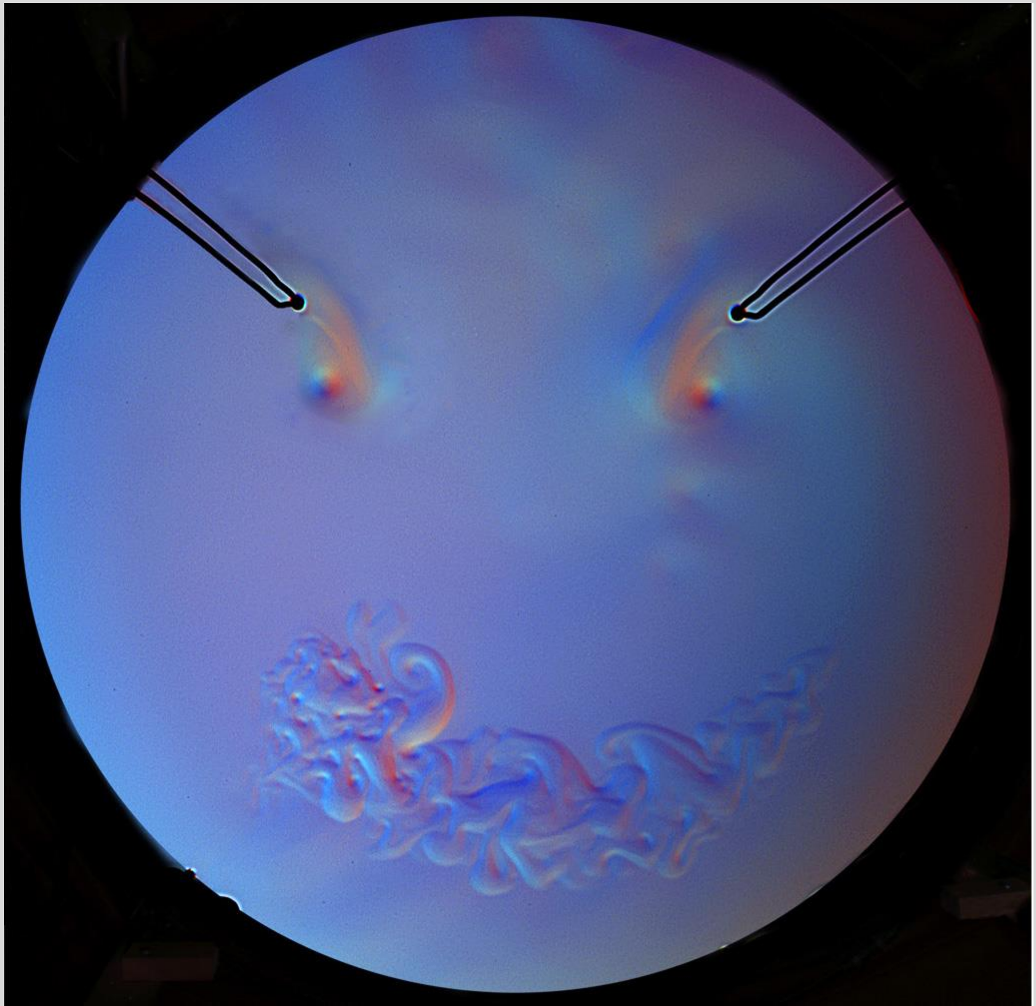
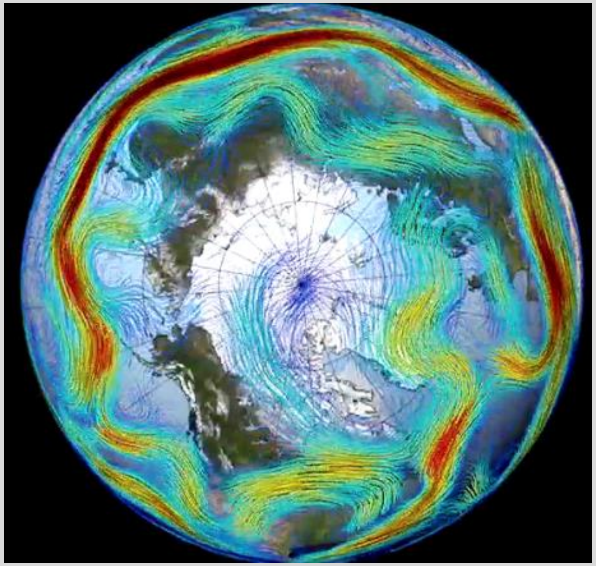
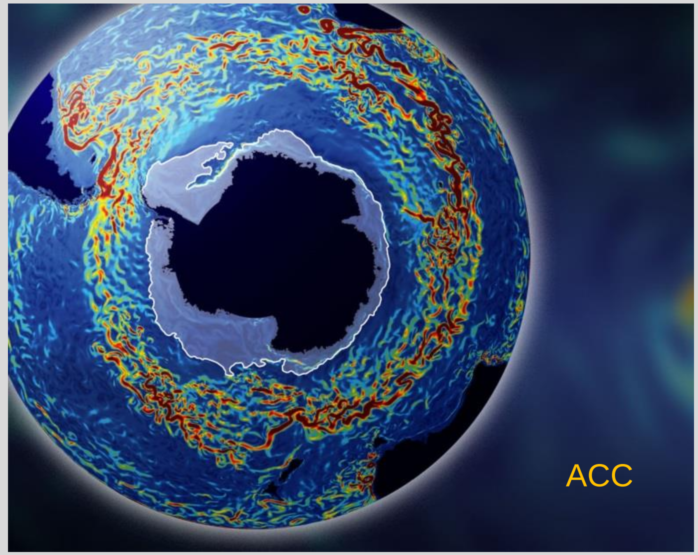
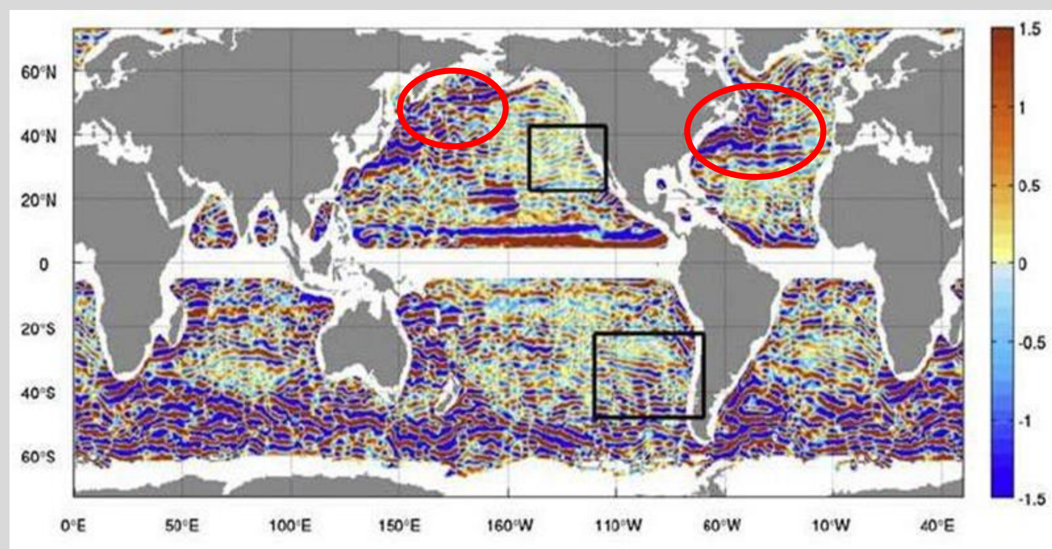


