Propagation of the low-modes internal waves through the ocean

Luc Rainville

Woods Hole Oceanographic Institution, Woods Hole, MA 02543

Abstract

The baroclinic tides play a significant role in the energy budget of the abyssal ocean. While the basic principles of generation and propagation are known, a clear understanding of these phenomena in the complex ocean environment is only now emerging. To advance this effort, we develop a ray model that quantifies the effects of spatially variable topography, stratification, and planetary vorticity on the horizontal propagation of internal gravity modes. Our objective is to identify "baroclinic shoals", where wave energy is spatially concentrated, and enhanced dissipation is expected.

The model is extended to investigate the propagation of internal waves through a barotropic mesoscale current field. The refraction of tidally generated internal waves at the Hawaiian Ridge is examined, using an ensemble of mesoscale background realizations derived from weekly Topex/Poseidon altimetric measurements. The path of mode 1 is only slightly affected by typical currents, although its phase becomes increasingly random as the propagation distance from the source increases. The effect of the currents becomes more dramatic as mode number increases. For modes 3 and higher, wave phase can vary between realizations by $\pm\pi$ only a few wavelengths from the source. This phase variability reduces the magnitude of the baroclinic signal seen in altimetric data, creating a fictitious energy loss along the propagation path.

In the TOPEX/Poseidon observations, the mode-1 M2 internal tide does appear to lose significant energy as it propagates south-westward from the Hawaiian Ridge. Our simulations suggest that phase modulation by mesoscale flows could be responsible for a large fraction of this apparent loss. In contrast, northeast-propagating internal tides encounter a less energetic mesoscale and should experience limited refraction. The apparent energy loss seen in the altimetric data on the north side of the ridge might indeed be real.

Effects of stratification, latitude and depth

To quantify the global propagation conditions, the group and phase velocities of low-frequencies internal wave modes are calculated using climatology from the *World Ocean Atlas* (S. Levitus, Ed.).

With $w(x,y,z) = \widehat{w}(z)\, e^{i(\vec{k}_H\cdot\vec{x} - \omega t)}$, the internal wave equation can be expressed as

$$\underbrace{\left[\frac{1}{N^2(z)}\frac{d^2}{dz^2}\right]\widehat{w}(z)}_{\text{Vertical modes}} + \underbrace{\left[\frac{1}{c_e^2}\right]}_{\frac{1}{c_e^2} = \frac{k_H^2}{\omega^2 - f^2}}\widehat{w}(z) = 0.$$

The group speed of each mode is

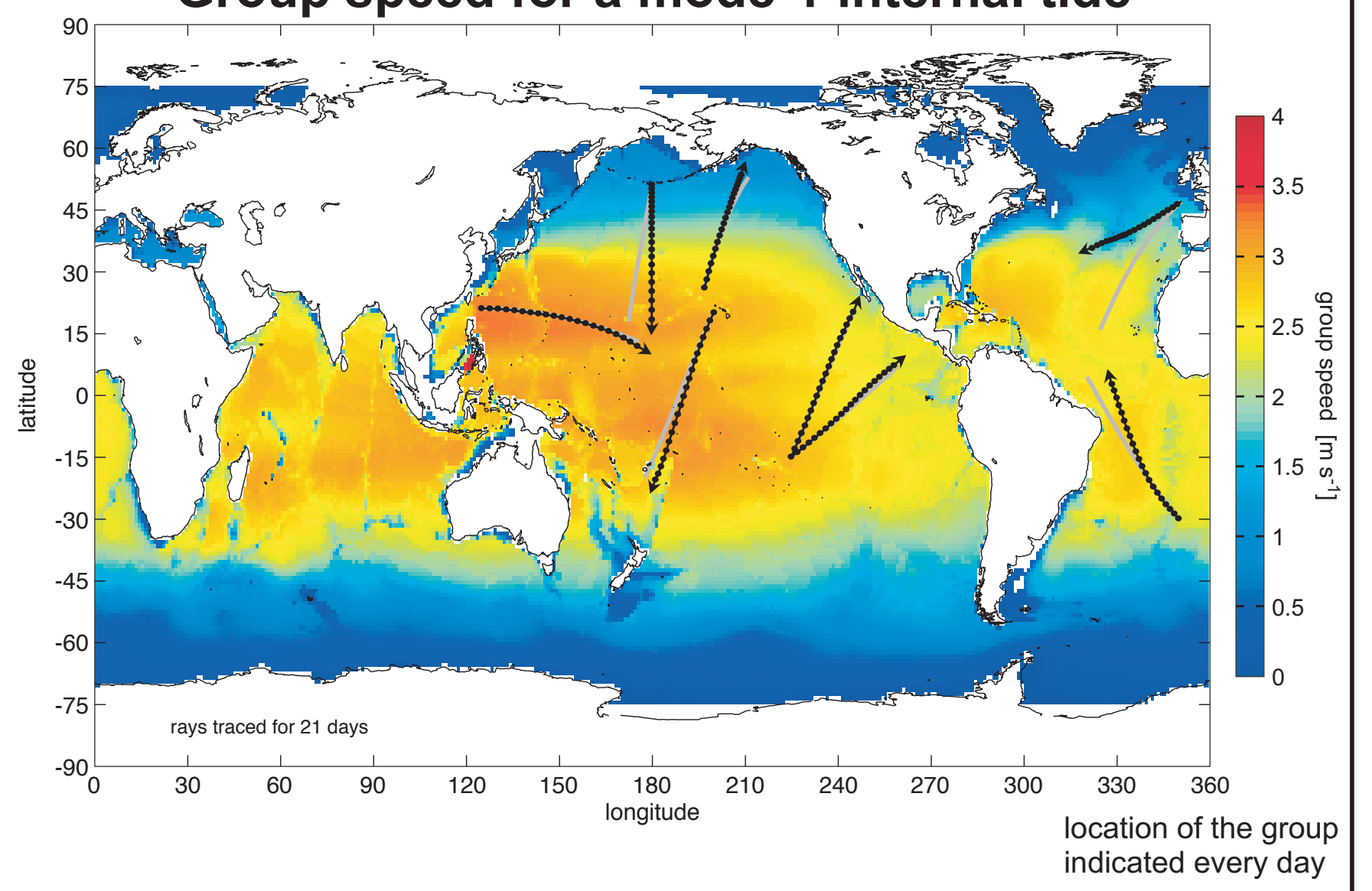
$$c_g \equiv \frac{\partial\omega}{\partial k_H} = \frac{\sqrt{\omega^2 - f^2}}{\omega}\, c_e$$

