ZONALLY ELONGATED TRANSIENT FLOWS IN THE OCEANS: PHENOMENOLOGY, ORIGINS AND ENERGETICS

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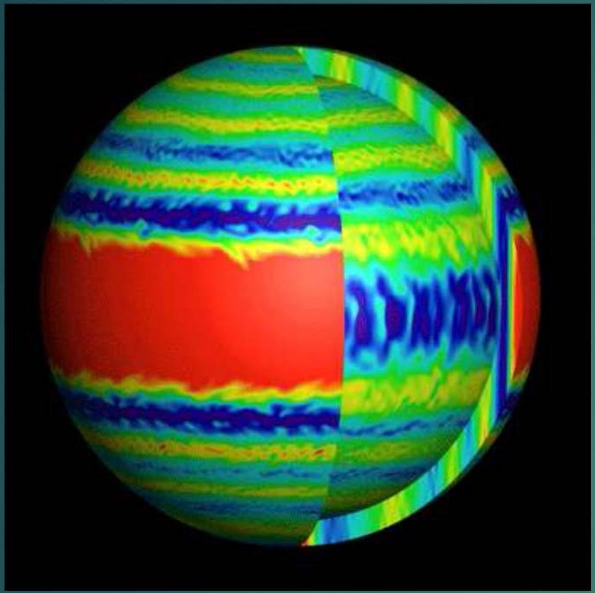
Zonal Jets in Planetary Atmospheres



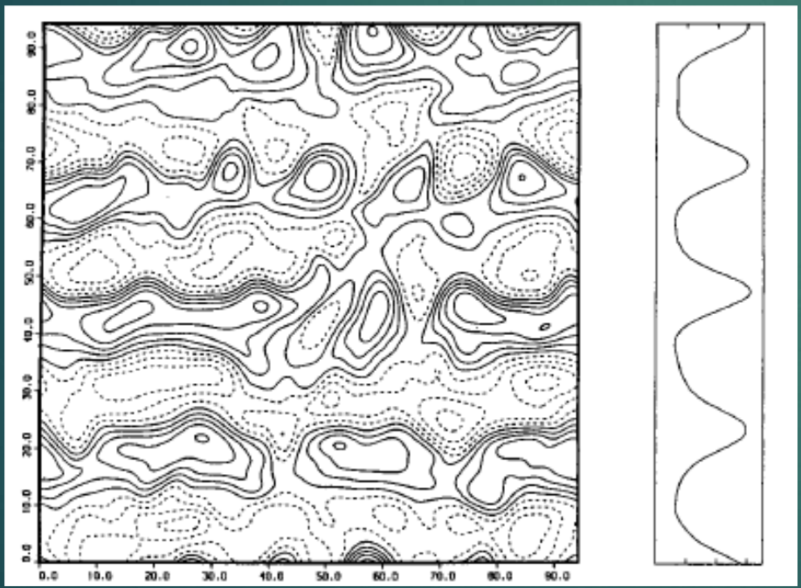
Snapshot of the azimuthal velocity field from the simulation of the Jupiter atmosphere circulation. Adopted from Heimpel et al. (2005).

Jupiter and Saturn bands. Both images were acquired by the Cassini ISS camera. credit: NASA.(after Sanchez-Lavega, *Zonal Jets,* Galperin and Read, eds)

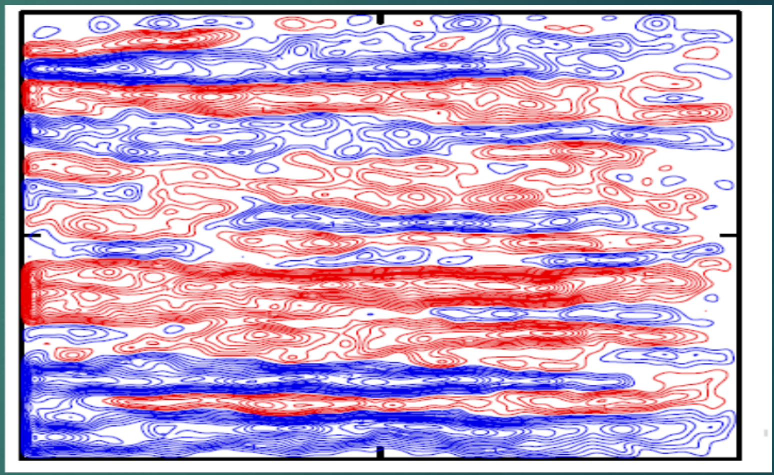
- Circulation in the atmospheres of gas planets is organized in well-pronounced zonal bands
- These zonal currents are estimated to extend in the vertical direction

