

The Long-term Evolution and Propagation of Mesoscale Eddies in the Ocean

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Observations

Wave Interpretation

Eddy Interpretation

Attributes

Linear vs

Nonlinear

Numerical Setup

Monopole

Eddy Seeding

QG Monopoles

Shape

Trapped Fluid

Zonal & Meridional

Speed

Monopole vs.

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Conclusions

Talk Overview

The Long-term Evolution and Propagation of Mesoscale Eddies in the Ocean

1. Review satellite altimetry observations: wave and eddy interpretations.
2. Show that linear Rossby waves fail to explain observations, nonlinear quasi-geostrophy (QG) is required.
3. Describe the properties of isolated quasi-geostrophic eddies.
4. Show that isolated eddy properties also apply to the observations.

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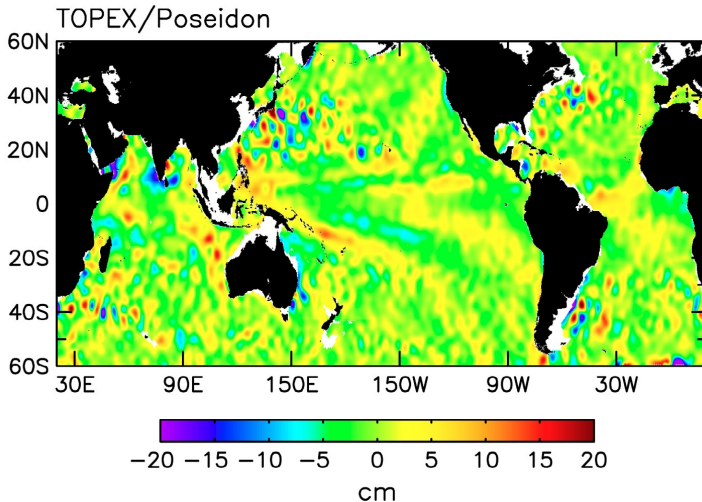
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Global Observations of Oceanic Rossby Waves [Chelton & Schlax, 1996]

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Rossby Wave Interpretation

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- Vertical structure: assumed first baroclinic mode.

Linear Quasi-Geostrophic Potential Vorticity Equation

$$\frac{\partial}{\partial t} (\nabla^2 \eta - \eta) + \frac{\partial \eta}{\partial x} = 0,$$

is solved by linear combinations of

$$\eta(x, y, t) = N_0 \cos(kx + ly - \omega t + \phi)$$

where

$$\omega = \frac{-k}{k^2 + l^2 + 1}.$$

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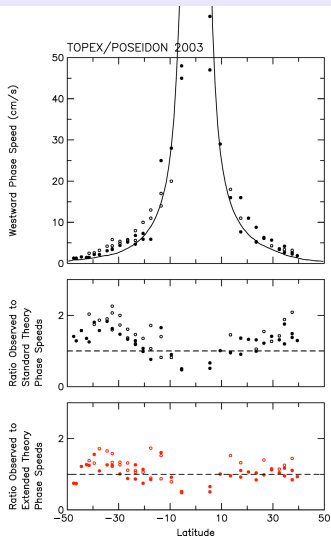
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Long Wave Phase Speed



- ▶ Feature resolution limited to ~ 200 km.
- ▶ Observed phase speed faster than the long wave limit.
- ▶ Result spurred new theories for faster phase speeds: mean flow effect, ocean-atmosphere interaction, topography effect, etc.

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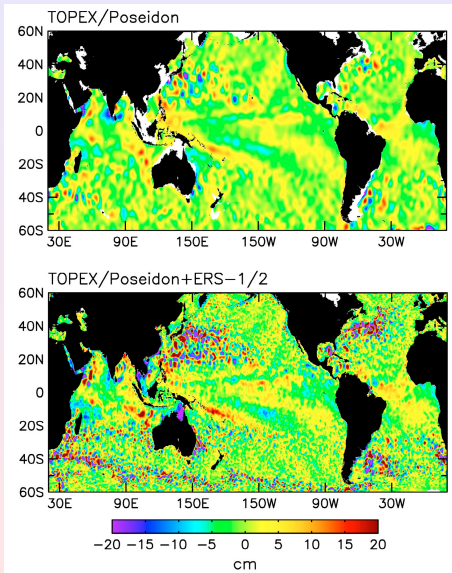
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Global Observations of Large Oceanic Eddies

