Advancing predictions of nearshore processes within coastal ecosystems

Ryan Lowe

21 March 2021

2nd Sea State CCI User Meeting

Drivers of coastal flooding and erosion

Shoreline water level

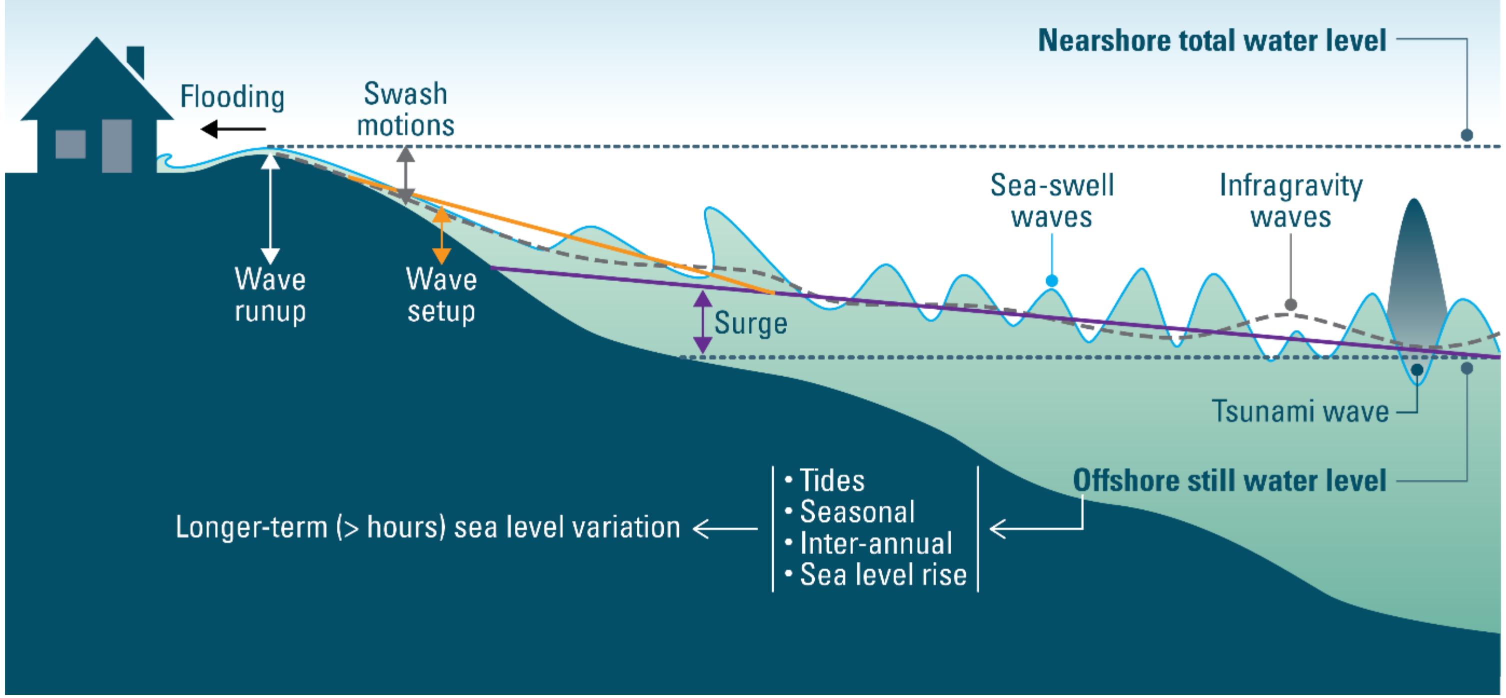
1. Tides and long term mean sea level variability +

2. Barometric pressure
Onshore wind stress } Storm surge

\+

Focus of this talk …

3. Swash motions
Wave setup } **Wave runup**

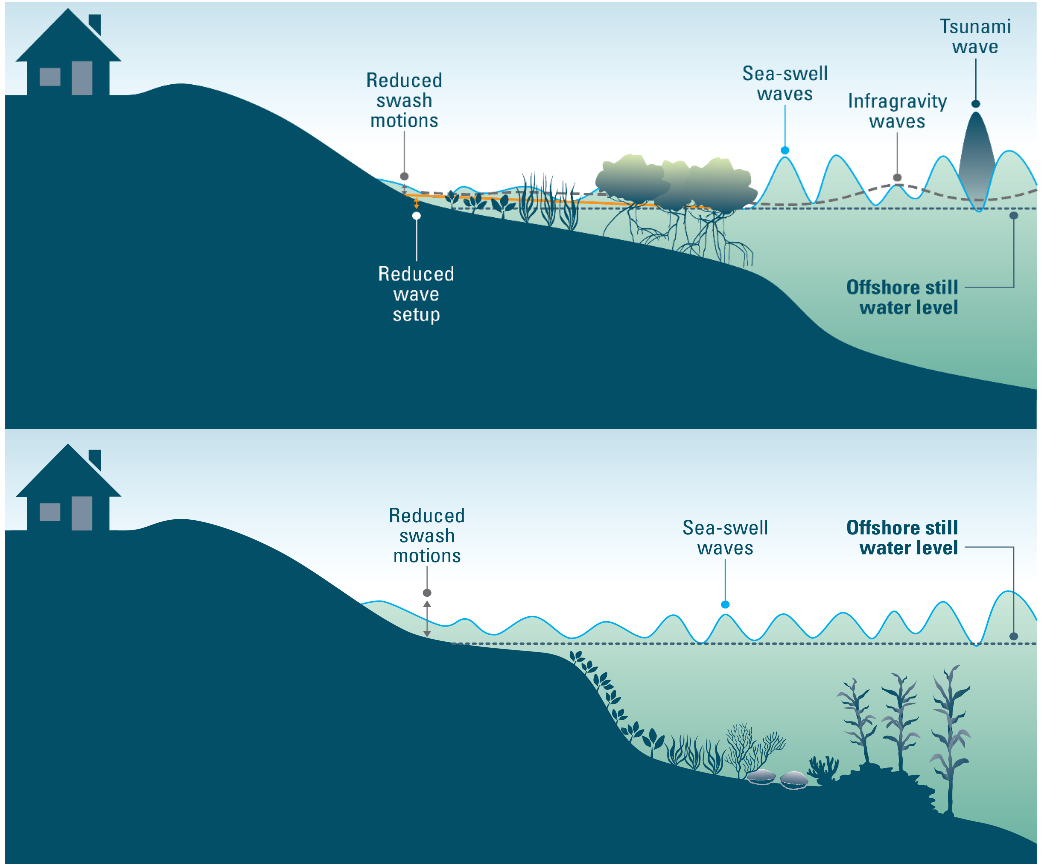


Mitigation of coastal hazard risk by ecosystems

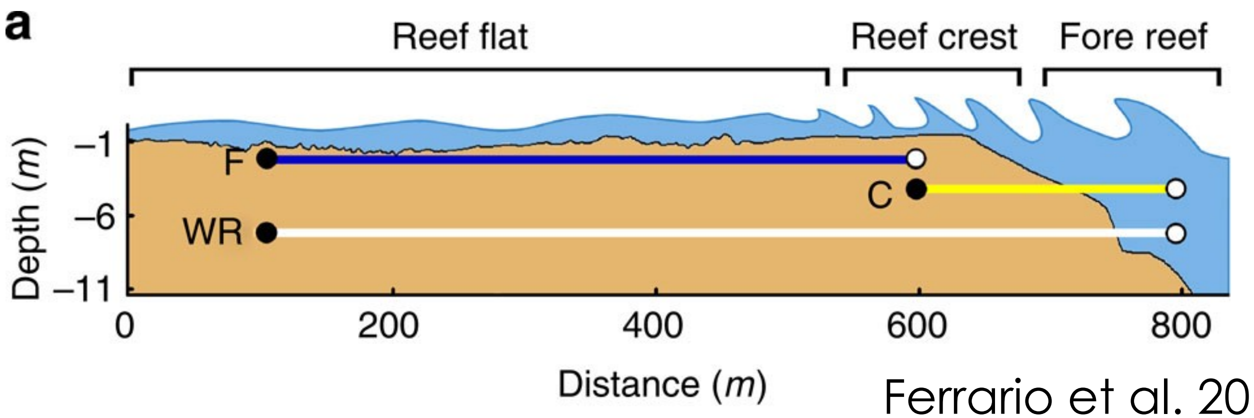
THE UNIVERSITY OF WESTERN AUSTRALIA

Two key physical mechanisms: 1. Wave attenuation through **drag dissipation**
2. Wave attenuation through **wave breaking**

Drag dissipation



Wave breaking



Ferrario et al. 2014

Examples: Dissipation by drag forces

Kelp forests

Seagrass meadows

Coral reefs

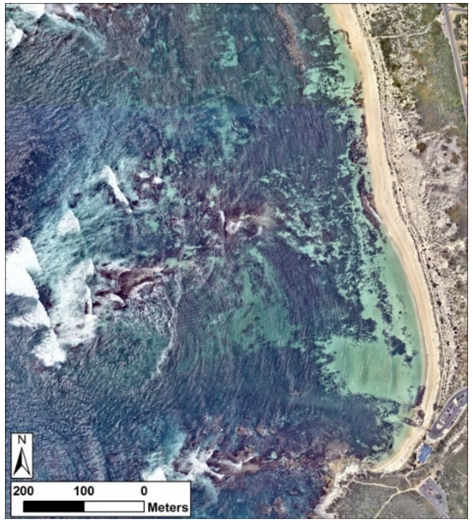
Mangroves

Salt marsh

Examples: Dissipation by wave breaking

Coral reefs

Temperate reefs



Oyster reefs

Artificial reefs

Use of ecosystems for nature-based coastal protection

- Over the past decade there has been a substantial growth in the proposed use of ecosystem features to enhance coastal protection
- Compared to coastal engineering design guidelines, quantitative "guidelines" for nature-based features are lacking -> can impede uptake