Zonal jets in Fluid Dynamics

- Stationary zonal jets are found in turbulent flows on a beta-plane (*Rhines* 1975; 1994)
- Non-linear dynamics plays a key role in maintaining *stationary zonal* jets in idealized studies (*Panetta* 1993; *Berloff et al.* 2009)

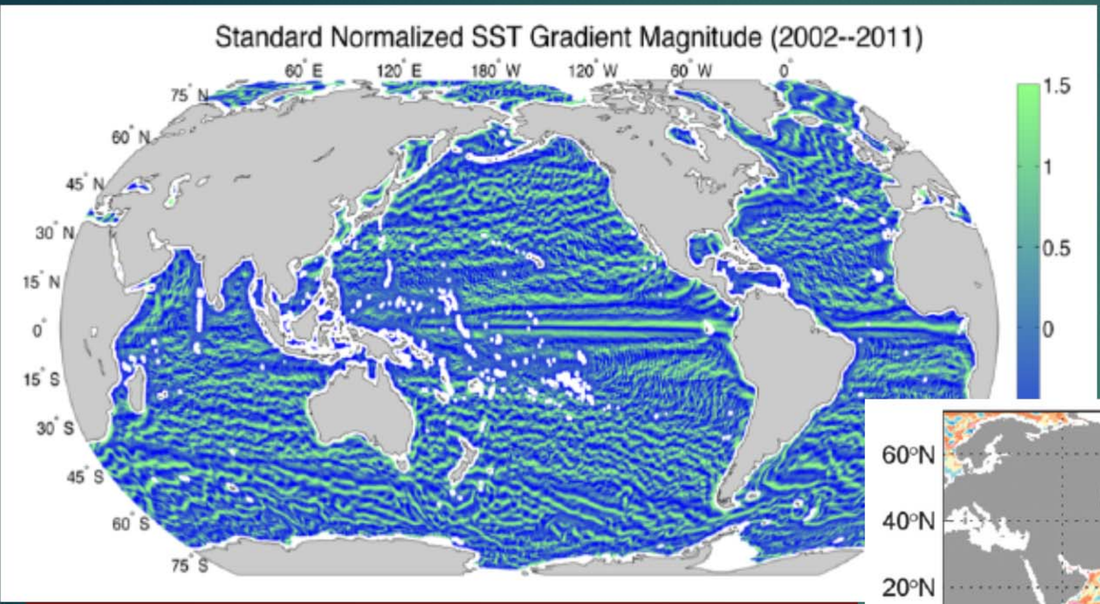


Upper-layer streamfunction in a regime relevant to Jovian atmosphere (*Panetta* 1993)



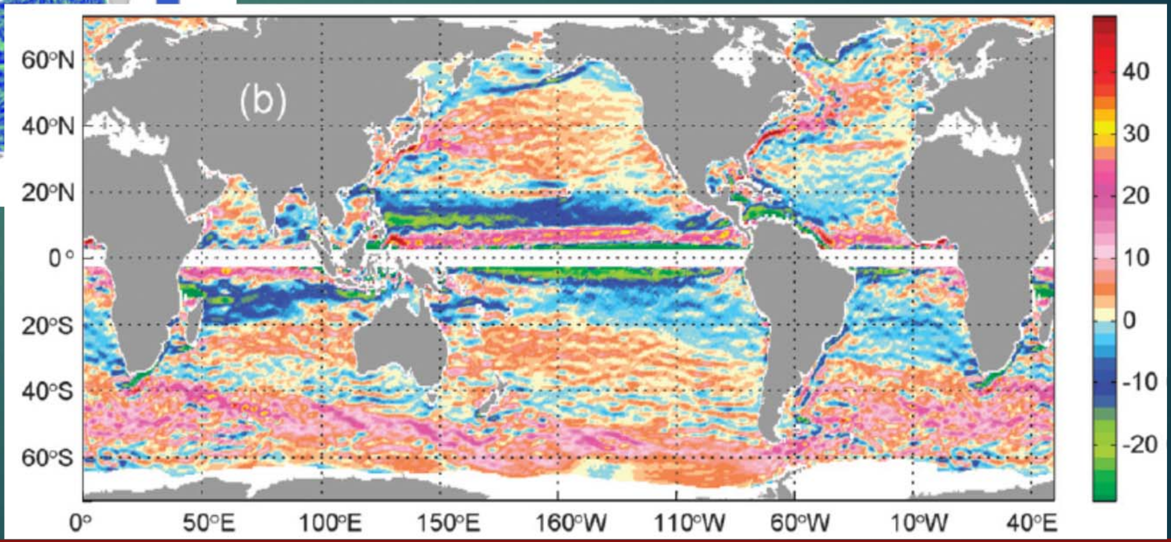
Jets in a QG model forced by random forcing (*Berloff*, 2005)