The phase speed of each mode is

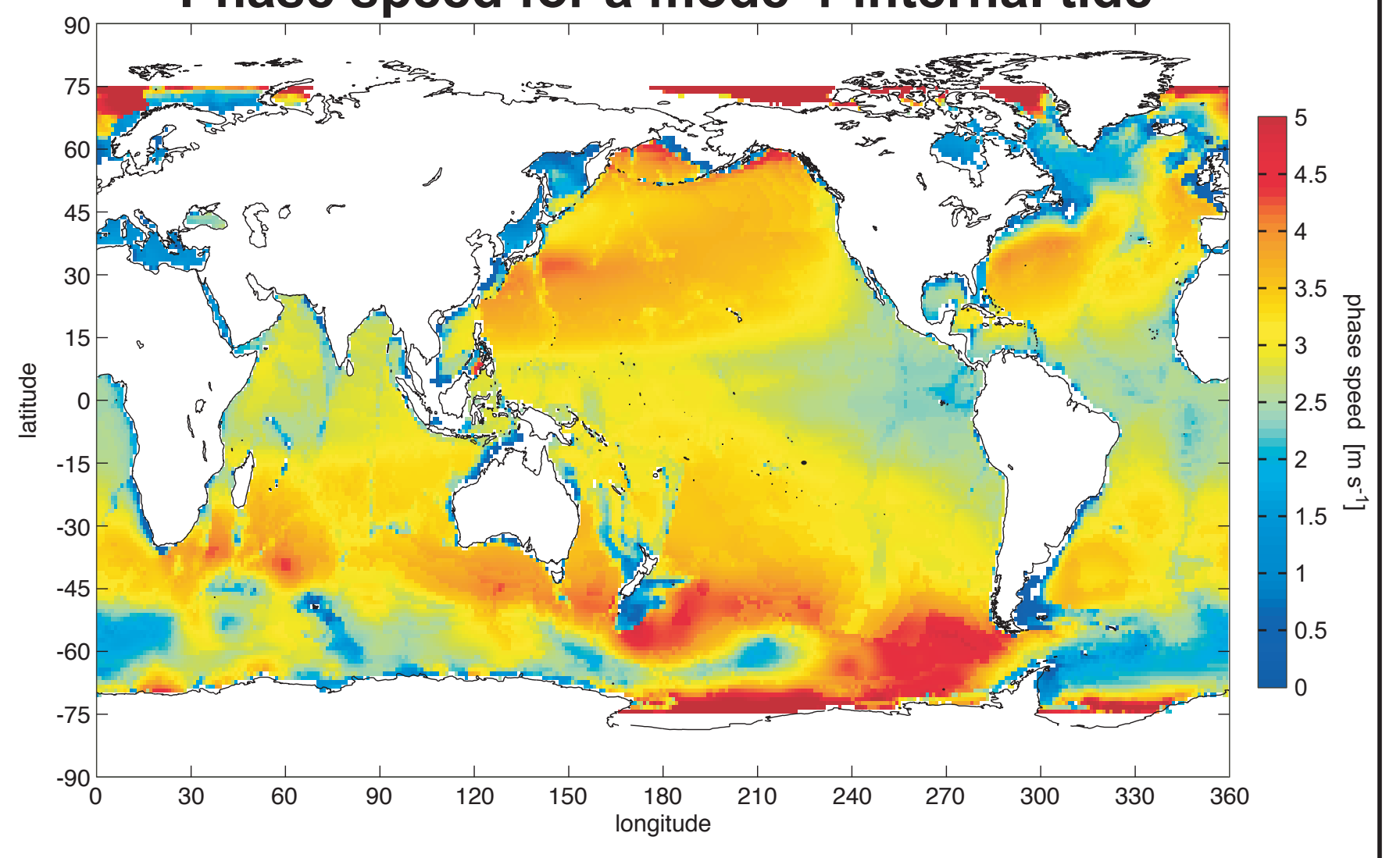
$$c_p \equiv \frac{\omega}{k_H} = \frac{\omega}{\sqrt{\omega^2 - f^2}}\, c_e$$

- c_e is a function of on stratification and depth. (for each mode)
- In addition, c_g and c_p are strong functions of latitude.