[Chelton et. al., 2007]

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[Chelton et. al., 2007]

(Global Altimetry Observations)

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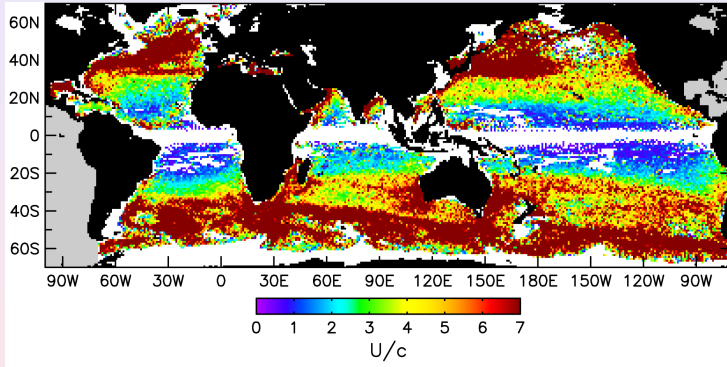
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Ratio of Fluid Speed (U) to Propagation Speed (c)



- $U > c$ suggests advection is important.

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Enhanced resolution $\implies$ new interpretation

- ▶ Feature resolution increased to ~ 100 km.
- ▶ Observations now appear to be dominated by eddies.
- ▶ Need to include the advection of relative vorticity.

Quasi-Geostrophic Potential Vorticity Equation

$$\frac{\partial}{\partial t} (\nabla^2 \eta - \eta) + \frac{\partial \eta}{\partial x} + \beta^{-1} \cdot J(\eta, \nabla^2 \eta) = 0,$$

where

$$J(a, b) = a_x b_y - a_y b_x.$$

and $\beta^{-1} = O(100)$.

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Focus on four observational attributes:

- Coherence. Structures trackable for long time periods.

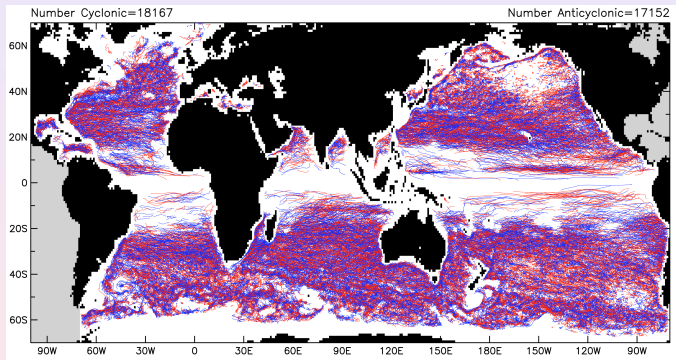


Figure: ~35,000 cyclonic and anti-cyclonic eddies with lifetimes greater than 16 weeks

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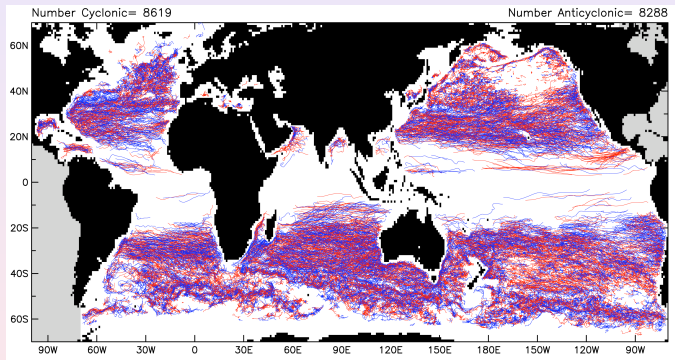


Figure: ~17,000 cyclonic and anti-cyclonic eddies with lifetimes greater than 6 months

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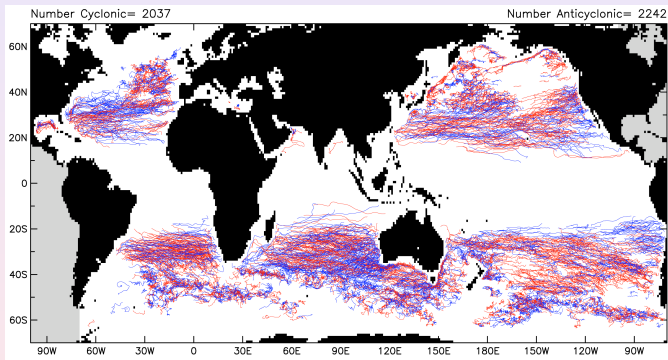