Zonally Elongated Anomalies in the Oceans



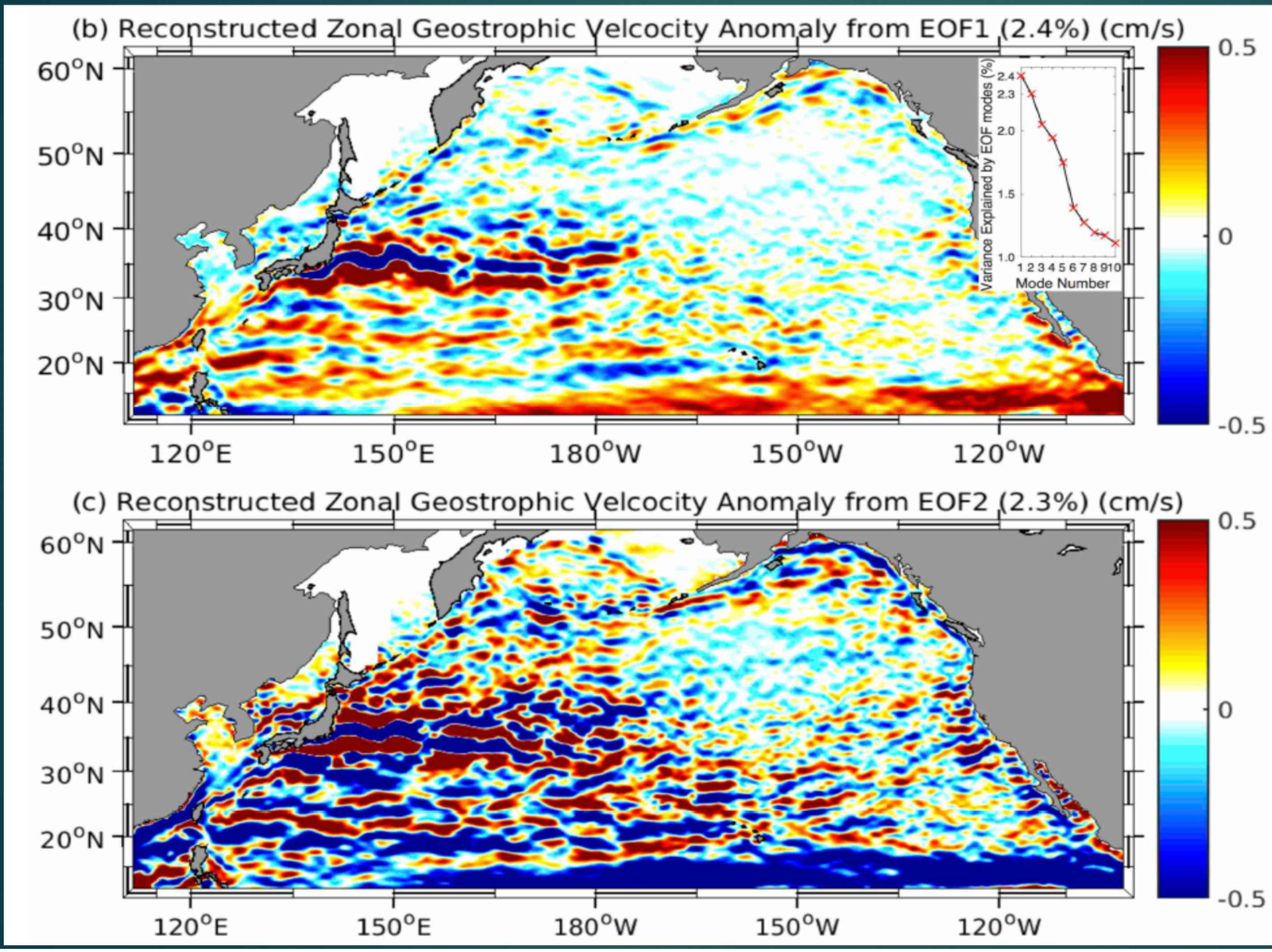
Normalized SST gradients; adapted from *Cornillon et al.* (*Zonal Jets,* Galperin and Read, eds.; see also *Buckingham et al.* 2014)

- Quasi-zonal bands are visible in satellite and in situ data, but they are
  - time-dependent
  - weaker than turbulent fluctuations ("eddies"), so some filtering/averaging is required



The mean geostrophic zonal velocity from satellite data (Maximenko et al. 2009)

Zonally Elongated Large-Scale Transients (ZELTs)

