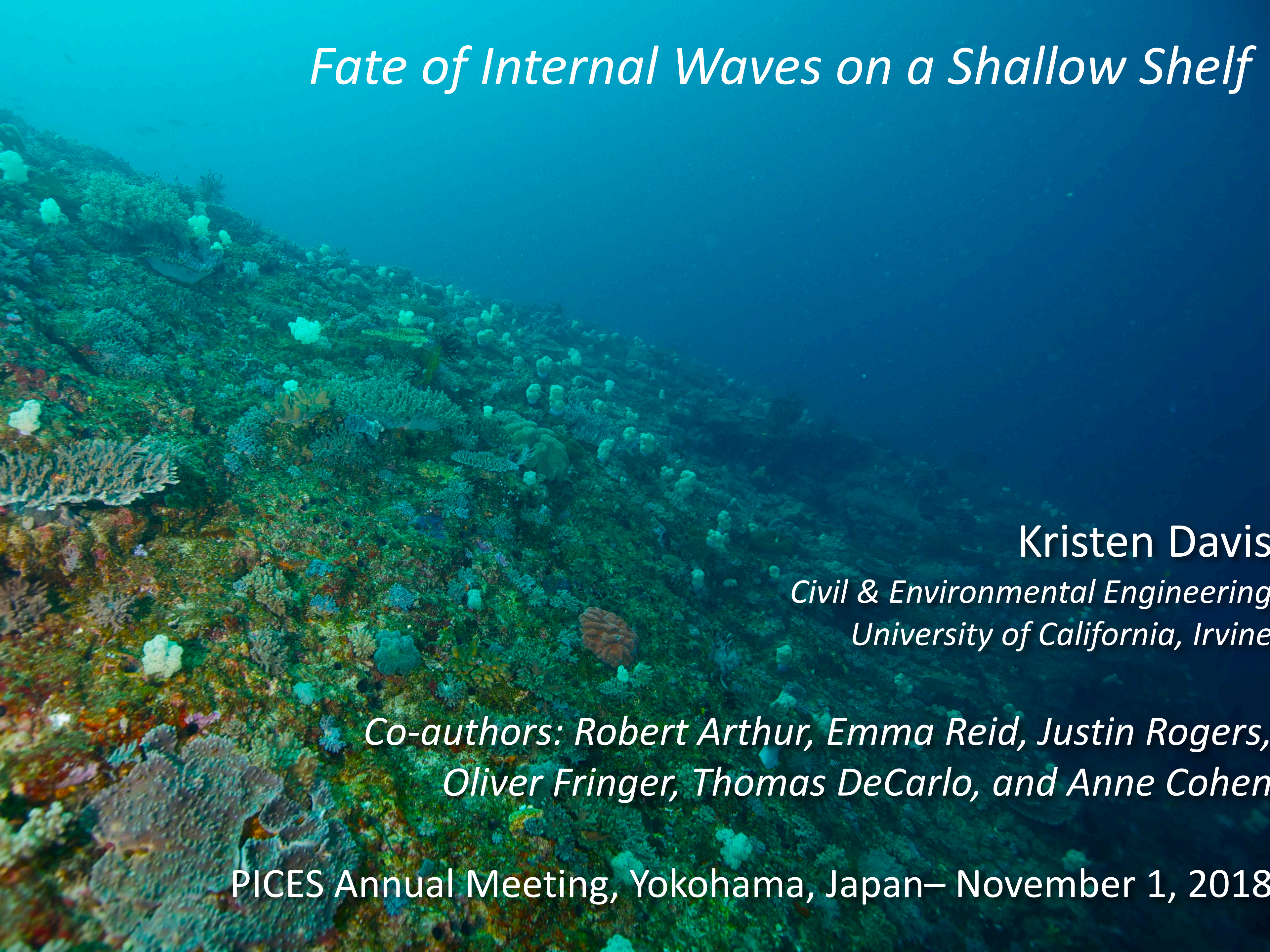


Fate of Internal Waves on a Shallow Shelf

Kristen Davis

Civil & Environmental Engineering

University of California, Irvine

Co-authors: Robert Arthur, Emma Reid, Justin Rogers, Oliver Fringer, Thomas DeCarlo, and Anne Cohen

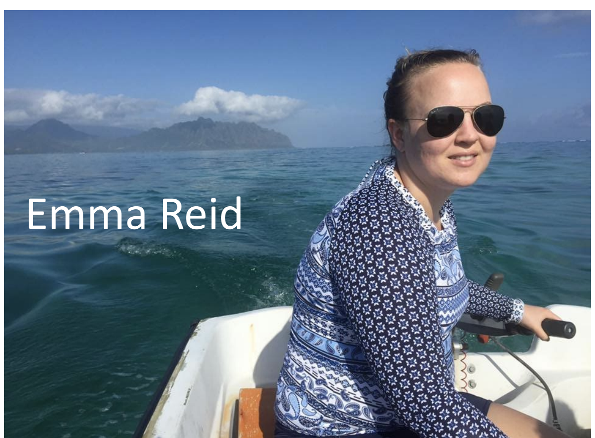
PICES Annual Meeting, Yokohama, Japan– November 1, 2018

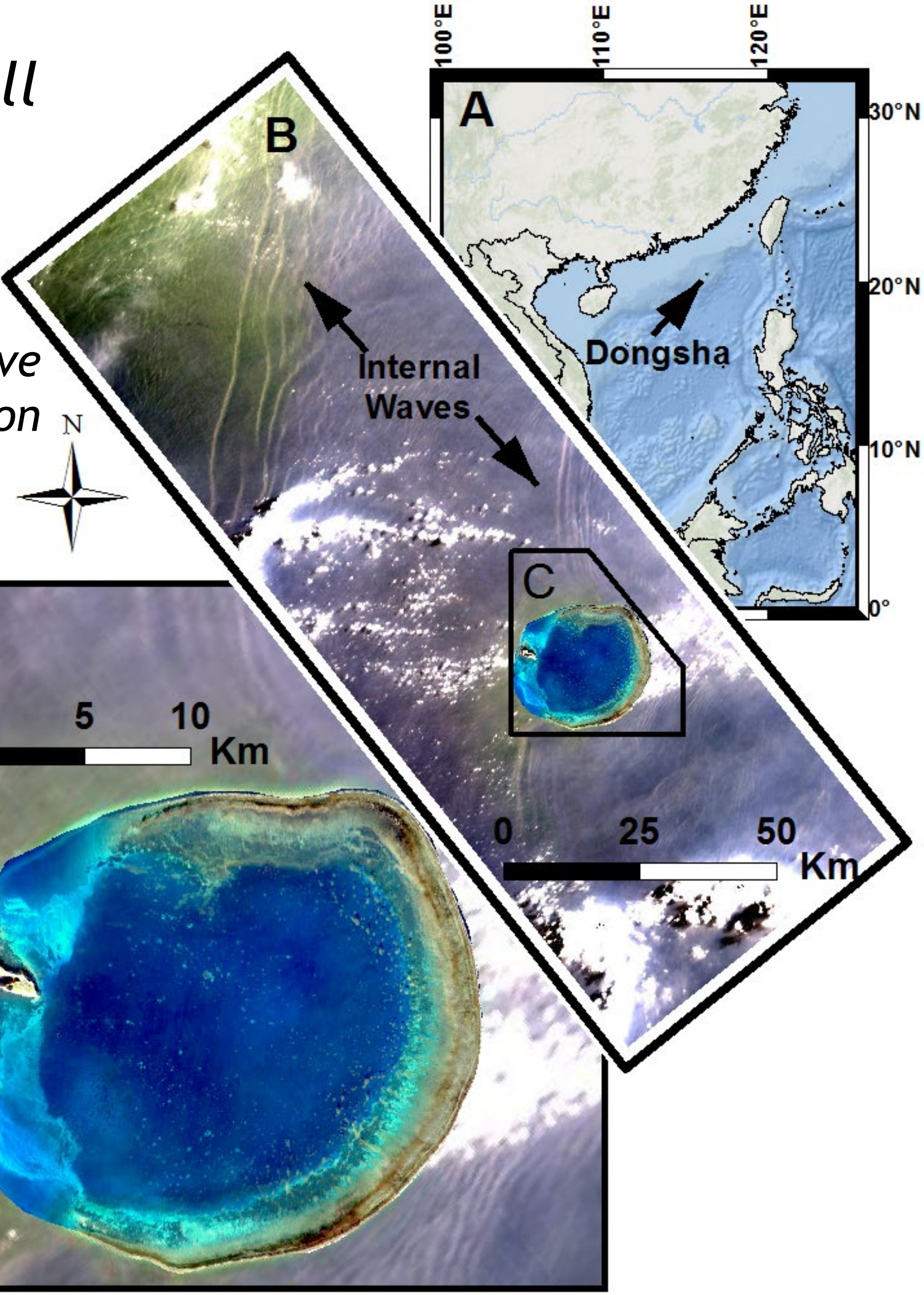
Internal Waves on Dongsha Atoll

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?*

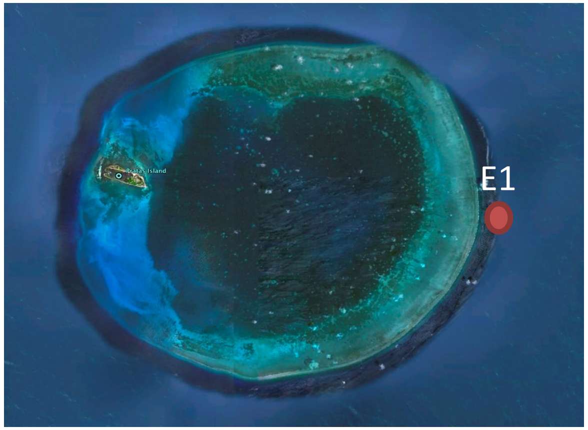
2. *How much do these internal waves shape the physical and chemical environment on the reef?*

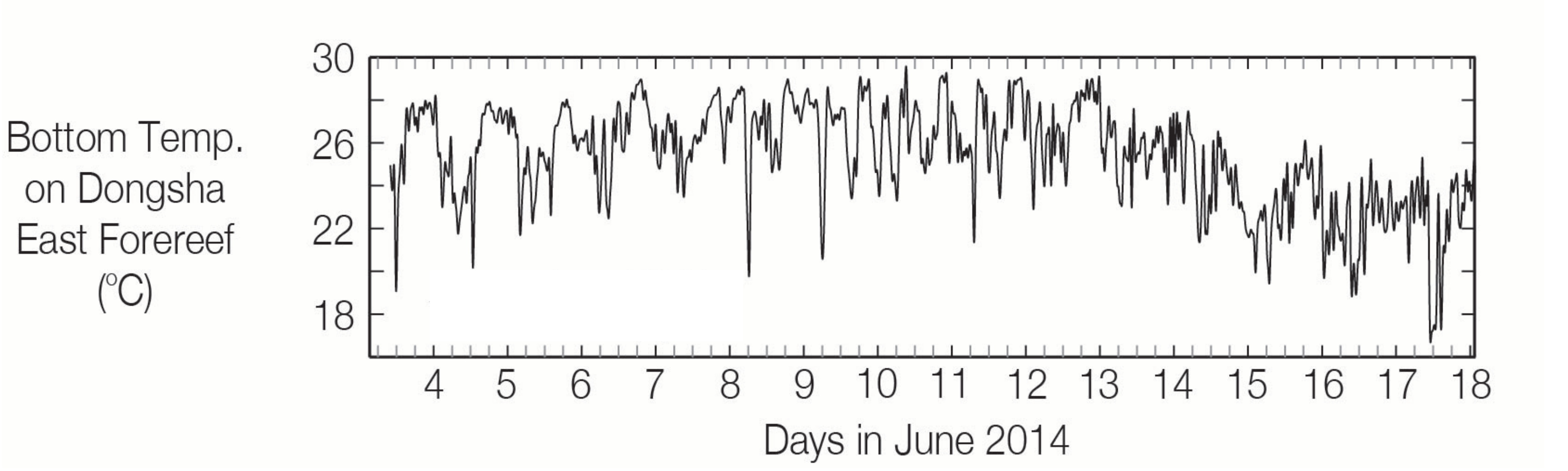




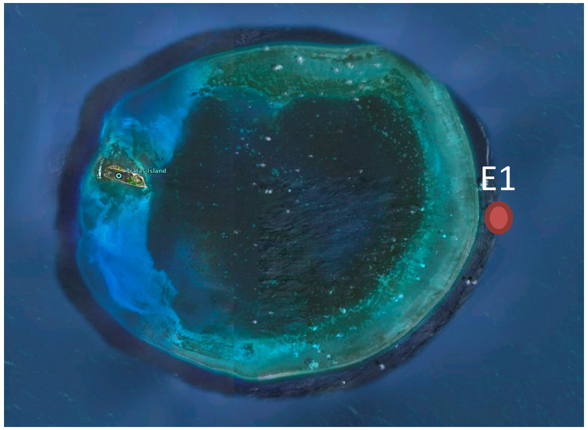
(DeCarlo et al., 2015, GRL)