Figure: ~4,000 cyclonic and anti-cyclonic eddies with lifetimes greater than 1 year

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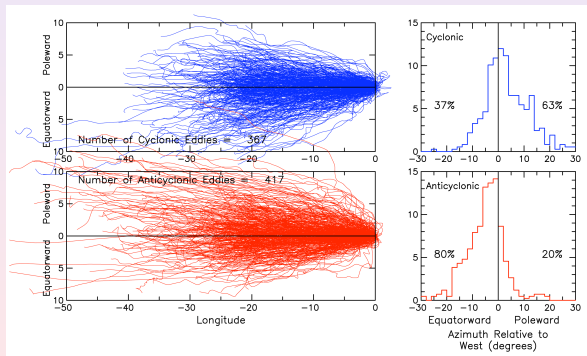
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Focus on four observational attributes:

- Coherence. Structures trackable for long time periods.
- Meridional deflection. Cyclonic eddies deflect poleward, anti-cyclonic deflect equatorward.



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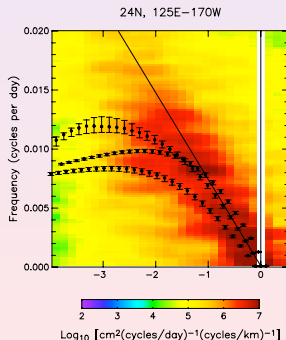
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Focus on four observational attributes:

- ▶ Coherence. Structures trackable for long time periods.
- ▶ Meridional deflection. Cyclonic eddies deflect poleward, anti-cyclonic deflect equatorward.
- ▶ Spectral properties. Wavenumber-frequency spectra appear non-dispersive.



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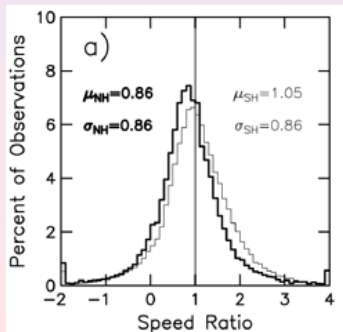
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- ▶ Meridional deflection. Cyclonic eddies deflect poleward, anti-cyclonic deflect equatorward.
- ▶ Spectral properties. Wavenumber-frequency spectra appear non-dispersive.
- ▶ Speed. Can we match observed speeds?



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- ▶ Spectral properties. Wavenumber-frequency spectra appear non-dispersive.
- ▶ Speed. Can we match observed speeds?

Can we explain any of this with linearized QG theory?

If not, how well does non-linear QG do?

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Numerical Setup

- ▶ Pseudo-spectral with Runge-Kutta time stepping.
- ▶ Sponge-layers on all the boundaries.
- ▶ Damping with spectral vanishing viscosity.

Modeled Equation

$$\frac{\partial}{\partial t} (\nabla^2 \eta - \eta) + \frac{\partial \eta}{\partial x} + \beta^{-1} \cdot J(\eta, \nabla^2 \eta) = 0,$$

where

$$\beta^{-1} = \begin{cases} 0 & \text{linearized ,} \\ 60 & \text{non-linear.} \end{cases}$$

at latitude 24 where $L_R = 47$ km, $c_k = 4.7$ cm/s and $(\beta_0 L_R)^{-1} = 12$ days.

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Linear Rossby Wave Dynamics

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(Linear Rossby Wave Dynamics)

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Nonlinear Quasigeostrophic Dynamics

(Nonlinear Quasigeostrophic Dynamics)

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Coherence?

- ▶ Linear model shows quick dispersion. Amplitude reduced to 10% of original after 150 days.
- ▶ Nonlinear QG model shows strong coherence. Amplitude still 75% of original after 365 days.

Meridional Deflection?

- ▶ Linear model shows no meridional deflection.
- ▶ QG model shows equatorward deflection for the anticyclonic eddy.

Symmetry of the Quasigeostrophic Potential Vorticity Equation

If $\eta(x, y, t)$ is a solution, then so is $\tilde{\eta} = -\eta(x, -y, t)$. This implies that what is true of anticyclonic eddies is also true of cyclonic eddies if you flip equatorward and poleward.