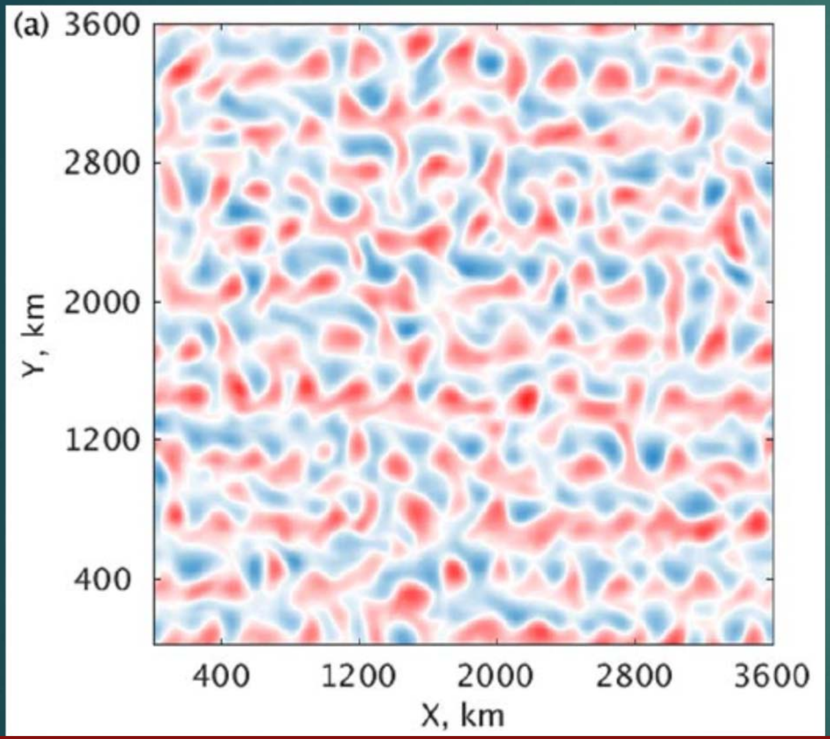


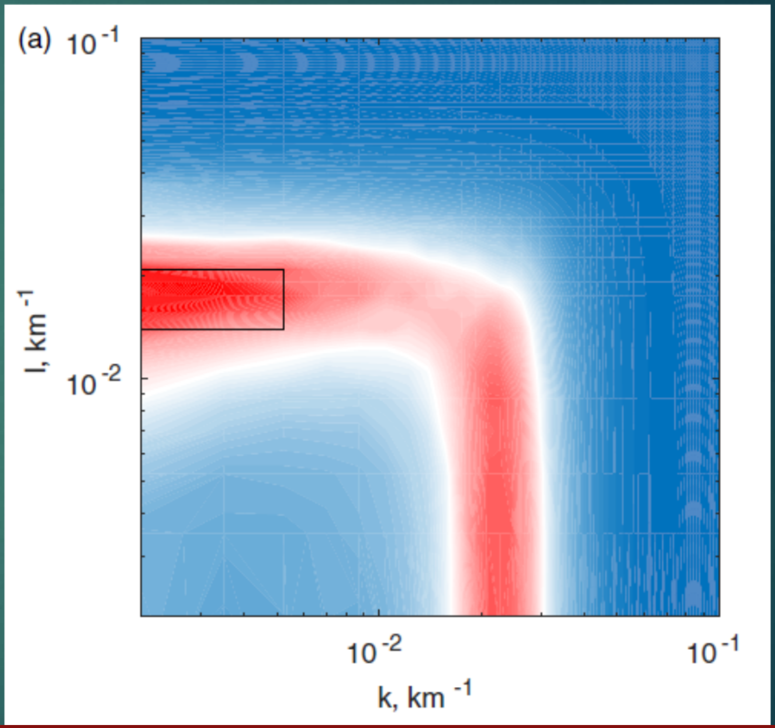
- Zonally elongated patterns are seen in leading modes of mesoscale variability
- These patterns have long zonal scales and are time-dependent

First two EOFs of the geostrophic zonal velocity anomalies from altimetry (after *Chen, Kamenkovich and Berloff*, 2016, in JPO)

ZELTs in idealized QG flows

- Two-layer QG simulations of a double-periodic flow forced with a broad baroclinic shear
- 2D wavenumber spectra reveal an anisotropic peak:

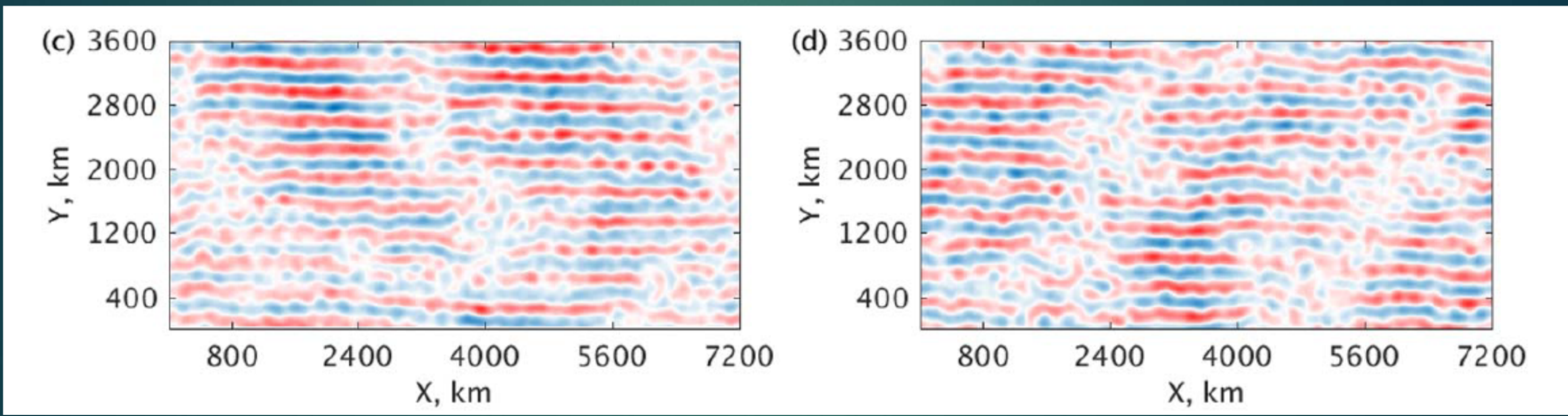




(**left**) Snapshot of the velocity streamfunction in the upper layer; **(right**) Wavenumber velocity spectrum, averaged in time. **(**after *Rudko, Kamenkovich, Iskandarani and Mariano*, 2018, in JPO)

ZELTs in idealized QG flows

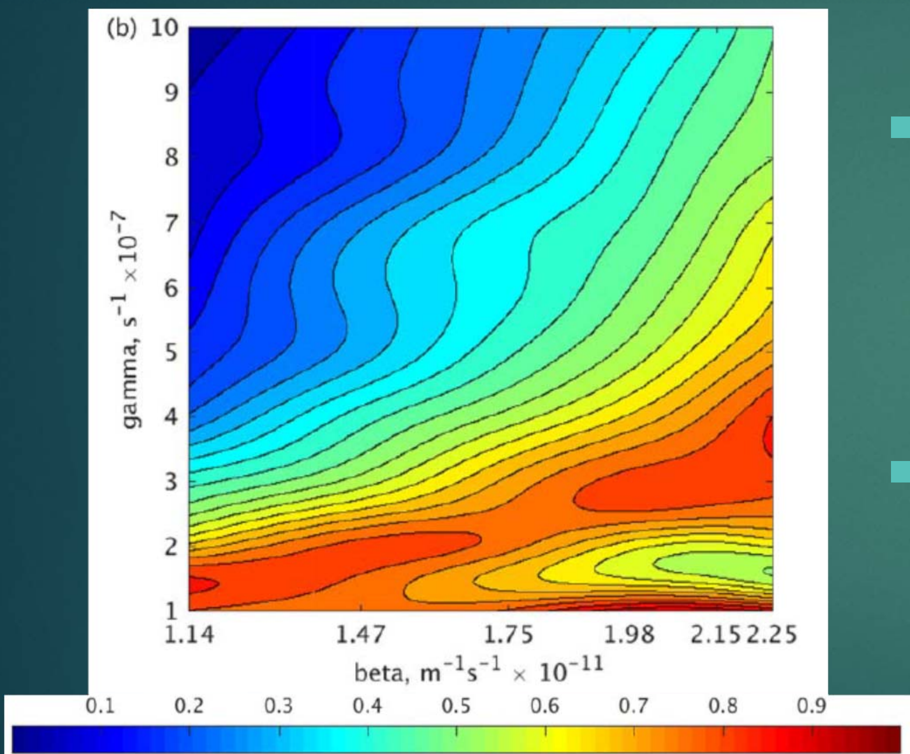
- Leading EOFs have zonally elongated structure
- Extended EOFs reveal westward propagation at 1.15 cm sec^{-1}



Two leading EOFs in the velocity streamfunction. (after *Rudko, Kamenkovich, Iskandarani and Mariano*, 2018, in JPO)

ZELTs: Sensitivity to parameters

ZELTs exist in a wide parameter range; most important parameters are β and bottom friction (γ)



- The degree of the anisotropy of the flow is quantified by (*Huang et al.* 2007):

$$\alpha = \frac{\langle u^2 \rangle - \langle v^2 \rangle}{\langle u^2 \rangle + \langle v^2 \rangle}$$

- We define ZELT-dominated regime as the one with α > 0.6 for EOF1.