Zonal Jets in the ocean and atmosphere: baroclinically instable regions



Jet stream in Southern hemisphere

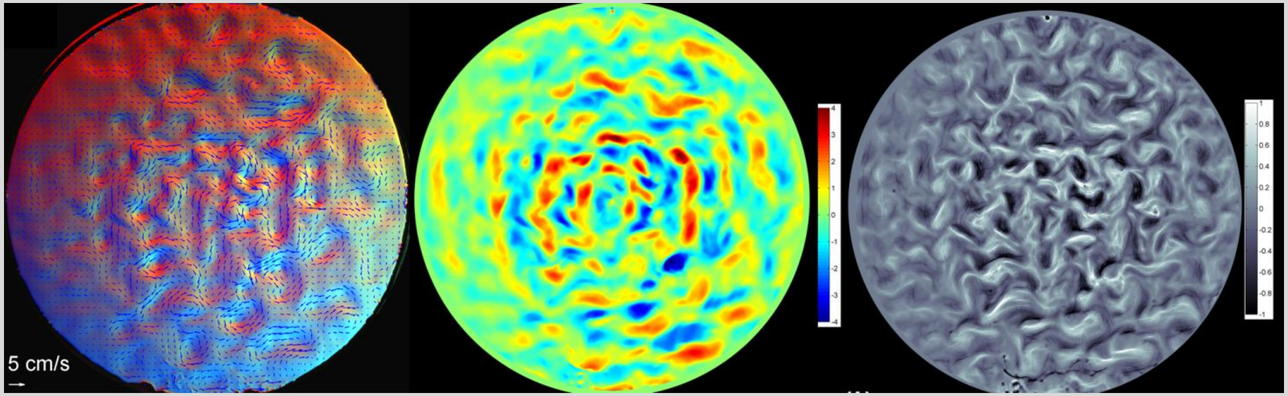




Satellite altimetry: mean surface geostrophic velocity. (Maximenko et al., 2008)

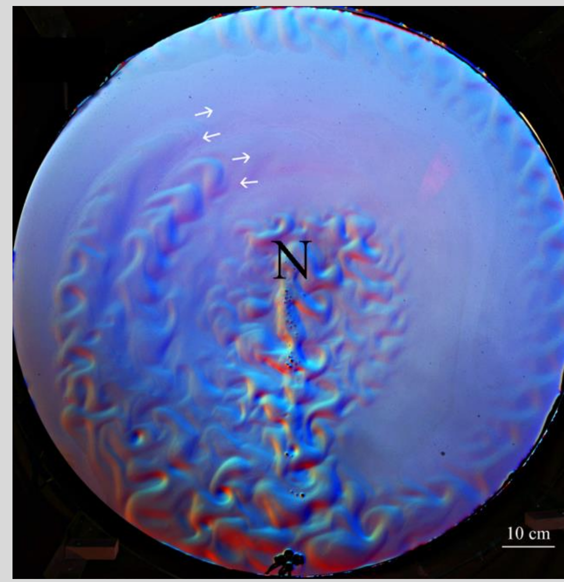
Zonal jets: Mechanisms

- "Rhines jets" occur due to transition between "eddies" and Rossby waves (Rhines 1975)



Barotropic turbulence generated by an array of magnets on polar β-plane

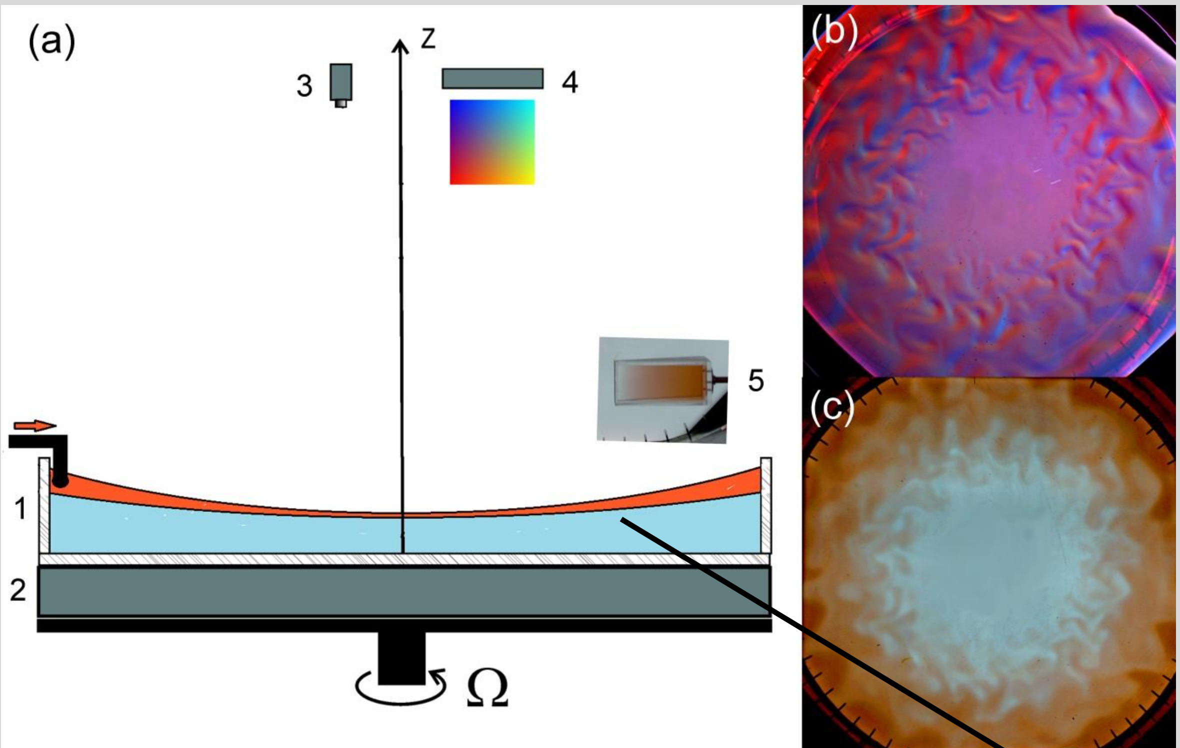
- "β-plumes" : radiation of Rossby waves by meanders, eddies (Afanasyev, O'Leary, Rhines, Lindahl 2012)