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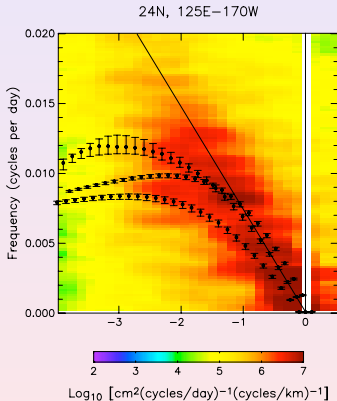
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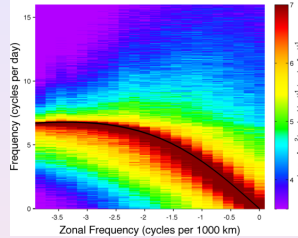
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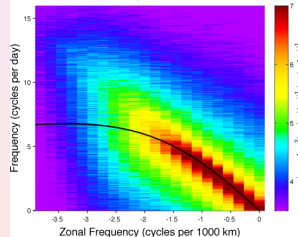
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Linear PSD, Latitude 24



QG PSD, Latitude 24



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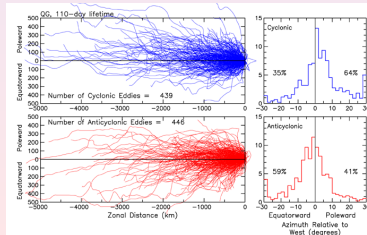
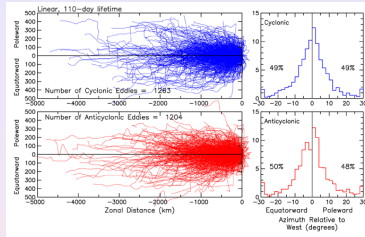
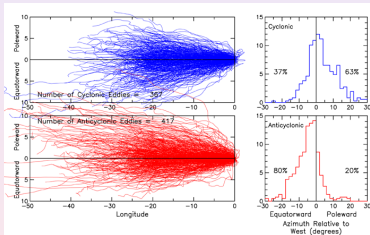
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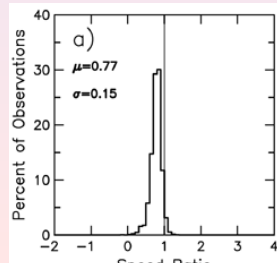
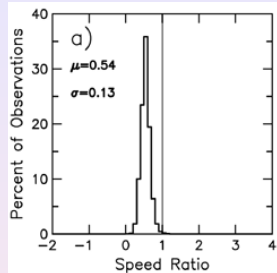
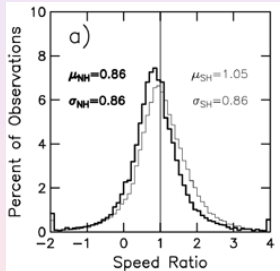
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Spectra?

- ▶ Nonlinear model is a far better match than the linear model.

Meridional Deflection?

- ▶ Linear model shows equal preference for meridional deflection, contrary to the observations.

Speed?

- ▶ Linear model shows eddies propagating too slowly, QG gets really close, but doesn't show enough variability.

The satellite altimetry signal more closely matches nonlinear quasi-geostrophic theory than linear Rossby wave theory.

- ▶ The observations show quasi-geostrophic eddies, and not linear Rossby waves.

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Quasi-geostrophic Monopoles

Primary Objective

Establish basic properties of evolution for quasi-geostrophic monopoles to compare to the observations and other theories.

- ▶ Shape.
- ▶ Fluid transport properties.
- ▶ Zonal and meridional speeds.
- ▶ Amplitude and length decay rates.
- ▶ Potential vorticity and energy.

(Nonlinear Quasigeostrophic Dynamics)

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Experimental Design

- ▶ Initialized with (5, 10, 15, 20) cm amplitudes and (40, 60, 80, 100, 120) km length scales.
- ▶ Allowed to evolve for 730 days.
- ▶ Nearly all evolved into quasi-stable state.
- ▶ Non-gaussian shapes also evolved into quasi-stable state.
- ▶ Focus on quasi-stable state.

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Formation of the β -gyre

Initial gaussian shape evolves to asymmetric shape within the first 12 days.