Anisotropy coefficient α as a function of β and bottom friction (γ)
(after *Rudko, Kamenkovich, Iskandarani and Mariano*, 2018, in JPO)

Dynamical origins of ZELTs

We can estimate relative importance of various nonlinear terms in the equations for perturbation ("eddy") barotropic (subscript "br") and baroclinic (subscript "bc") PV

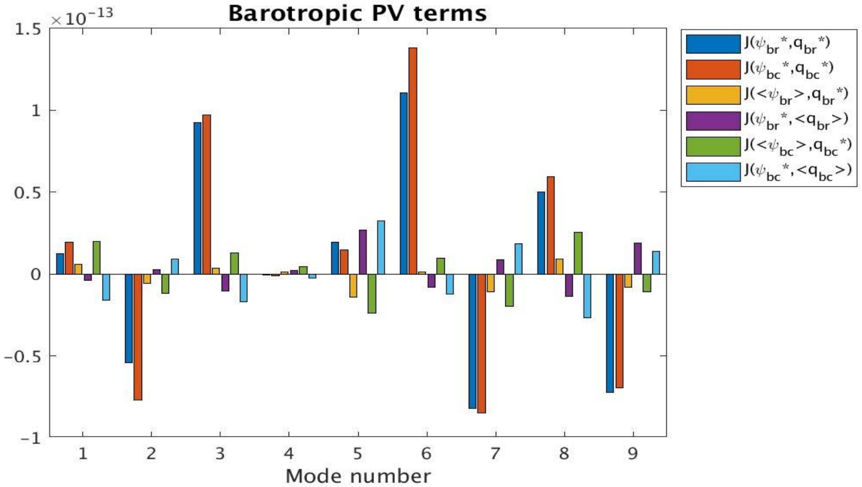
$$\frac{\partial q_{br}^*}{\partial t} = -\mathrm{J}(\langle\psi_{br}\rangle, q_{br}^*) - \mathrm{J}(\psi_{br}^*, \langle q_{br}\rangle) - \mathrm{J}(\psi_{br}^*, q_{br}^*)$$
$$-\theta_{11}\theta_{12}\{\mathrm{J}(\langle\psi_{bc}\rangle, q_{bc}^*) + \mathrm{J}(\psi_{bc}^*, \langle q_{bc}\rangle) + \mathrm{J}(\psi_{bc}^*, q_{bc}^*)\} + Linear\ terms$$

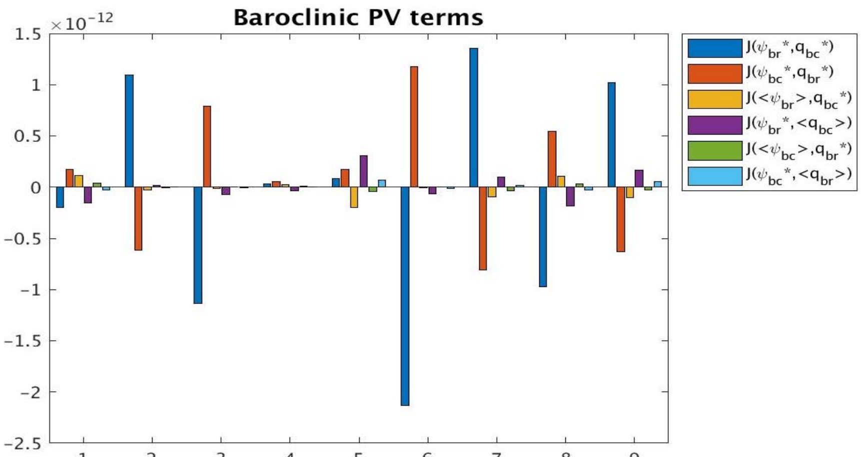
$$\frac{\partial q_{bc}^*}{\partial t} = -\mathrm{J}(\langle\psi_{br}\rangle, q_{bc}^*) - \mathrm{J}(\psi_{br}^*, \langle q_{bc}\rangle) - \mathrm{J}(\psi_{br}^*, q_{bc}^*)$$
$$-\mathrm{J}(\langle\psi_{bc}\rangle, q_{br}^*) - \mathrm{J}(\psi_{bc}^*, \langle q_{br}\rangle) - \mathrm{J}(\psi_{bc}^*, q_{br}^*)$$
$$-(\theta_{11}^2 - \theta_{12}^2)\{\mathrm{J}(\langle\psi_{bc}\rangle, q_{bc}^*) + \mathrm{J}(\psi_{bc}^*, \langle q_{bc}\rangle) + \mathrm{J}(\psi_{bc}^*, q_{bc}^*)\} + Linear\ terms$$

where <…> stand for the zonal-mean * denote deviations from the zonal mean ("eddies") and $\theta_{11} = \frac{H_1}{H_1+H_2}$, $\theta_{12} = \frac{H_2}{H_1+H_2}$