Engineering With Nature

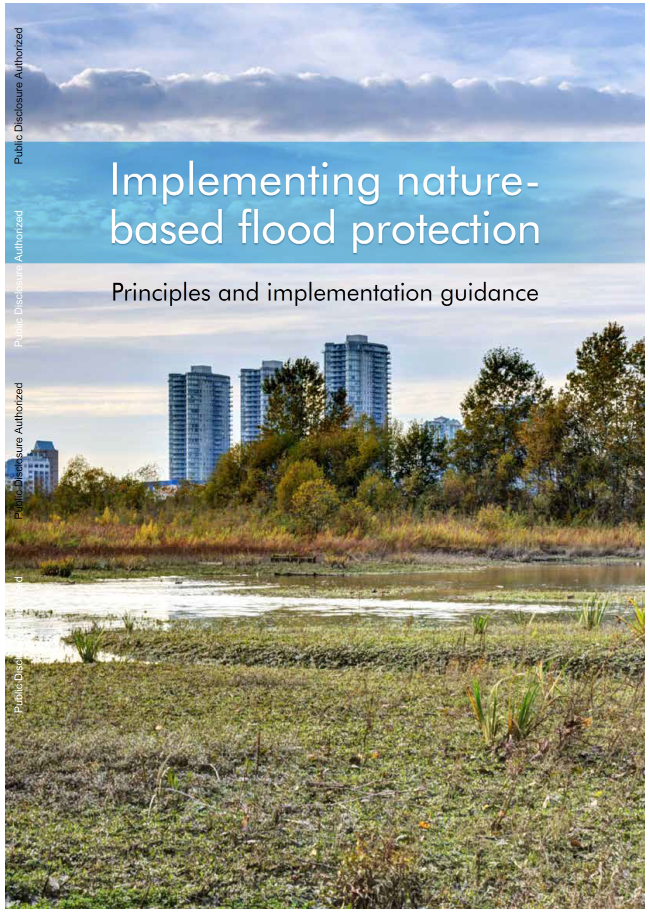
Working with Nature

Building with Nature

Creating, implementing and upscaling Nature-based Solutions

Editors

Erik van Eekelen
Matthijs Bouw



Implementing nature-based flood protection

Principles and implementation guidance

Physical process: 1. Wave dissipation by canopy drag forces (Lowe et al. 2005a , 2007 - JGR)

1D wave energy equation:

$$\frac{\partial\left(Ec_g\right)}{\partial x} = -\varepsilon_d = -\overline{F_d U}$$

with

Parameterising canopy drag forces:

$$F_d = \frac{1}{2}\rho C_d \lambda_f \left|U\right|U$$

ε_d = rate of wave energy dissipation by ecosystem drag forces

Wave attenuation increases with:

U = velocity within the ecosystem

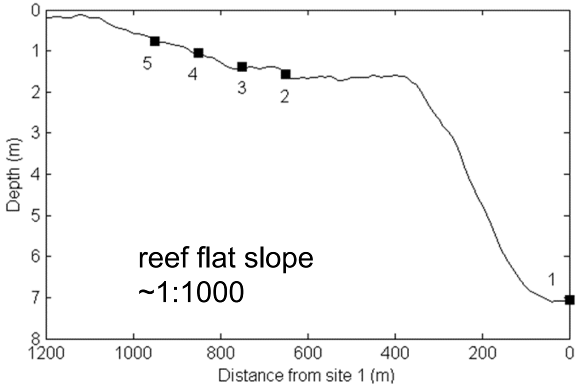
$\boldsymbol{\lambda_f}$ = ecosystem frontal area per unit bed area (projected into flow)

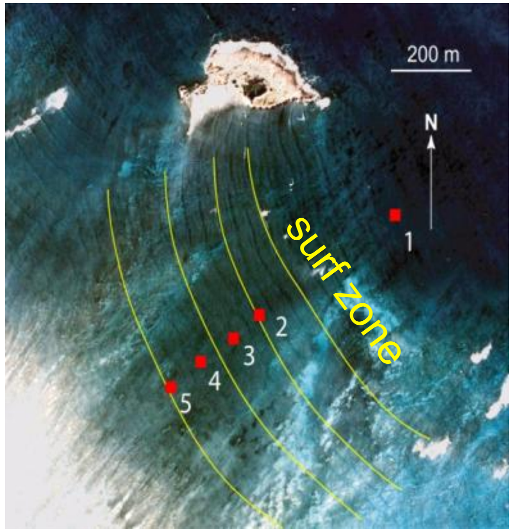
$\mathbf{C_d}$ = ecosystem drag coefficient

Large roughness (canopies) formed by coastal ecosystems

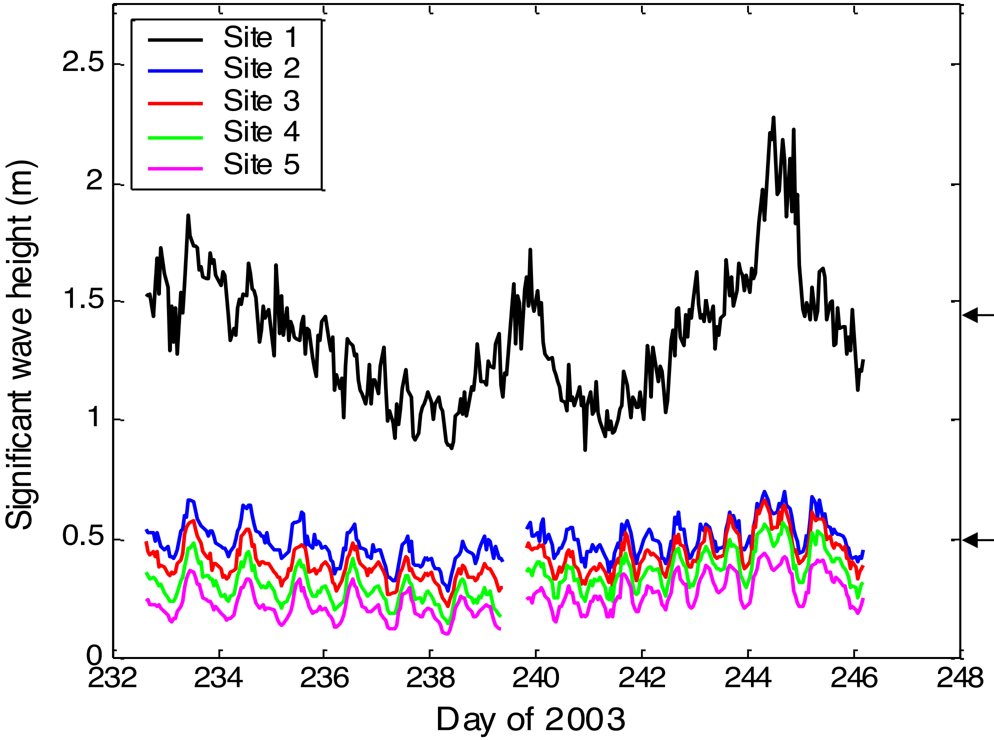
Alternatively, F_d can be parameterised using analogous porous media flow theory (Lowe et al. 2008 – L&O)

Wave transformation over a coral reef: Importance of drag dissipation (Lowe et al. 2005b - JGR)





- Typically ~60% of incident wave energy was dissipated by bottom friction on this reef



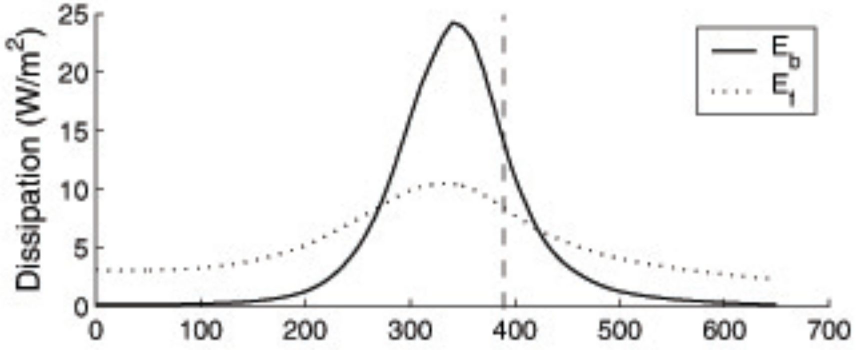
forereef

wave breaking + bottom friction

reef flat

bottom friction

Cross-shore partitioning of wave dissipation (mild-sloping ~1:50 Kaneohe Bay reef)



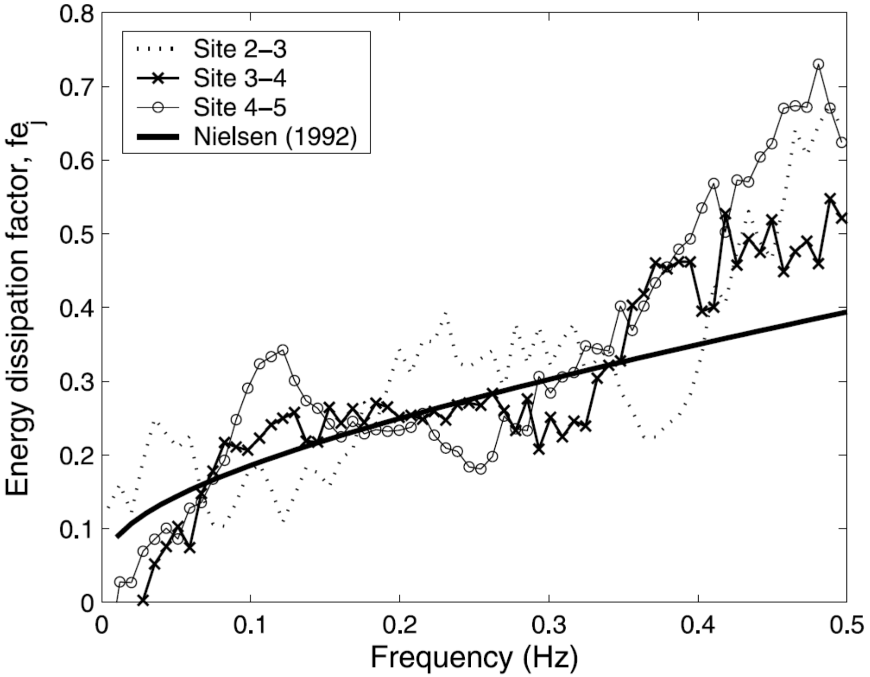
Wave transformation over a coral reef: Importance of drag dissipation (Lowe et al. 2005b, JGR)