β-plumes due to baroclinic meanders generated by a linear heat source

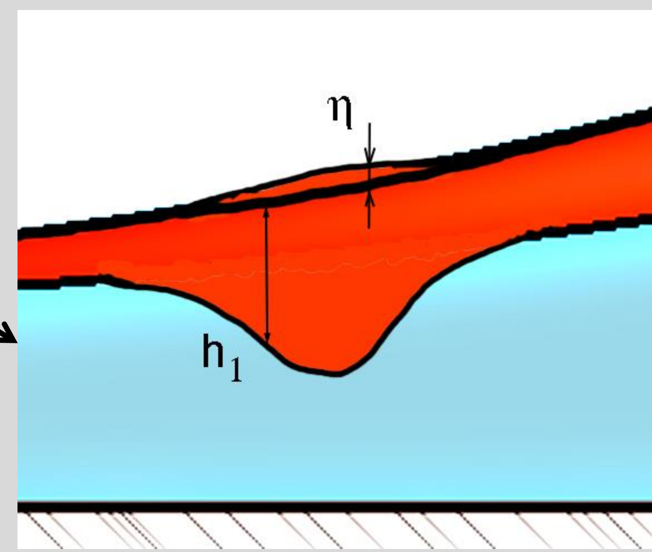
- "Noodle instability": secondary instability of the baroclinically unstable flow (Berloff, Kamenkovich, Pedlosky 2009)

Lab experiments: Altimetric Imaging Velocimetry (AIV) and Optical Thickness Velocimetry (OTV)



“Black and white” altimetry (Rhines, Lindahl and Mendez, JFM 2006)

Color altimetry (Afanasyev, Rhines and Lindahl, Exp. Fluids 2009)



$$h(r) = H_0 + \frac{\Omega_0^2}{2g}\left(r^2 - \frac{D^2}{8}\right)$$ “Geoid”

AIV / OTV : velocity from the surface/interface slope

AIV measures the slope of the surface elevation field η in each pixel of the image of the flow

$$\nabla \eta = \left(\frac{\partial \eta}{\partial x}, \frac{\partial \eta}{\partial y} \right)$$

The velocity field is calculated using the geostrophic relation

$$\mathbf{V}_g = \frac{g}{f_0} \left(\mathbf{n} \times \nabla \eta \right) = \frac{g}{f_0} \left(-\frac{\partial \eta}{\partial y}, \frac{\partial \eta}{\partial x} \right)$$

Barotropic velocity (by AIV)

$$\mathbf{V}_{g\,bc} = -\frac{g'}{f_o} \left(\boldsymbol{n} \times \nabla h_1 \right)$$

Baroclinic velocity (by OTV)

$$\mathbf{v}_1 = \mathbf{V}$$

Upper layer

$$\mathbf{v}_2 = \mathbf{V} + \mathbf{V}_{bc}$$

Lower layer

AIV / OTV: velocity from the surface slope

Full shallow water equation:

$$\frac{\partial \vec{V}}{\partial t} = -\nabla\left(\frac{1}{2}V^2 + g\eta\right) + \left(2\vec{\Omega} + \nabla\times\vec{V}\right)\times\vec{V}$$

$$\vec{V} = \vec{V}_g - \frac{g}{f_0^2}\frac{\partial}{\partial t}\nabla\eta - \frac{g^2}{f_0^3}J(\eta,\nabla\eta)$$

geostrophic unsteady nonlinear

AIV: Resolution

- 4 million velocity vectors at 5 – 10 frames per second
- typical experiment (30 min – 1 hour) generates hundreds of Gbytes of data
- spatial scales from 0.5 mm to 1.1 m
- velocity from 1 mm/s to 10 cm/s
- typical surface elevation 100 μm

Dynamic similarity to polar β-plane

$f = 2\Omega \sin\varphi,$ $\quad f \approx 2\Omega \sin\varphi_0 + \frac{2\Omega \cos\varphi_0}{a} y$ β-plane

$f \approx 2\Omega\left(1 - \frac{\phi^2}{2}\right) = 2\Omega - \frac{\Omega}{a^2} r^2 = f_0 - \gamma r^2$ Near the pole, colatitude $\phi = 90^0 - \varphi \rightarrow 0$

- Rotating tank: conservation of potential vorticity (PV)

$$q = \frac{2\Omega_0 + \zeta}{h} = \frac{1}{H_0}\left[\zeta + 2\Omega_0\left(1 - \frac{\Omega_0^2}{2gH_0}\left(r^2 - \frac{D^2}{8}\right)\right)\right]$$

- The polar β-plane (γ-plane)