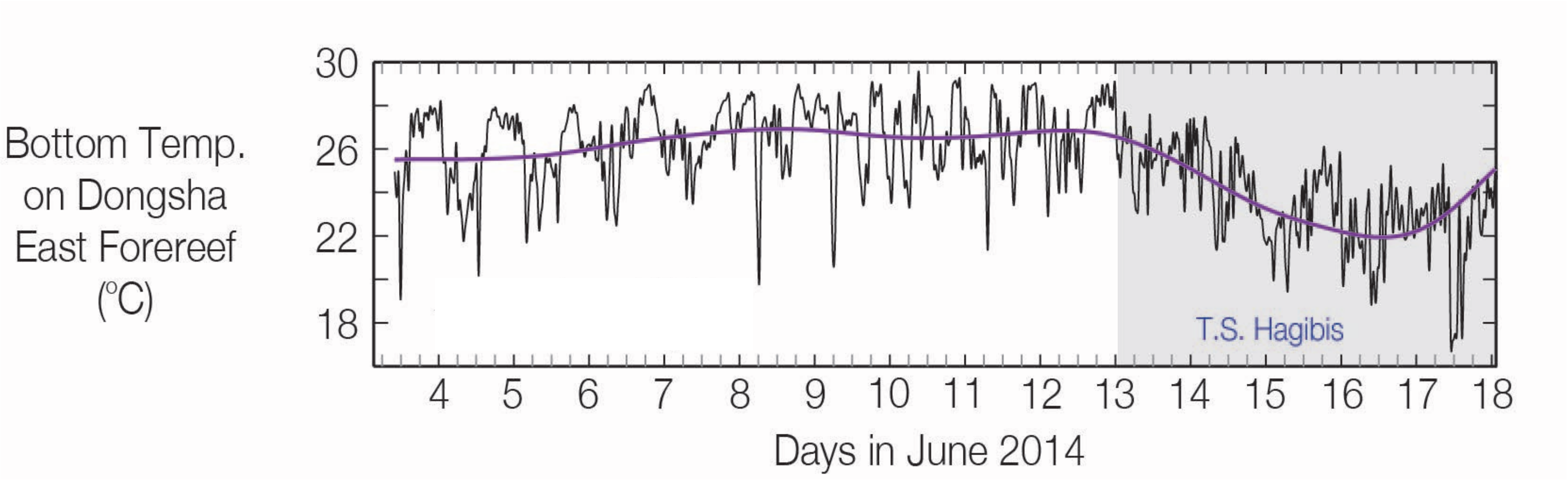
Internal wave "weather" on Dongsha Atoll fore reef





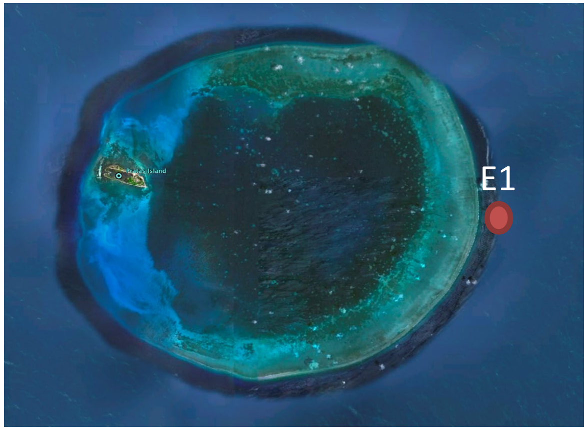
Internal wave "weather" on Dongsha Atoll fore reef

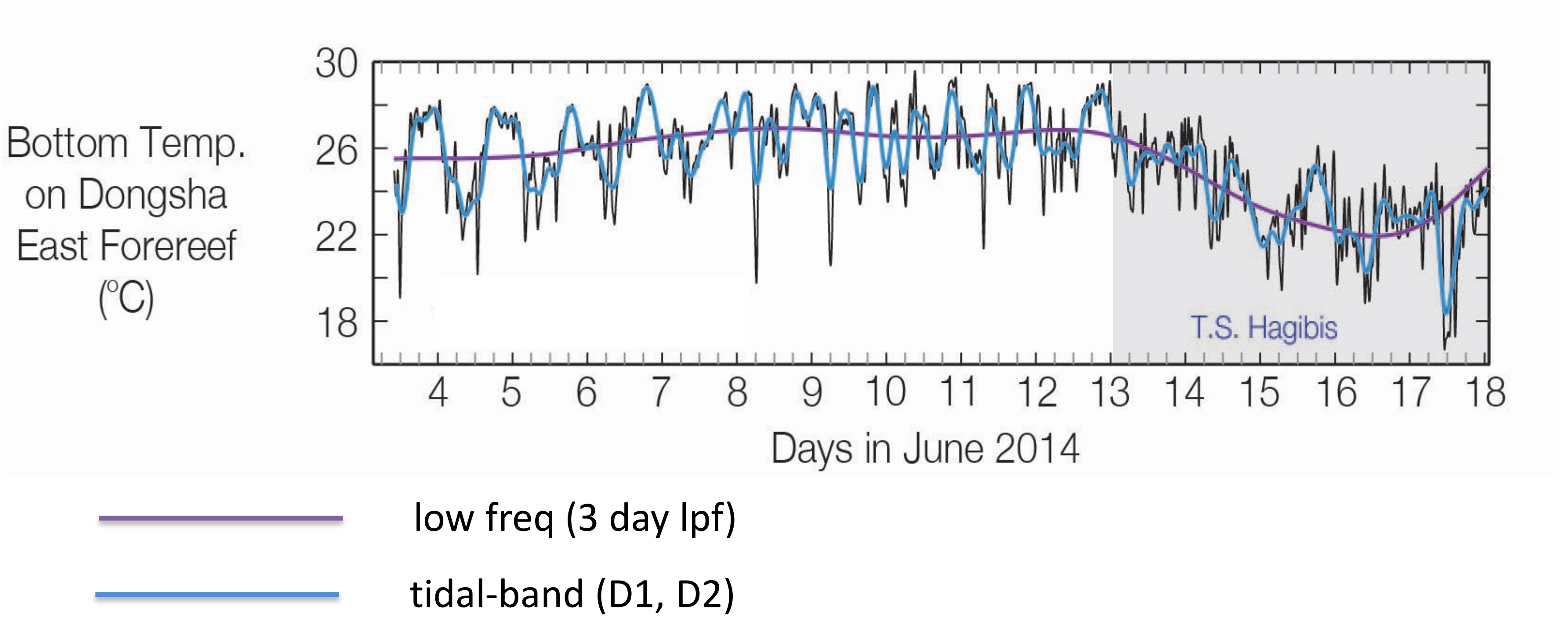




low freq (3 day lpf)

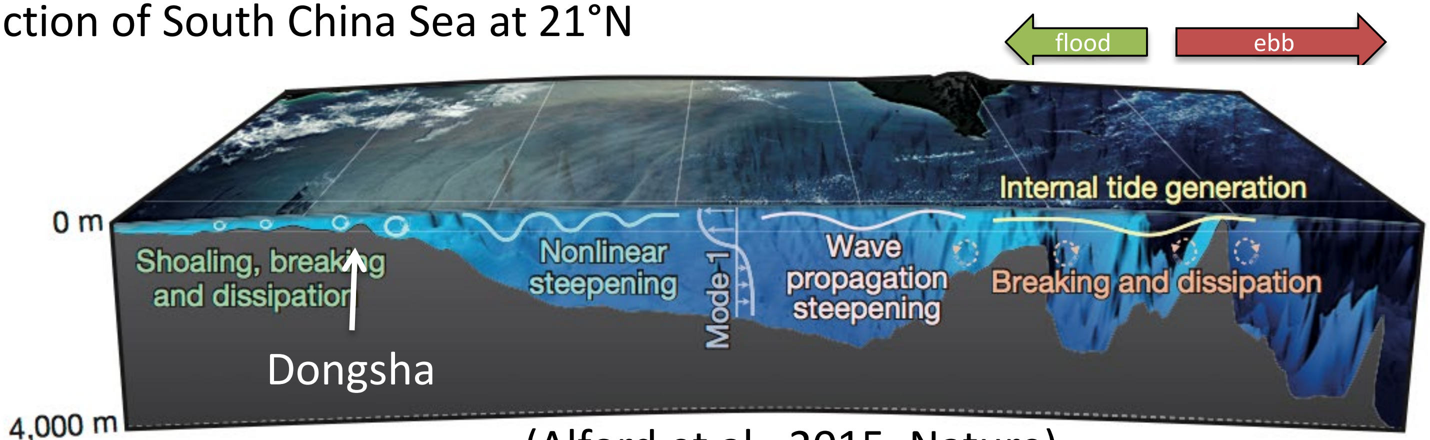
Internal wave "weather" on Dongsha Atoll fore reef