Frequency-dependent frictional dissipation

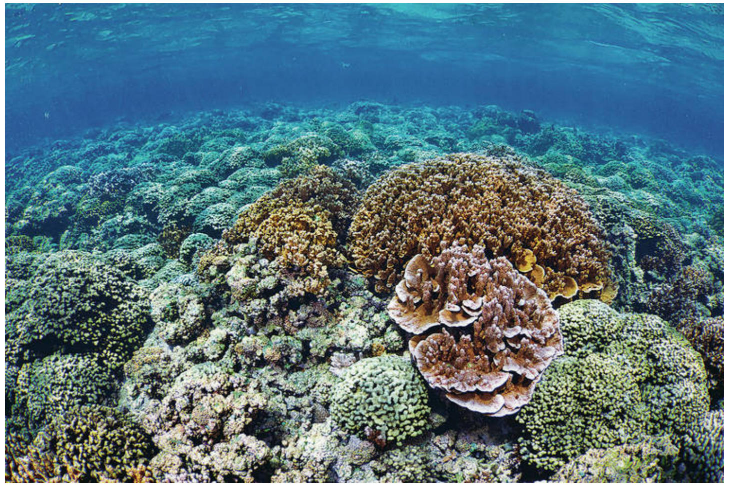
$$\boxed{\varepsilon_{d,j} = \frac{1}{4}\rho f_{e,j} u_{b,r} u_{b,j}^2}$$

(e.g., Madsen 1994)

$f_{e,j}$ = energy dissipation factor (*j-th* frequency component)



Typical wave friction factors:
- Coral reefs: f_w ~0.3-1.0
- Beaches: f_w ~0.01-0.1



<u>Higher frequency waves are more dissipative</u>

- **Due to wave-canopy interactions: Lowe et al. (2005a, 2007) - JGR**
- **Need to account for how canopy flow attenuation varies across different wave frequencies**

Velocity inside the ecosystem (*U*)

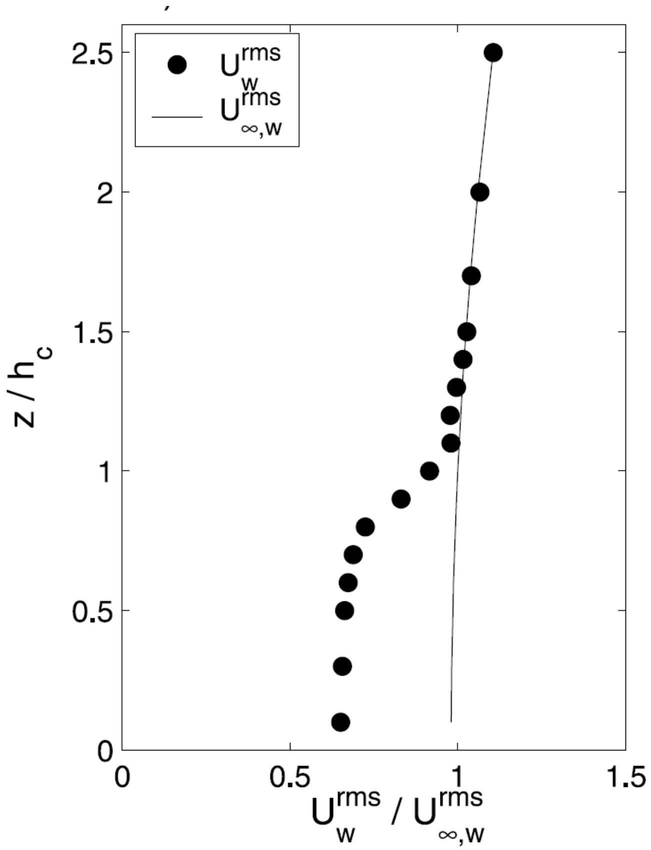
$$\epsilon_d = -F_d U$$

$$F_d = 1/2\ \rho C_d \lambda_f |U| U$$

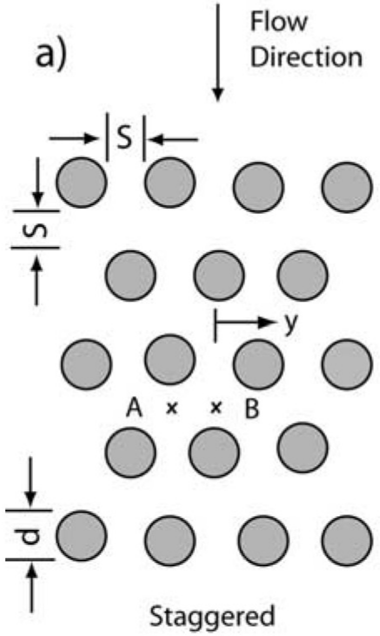
Flow attenuation parameter:

$$\alpha(f) = \frac{\text{velocity INSIDE canopy}}{\text{velocity ABOVE canopy}}$$

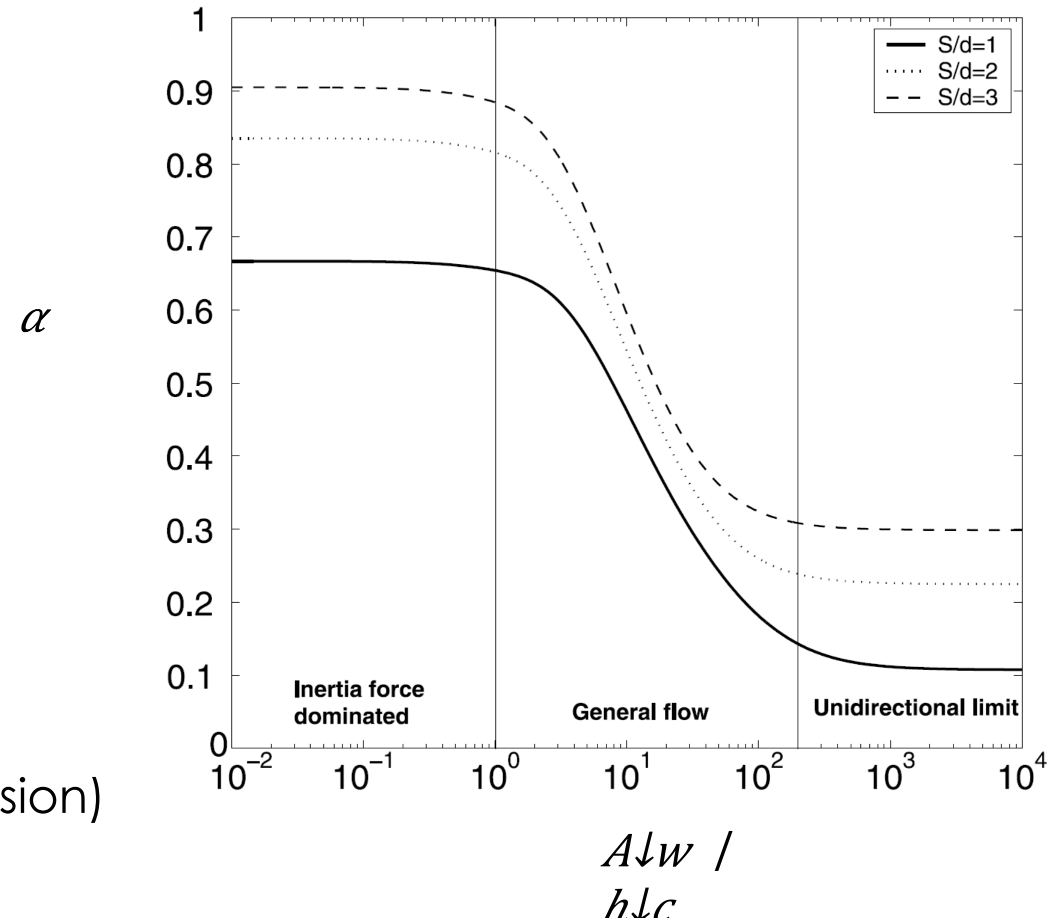
Canopy flow model (Lowe et al. 2005a, JGR)



Frequency dependent



A_w (wave orbital excursion)



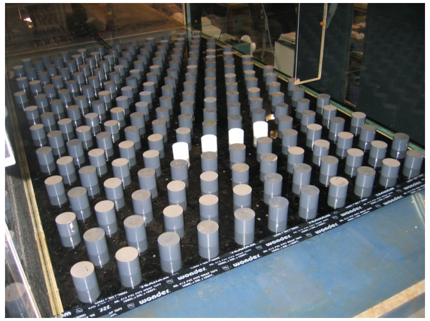
Velocity inside the ecosystem (*U*)

$$\epsilon_d = -F_d U$$

$$F_d = 1/2\ \rho C_d \lambda_f |U| U$$

- Due to canopy forces (drag and inertial), flows can be <u>much</u> lower than that above the ecosystem ($\alpha = U_{within} / U_{above}$)