Group speed for a mode-1 internal tide



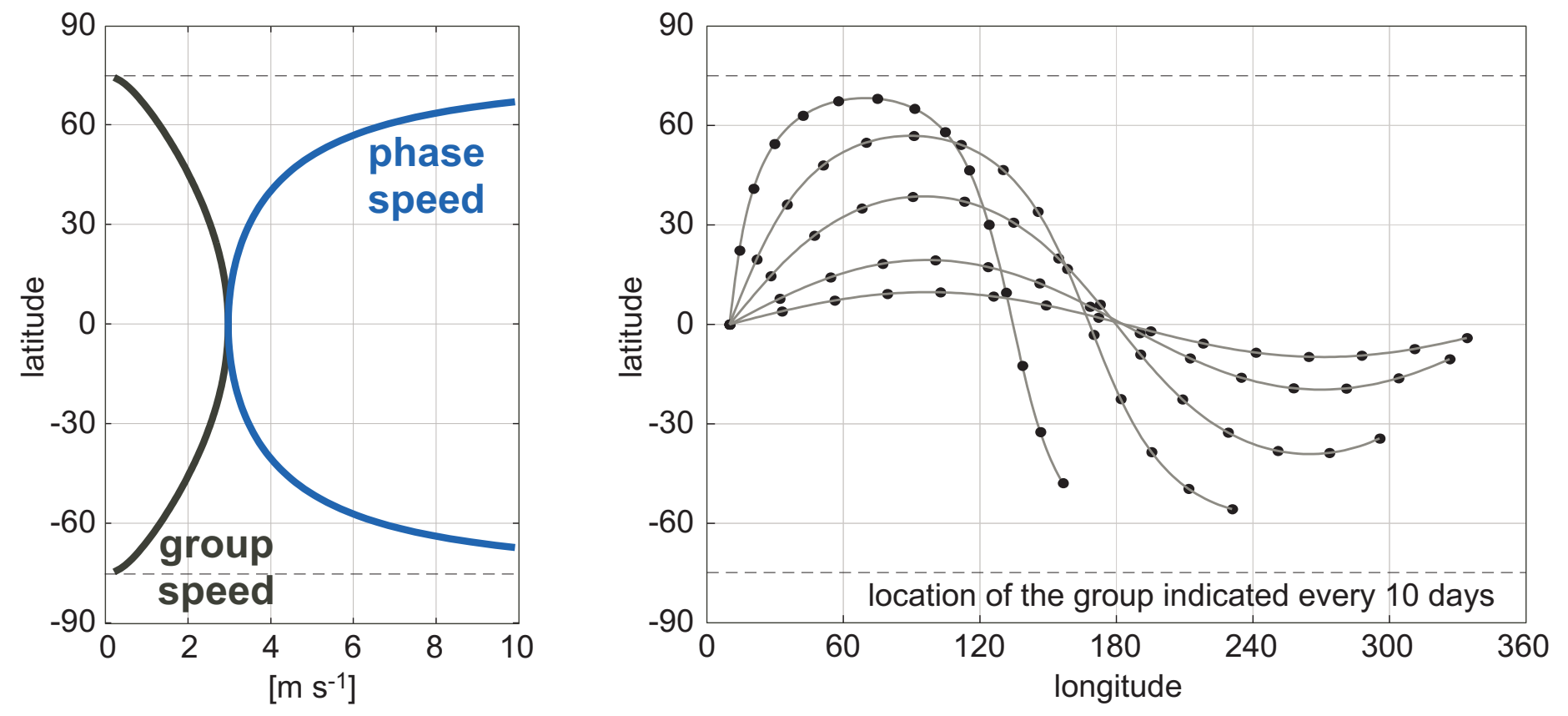
Phase speed for a mode-1 internal tide



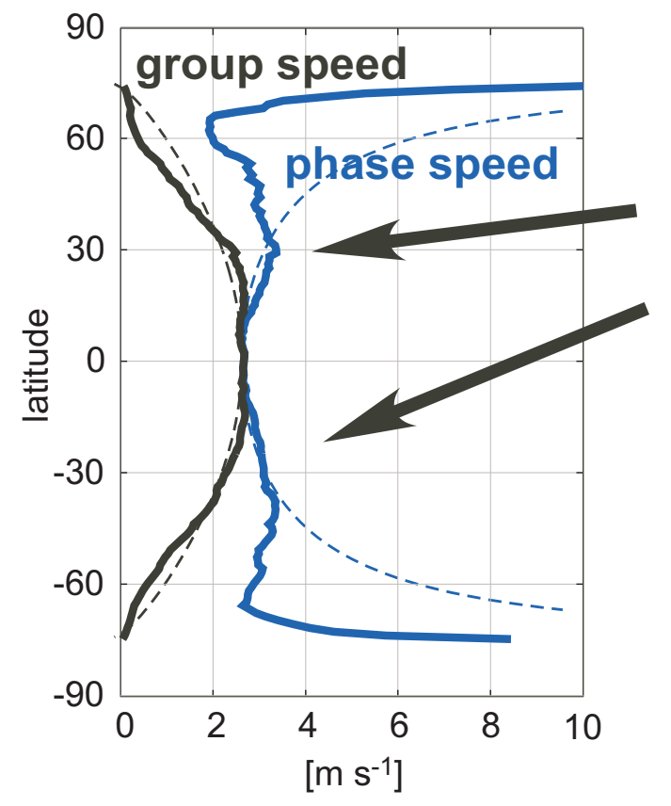
Rays are refracted away from regions of large phase velocity.

Latitude

Taking a constant c_e, a mode 1 internal tide is refracted towards the equatorial wave guide.



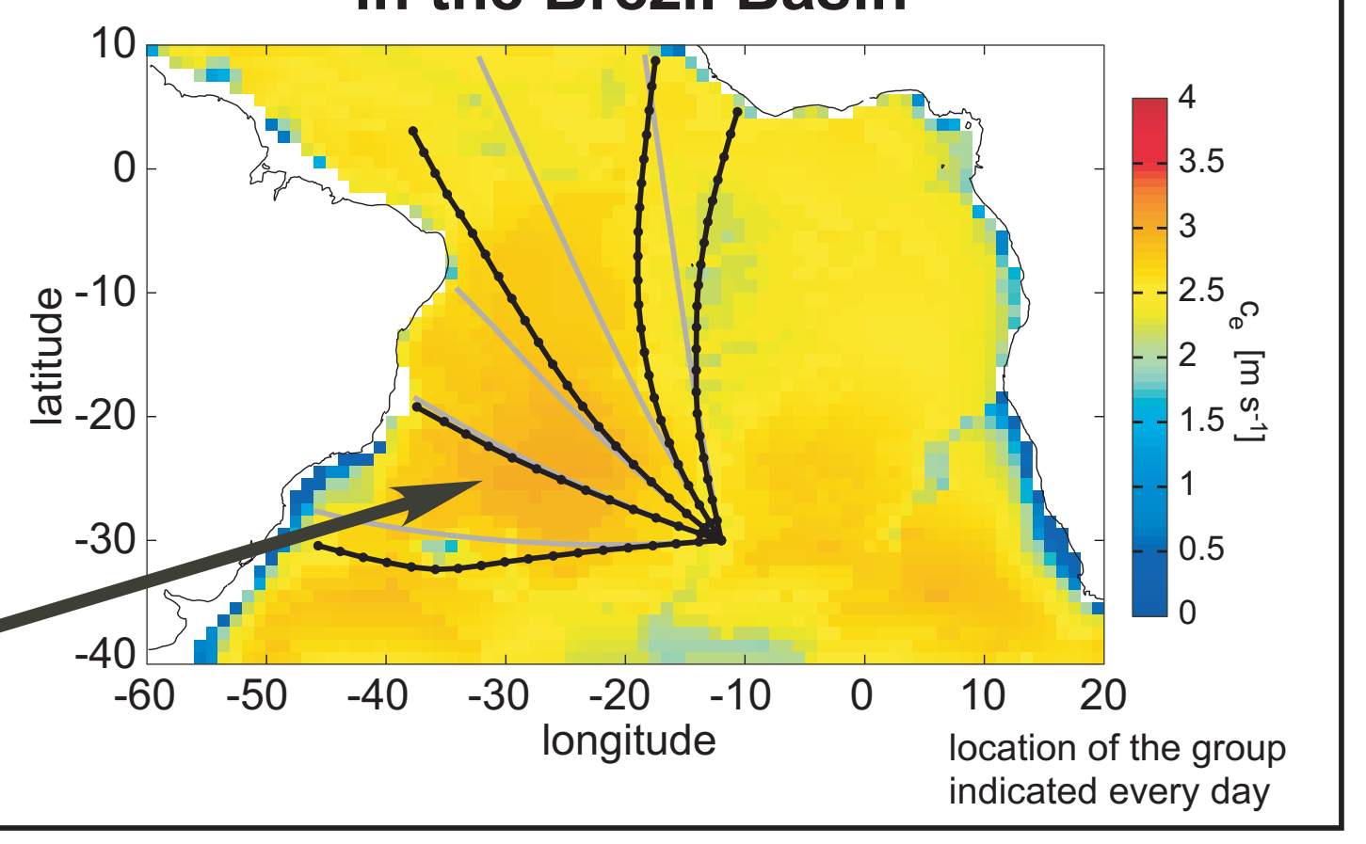
Stratification



The observed zonal average of c_g and c_p sharply drops at 30° because of changes in the stratification between the sub-tropical and the subpolar gyres.