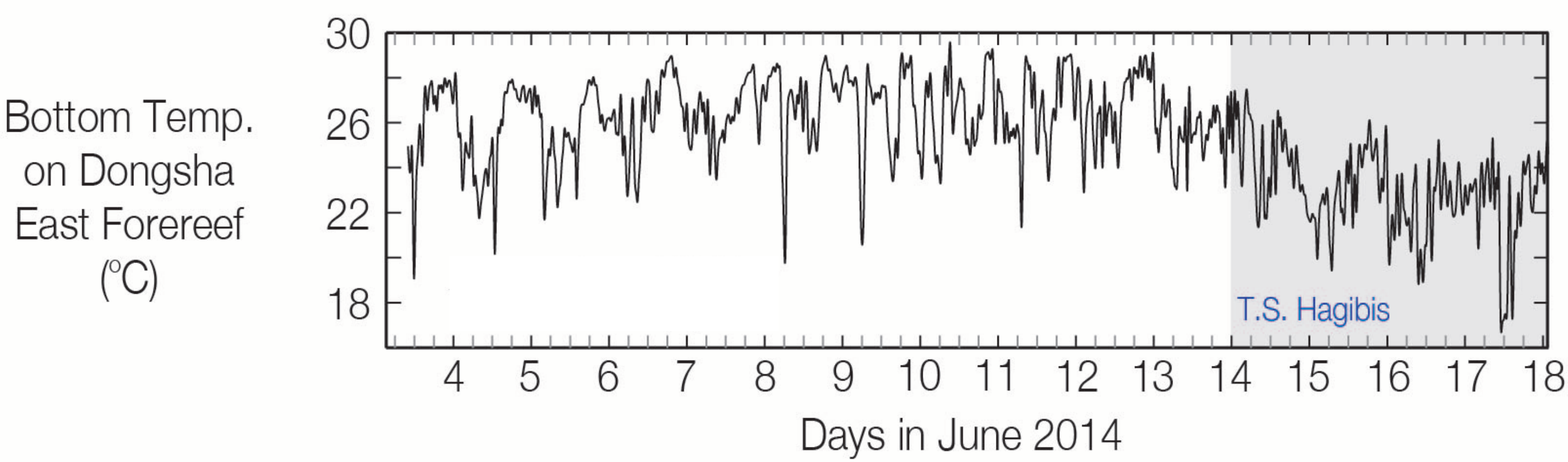


Internal wave "weather" on Dongsha Atoll fore reef

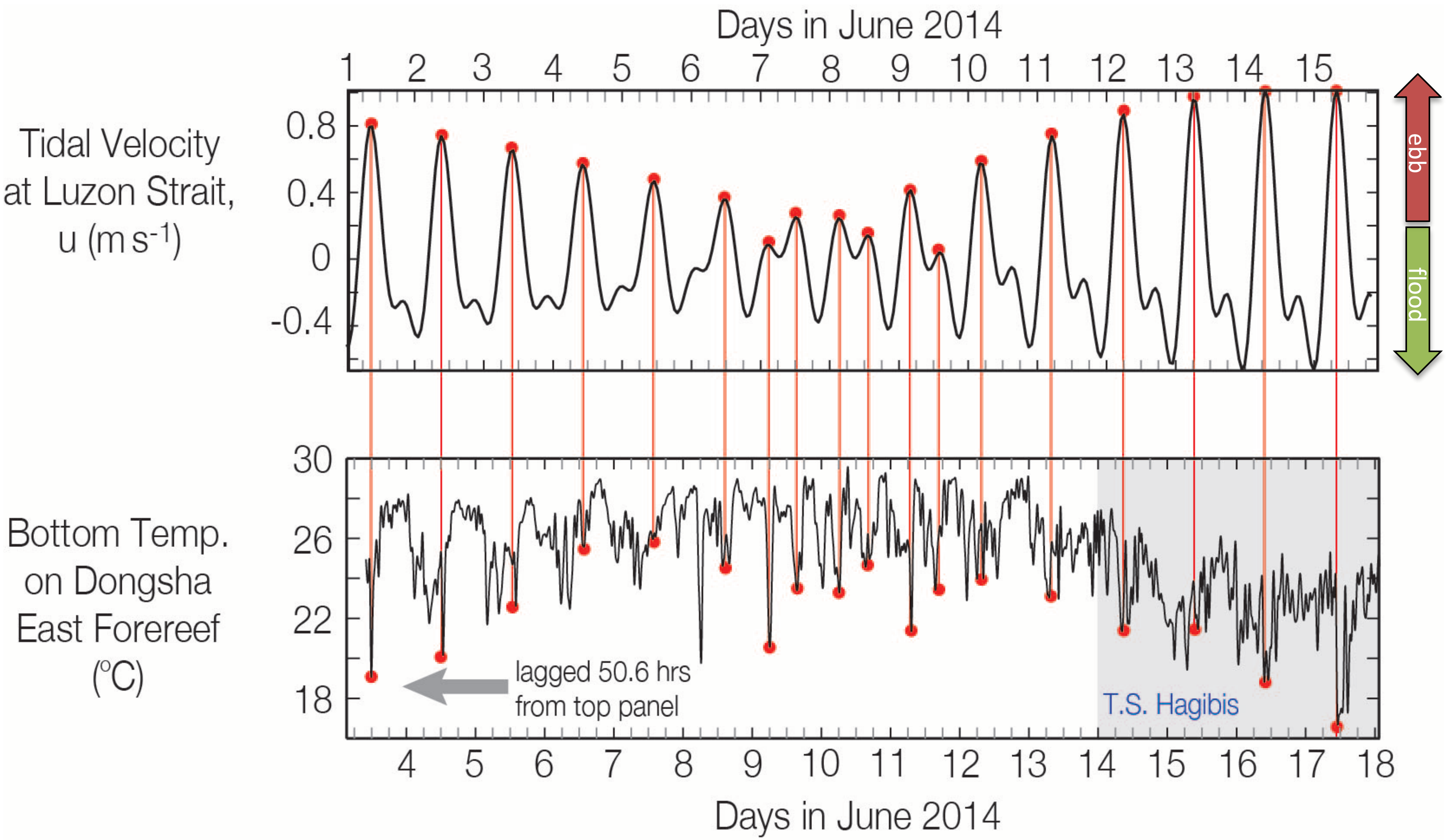
Section of South China Sea at 21°N



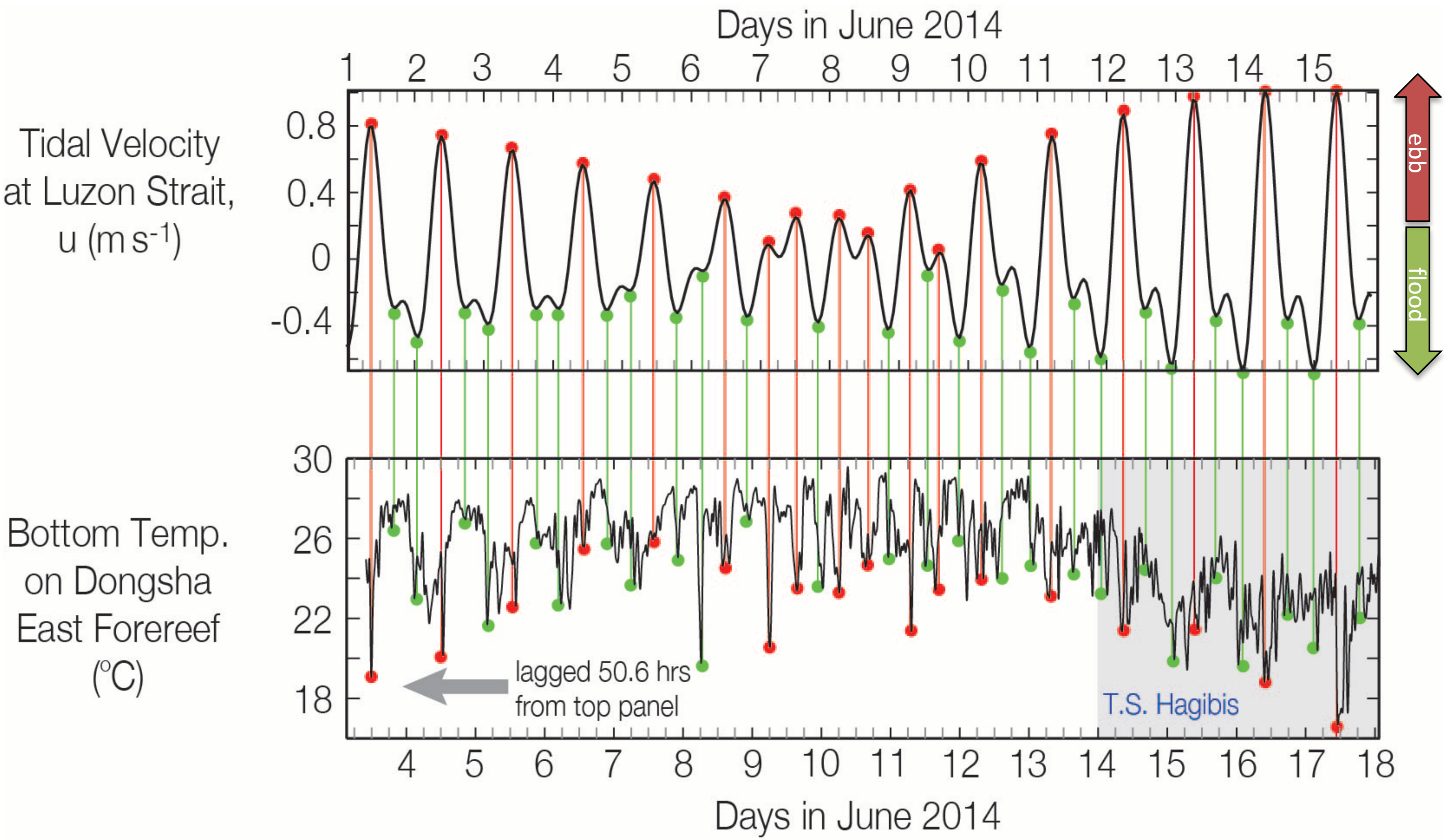
(Alford et al., 2015, Nature)



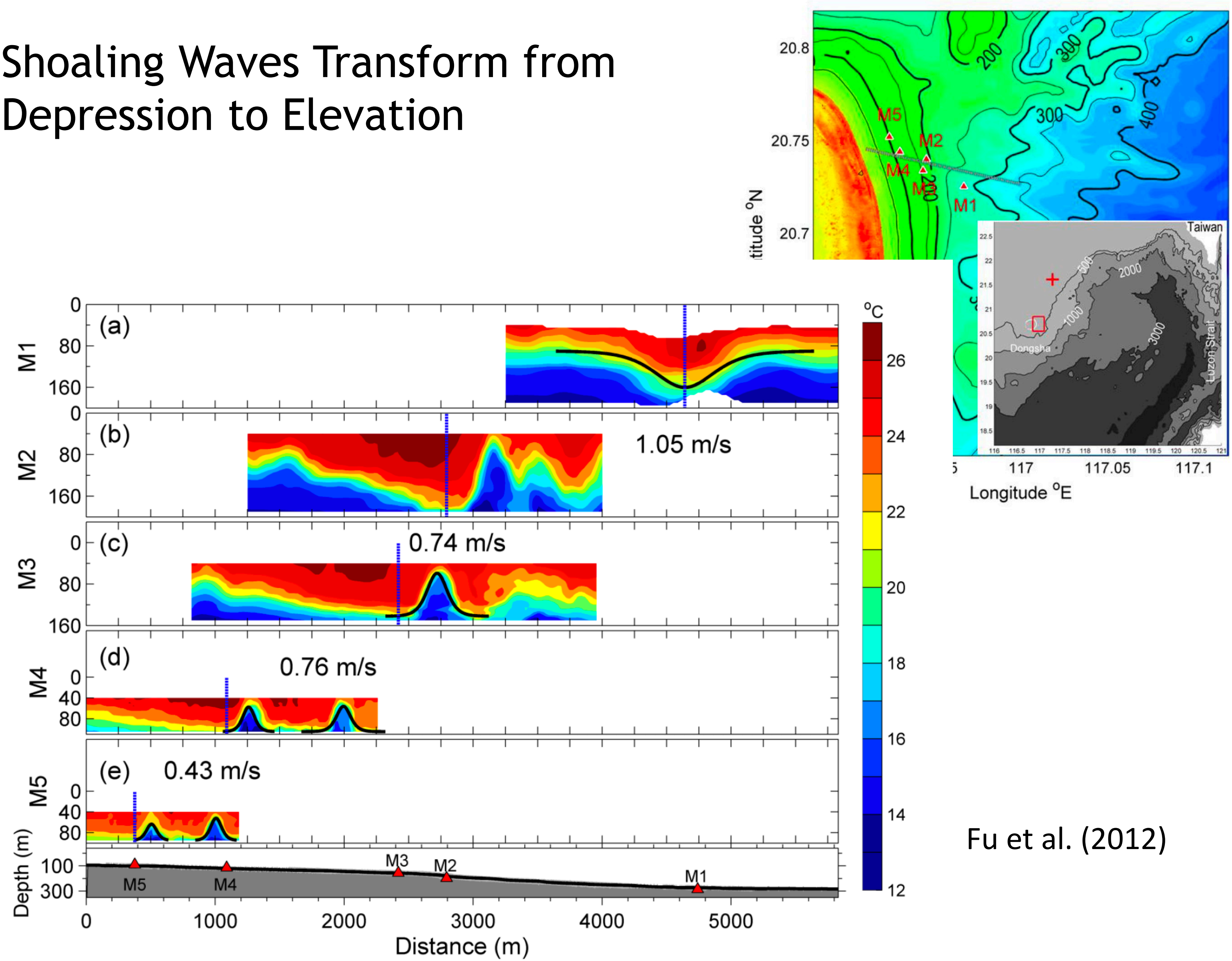
Internal wave "weather" on Dongsha Atoll fore reef



Internal wave "weather" on Dongsha Atoll fore reef



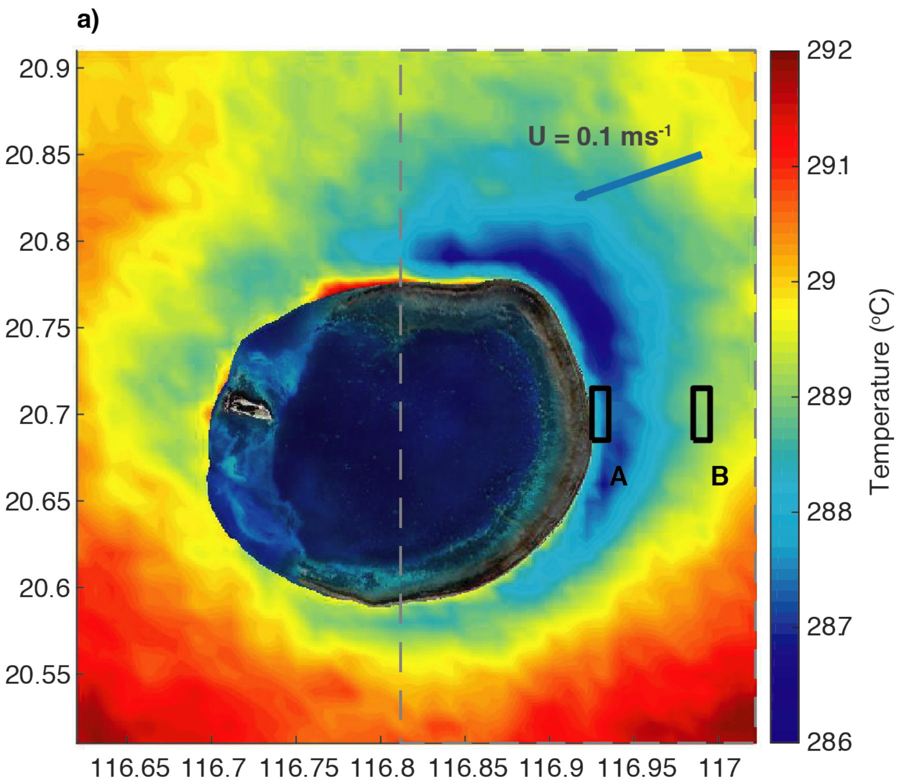
Shoaling Waves Transform from Depression to Elevation



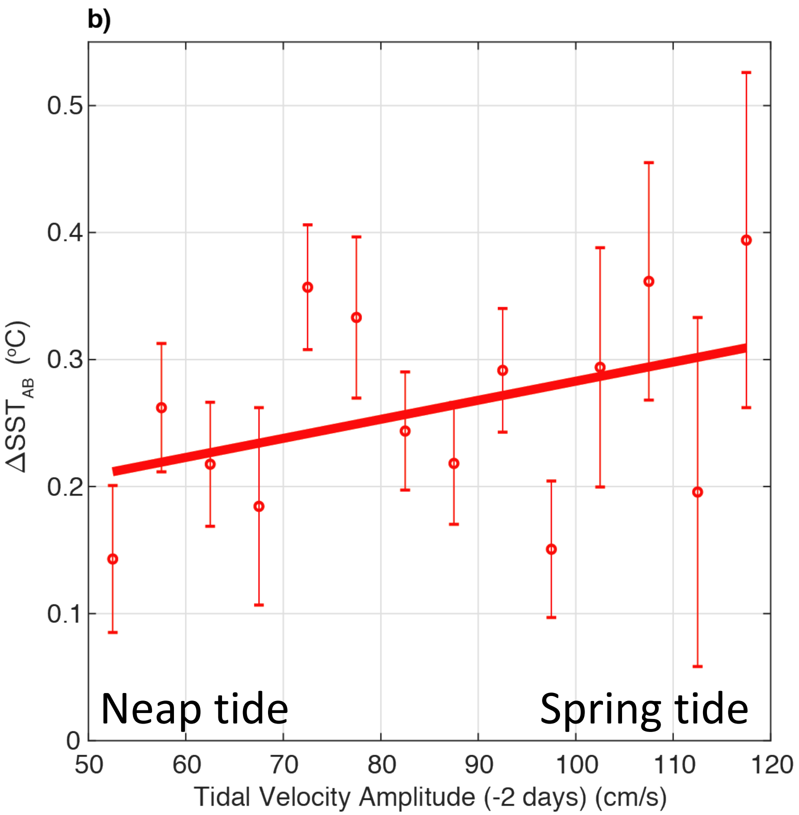
Fu et al. (2012)

