Fate of Internal Waves on a Shallow Shelf

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Internal Waves on Dongsha Atoll

June 2014

1. What characteristics of the shelf (geometry, stratification, shear conditions) and incident internal wave field determine the form, distribution of energy, and resultant mixing for internal waves on the inner shelf?

2. How much do these internal waves shape the physical and chemical environment on the reef?

(DeCarlo et al., 2015, GRL)
Internal wave “weather” on Dongsha Atoll fore reef

Bottom Temp. on Dongsha East Forereef (°C)

Days in June 2014
Internal wave “weather” on Dongsha Atoll fore reef

Bottom Temp. on Dongsha East Forereef (°C)

Days in June 2014

low freq (3 day lpf)
Internal wave “weather” on Dongsha Atoll fore reef

Bottom Temp. on Dongsha East Forereef (°C)

Days in June 2014

- low freq (3 day lpf)
- tidal-band (D1, D2)
Internal wave “weather” on Dongsha Atoll fore reef

Section of South China Sea at 21°N

(Alford et al., 2015, Nature)

Bottom Temp. on Dongsha East Forereef (°C)

Days in June 2014

T.S. Hagibis
Internal wave “weather” on Dongsha Atoll fore reef

Tidal Velocity at Luzon Strait, $u$ (m s$^{-1}$)

Bottom Temp. on Dongsha East Forereef (°C)

Days in June 2014
Internal wave “weather” on Dongsha Atoll fore reef

Tidal Velocity at Luzon Strait, $u$ (m s$^{-1}$)

Bottom Temp. on Dongsha East Fore reef (°C)

Days in June 2014

T.S. Hagibis

lagged 50.6 hrs from top panel
Shoaling Waves Transform from Depression to Elevation

Fu et al. (2012)
Shoaling Internal Waves Transport Deep, Cool Water to the Inner Shelf (and onto the 1m deep reef flat!)

MODIS SST
(June-Aug, 2002-2017)

IW “Cooling” of SST vs. Generation forcing (~500 km away)

(Reid et al., submitted to L&O)
Distributed Temperature Sensing (DTS) Principles

DTS Unit
- Pulsed Laser
- Directional Coupler
- Optical Receiver
- Signal Processing

Optical Fiber
- Laser Pulse
- Raman Backscattering

Spectrum of Backscattered Light
- Incident Light
- Anti-Stokes Signal (strongly temp dependent)
- Stokes Signal (weakly temp dependent)

Graphs:
- Return Signal Intensity vs Return Signal Wavelength
- Temperature vs Distance Along Cable

Animation adapted from sensortran.com
Surveying the Fiber Optic Cable
Internal waves on the fore reef slope

- Induce extreme temperature changes (8°C in < 1 minute)
- Trapping of cool water in reef grooves, i.e. "internal tidepools"
- Internal wave reflection
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Internal wave reflection and transmission

Reflecting internal waves seen in a space-time representation from surface photographs of surface signatures in a fjord (Bourgault et al, 2011)

Reflected waves have, on average, 60% lower speed than incident waves.
Internal wave reflection off the Dongsha Slope

Bai et al. (2017, JGR)
Nonhydrostatic Simulations (SUNTANS courtesy of Justin Rogers and Oliver Fringer)

**Insights developed from numerical runs:**
- Strong nearbed offshore-directed jet preceding an internal wave arrival on the slope is due to wave-topography interaction, “internal wave run down”.
- Shoaling internal wave alters the nearshore stratification and shear environment.
- Internal wave reflection is predicted off of the steep section of the Dongsha slope.
Nonhydrostatic Simulations

A. Wave Propagation, $u$ (cm/s) & $\rho$

G. Virtual DTS

B C D E F

Incident
Reflection

H. Bottom Velocity

incidence
reflection

I. Net Energy Flux

$\int F_z \, dt$ (10$^7$ J/m)

onshore
offshore

(-)

(\Sigma)

(+)
1. Construct a time series of density profiles from DTS and CT sensors on vertical mooring.

- Of the 70 incident/reflected pairs, only 20 could be predicted from the DJL model.

- Reflectance Ratio was highly variable in time, ranging from $R = \sim 0$ to 0.4.

2. Use the Dubriel-Jacotin-Long equation to predict the kinetic and available potential energy (APE) density at the observed incident and reflected wave speeds (Lamb, 2002; ref).

$$\nabla^2 \eta + \frac{N^2 (z - \eta)}{c^2} \eta = 0,$$
The Fate of Internal Waves on the Inner Shelf

The “fate” of internal waves – whether transmitted into shallow waters or reflected back offshore – is mediated by local water column density and shear structure - often determined by previous shoaling internal waves.
Topographic Blocking and near bed currents influence IW reflection

Laboratory and numerical studies of IWs interacting with topographic obstructions find a “blocking parameter”, $B = h/H_2$ predicts the loss of energy from the incident wave into reflected and transmitted waves.

(Wessels & Hutter, 1996)

$B < 0.6$; wave is transmitted
$B > 0.8$; partial reflection is apparent
$B > 1$; total reflection is possible

Surface-referenced Blocking Parameter: $B_s = H_1/d$
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![Diagram](image.png)
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(Wessels & Hutter, 1996)

<table>
<thead>
<tr>
<th>Value of $B$</th>
<th>Nature of Reflection</th>
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</thead>
<tbody>
<tr>
<td>$B &lt; 0.6$</td>
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Surface-referenced Blocking Parameter: $B_s = H_1/d$

reflected waves avg. $B_s = 0.99$
transmitted waves avg. $B_s = 0.63$
Internal wave influence on the shallow reef flat

Construct a simple heat budget to predict water temperature on the reef flat:

\[ \rho c_p h \frac{\partial \langle T \rangle}{\partial t} = -\rho c_p h \langle \bar{u} \rangle \frac{\partial \langle T \rangle}{\partial x} + Q_N \]

- advective heat flux
- atmosphere-ocean heat flux

**Observed**

R² = 0.64, p < 0.001

**Hour of Day**

- Reef Warming
- Reef Cooling
Internal wave influence on the shallow reef flat

Observed temperature on the reef flat

Temperature predicted from heat budget:

$$\rho c_p h \frac{\partial \langle T \rangle}{\partial t} = -\rho c_p h \langle \bar{u} \rangle \frac{\partial \langle T \rangle}{\partial x} + Q_N$$

Estimate of temperature “without internal waves” using boundary condition at “B”
• Internal waves set the offshore “initial condition” for water coming onto the flat
• Internal waves cool water temperatures on the flat by up to 2°C
• Nitrate flux to the reef flat is four times as large with internal wave influence.
Summary & Conclusions

• The spatially-continuous perspective of temperature afforded by the DTS instrument reveals that internal waves, often thought of as deep-ocean phenomena, are not uncommon in nearshore coastal waters, transporting heat (or cold!) and nutrients to coastal benthic communities.

• The reflectance ratio is highly variable in time with up to 40% of the incident internal wave energy can be reflected off of the steep Dongsha slope.

• The “fate” of internal waves on the shelf – whether transmitted into shallow waters or reflected back offshore - is mediated by the highly dynamic stratification and near bed currents at the slope break and is, thus, strongly affected by wave-wave interactions.
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