Two groups of terms that represent interactions between; (1) eddies ("eddy-eddy" terms); and (2) eddies and the mean ("eddy-mean" terms)

Which nonlinear terms are most important in ZELT dynamics?





Projection of NL terms in PV balances on 9 first EOFs. $\beta=2.15\times10^{-11}$ $m^{-1}s^{-1}$, $\gamma=3\times10^{-7}$ s^{-1}

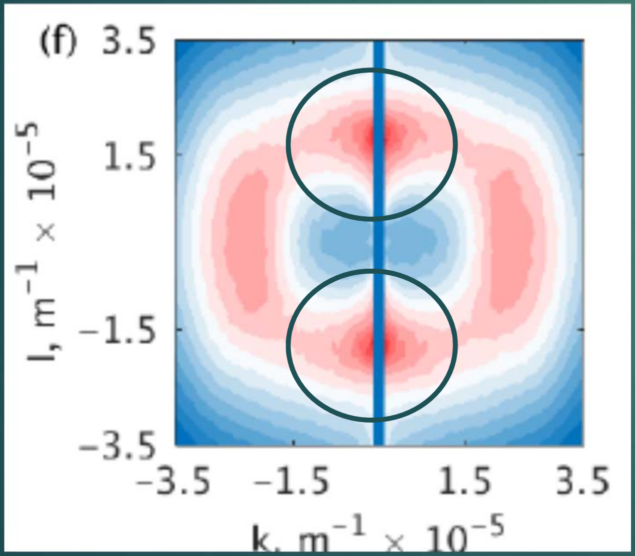
We project each of the nonlinear terms on EOFs with $\alpha>0.6$:

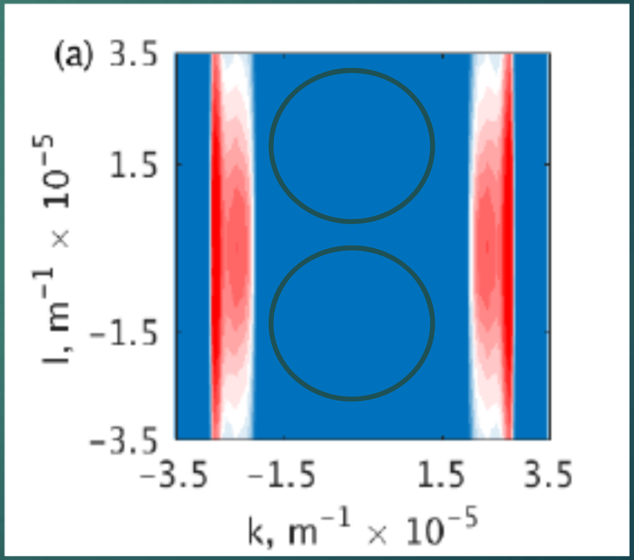
- Barotropic balance is dominated by "eddy-eddy" terms: $J(\psi^*_{br}, q^*_{br})$ and $J(\psi^*_{bc}, q^*_{bc})$
- These terms *act together*

- Baroclinic balance is dominated by "eddy-eddy" terms: $J(\psi^*_{br}, q^*_{bc})$ and $J(\psi^*_{bc}, q^*_{br})$
- These terms *counteract each other*

Importance of eddy-eddy interactions. Reduced dynamics models

- We run an experiment with all nonlinear "eddy-eddy" terms turned off
- The resulting 2D wavenumber spectrum shows no power in the "ZELT" part
- **Nonlinear eddy-eddy interactions play a key role in ZELT dynamics**