Depth

Mode 1 internal tide in the Brezil Basin



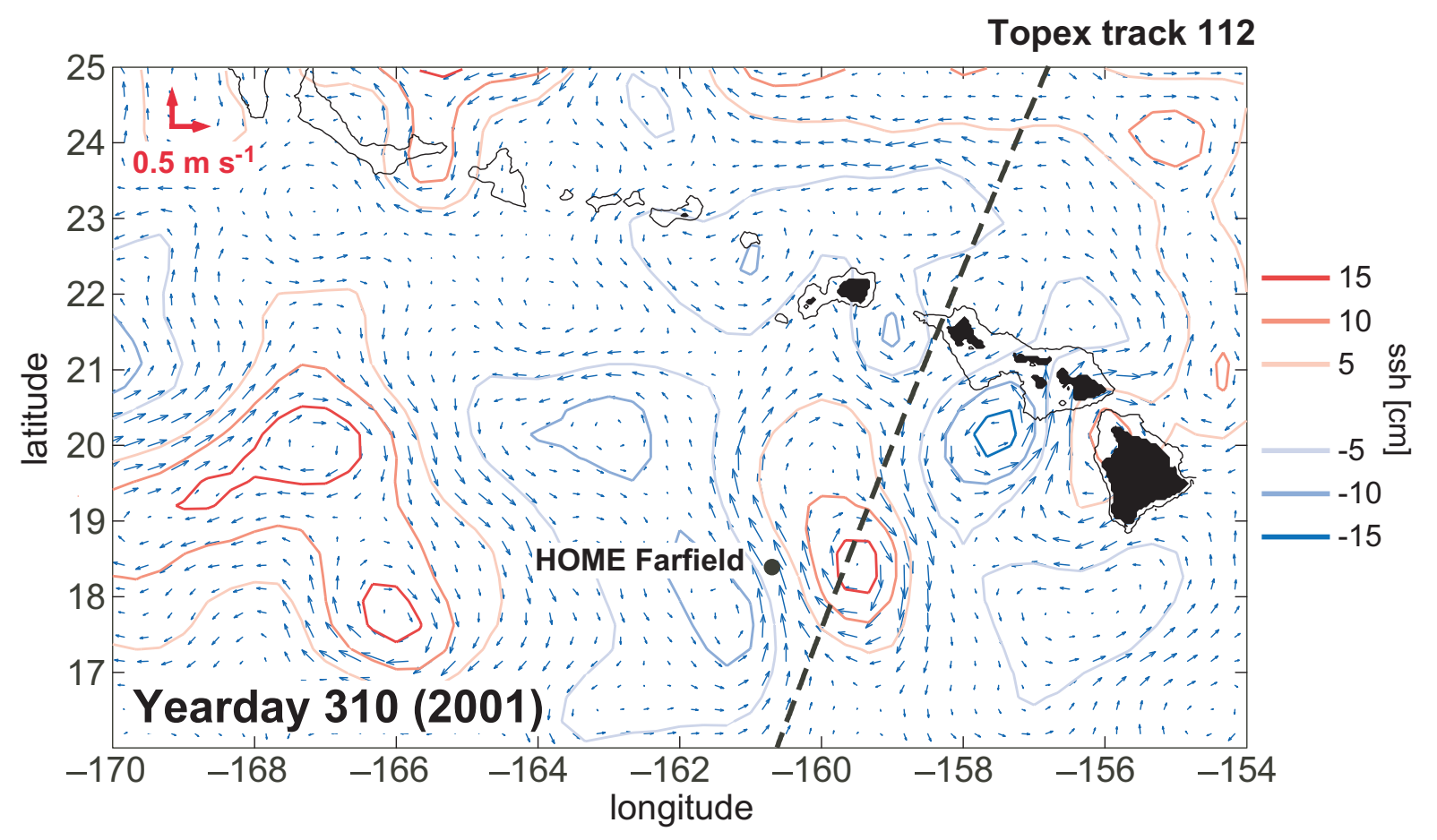
In the South Atlantic, rays curve away from the deep basin when $c_e(x,y)$ is used instead of a constant c_e.

Mesoscale velocity field from altimetry

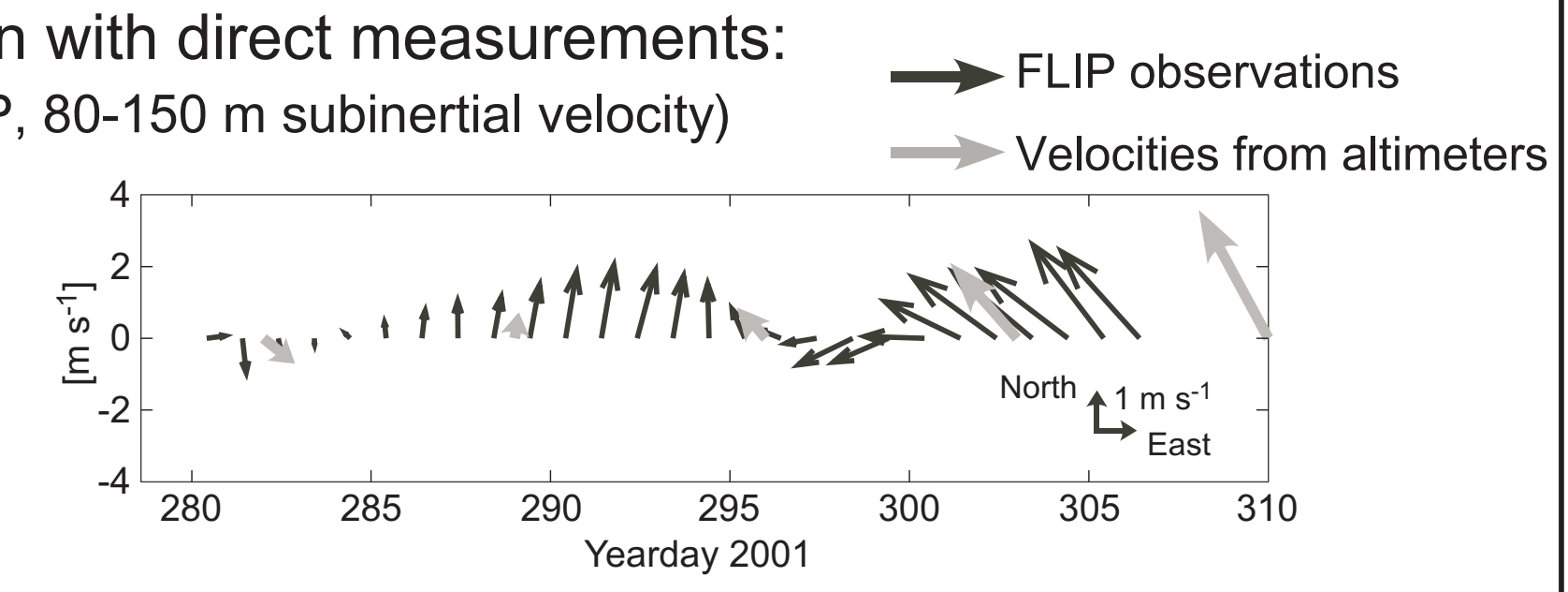
The sea surface height anomalies ζ measured by satellite altimeters (and mapped by the AVISO collaboration) can be used to determine the surface mesoscale currents:

$$U_{sfc}(x,y) = \frac{-g}{f}\frac{\partial\zeta}{\partial y}$$

$$V_{sfc}(x,y) = \frac{g}{f}\frac{\partial\zeta}{\partial x}$$

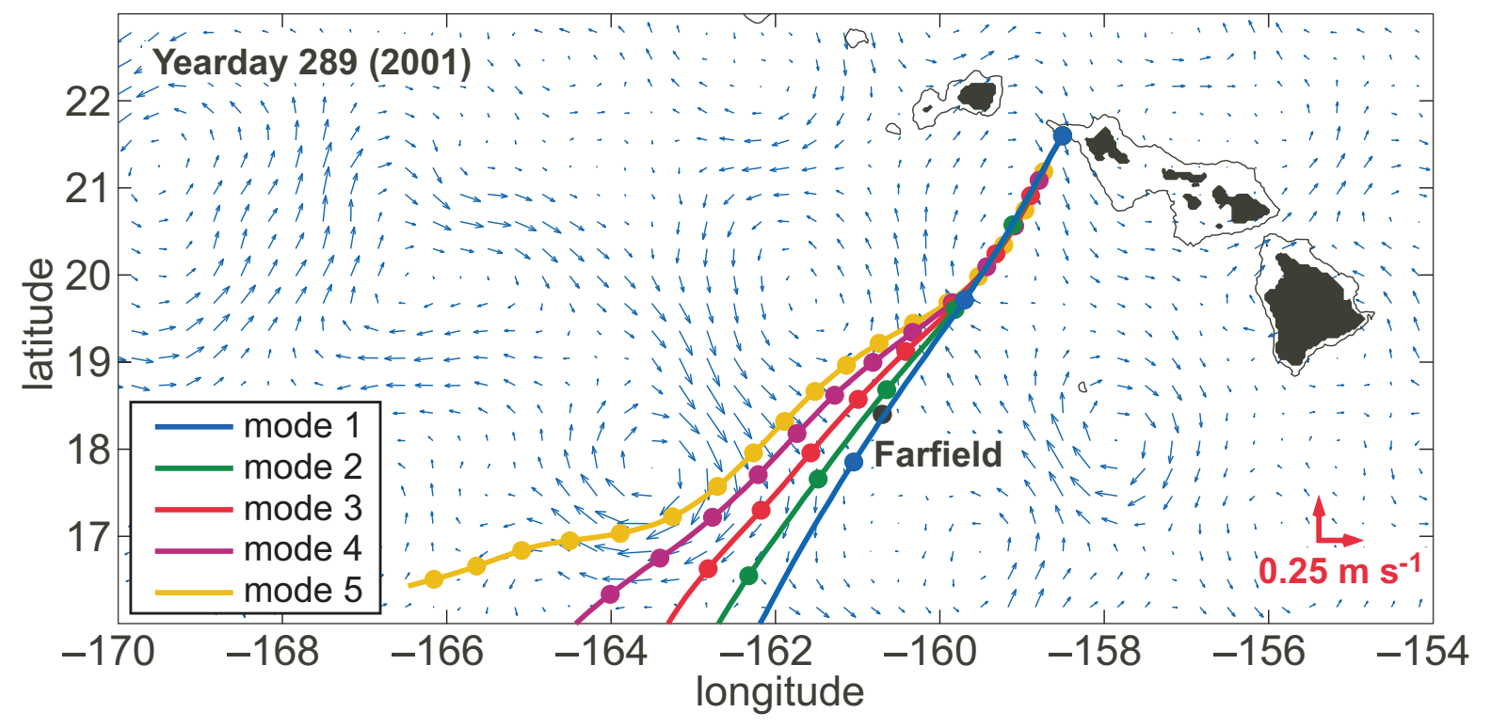


Comparison with direct measurements:
(R/P FLIP, 80-150 m subinertial velocity)



A ray model was developed to include the effect of advection on the propagation of internal waves.

- internal tide generated in the Kauai Channel, perpendicular to the Ridge.
- propagate through the barotropic mesoscale currents
- barotropic currents = $\frac{1}{2}\vec{U}_{sfc}$
- positions every 24 h are indicated.

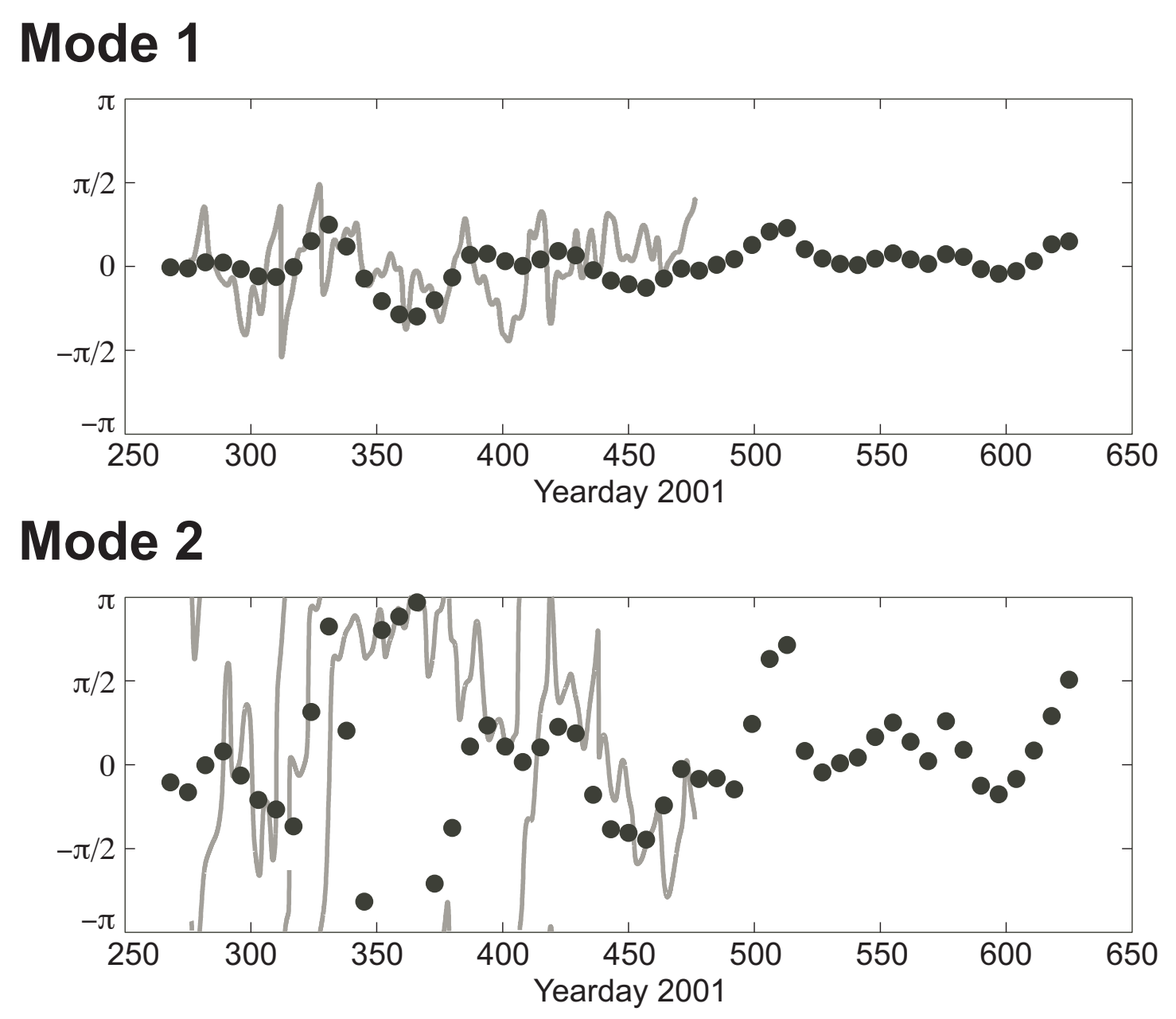


Significant deviations of the propagation paths are seen, especially for higher modes.

430 km away from the Ridge (Farfield site), phases from the model agree well with observations, and show significant variations.