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

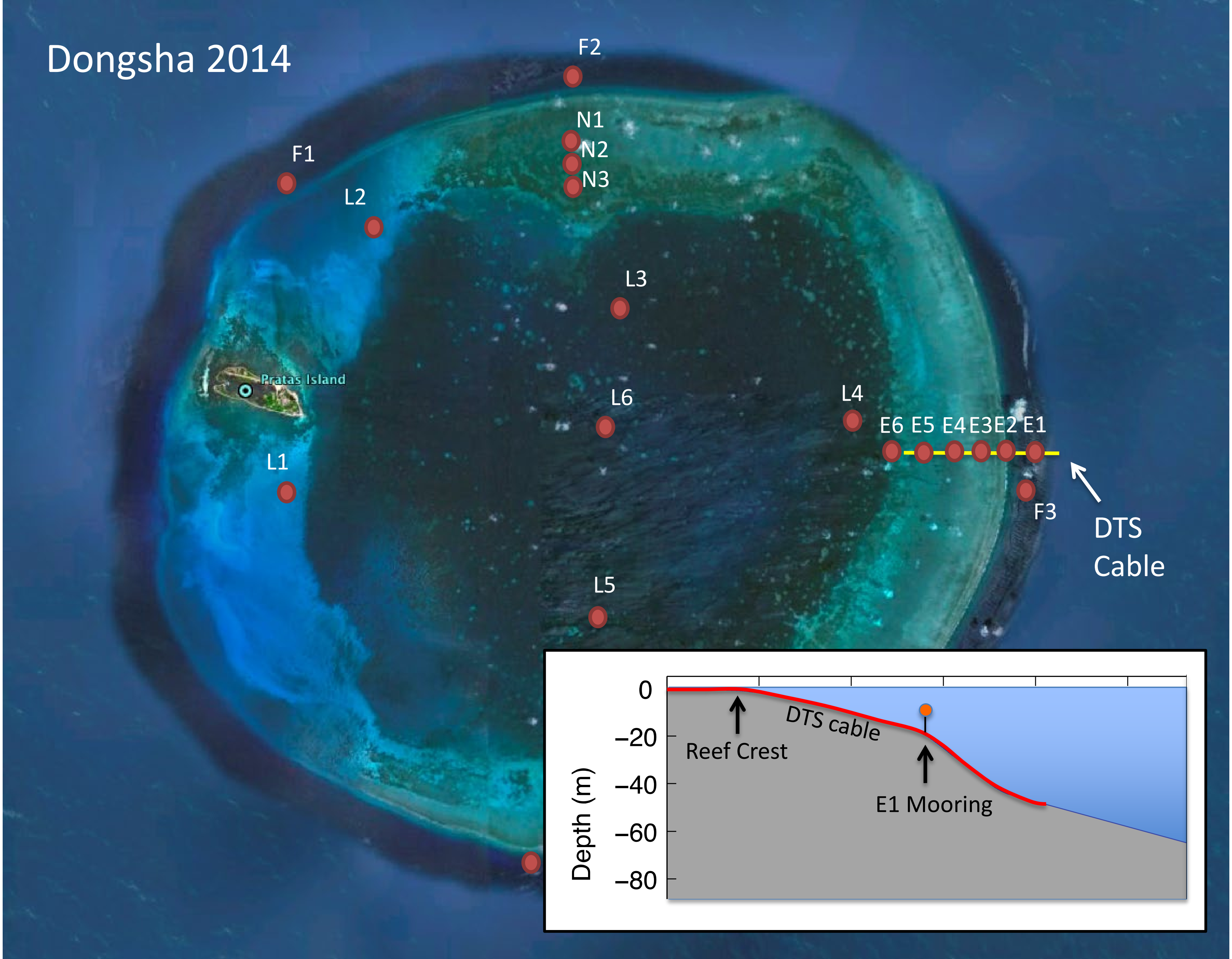
MODIS SST
(*June-Aug, 2002-2017*)



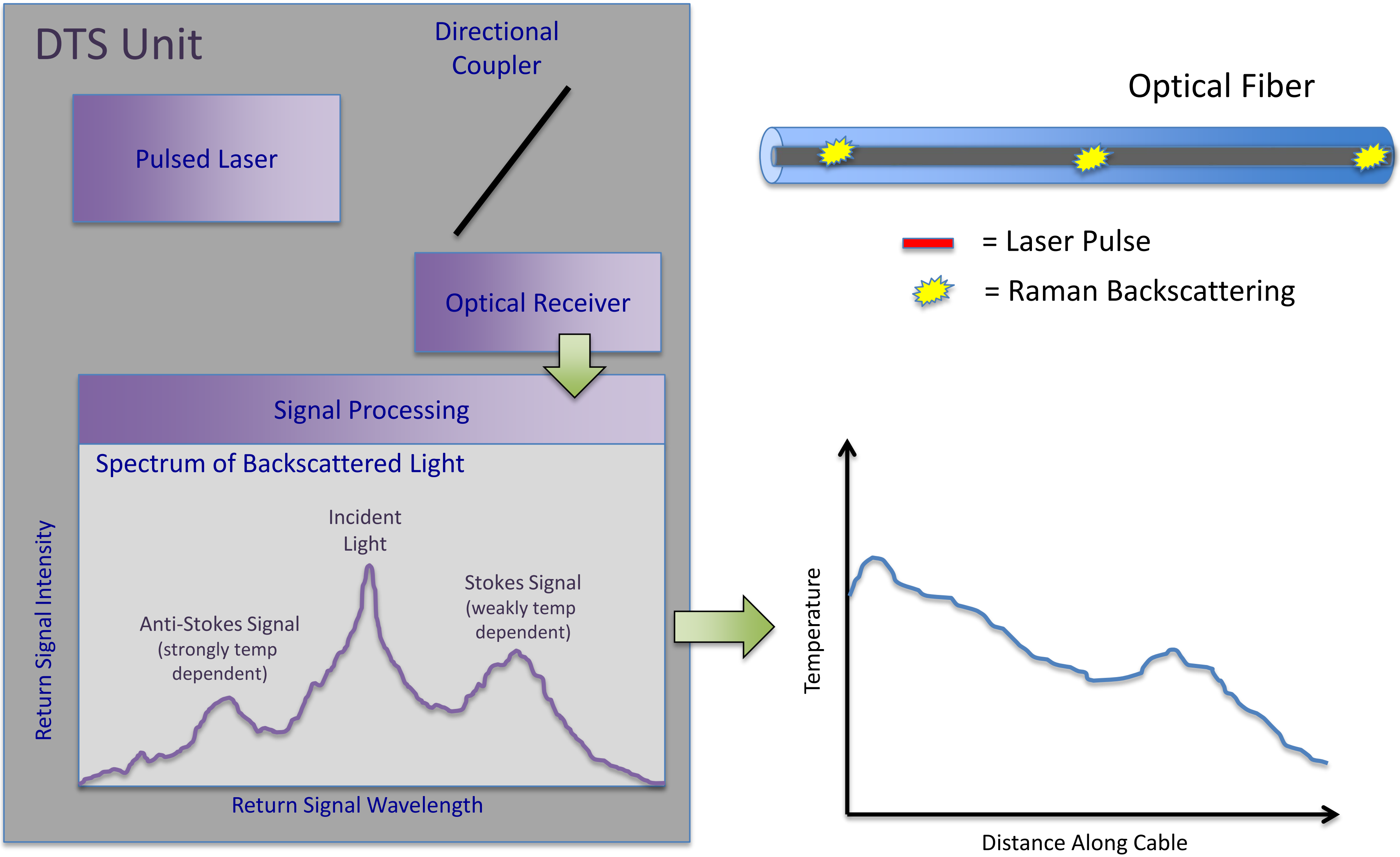
IW "Cooling" of SST vs. Generation forcing (~500 km away)



(Reid et al., submitted to L&O)


Dongsha 2014
F2
N1
N2
N3
F1
L2
L3
Pratas Island
L6
L4
E6 E5 E4 E3 E2 E1
L1
F3
DTS
Cable
L5
0
−20
−40
−60
−80
Depth (m)
DTS cable
Reef Crest
E1 Mooring