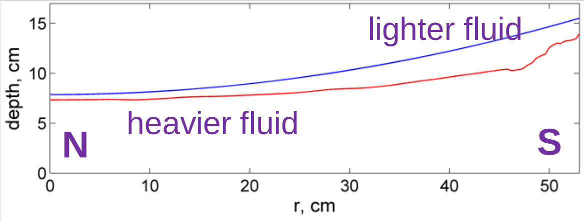
$$f = f_0\left(1 - \gamma r^2\right)$$

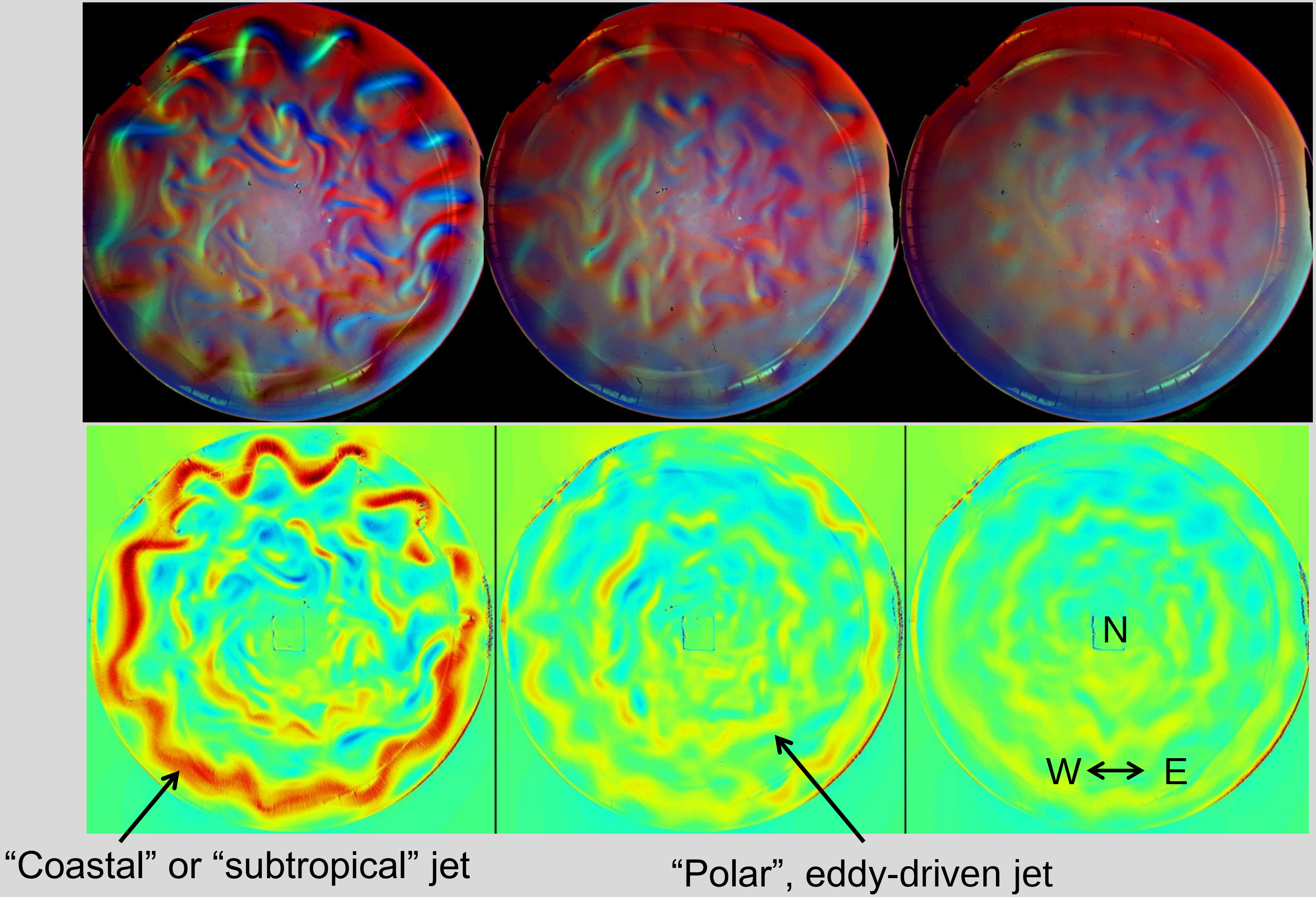
Laboratory	Earth
$\gamma = \frac{\Omega_0^3}{gH_0}$	$\gamma = \Omega_o / a^2$