Idealised canopies



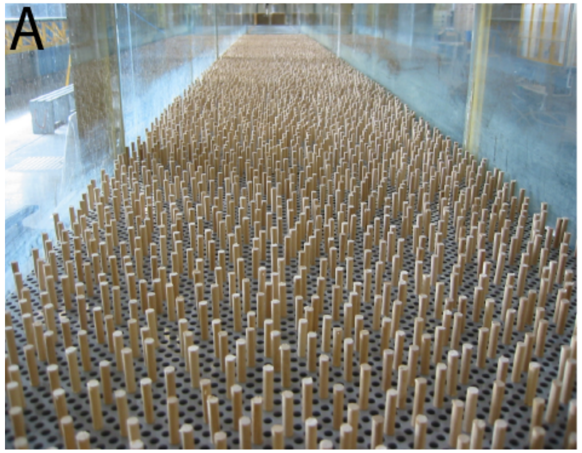
Corals

Aquatic vegetation

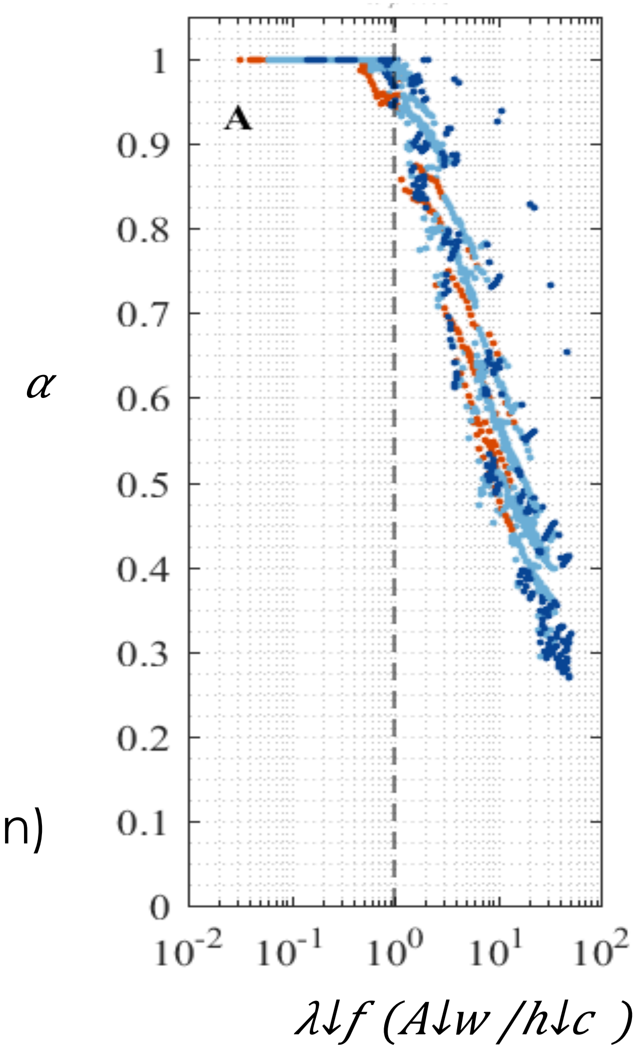
also field studies...

Example

(van Rooijen et al. 2021)



A_w (wave orbital excursion)

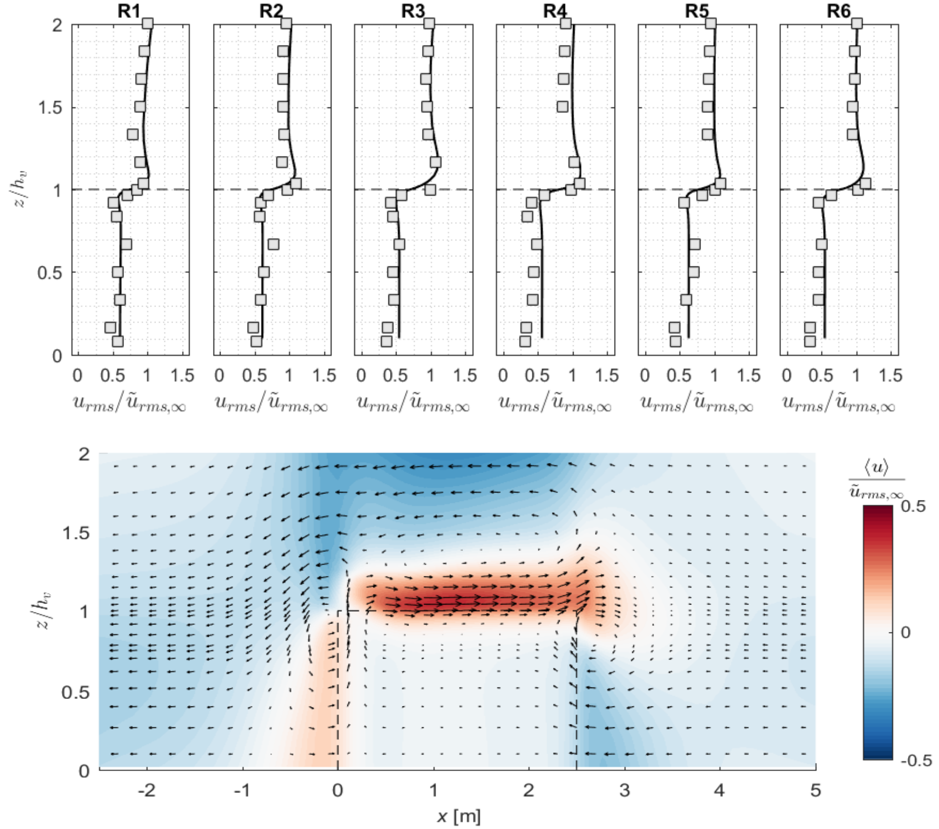


Incorporation of canopy models into coastal hydrodynamic models

THE UNIVERSITY OF WESTERN AUSTRALIA

3D model (SWASH)

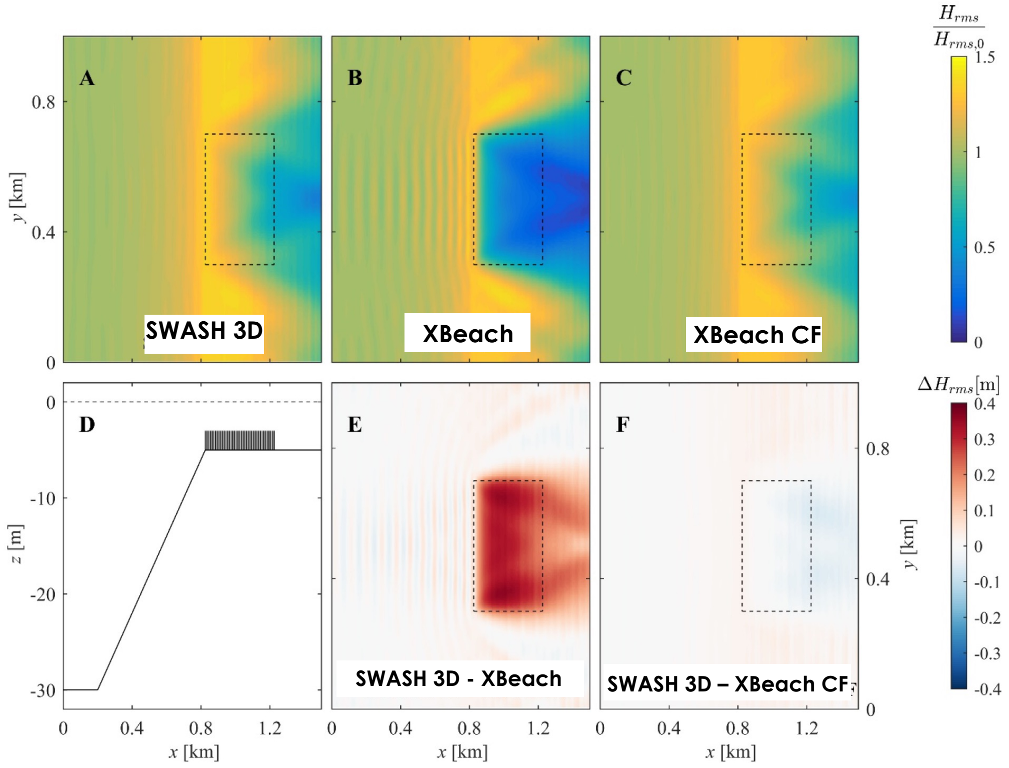
SWASH
Simulating WAves till SHore



Van Rooijen et al. (2020), JGR

Depth-averaged model (Xbeach)

(implementation of Lowe et al. 2005 canopy model)

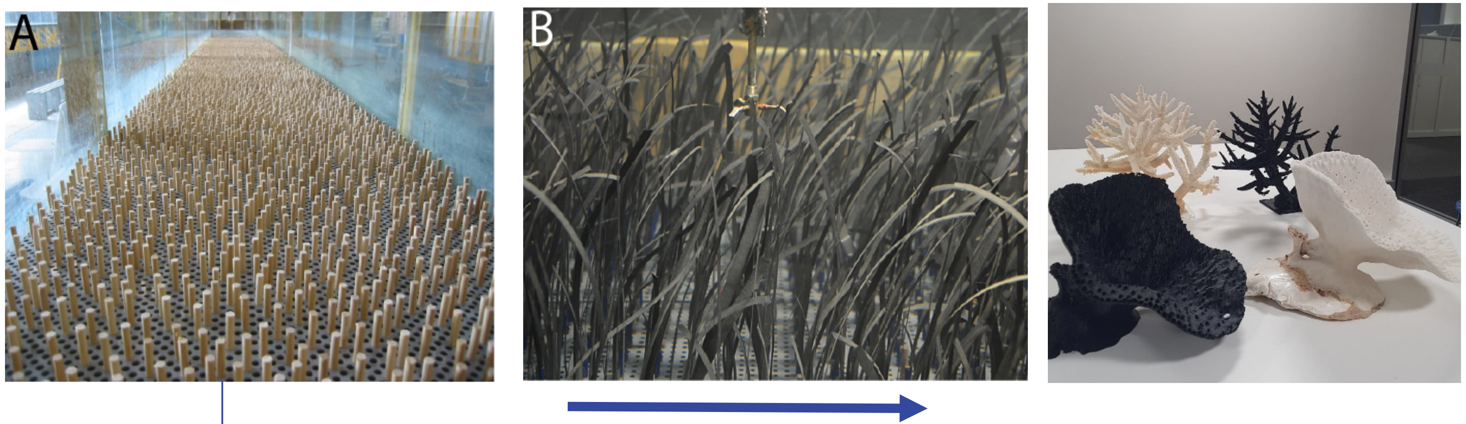


Van Rooijen et al. (2021), in review

Drag "coefficient" (C_d)

$$\epsilon_d = -F_d U$$
$$F_d = 1/2\ \rho C_d \lambda_f |U|U$$

- C_d = f(shape, ecosystem 'density', flexibility, flow conditions)
- Most effective way to determine C_d is to directly measure drag forces on ecosystem element
- Alternative approaches using turbulent porous media theory