Distributed Temperature Sensing (DTS) Principles

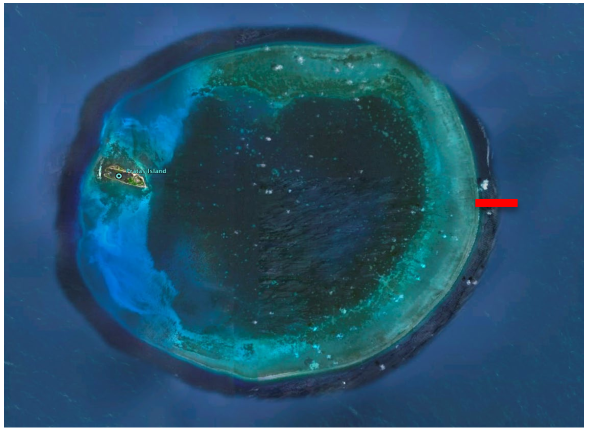


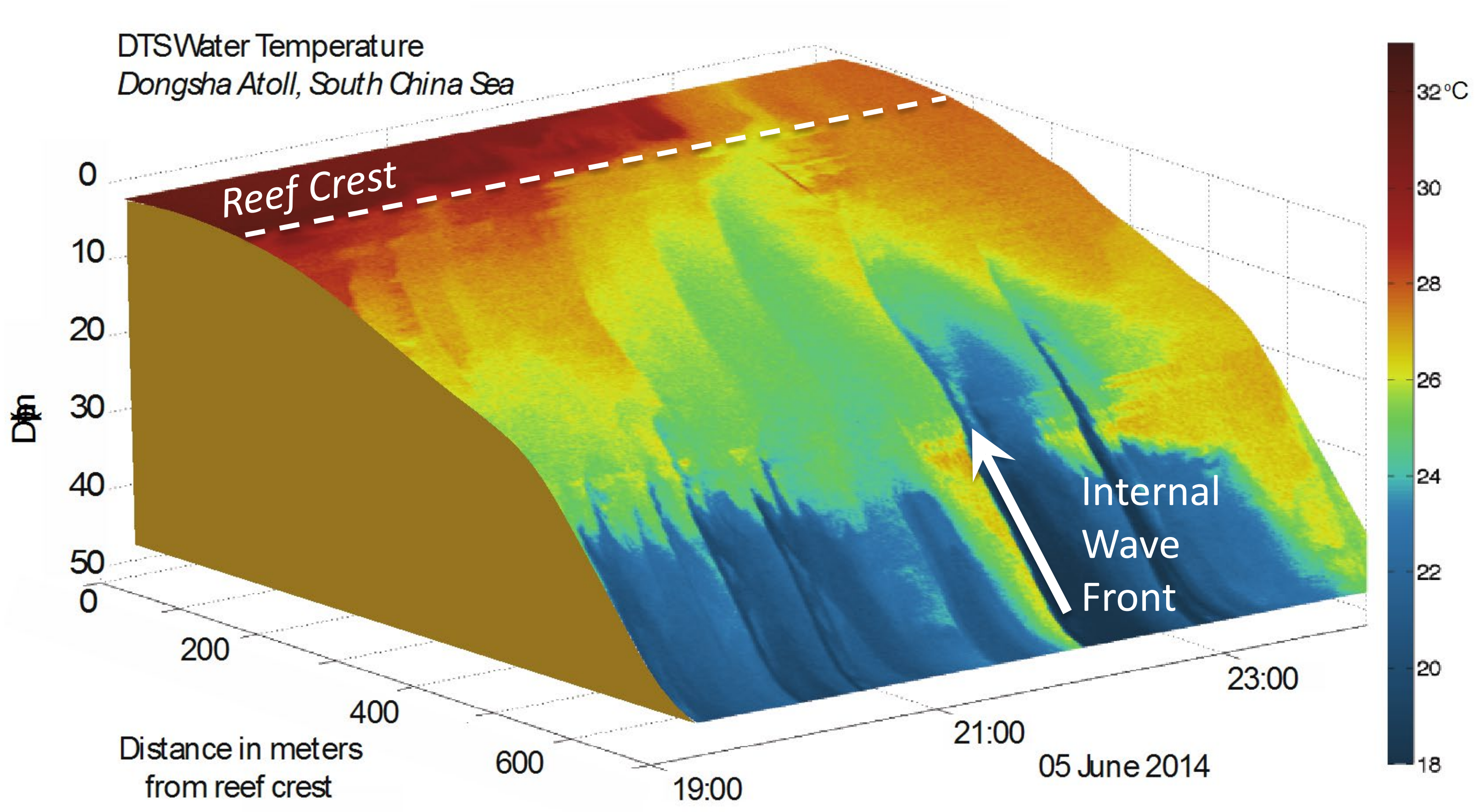
Animation adapted from sensortran.com

Surveying the Fiber Optic Cable

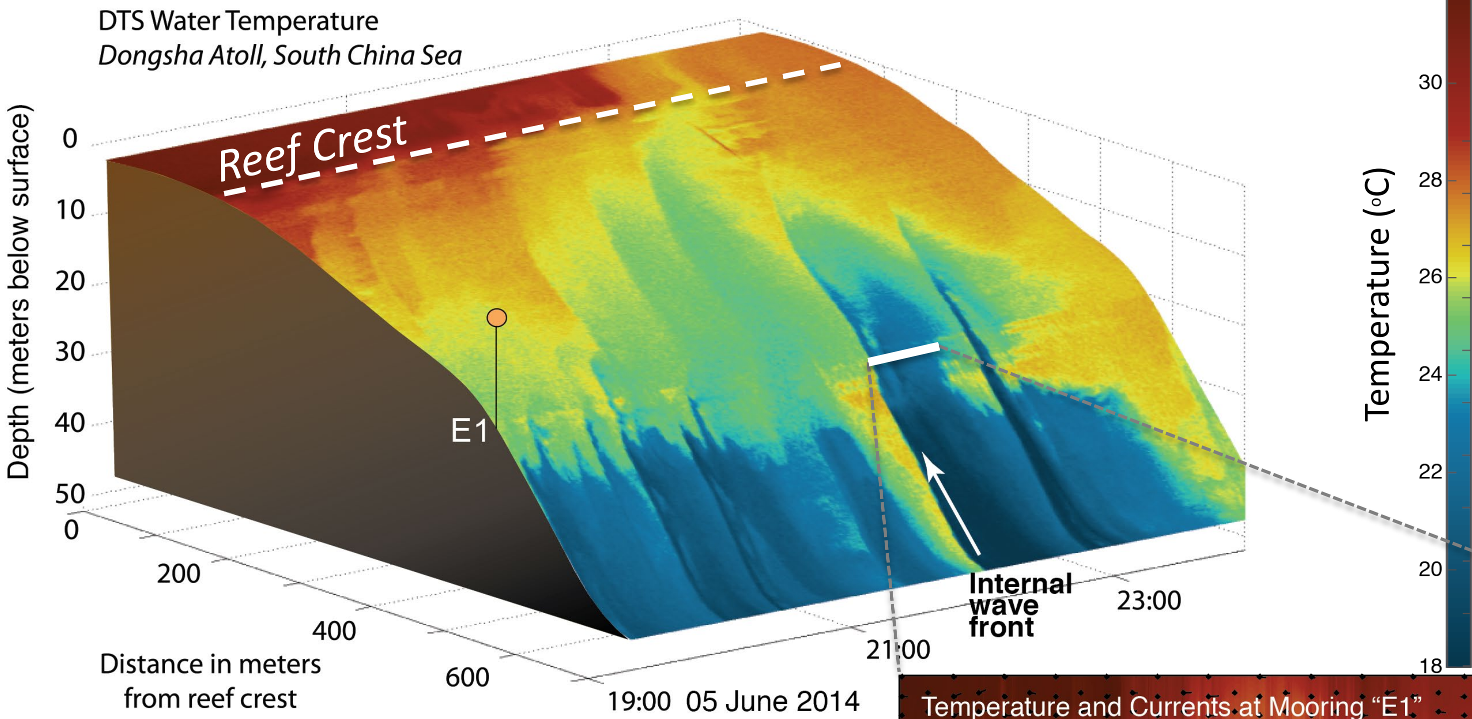
Internal waves on the fore reef slope

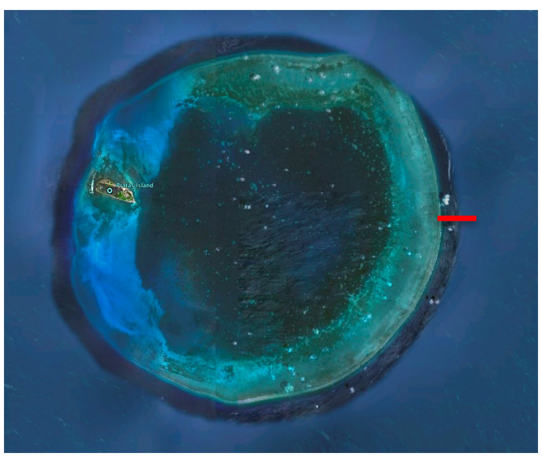
- Induce extreme temperature changes (8°C in < 1 minute)
- Trapping of cool water in reef grooves, i.e. ”internal tidepools”
- Internal wave reflection

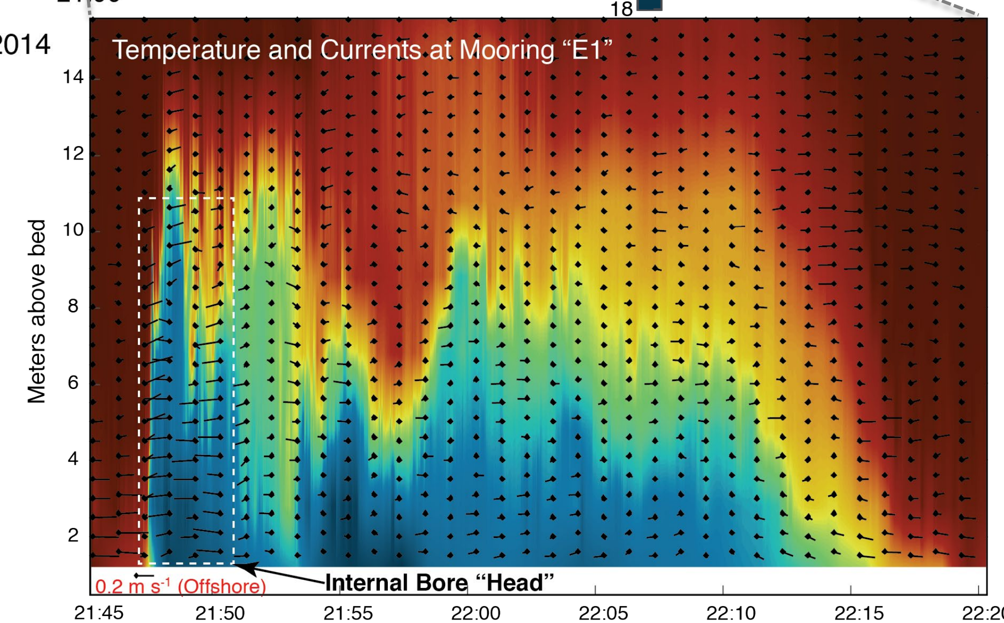




Internal wave swash zone







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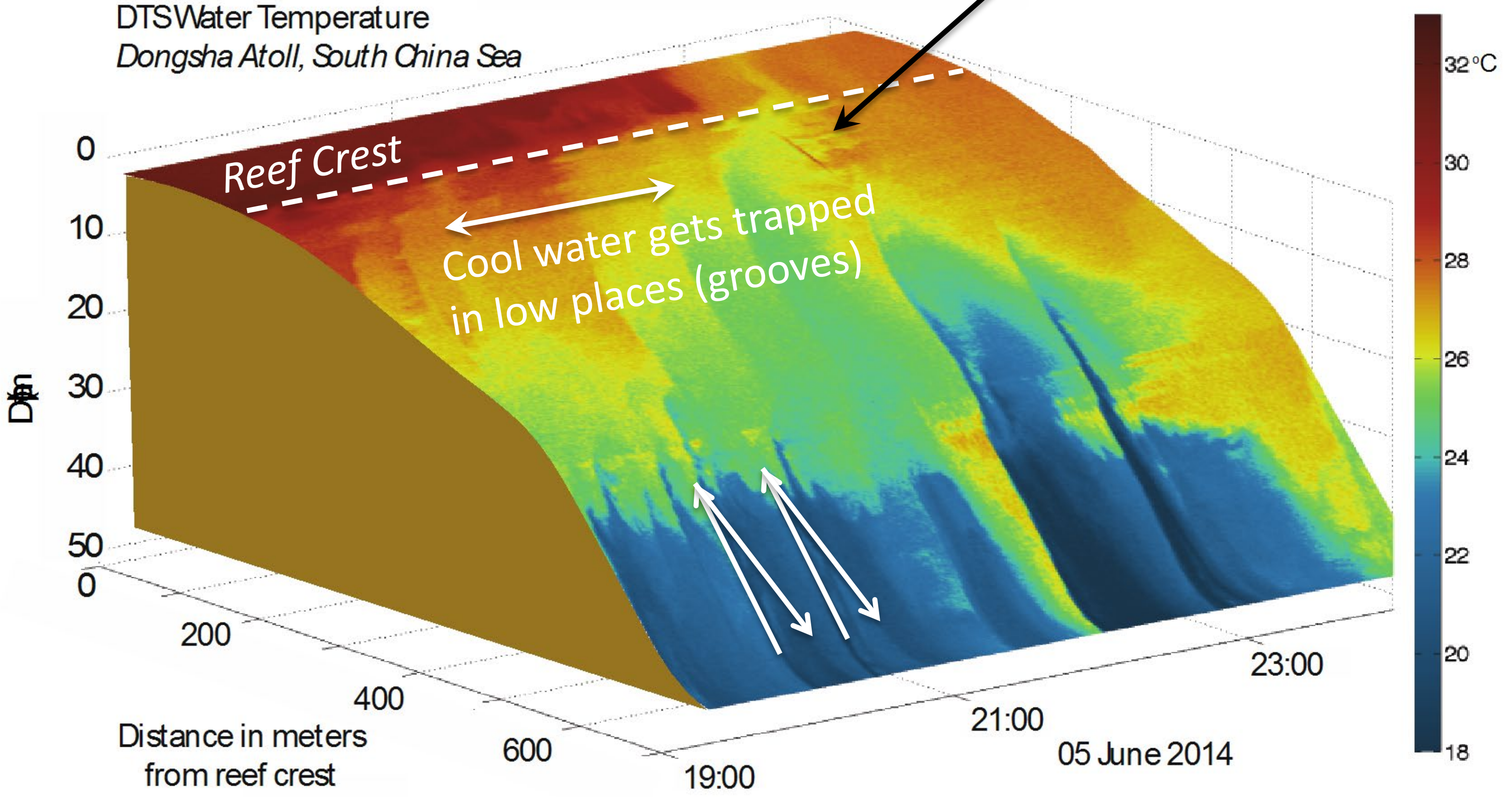
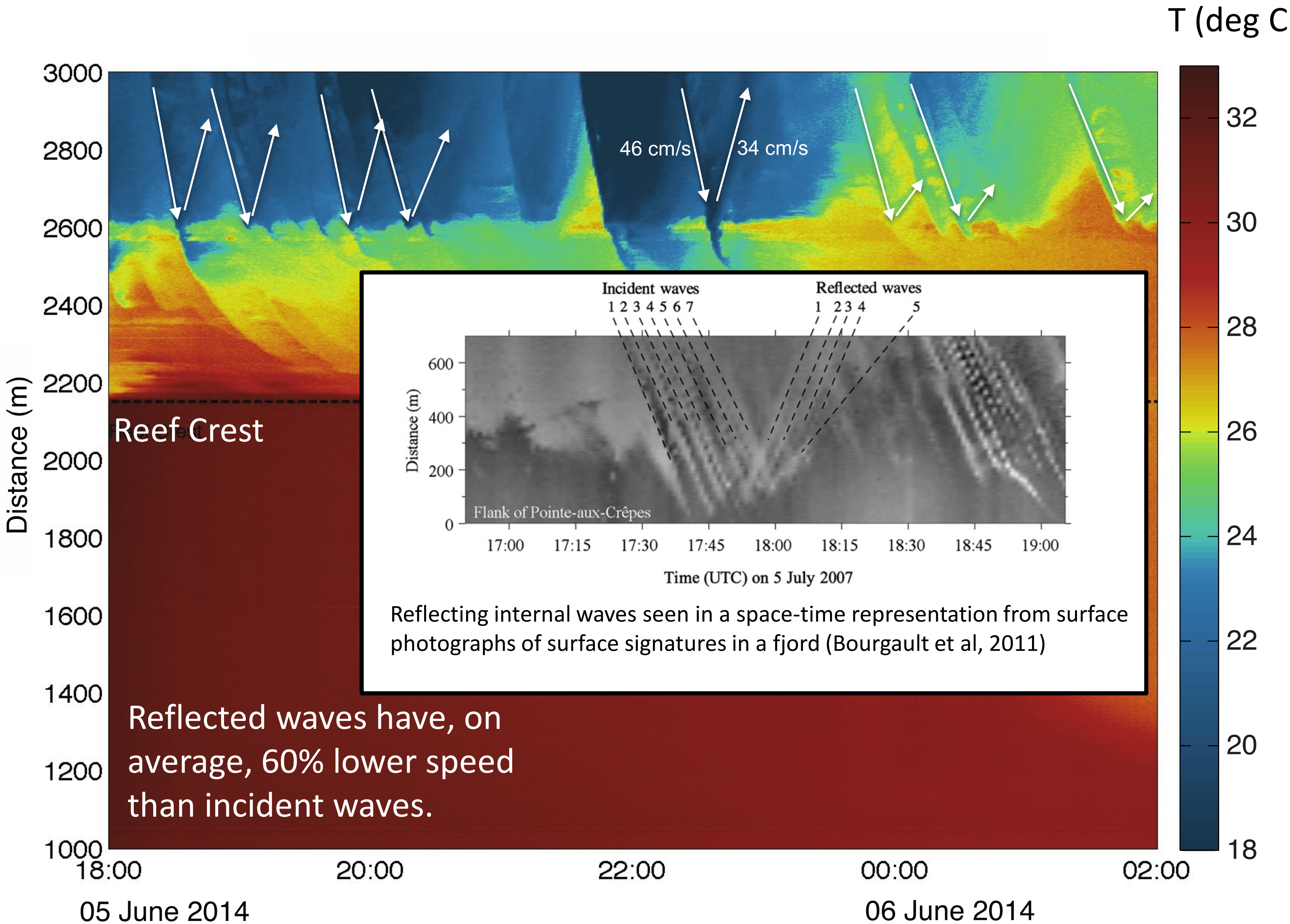
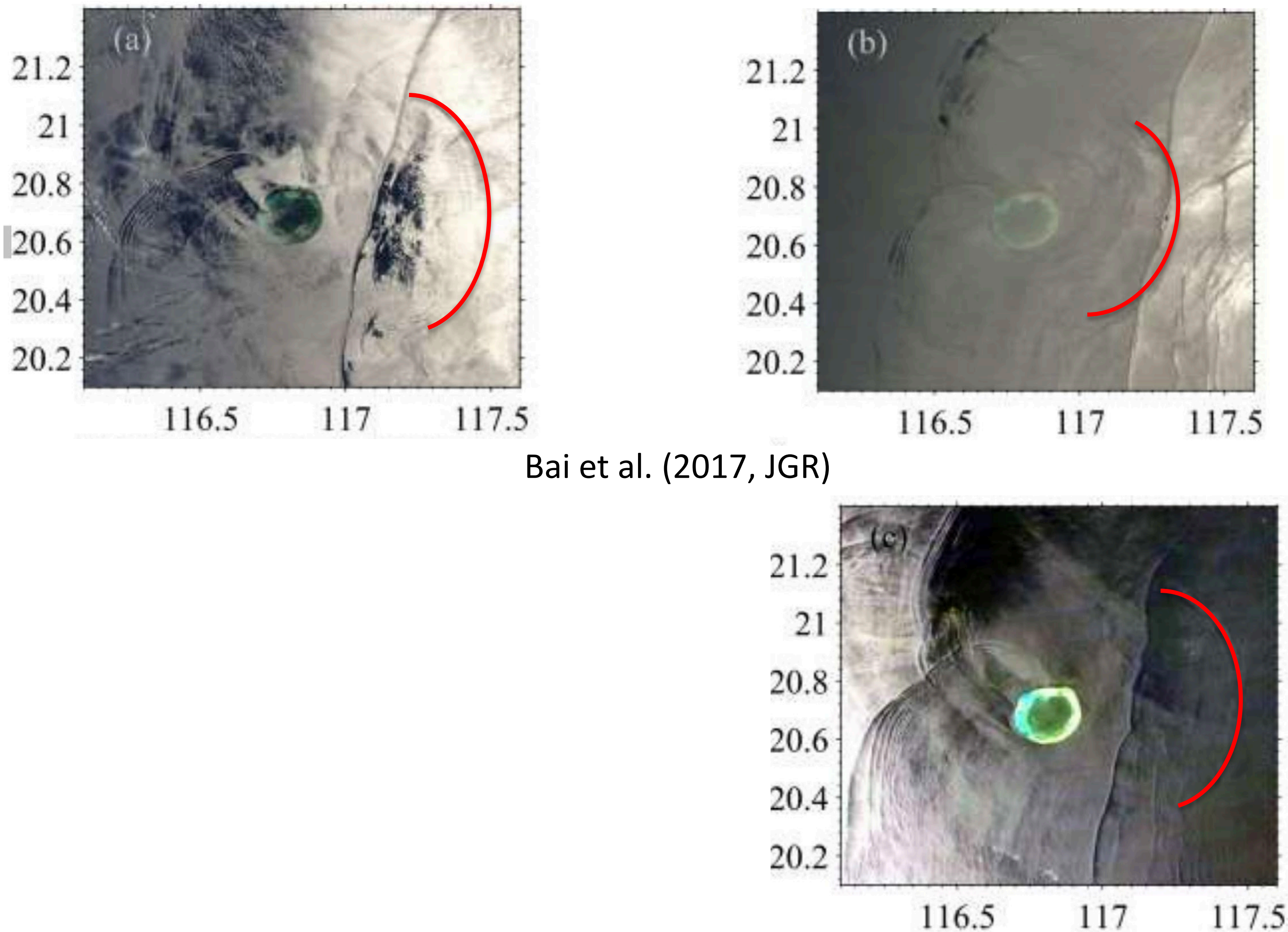