- Local β-plane can be introduced at “midlatitudes” at radius r_0

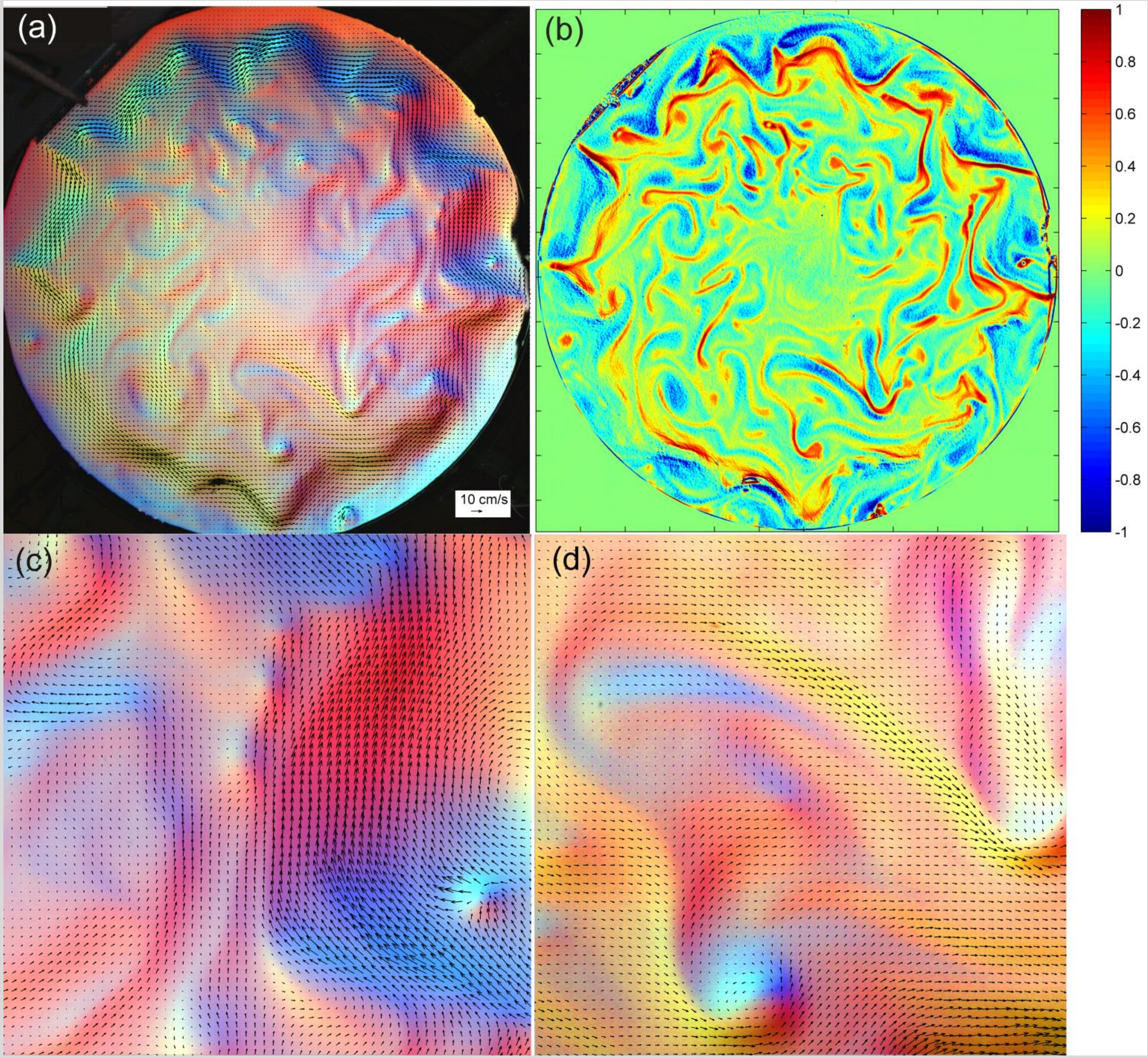
$$\beta = 2\Omega^3 r_0 / gh(r_0)$$

Baroclinically unstable flow visualized by the altimetry: evolution

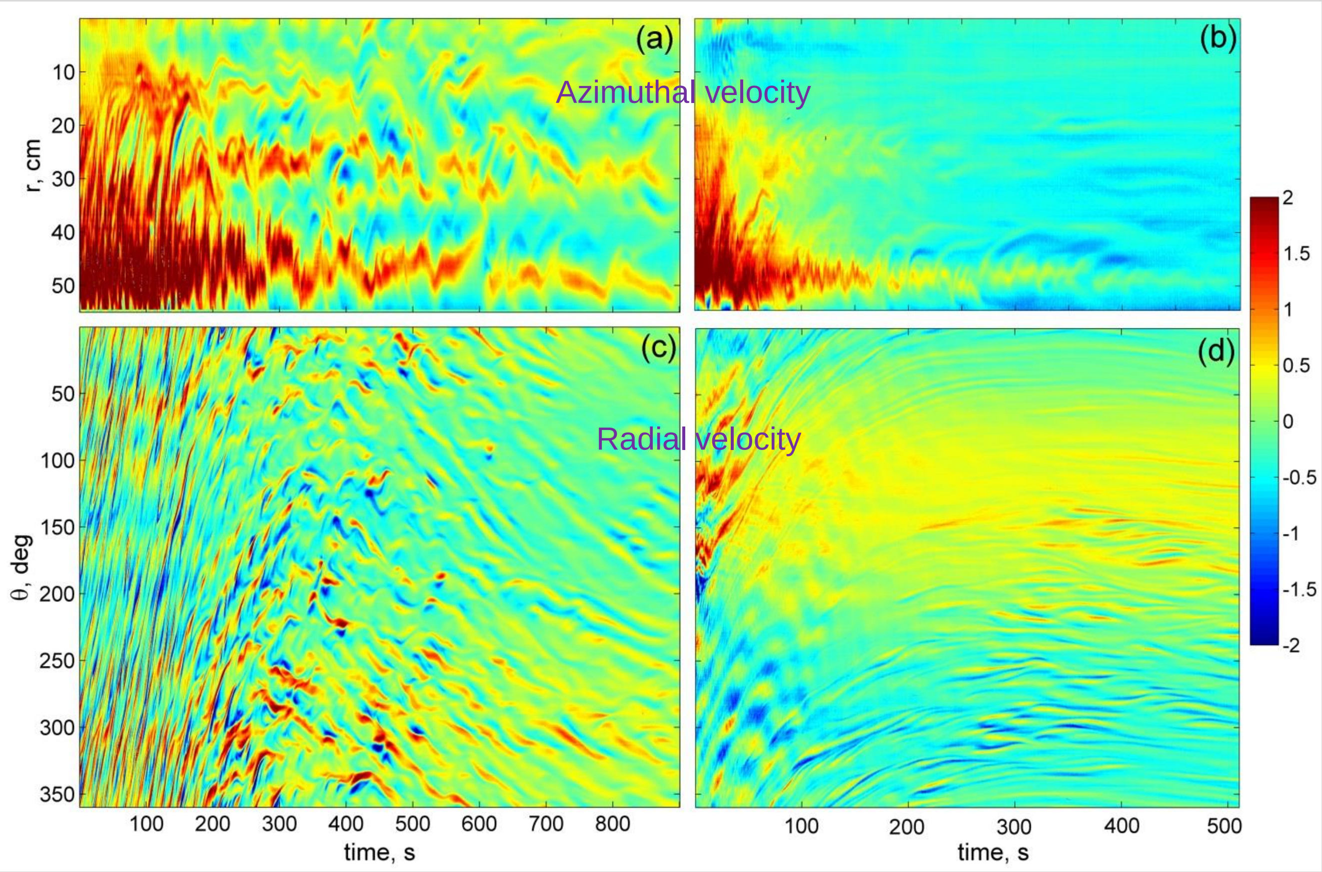




Baroclinically unstable flow visualized by the altimetry: baroclinic meanders, filaments and eddies