- ▶ First described by [Fiorino and Elsberry, 1989].
- ▶ Analytical prediction does pretty well [Sutyrin and Flierl, 1994], [Reznik and Dewar, 1994]...
- ▶ ... until Rossby wave radiation dominates the evolution.

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Historical Background: 'Quasi-Stable' State

'Quasi-Stable' State Hypothesis

After 12 days the monopole tends quickly towards a quasi-stable slowly decaying state.

[McWilliams & Flierl, 1979]

- ▶ Meridional & zonal propagation speeds then asymptote towards length dependent phase speeds (60-80 days).
- ▶ Amplitude decay determined by damping.

[Sutyrin, et. al, 1994]

- ▶ At 200 days a tripole emerges, visible in potential vorticity field.
- ▶ Translation and reorganization into tripole is strongly amplitude dependent.
- ▶ Tripole formation is an inviscid process.

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'Quasi-Stable' State Hypothesis

After 12 days the monopole tends quickly towards a quasi-stable slowly decaying state.

[Korotaev, 1997]

- ▶ Amplitude decay actually determined by Rossby wave radiation [Flierl, 1984].
- ▶ Analytical prediction for speed off by 30% after about 80 days.

[Reznik, et. al, 2000]

- ▶ Analytical predictions of speed are qualitatively good for 200 days.
- ▶ Qualitatively bad after 200 days.

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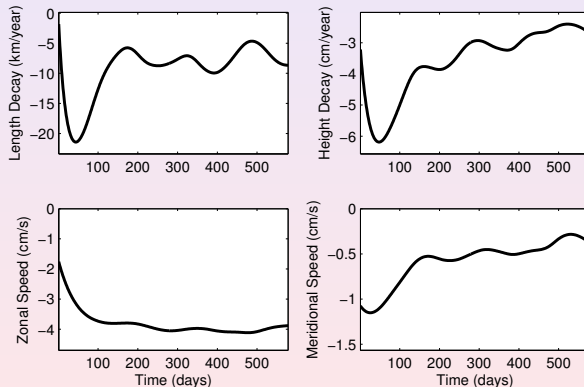
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- Do the changes in eddy properties show a quasi-stable state at 80 days?



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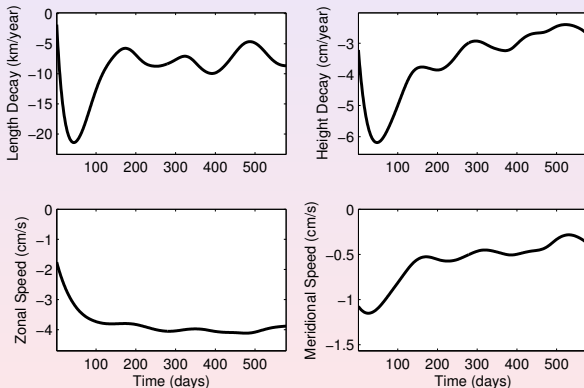
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Monopole Evolution: Three States

1. Formation of the β -gyre during the first 10 days.
2. Adjustment period up to 200 days.
3. Quasi-stable slowly decaying state after 200 days.



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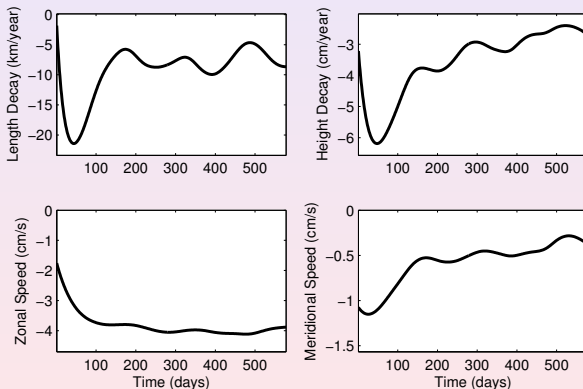
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Monopole Evolution: Three States

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3. Quasi-stable slowly decaying state after 200 days.



- This quasi-stable state is the focus.