Internal wave reflection and transmission



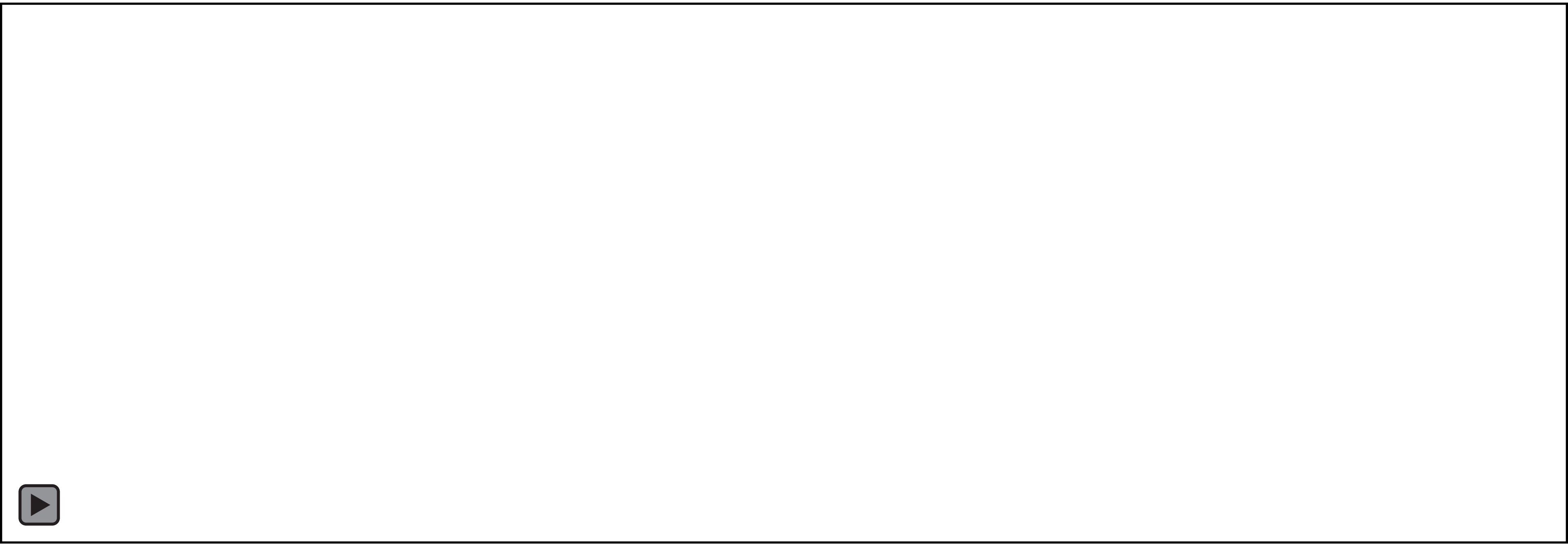
Reflecting internal waves seen in a space-time representation from surface photographs of surface signatures in a fjord (Bourgault et al, 2011)

Internal wave reflection off the Dongsha Slope



Bai et al. (2017, JGR)

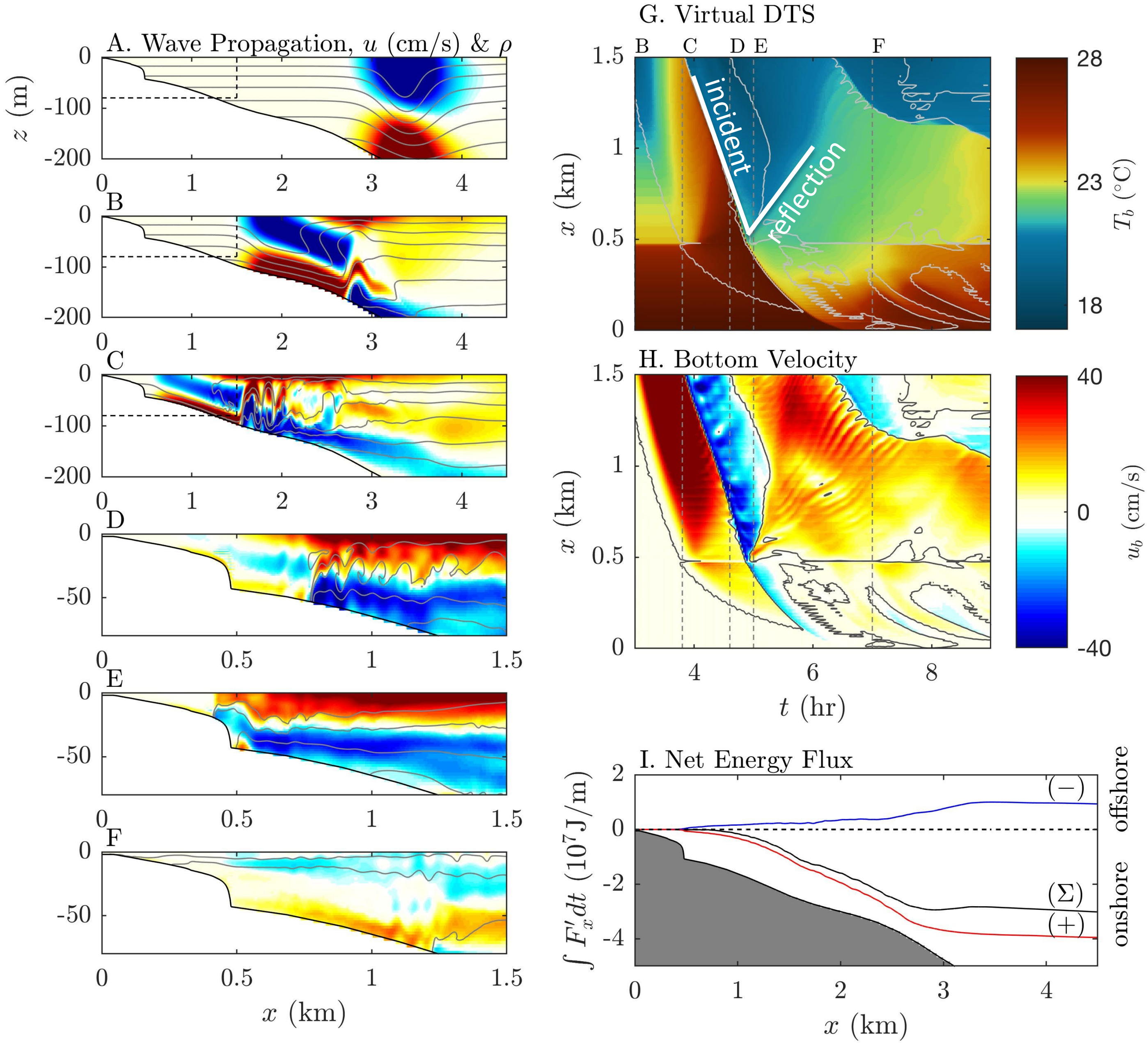
Nonhydrostatic Simulations (SUNTANS courtesy of Justin Rogers and Oliver Fringer)



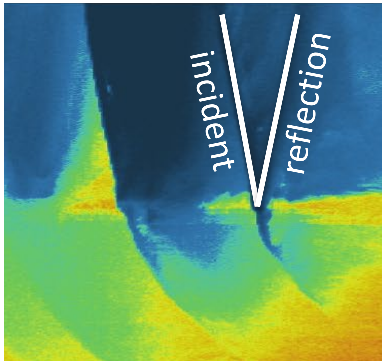
Insights developed from numerical runs:

- 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.

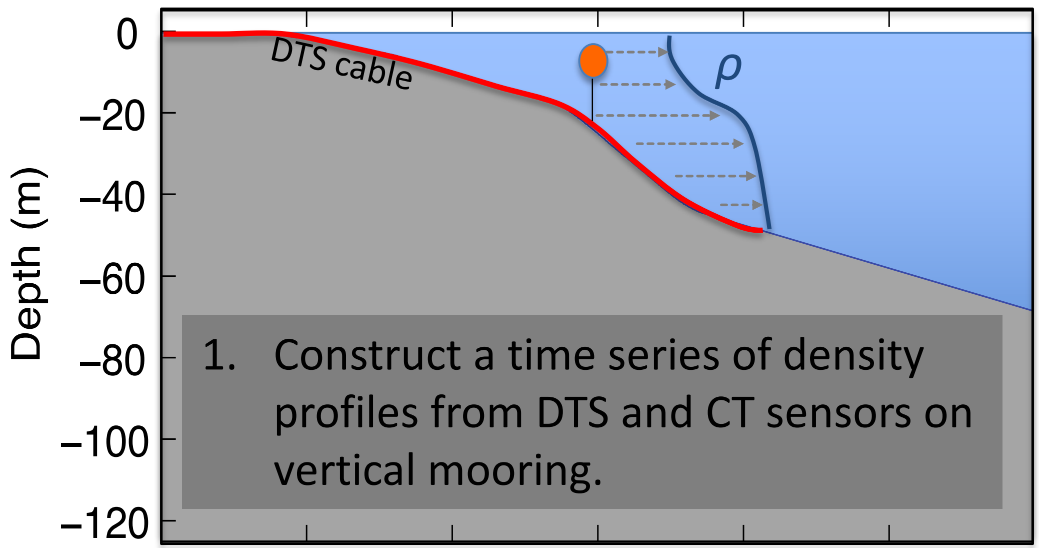
Nonhydrostatic Simulations



DTS Observations

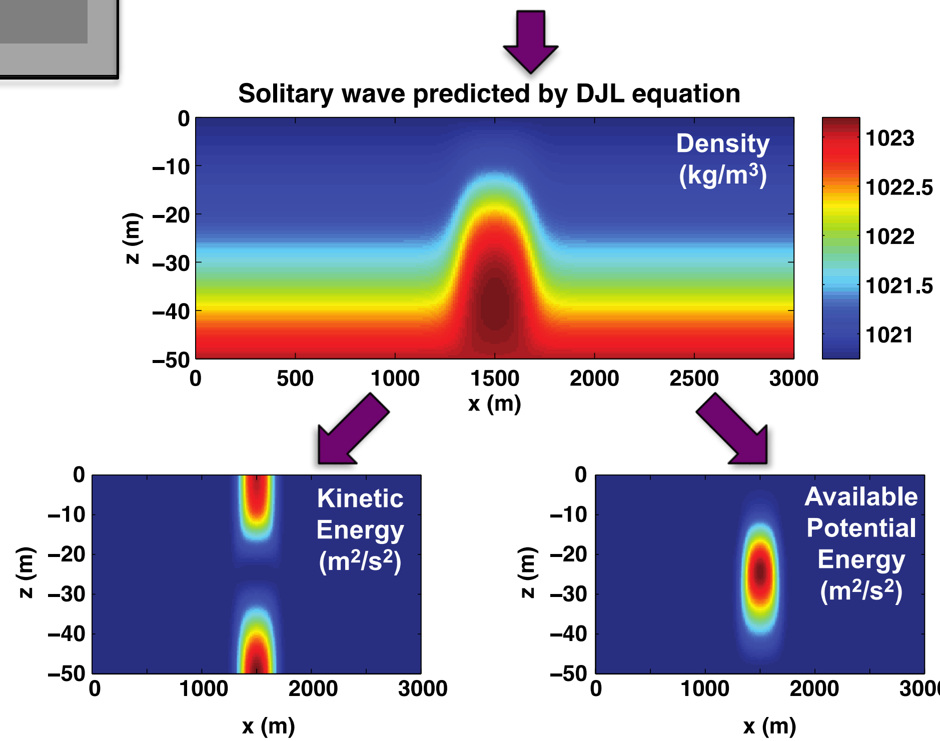


Estimating the Reflectance Ratio, $R = E_r / E_i$



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).