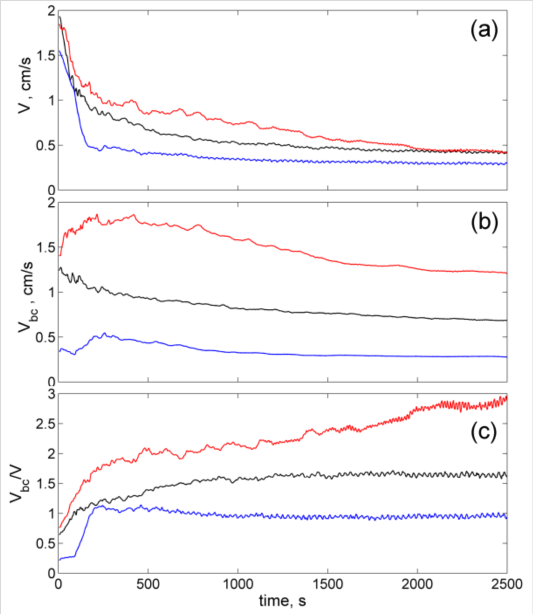


Baroclinically unstable flow : evolution



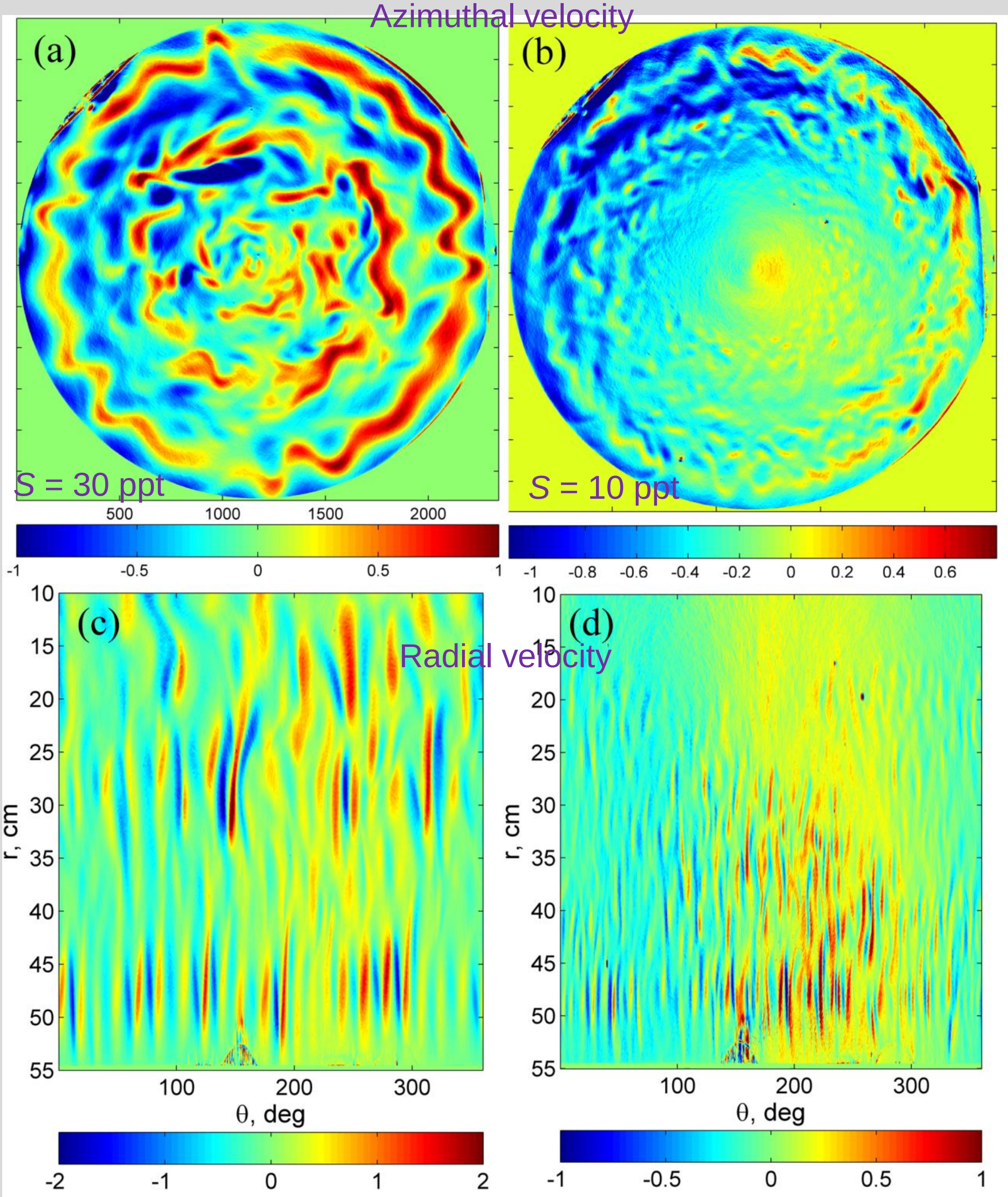
S = 30 ppt and *S* = 10 ppt

RMS barotropic and baroclinic velocity



S = 15 (blue), 45 (black) and 65 ppt (red)

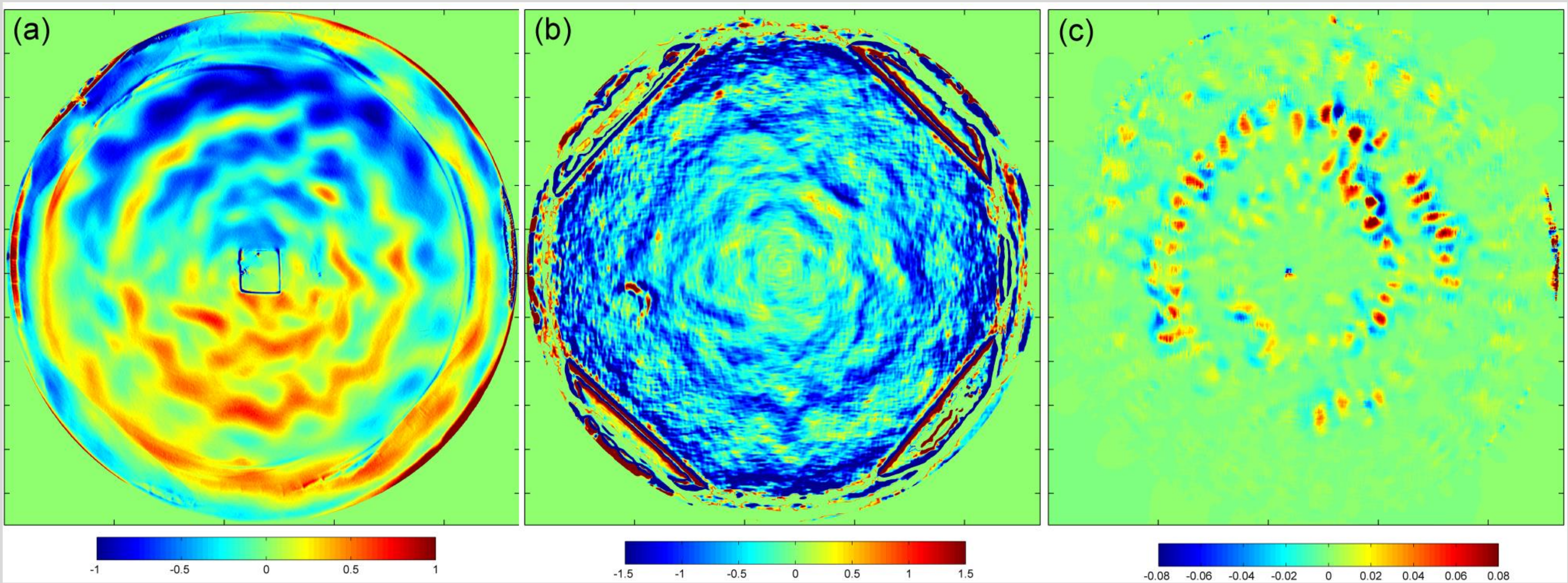
Jet scaling



Radial perturbation velocity is coherent in the radial direction: meridional jets (a.k.a. “noodles”, Berloff et al. 2009) ?

