Observations of deep near-inertial waves interacting with large- and meso-scale currents in the Kuroshio Extension

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Propagation of near-inertial waves (NIWs)

A simple model predicts that NIWs propagate downward and equatorward

Garrett (2001)

Fig. 1. Schematic of the ray for inertial waves generated at the surface and propagating equatorward and downward. The frequency $\omega$ is fixed, but the Coriolis frequency is a function of meridional distance $y$.

Alford (2003)

Supported by observational evidence
Propagation of near-inertial waves (NIWs)

However,

1) Theory ignored the effect of variable background current shear and stratification that can change the propagation path of the NIW energy.

2) Observations have been scarce in regions of strong background shear such as western boundary currents.
Gulf Stream can create a “desert” for NIW energy (from simulation)

Predicting that “inertial chimney” (Lee and Niiler, 1998) associated with anti-cyclonic eddy activities prevents further propagation of NIWs to the south
Kuroshio Extension System Study
(KESS, May 2004 - June 2006)
www.uskess.org

- 600 km x 600 km array
- 46 near-bottom current sensors (RCM11)
  (~50 m above the bottom, ~90 km spacing, 5300-6100 m depth)
Upper- and deep-flow variabilities in the Kuroshio Extension

- Colored contours: deep pressure fields
- Black and gray contours: upper flow fields
- Black arrows: observed deep flows
- Gray arrows: OI mapped flows using both U and $P_{bot}$
Wind stress

ML NIW

Bandpass filtered Inertial current (u)
Wind, ML NIW & Deep NIW

Wind stress

ML NIW

Bandpass filtered Inertial current (u)
Change of NIWs across the KE

North

Kuroshio

South

Bandpass filtered Inertial current (u)
Wintertime-mean upper and deep maps of NIW energy vs. relative vorticity.

**ML NIW**

(a) $E_i^{ML}$ (J m$^{-2}$)

**deep NIW**

(b) $E_i$ (J m$^{-3}$)

**relative vorticity**

(c) Upper $\zeta$

From wind

deep currents

SSH

11/2004-04/2005

4/24/2009

Park/URI
What can cause the high NIW energy north of the KE?

Reflection of NIWs to the North by the positive vorticity barrier of the Kuroshio

Advection of NIWs to the East

Zhai et al. (2004)
Relationship between deep NIWs and deep mesoscale eddies

- Deep NIW energy maps for four separate 10-day periods
- Black contours: 10-day-mean positive bottom pressure fields (i.e., anticyclonic)
- Red contours: 10-day-mean Kuroshio locations

4/24/2009 Park/URI
Scatter plots of 10-day-mean deep NIW energy vs. upper and deep relative vorticity.

Upper $\zeta$ vs. $Ei_d$

Deep $\zeta$ vs. $Ei_d$

Least square fit
Summary

- We observed a sharp factor-of-5 decrease of wintertime-mean deep NIW energy across the KE with large values on the north side of the KE.
- Blockage of NIW energy by the KE can create areas of relatively little NIW energy such as the NIW energy desert in subtropical gyres.
- Localized episodic high deep near-inertial events are found to be associated with deep anticyclones rather than upper ones.
- Meaningful estimation of NIW energy input to the deep ocean should consider large- and meso-scale flows.
CPIES

(Current-and-Pressure-recording Inverted Echo Sounder)

- Emits 12 kHz sound pulses
- Measures round trip travel times of acoustic pulses from the bottom to the surface
- Measures bottom pressure with resolution < 1mm
- Measures deep current

50 meter x 8mm cable

Aanderaa Doppler current sensor, model 3820R, p/n 0973820R

URI-GSO Inverted Echo Sounder (pressure sensor option)

Expendable anchor plates + platform
ML and Deep NIWs vs. SSH

Mixed-layer near-inertial currents (cm/s)

50°N
40°N
30°N
20°N
140°E 150°E 160°E 170°E

Near bottom KE [cm²/s²]

Absolute dynamic topography (m)

4/24/2009 Park/URI
PSD of deep currents

North of the KE
⇒ High PSD

South of the KE
⇒ Low PSD
Wintertime-mean upper and deep maps of NIWs vs. relative vorticity

Nov-Jan

ML NIW  deep NIW  relative vorticity

Feb-Apr

4/24/2009
Ocean needs 2.1 TW

- Ocean mixing maintains oceanic stratification and MOC

- Major energy source for mixing
  \[ \Rightarrow \text{Tides (0.9 TW) and winds (1.2 TW)} \]
  by Munk and Wunsch (1998)

- Wind-induced near-inertial waves
  \[ \Rightarrow 0.4-0.7 \text{ TW} \]
  (e.g., Watanabe and Hibiya, 2002; Alford, 2003)