$$\nabla^2 \eta + \frac{N^2(z-\eta)}{c^2} \eta = 0,$$

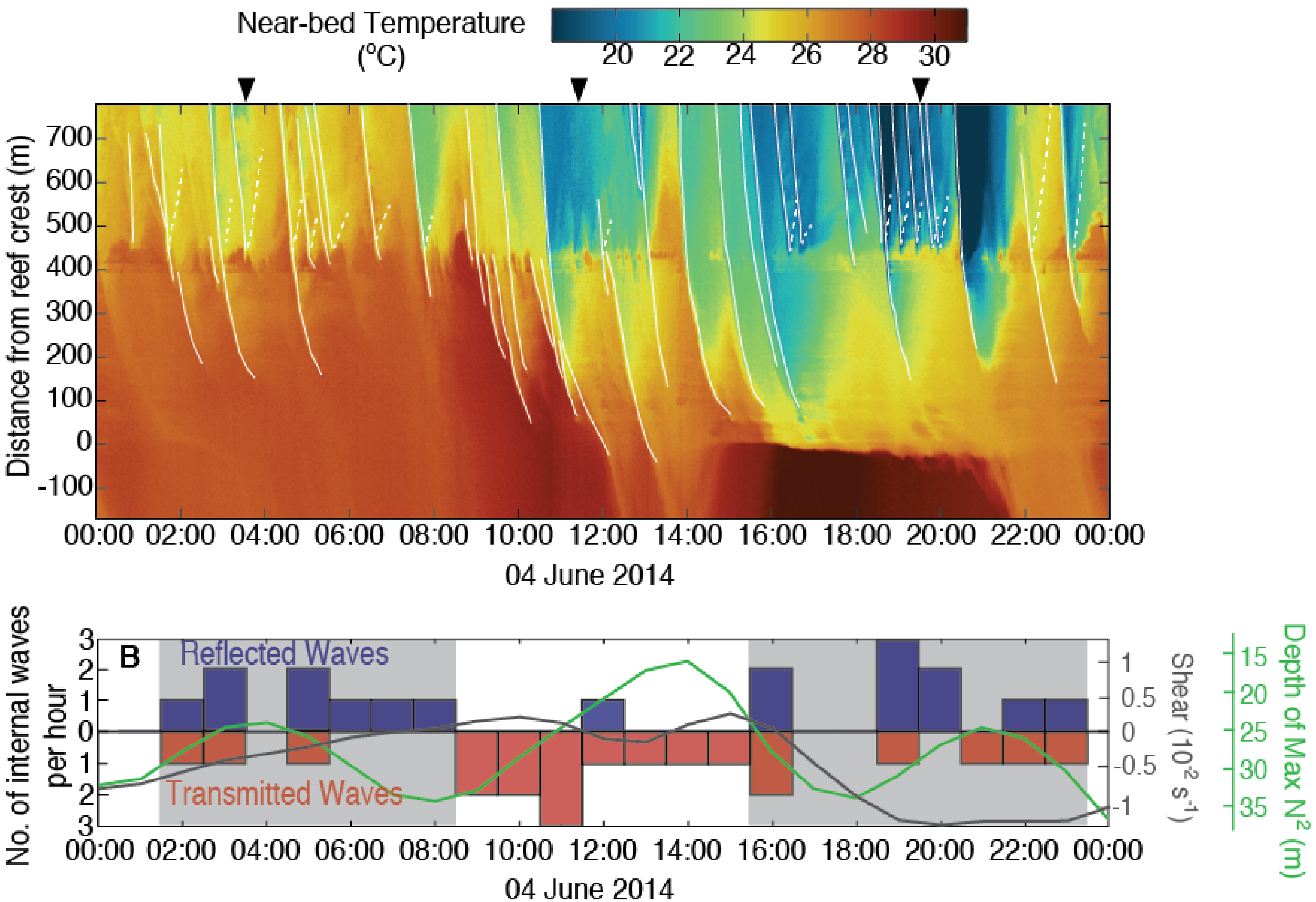


- Of the 70 incident/reflected pairs, only 20 could be predicted from the DJL model

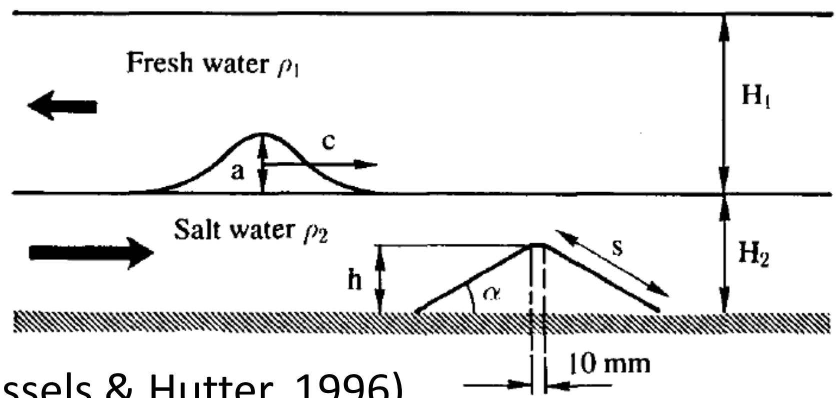
- Reflectance Ratio was highly variable in time, ranging from R = ~0 to 0.4.

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



(Wessels & Hutter, 1996)

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

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

Surface-referenced Blocking Parameter: $\boldsymbol{B_s = H_1/d}$

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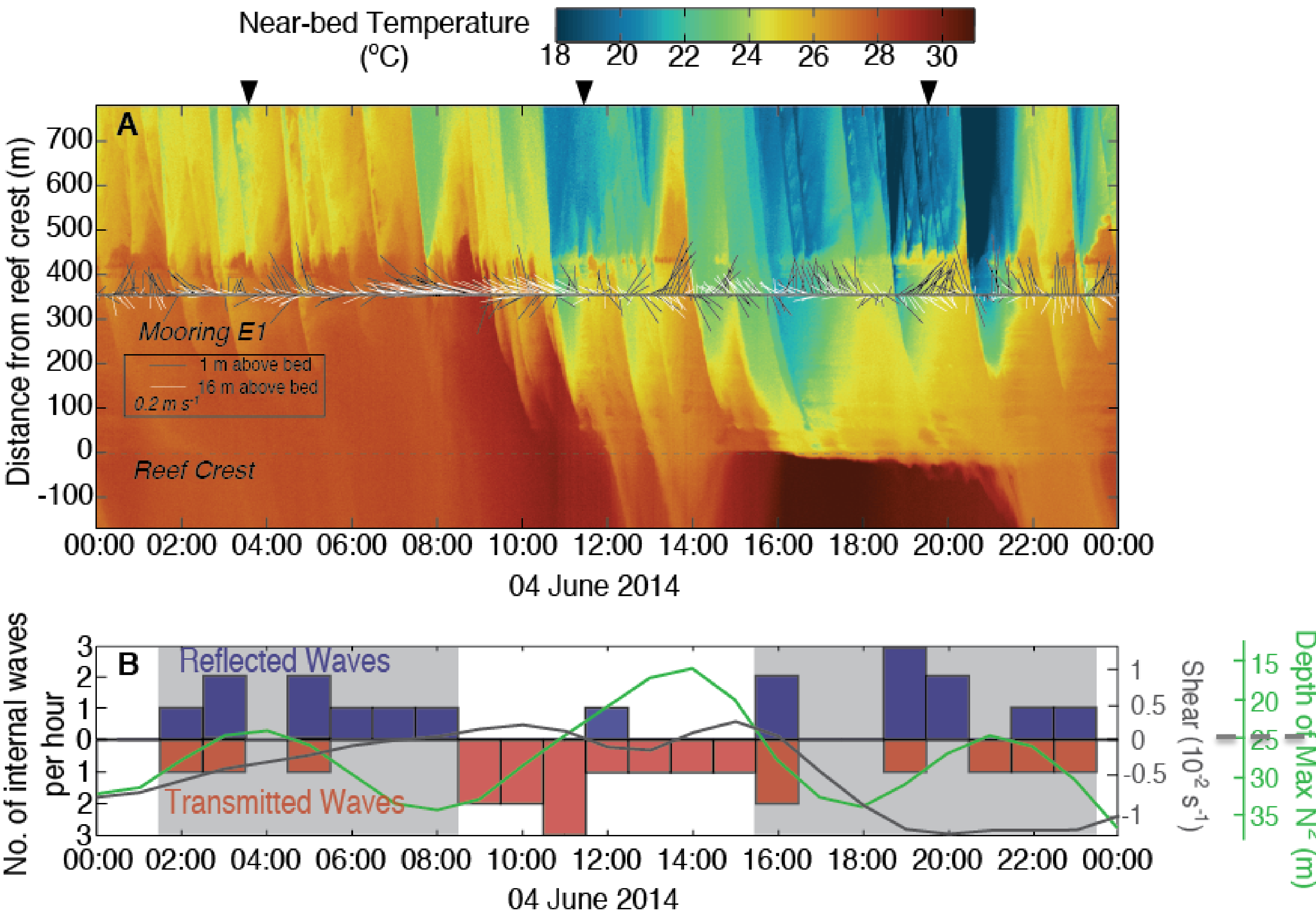
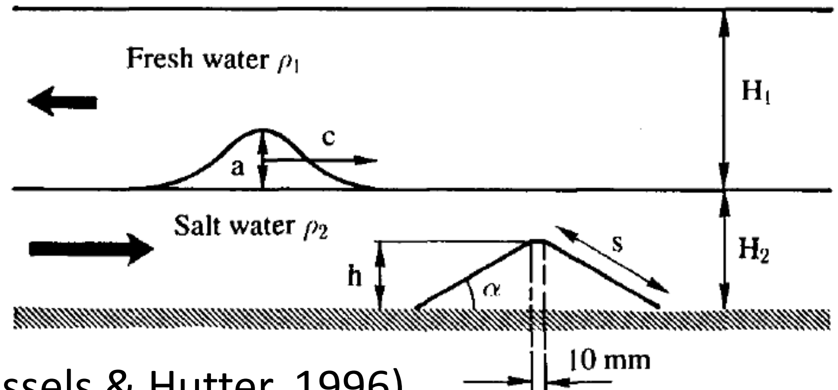


$B_s < 1$

Depth of slope break

$B_s > 1$

Topographic Blocking and near bed currents influence IW reflection



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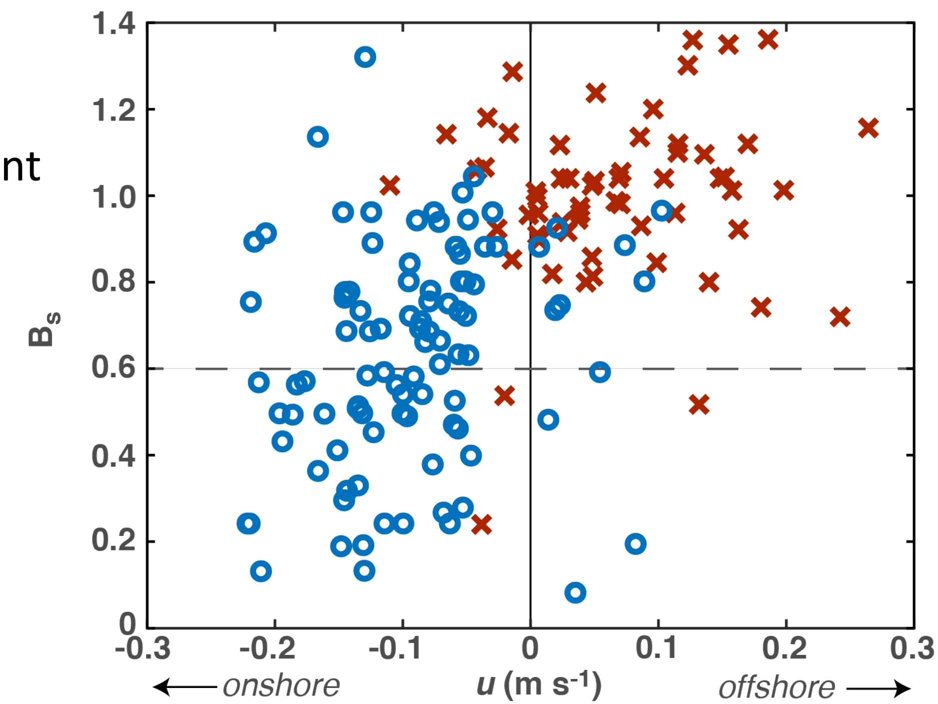
reflected waves avg. B_s = 0.99

transmitted waves avg. B_s = 0.63

Dongsha Atoll Internal Waves (4-11 June 2014)