Comparison of the internal tide phase at the Farfield site (430 km)

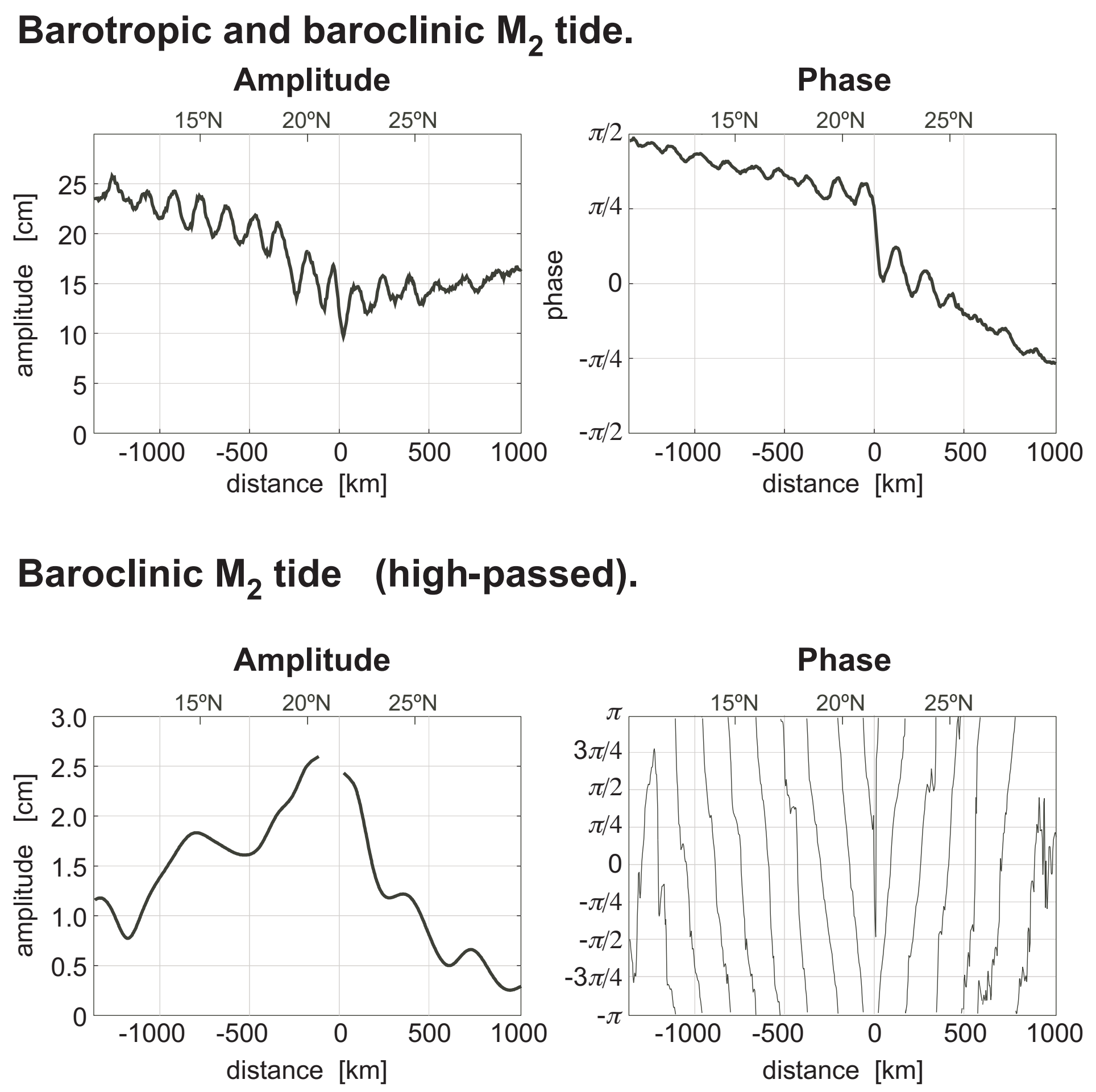
- ● Predicted by the propagation model through mesocale field $\frac{1}{2}\vec{U}_{sfc}$
- — Observed from fits on isopycnal displacements obtained from a mooring



Note: phase are offset so that in the absence of current, modes would arrive with a phase equal to zero.

TOPEX track 112

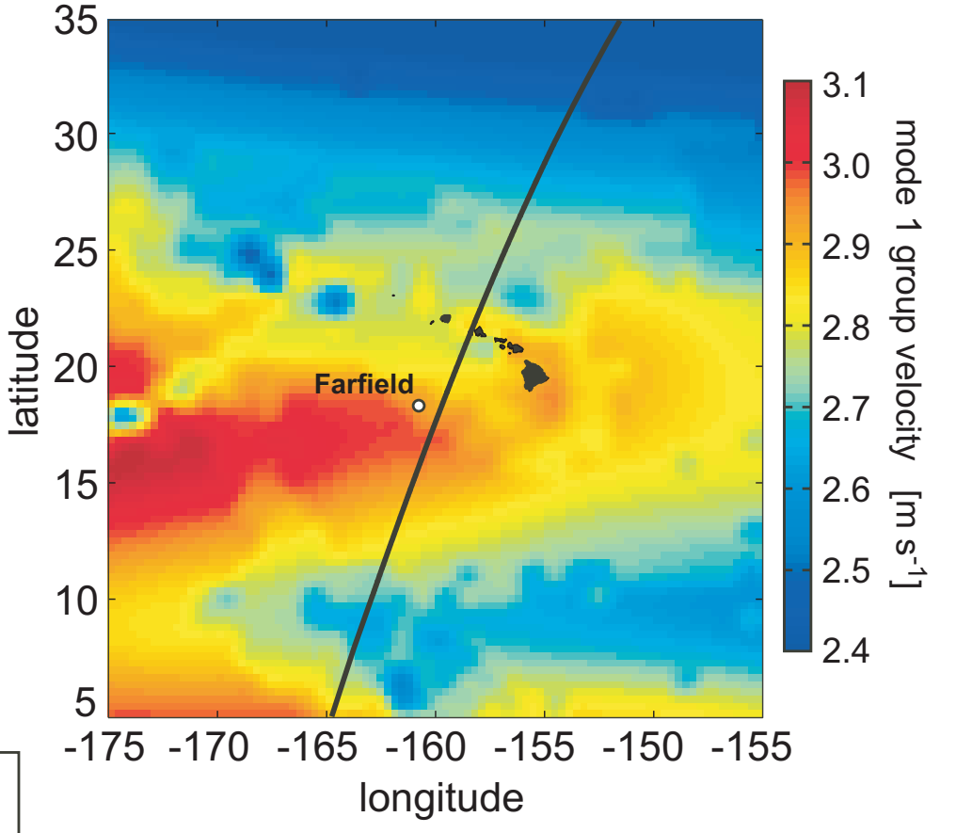
Band-passing the sea surface elevations measured by Topex around the frequency where M_2 is aliased, the sea surface elevation at the M_2 can be obtained (Ray and Mitchum, 1996, 1997).