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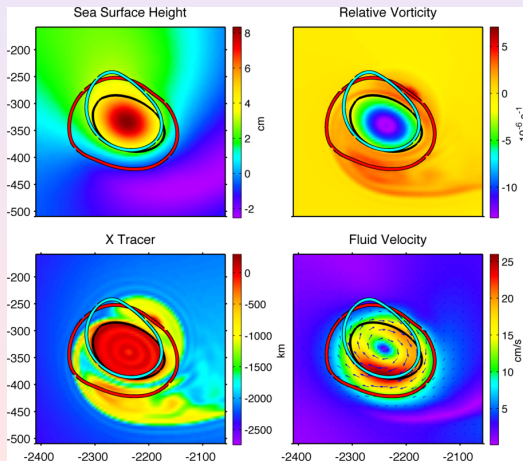
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Shape Properties

Three contours:

1. E-folding height contour
2. Relative vorticity zero contour
3. Trapped fluid contour



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Conclusions

Trapped Fluid: Passive Tracer

(Linear Rossby Wave Tracer Field)

(QG Tracer Field)

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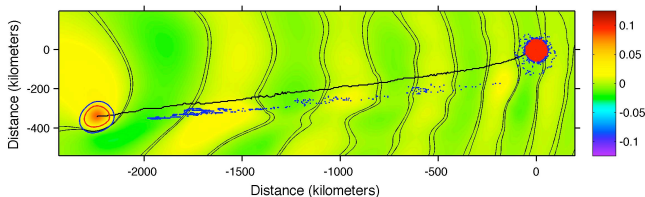
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Conclusions

Trapped Fluid: Floats

- ▶ Eddy path
- ▶ Original location of floats found in the eddy **core** on day 675.
- ▶ Original location of floats found in the eddy **ring** on day 675.



Potential Vorticity Conservation

The floats were also used to diagnose the changes in the contribution of PV conservation.

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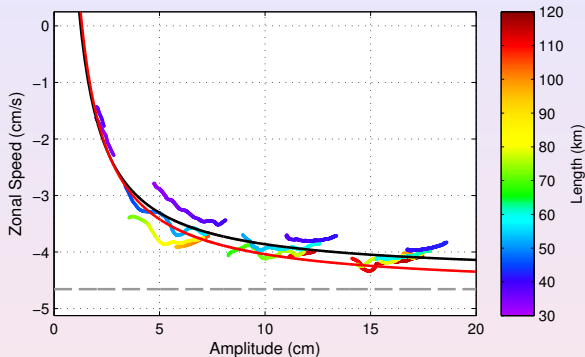
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Experimental Zonal Speed versus Amplitude



- ▶ Black line best fit: $c_x(A) = 5.5A^{-1} - 4.4$ cm/s
- ▶ Red line prediction: $c_x(A) = \beta_0 L_R^2 \left(\frac{N_{QG}}{|A|} - 1 \right)$.
- ▶ Strong speed dependence on amplitude.

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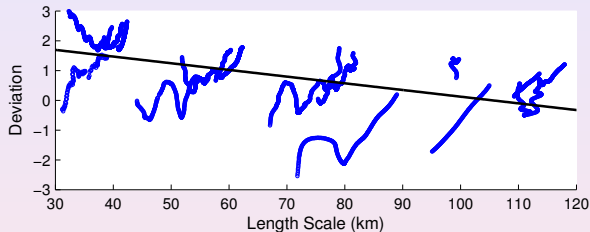
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Experimental Zonal Speed versus Length

Deviation of the eddy speed from the predicted relationship, normalized by the variability.



- Weak speed dependence on length scale.

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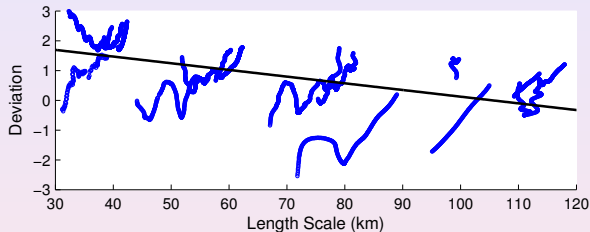
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Experimental Zonal Speed versus Length

Deviation of the eddy speed from the predicted relationship, normalized by the variability.



- Weak speed dependence on length scale.

Conclusion:

- Bigger amplitude, bigger length scale imply faster westward propagation.