Eddy forcing

Barotropic velocity | Baroclinic velocity | Reynolds stress

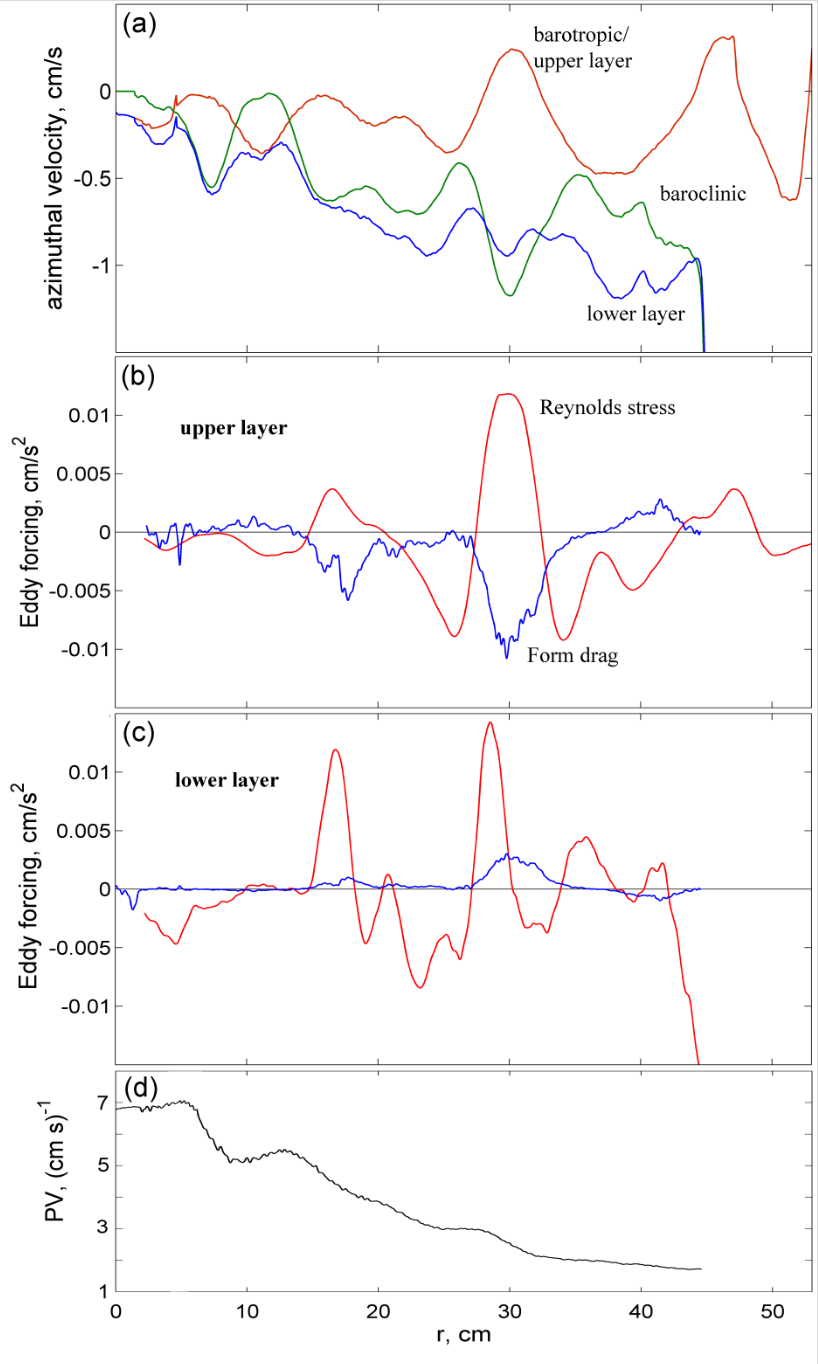


$$\frac{\partial \bar{u}_n}{\partial t} \approx \begin{cases} -\dfrac{D_{1.5}}{\bar{h}_1} - \dfrac{\partial R_1}{\partial y}, & n = 1 \\ \dfrac{D_{1.5}}{\bar{h}_2} - \dfrac{\partial R_2}{\partial y} - f_{bot}, & n = 2 \end{cases}$$

$$D_{1.5} = -f_0 \overline{v'_{1.5} \eta'_{1.5}}$$ Form drag

$$R_n = \overline{u'_n v'_n}$$ Reynolds stress

Eddy forcing



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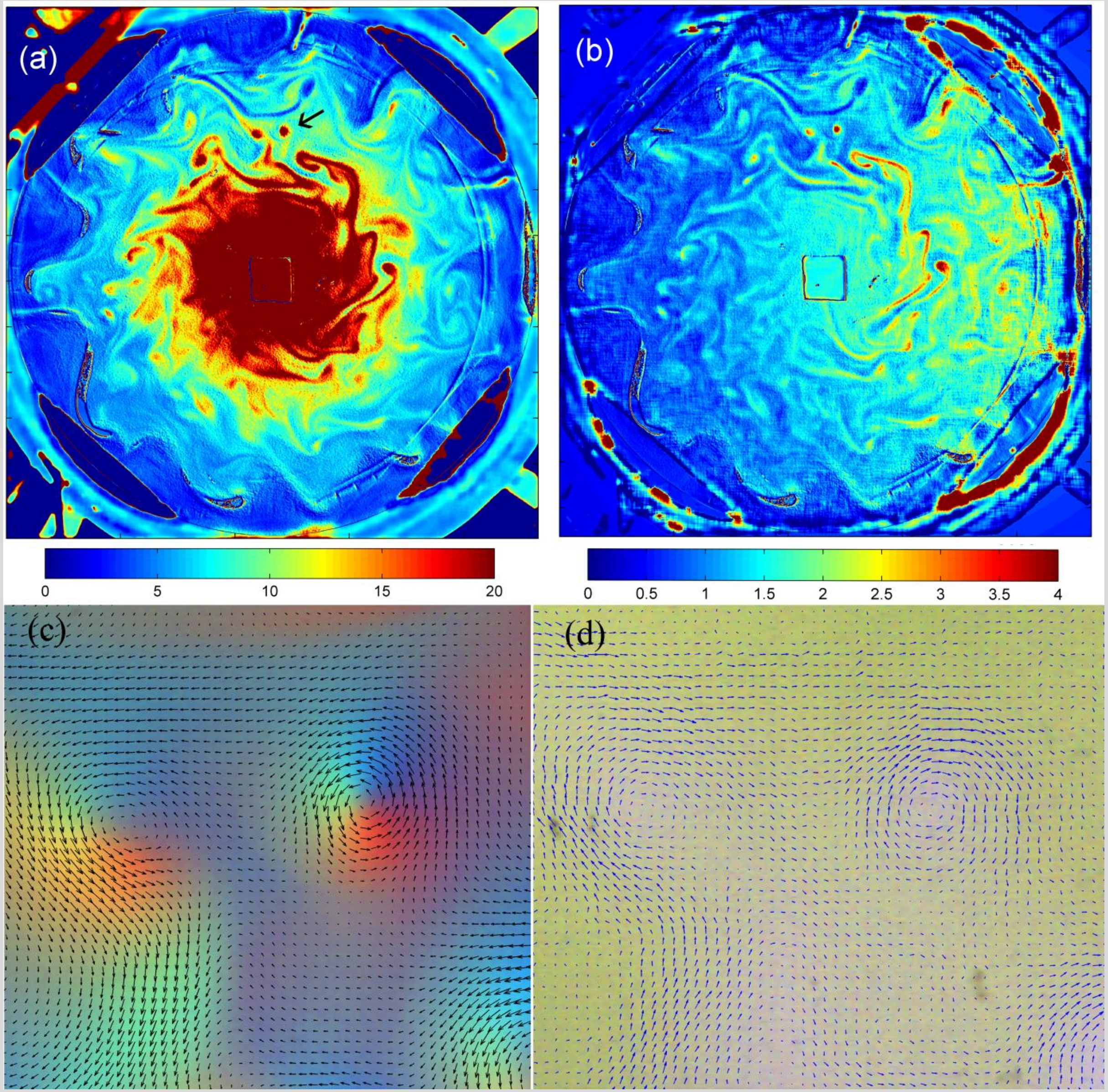
$$D_{1.5} = -f_0 \overline{v'_{1.5}\eta'_{1.5}}$$ Form drag