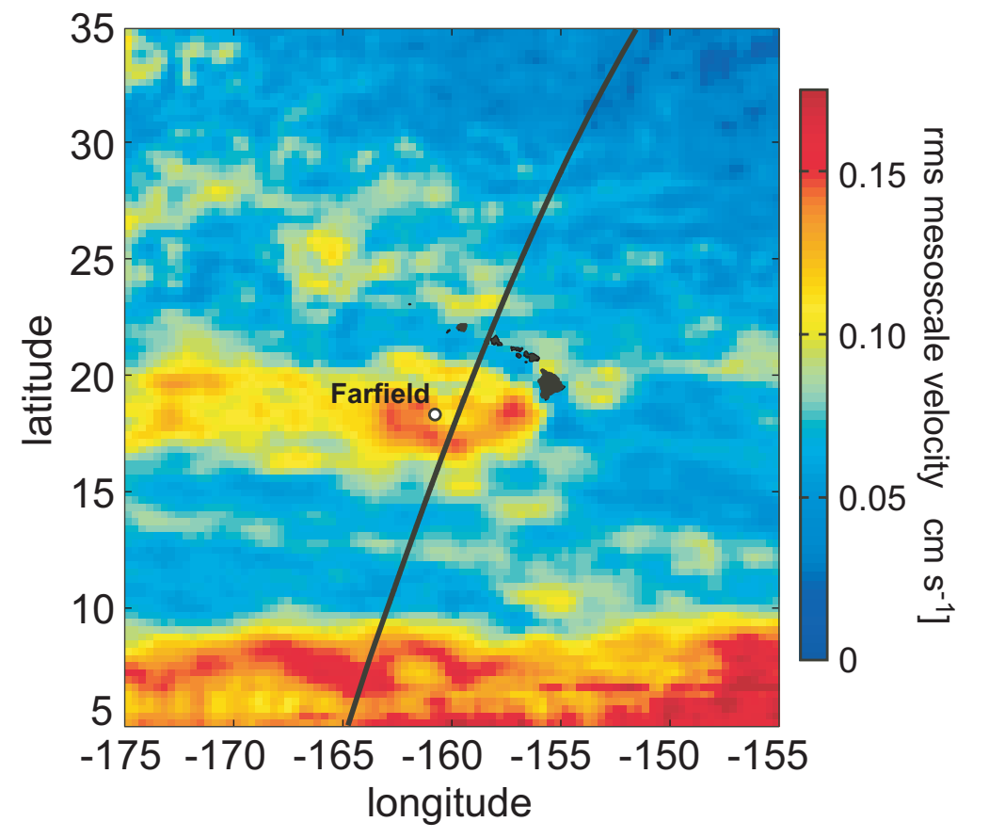
Topex data provided by Dr. R. Ray.

- inhomegeneous c_e
- mesoscale eddies

mode 1 group velocity



rms mesoscale velocity

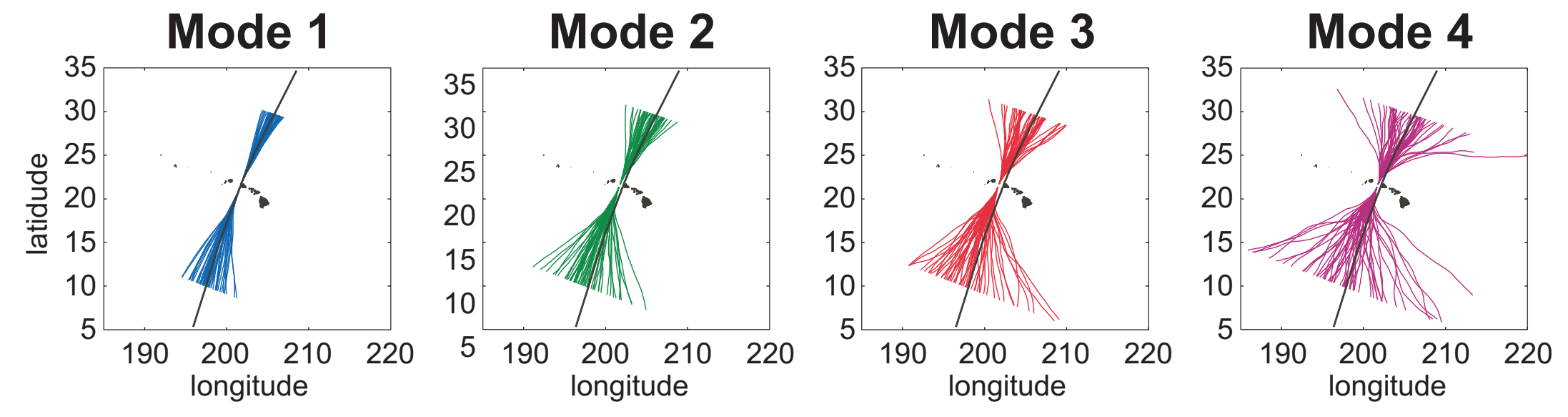


Loss of phase coherence

Propagate internal wave modes 1-4 through the mesoscale field for each week from Sept. 2001 to Sept. 2002.

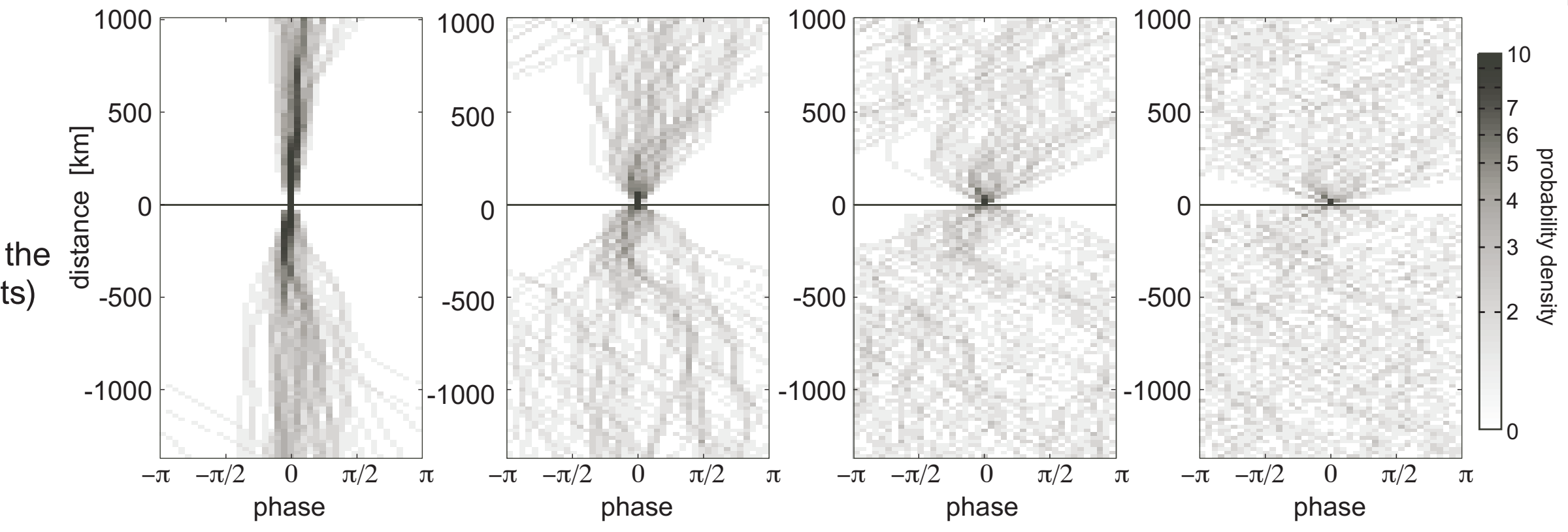
Propagation paths

with $\frac{1}{2}\vec{U}_{sfc}$



Phase vs distance

(offset to be zero in the absence of currents)