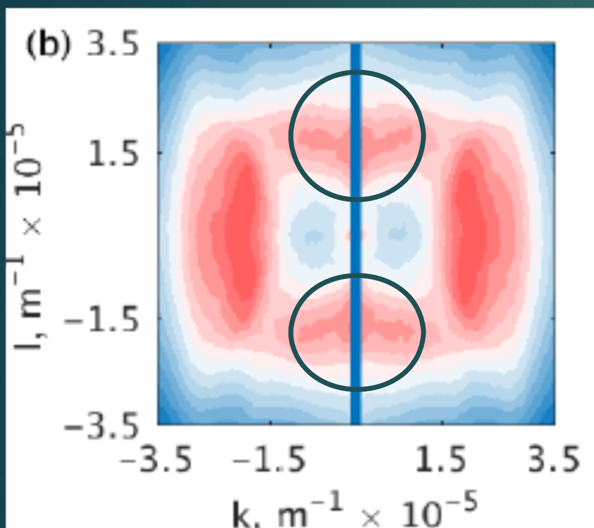


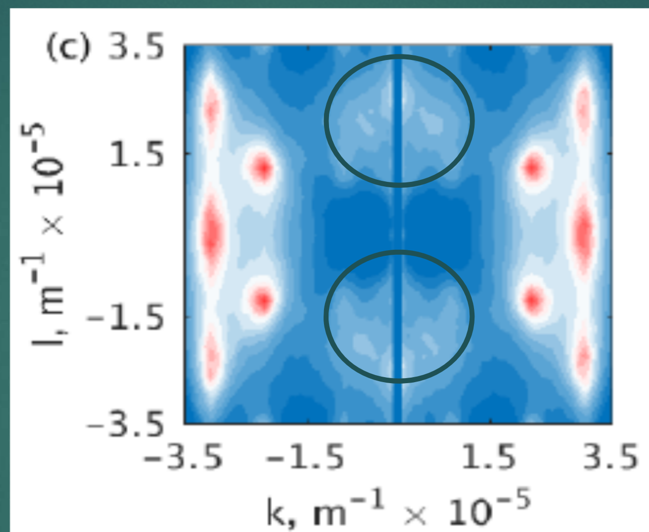


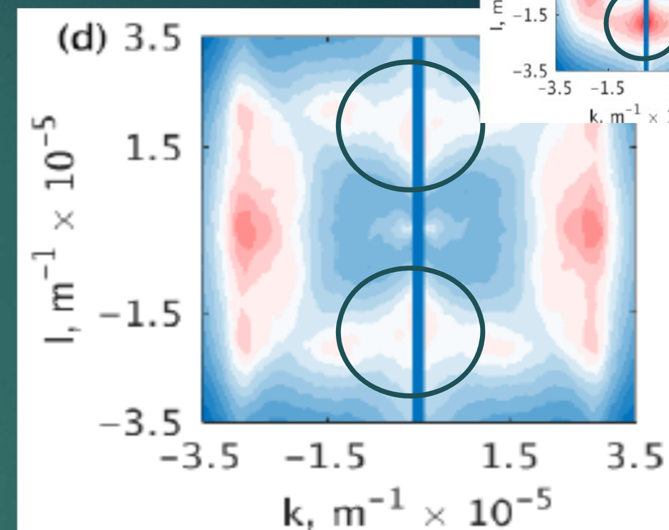
Two-dimensional wavenumber spectra. Anisotorpic part with k<<l is shown by black circles. **(left) Control run**; **(right) Sensitivity run with no eddy-eddy forcing**

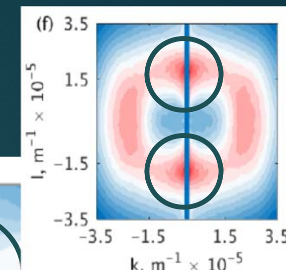
What types of eddy-eddy forcing are most important?

We run simulations with specific components of the "eddy-eddy" terms turned off









$J(\psi_{br}^{*}, q_{br}^{*})=0$. No energy transfer within the BRT mode

$J(\psi_{bc}^{*}, q_{br}^{*}) = J(\psi_{bc}^{*}, q_{bc}^{*})_{bc}=0$ No energy transfer within the BCL mode

$J(\psi_{br}^{*}, q_{bc}^{*}) = J(\psi_{bc}^{*}, q_{bc}^{*})_{br}=0$ No energy transfer between the BCL and BRT modes

- Energy transfers that involve baroclinic modes are essential for ZELT existence
- Interactions between barotropic modes are of secondary importance

Conclusions

- Large-scale, zonally-elongated transients (ZELTs) exist in a wide range of environmental parameters relevant to oceanic flows
- ZELTs are revealed by wavenumber spectra and leading EOFs of mesoscale variability
- ZELTs are nonlinear phenomena, owing their existence to anisotropic upscale energy cascade
- The major contribution to this energy transfer comes from the baroclinic-baroclinic and mixed-mode eddy interactions, while barotropic-barotropic interactions are of secondary to no importance
- The anisotropy of the mesoscale flow has potentially important implications for the energy transformation as well as for the transport of various oceanic properties

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