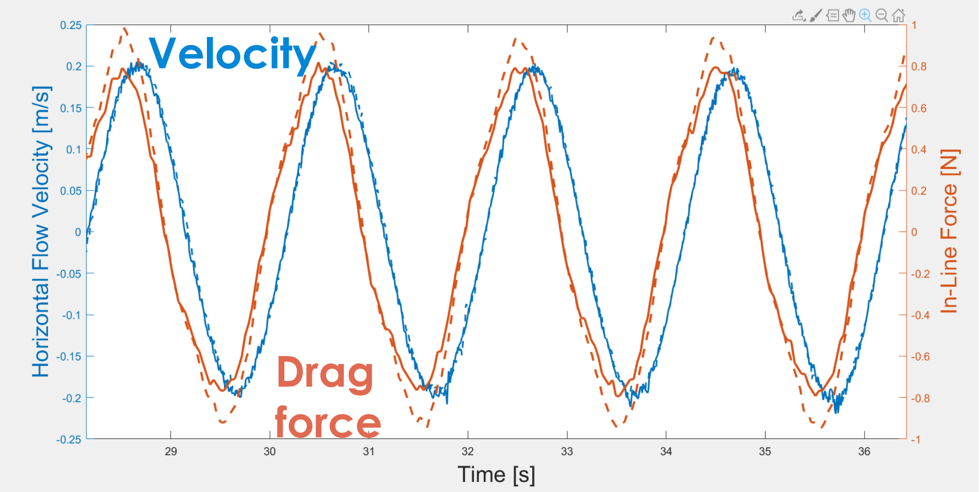
Increasing morphological complexity

C_d ≈ 1-2

(Etminan et al., *Coastal Eng.*, 2019)

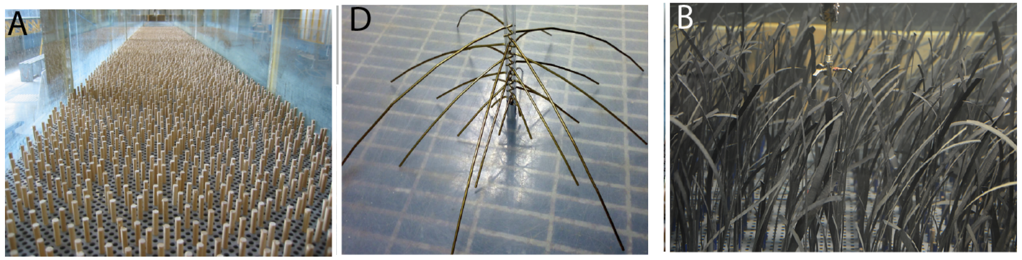
Australia Research Council Discovery Project (2020-2023)

Coral load cell measurements



Ecosystem frontal area (λ_f) - challenges with flexibility and complex geometries

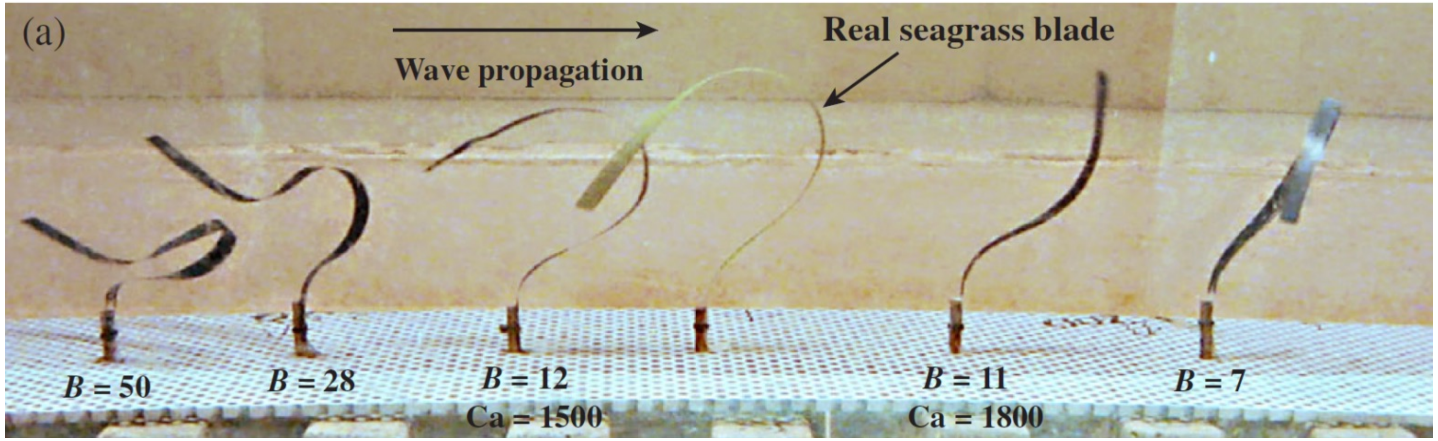
THE UNIVERSITY OF WESTERN AUSTRALIA



Increasing difficulty →

λ_f = frontal area per per plan area

$$\epsilon_d = -F_d U$$
$$F_d = 1/2 \;\rho C_d \lambda_f |U|U$$



(Abdolahpour *et al*., L&O, 2019)

- Critically-important to accurately mimic dynamic behavior of seagrass:

Ca = drag/rigidity B = buoyancy/rigidity

“Effective” height (= f(B,Ca)) used to redefine λ_f

Physical process: 2. Coastal protection by wave breaking (e.g. reef structures)

Dissipation of sea-swell waves is only one part of the problem

✓ Need to consider all of the processes that drive wave runup and sediment transport

Energy transfer during breaking

Incident sea-swell waves (~5-25 sec period)

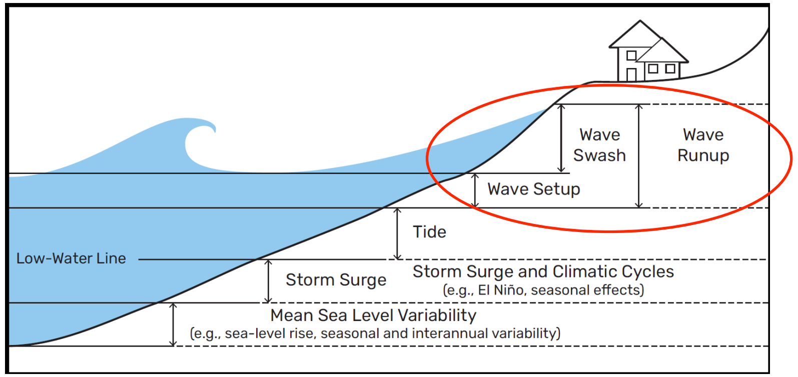
wave-driven mean currents

wave setup

infragravity waves (25+ sec)

+

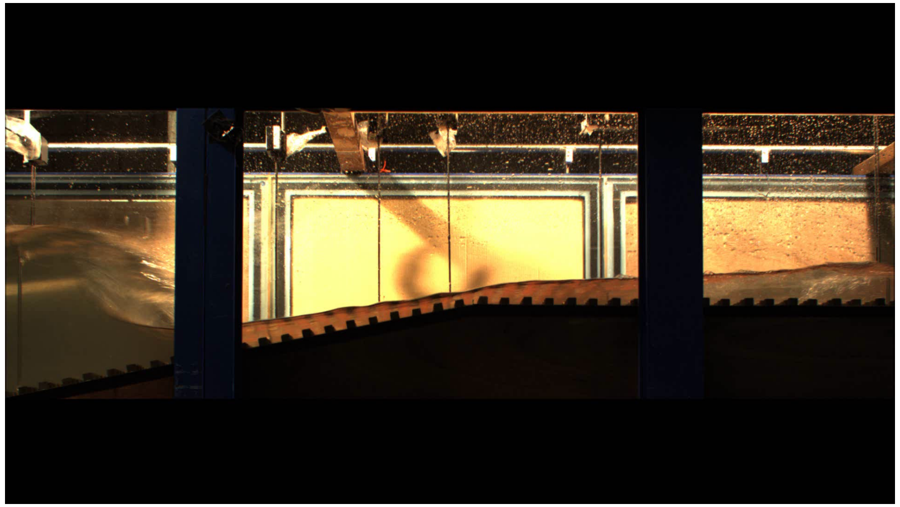
dissipation (e.g. heat)