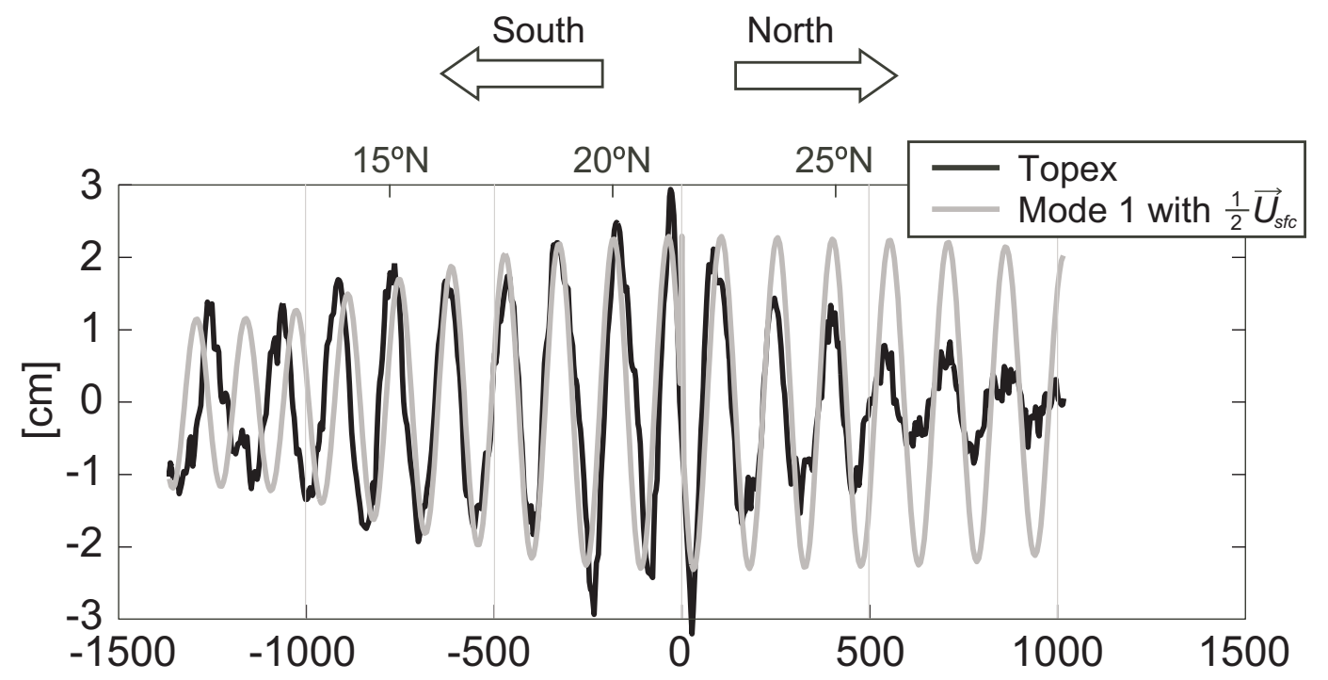


Mode 1 is relatively coherent to large distances.

Higher modes rapidly lose phase coherence.

When measuring the sea surface manifestation of the internal tide, the effect of losing phase coherence is an apparent decrease in amplitude.

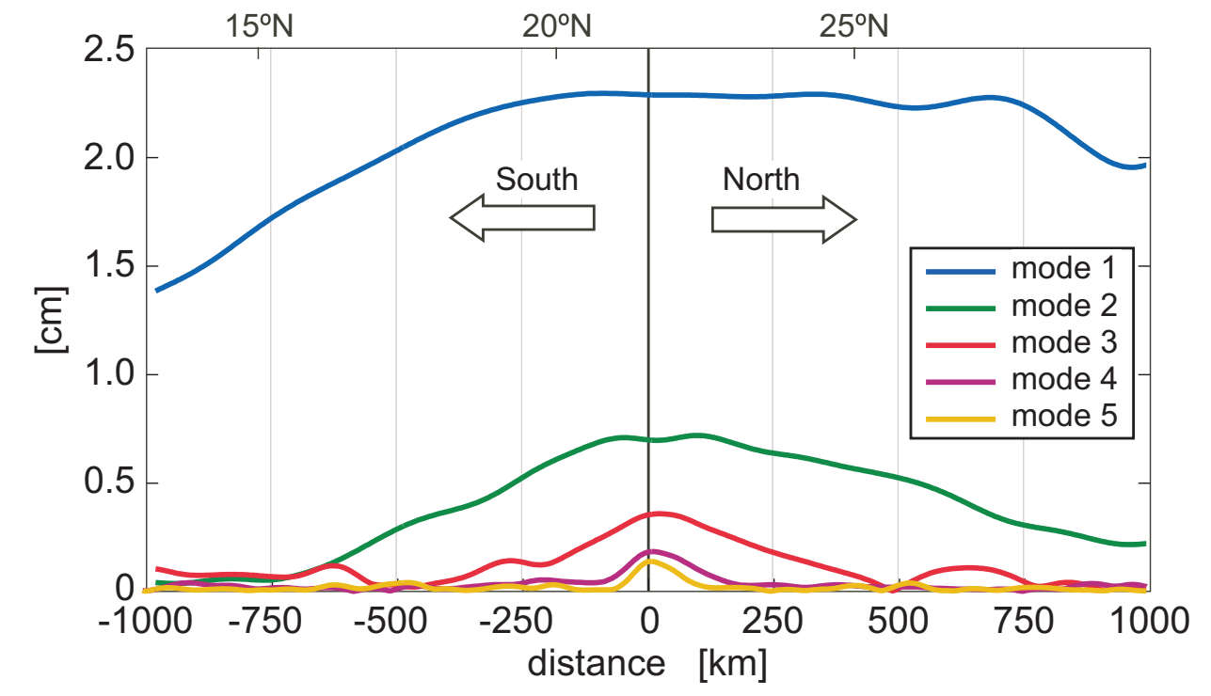
For example: mode 1 with maximum isopycnal displacement of 10 m propagated through barotropic mesoscale currents



South of the Ridge:	• large mesoscale variability. • not necessary to invoke dissipation.
North of the Ridge:	• mesoscale variability to small to explain observed decrease of the signal.

Higher modes have a smaller sea surface manifestation and lose coherence more rapidly.

with $\frac{1}{2}\vec{U}_{sfc}$



Summary

Over the world ocean, the phase and group speeds of the low-mode internal tide are found to be far from uniform.

- ***Latitude***, ***stratification***, and ***bathymetry*** significantly affect the propagation.
- Waves are refracted away from regions of large phase speed (near the critical latitude, highly stratified, or deep basins).
- Effects are more or less the same for all modes.

Mesoscale currents signaficanlty affect the propagation paths and the phase coherence of the internal tide.

- Predictions from a ray model including advection agree well with observations for $\frac{1}{2}\vec{U}$sfc.
- Modes 3 and higher are completely incoherent only a few wavelengths from their source.
- Along Topex track 112 (near Hawaii), the loss of phase coherence can explain the observed decrease in sea surface manifestation of the internal tide south of the Ridge.
- North of the Ridge, the internal tide should remain phase locked, but is observed to decrease rapidly.
  - This might be due to more effective nonlinear interactions around 30°N. (e.g. subharmonic instability [Hibiya et al., MacKinnon et al.])

$$M_2 \longrightarrow \frac{1}{2}M_2$$

Acknowledgments

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Corresponding author: Luc Rainville <lrainville@whoi.edu>