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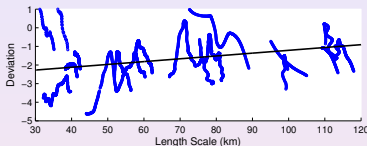
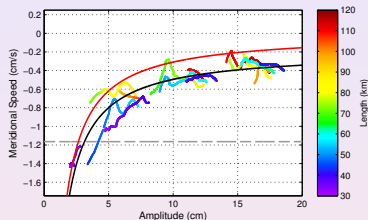
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Experimental Meridional Speed

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- ▶ Black line best fit: $c_y(A) = -3.0A^{-1} - 0.19$ cm/s
- ▶ Red line prediction: $c_y(A) = -\frac{\beta_0 L_R^2}{2} \frac{N_{QG}}{A}$.
- ▶ Strong speed dependence on amplitude, weak dependence on length.

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Monopole vs. Eddy Seeding

Although the isolated eddies and a basin of eddies are both governed by the same equation, it is not necessarily true that the properties of one experiment applies to the other.

1. How do the spectra compare between the different experiments?
2. Do the predicted monopole speeds apply to the basin of eddies?

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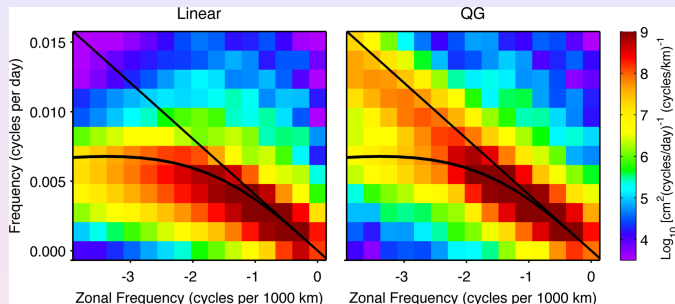
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**Monopole vs.
Eddy Seeding**

Conclusions

Monopole vs. Eddy Seeding: The Spectra

Do the spectral properties of an isolated monopole match those of a basin filled with eddies?



- ▶ Linear PSD for the monopole looks the same.
- ▶ Nonlinear spectrum shows two differences:
 1. Distinct band following dispersion relation; more free space.
 2. More power at higher wavenumbers; less up-scale energy cascade.

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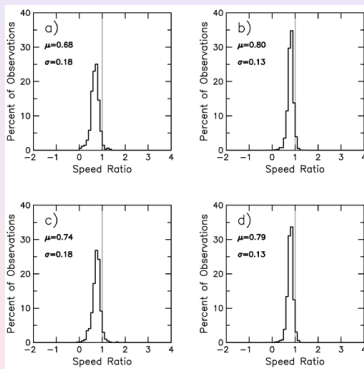
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Monopole vs. Eddy Seeding: The Speeds

Eddies with the a) smallest 1/3 amplitudes; b) largest 1/3 amplitudes; c) smallest 1/3 length scales; and d) largest 1/3 length scales.



- Confirms that the monopoles obey the same relationship even with eddy-eddy interactions.

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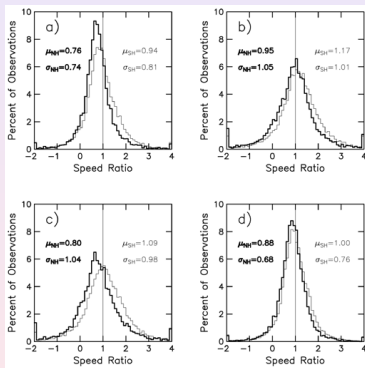
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Speeds of Eddies from Altimeter Observations

Eddies with the a) smallest 1/3 amplitudes; b) largest 1/3 amplitudes; c) smallest 1/3 length scales; and d) largest 1/3 length scales.



- Follows the same pattern as nonlinear quasigeostrophic theory, but with greater variability.

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Conclusions

- ▶ Linear Rossby wave dynamics fails to explain the satellite altimetry signal.
- ▶ Quasi-geostrophy explains coherence, meridional deflection, spectra, propagation speed dependence.
- ▶ Quasi-geostrophy cannot explain the observed variability in propagation speeds.
- ▶ There are **three** states during monopole evolution: β -gyre formation, adjustment and quasi-stable.
- ▶ Eddy core (region within RV zero contour) never entrains new fluid, only loses original fluid.
- ▶ Eddy ring (region between trapped fluid contour and the core) continuously acquires and deposits fluid.
- ▶ Eddy propagation rates governed by amplitude & length, matching observations.