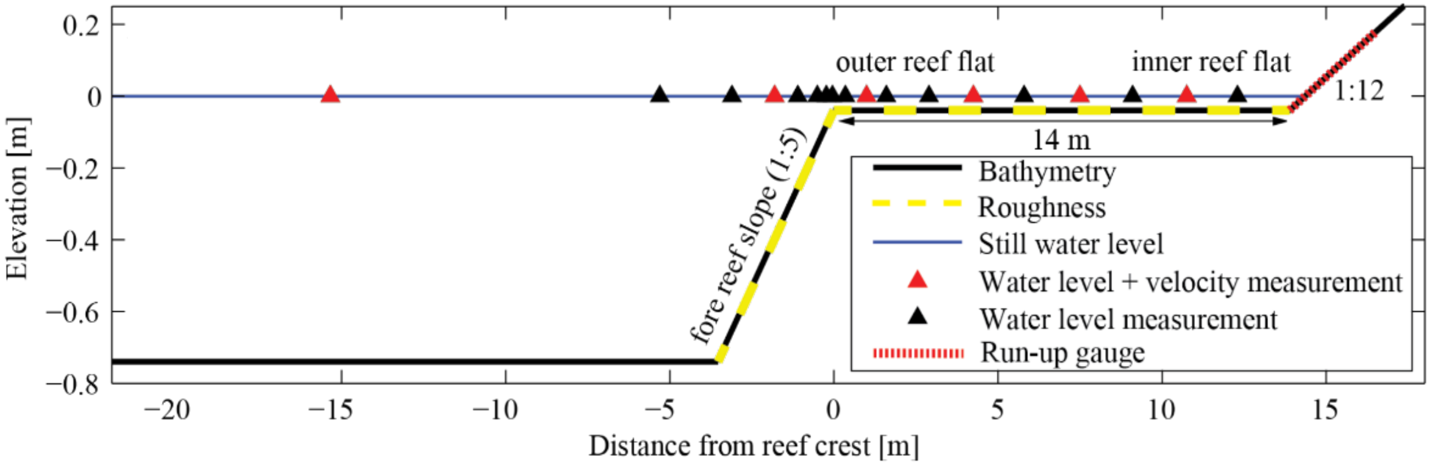


Wave transformation over reefs (cross-shore dynamics): insight from physical modelling

- 55-m long flume
- 1:36 geometry scaling
- 14 m long reef flat (500 m in prototype)
- 1:5 fore reef slope
- 1:12 beach slope

- Smooth and rough bed
- 16 wave and water level cases
- 18 wave gauges + 6 velocimeters
- Runup gauge



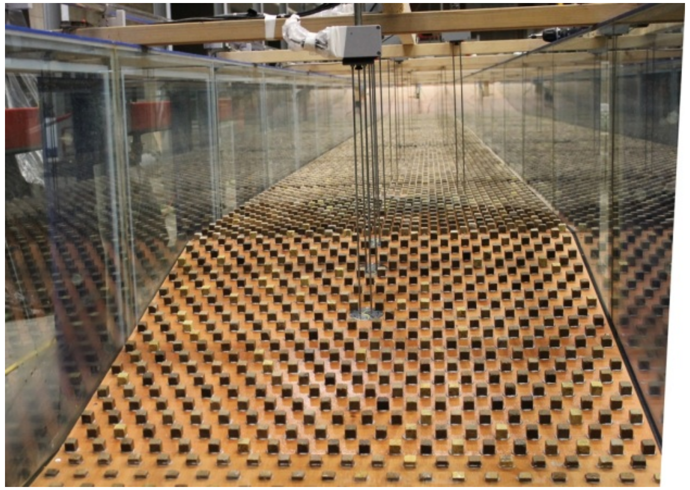


Buckley et al. 2015; 2016; 2018; 2020

Wave transformation over reefs (cross-shore dynamics): insight from physical modelling

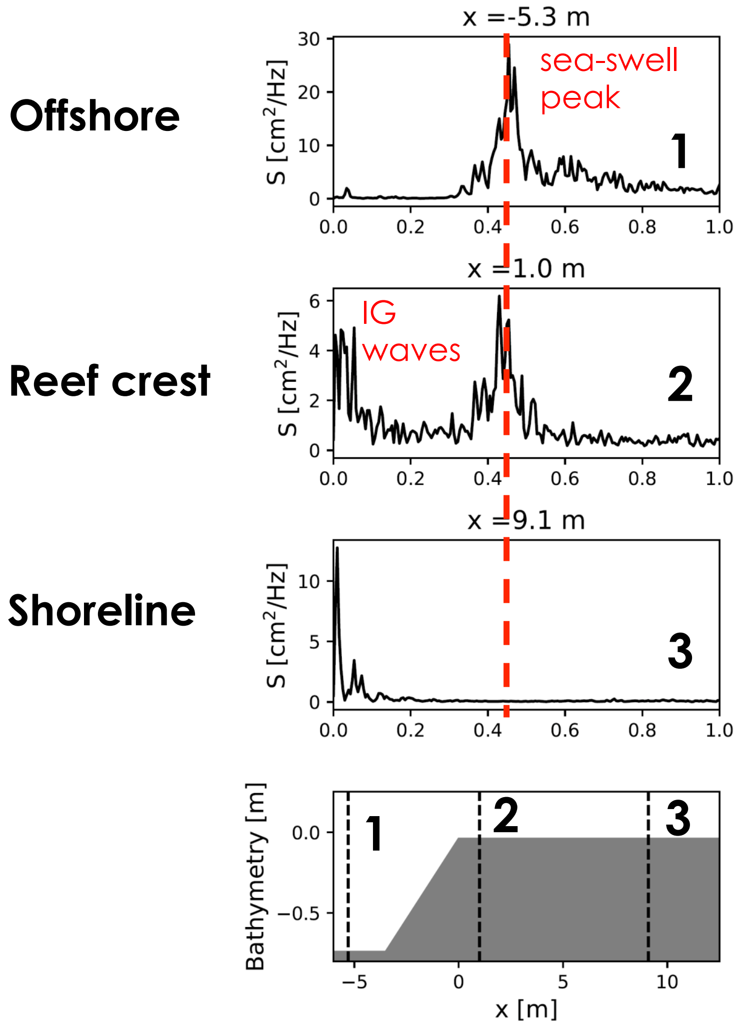
Smooth and rough bed

- 1.5 cm (54 cm in prototype) concrete cubes
- ~6,000 cubes
- Roughness provides bulk frictional dissipation similar to natural reefs (wave friction factors ~0.2)



Wave transformation over reefs (smooth reef example)

Spectral evolution



Bulk wave parameters

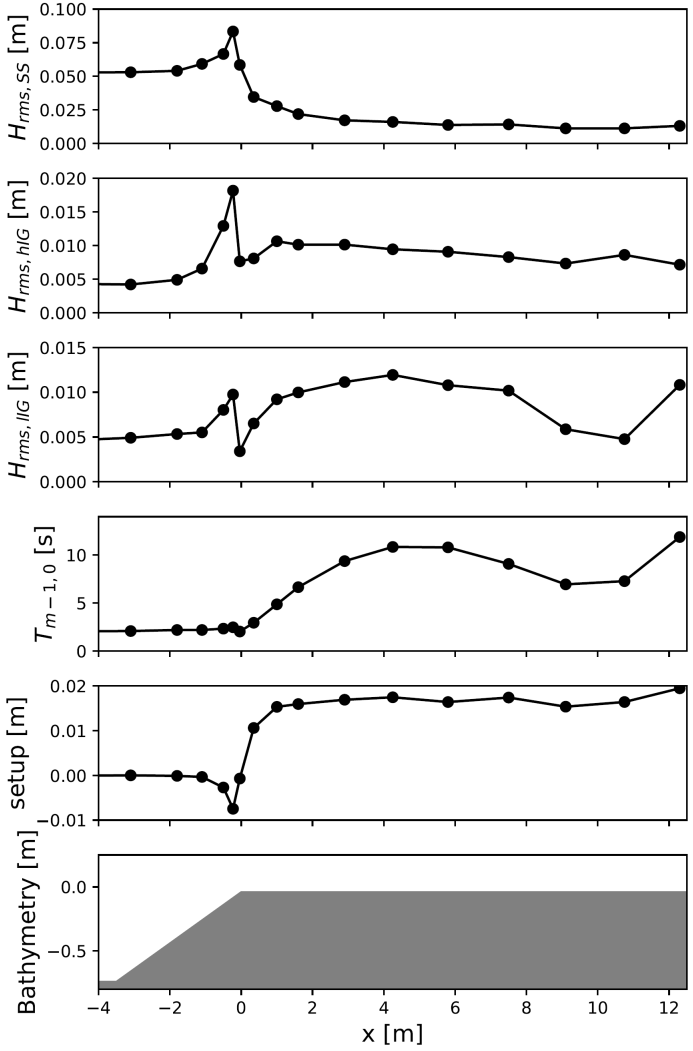
Sea swell wave height (5-25 seconds)

High frequency IG wave height (25-100 seconds)

Low frequency IG wave height (100+ seconds)

Spectral period

Wave setup



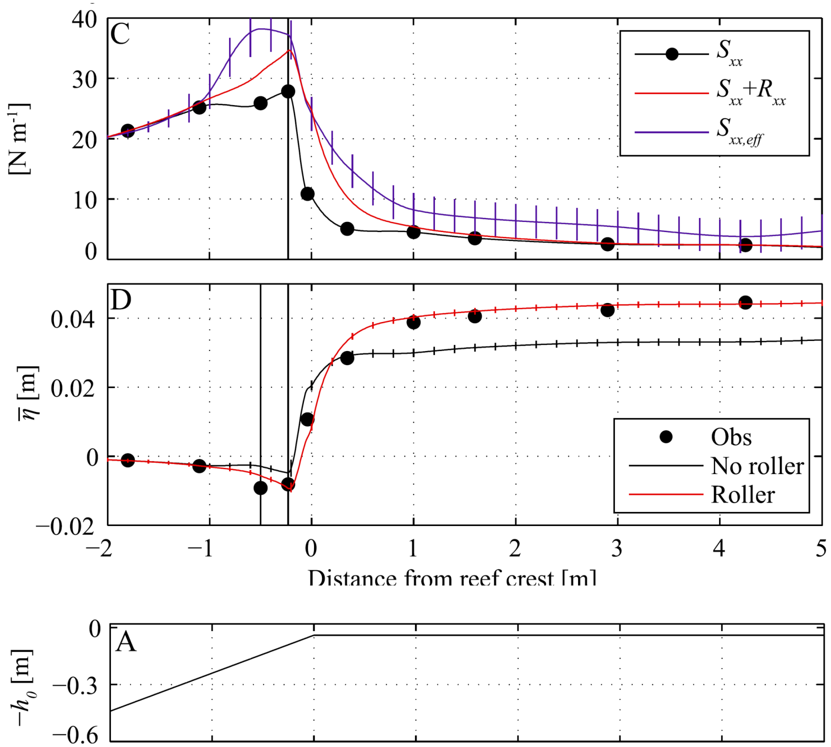
Buckley et al. 2018

Enhanced setup over steep reefs (influence of the 'roller')

Buckley et al. 2015, JPO

Radiation Stresses (S_{xx})

Wave setup



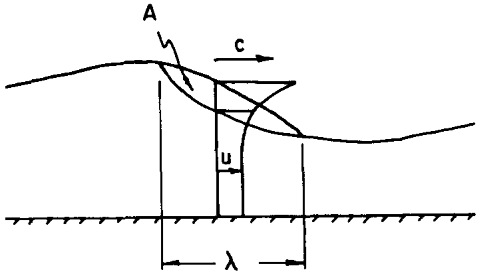


Fig. 6. The roller of a surf zone wave.