$$R_n = \overline{u'_n v'_n}$$ Reynolds stress

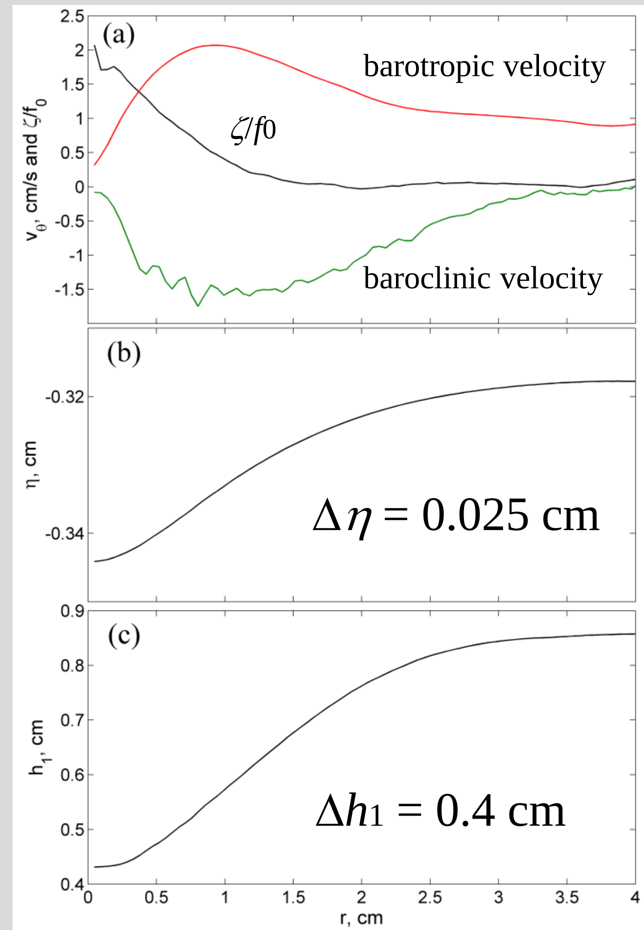
$$v_{1.5} = (v_1 + v_2)/2$$

$$\eta'_{1.5} = \bar{h}_1 - h_1$$

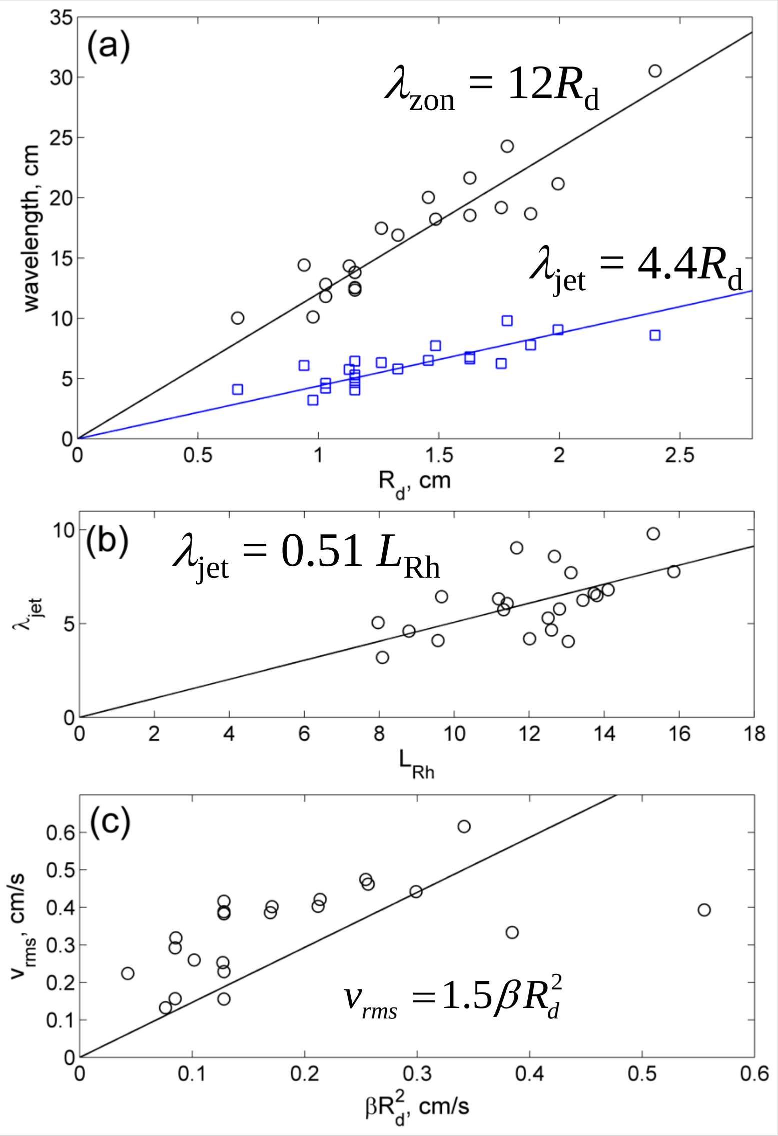
Eddies



- All eddies are cyclonic
- Lifetime ~ 2 – 10 “days”
- Strongly baroclinic, “surface intensified”



Jet scaling



Rhines scale

$$L_{Rh} = 2\pi(V_{rms}/\beta)^{1/2}$$

Radius of deformation

$$R_d = (g' H_0/2)^{1/2}/f_0$$

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Conclusions

- Zonal jets are created in a baroclinically unstable flow.
- Jets are driven by eddy forcing which is provided by baroclinic meanders and filaments on the β-plane.
- The meridional wavelength of the jets varies linearly with the baroclinic radius of deformation.
- The jet wavelength is in good agreement with the (modified) Rhines scale.
- rms radial velocity in an equilibrated baroclinically unstable flow is proportional to βR_d.

Flow generated by a distributed thermal forcing