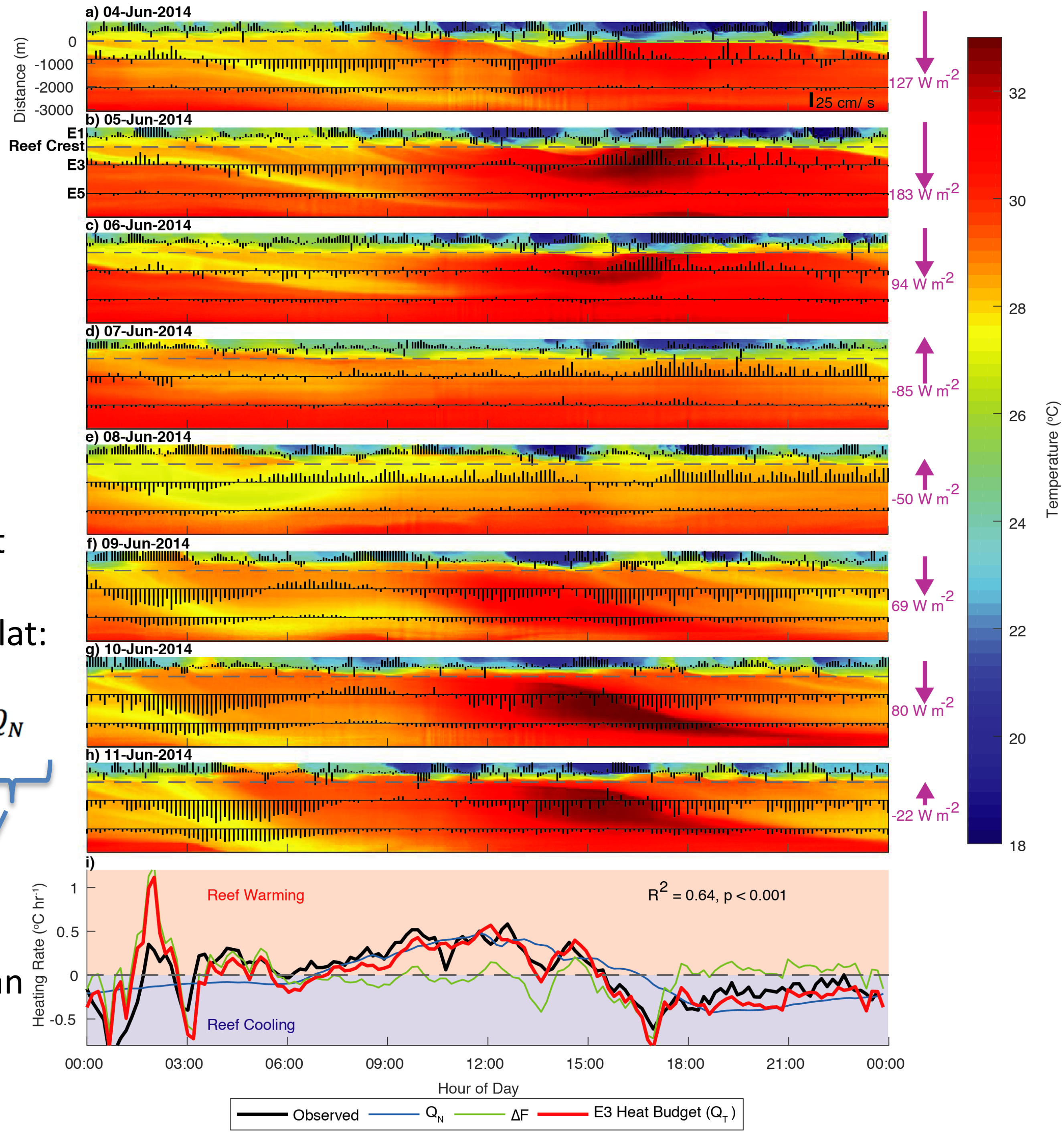
Internal wave influence on the shallow reef flat

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

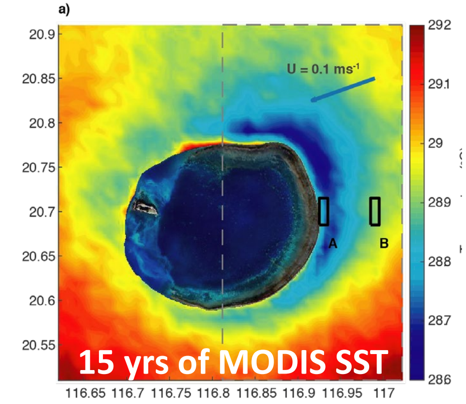
$$\rho c_p h \frac{\partial \langle \bar{T} \rangle}{\partial t} = -\rho c_p h \langle \bar{u} \rangle \frac{\partial \langle \bar{T} \rangle}{\partial x} + Q_N$$

advective heat flux

atmosphere-ocean heat flux



Internal wave influence on the shallow reef flat



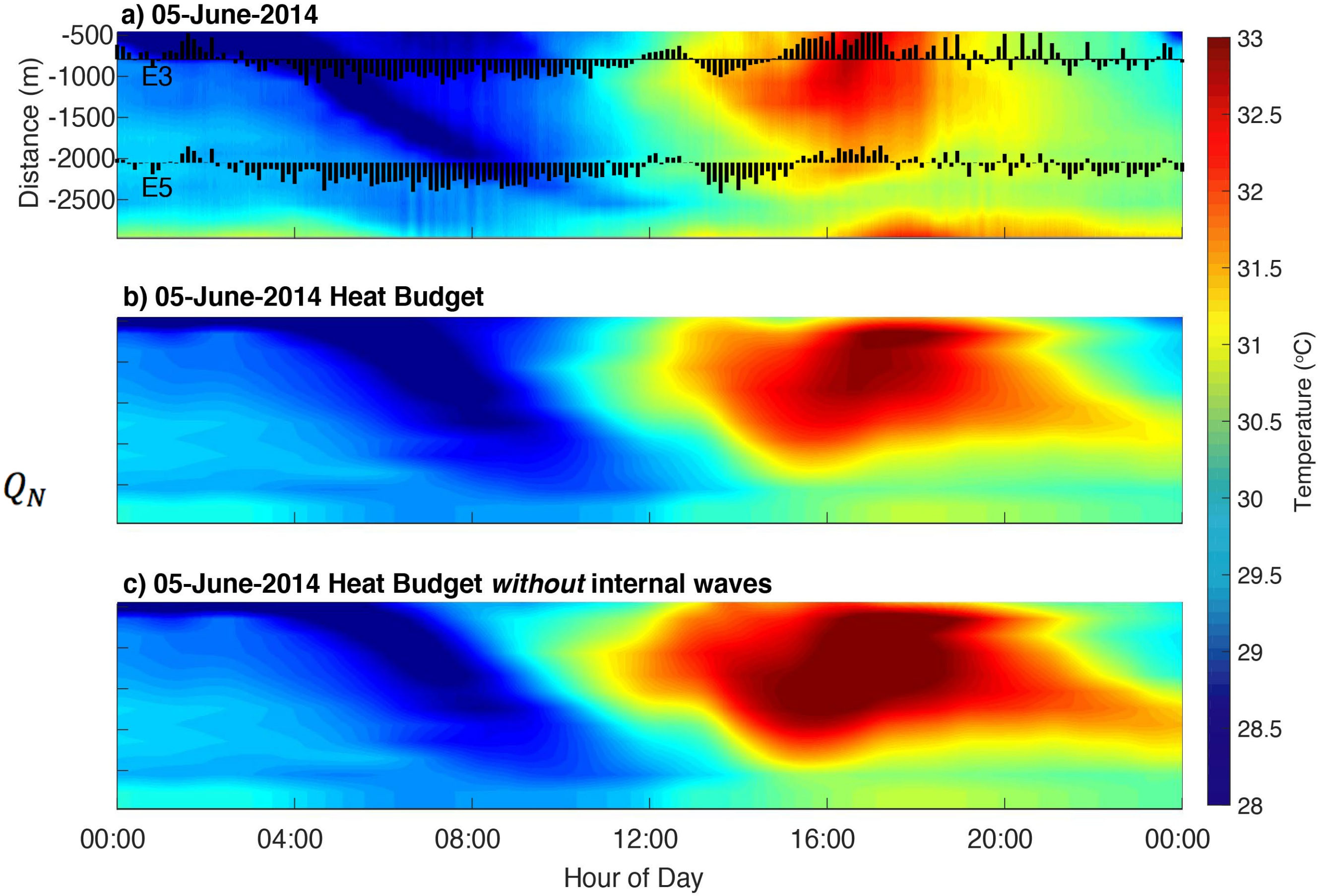
(Reid et al., submitted to L&O)

Observed temperature on the reef flat

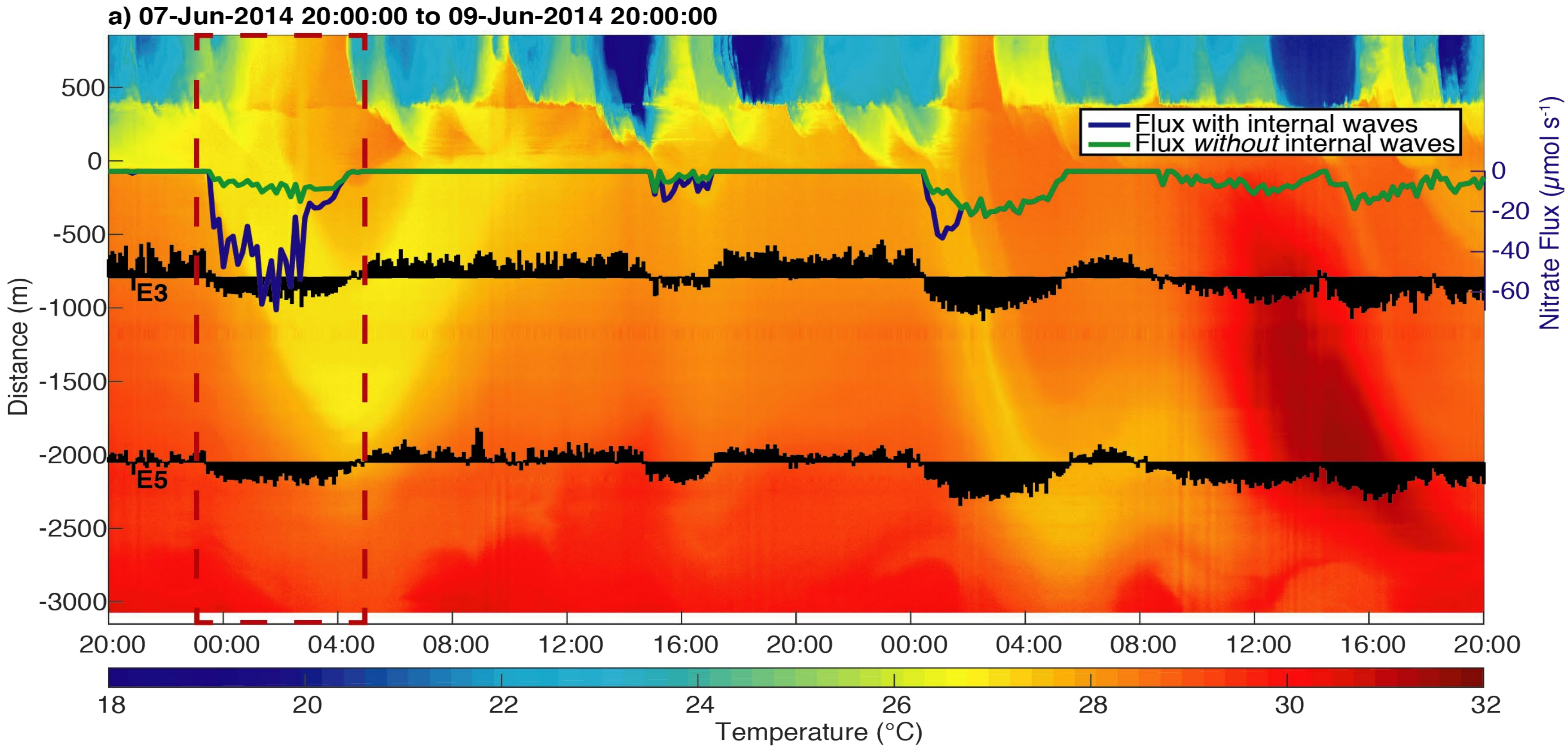
Temperature predicted from heat budget:

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

Estimate of temperature "without internal waves" using boundary condition at "B"



Internal wave influence on the shallow reef



- 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.

Acknowledgements

Contributors to this work include:

Aryan Safaie, *University of California, Irvine*
Emma Reid, *University of California, Irvine*
Anne Cohen, *Woods Hole Oceanographic Inst.*
Tom DeCarlo, *Woods Hole Oceanographic Inst.*
Steve Lentz, *Woods Hole Oceanographic Inst.*
George Wong, *Academia Sinica, Taipai, Taiwan*
Pat Lohmann, *Woods Hole Oceanographic Inst.*

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