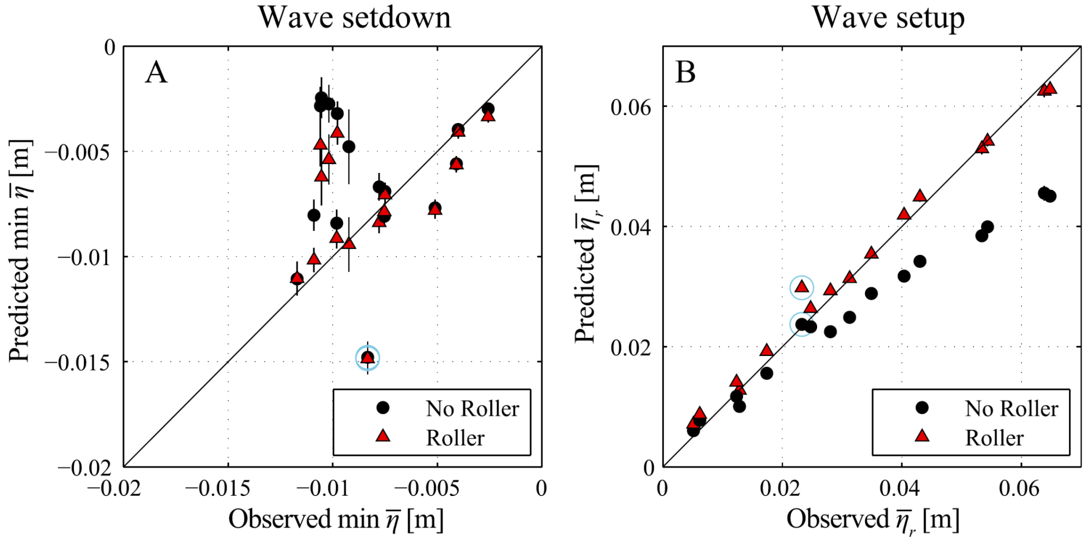
Parametric roller model

Svendsen, 1984a, 1984b; Reniers and Battjes, 1997

1. Wave forces (radiation stresses) are delayed due to the roller -> conversion of PE to KE prior to dissipation
2. Setup generation is more efficient in shallow water:

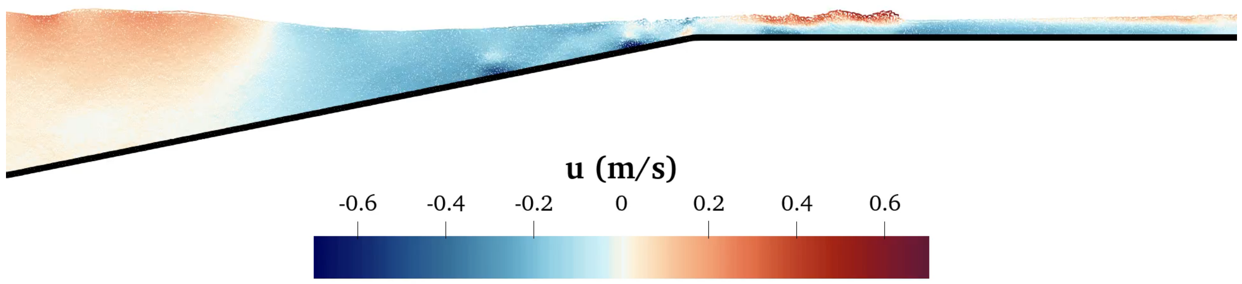
$$\boxed{\frac{\partial \bar{\eta}}{\partial x} = -\frac{1}{\rho g h}\frac{\partial S_{xx}}{\partial x}}$$

3. Setup is enhanced on the steep slopes of reefs (not predicted by LWT)

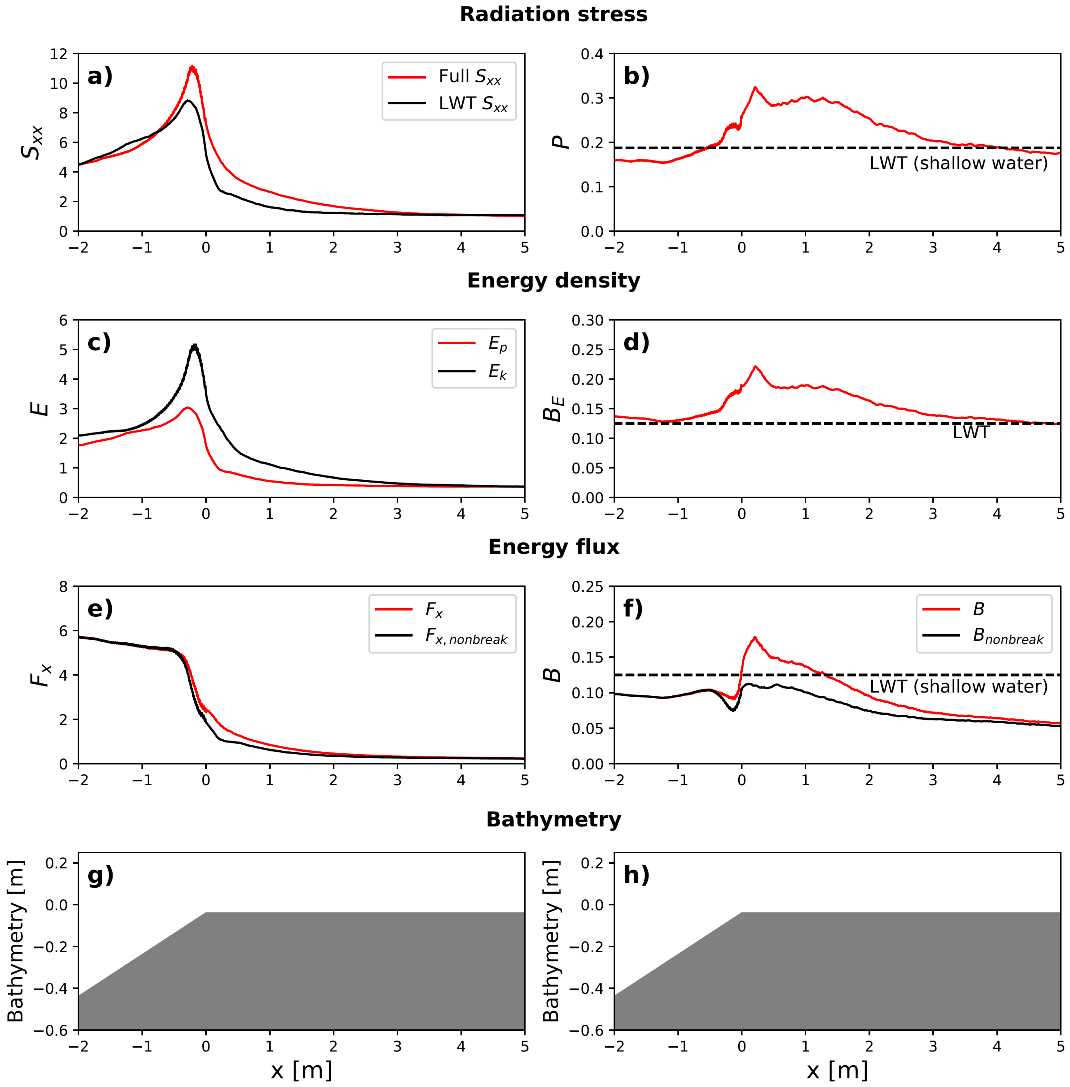


Challenges for conventional wave models

Insight from high-resolution CFD models (Smoothed Particle Hydrodynamics (SPH) simulations)



(Lowe et al. 2019, Ocean Modelling; Lowe at al. 2021, in prep)

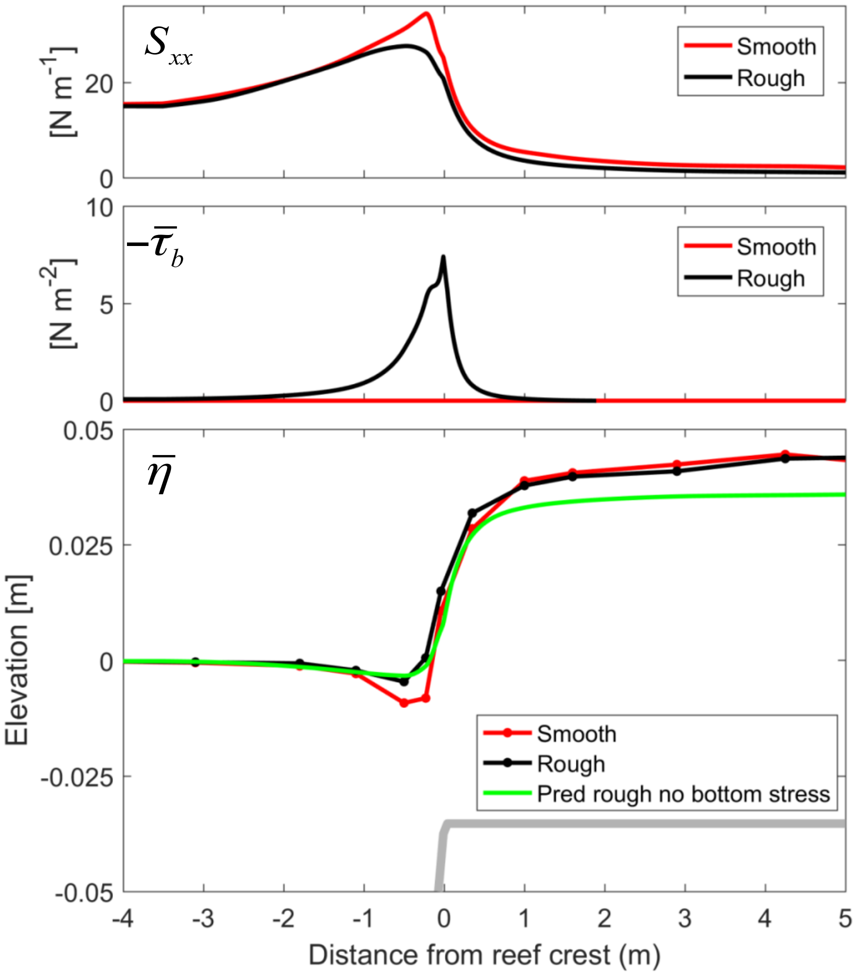


Influence of bottom roughness on wave setup

Buckley et al. 2016, JPO

THE UNIVERSITY OF WESTERN AUSTRALIA

Example (Run 4)



Radiation stresses

- Reduced by wave dissipation by roughness

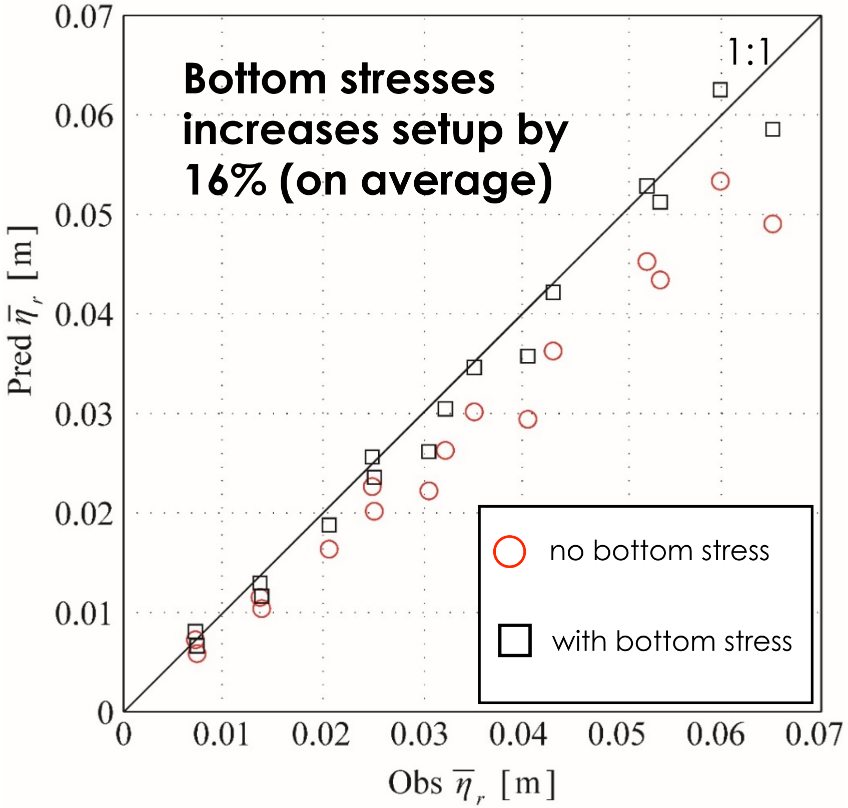
Mean bottom stress

- Significant for rough case

Setup

- Similar reef flat setup
- Differences in setdown

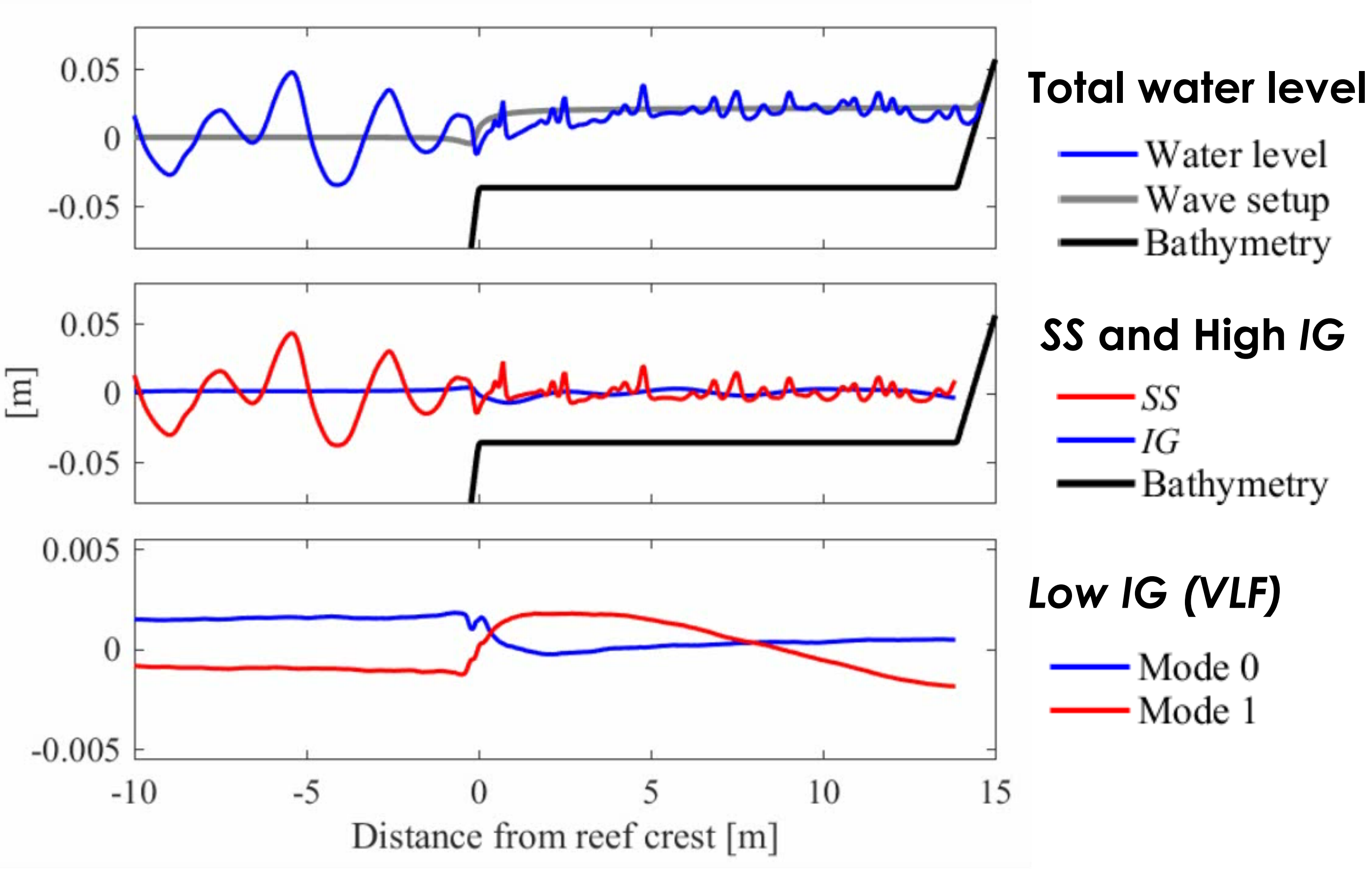
$$\boxed{\underbrace{\rho g h \frac{\partial \overline{\eta}}{\partial x}}_{\text{Pressure (setup) gradient}} = \underbrace{-\frac{\partial S_{xx}}{\partial x}}_{\text{Radiation stress gradient}} \underbrace{-\overline{\tau_b}}_{\text{Mean bottom stress}} = 0}$$



Bottom stresses increases setup by 16% (on average)

Importance of low frequency waves (standing / resonant motions)

SWASH simulations

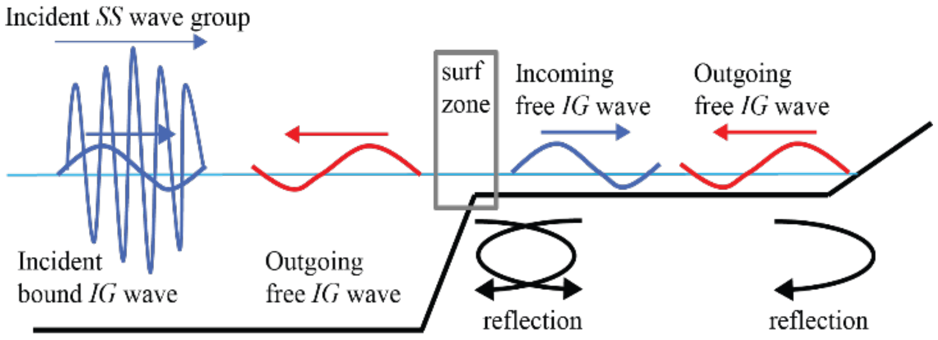


Total water level

SS* and High *IG

Low IG (VLF)

IG motions become amplified with resonance



Buckley et al. 2018, JGR

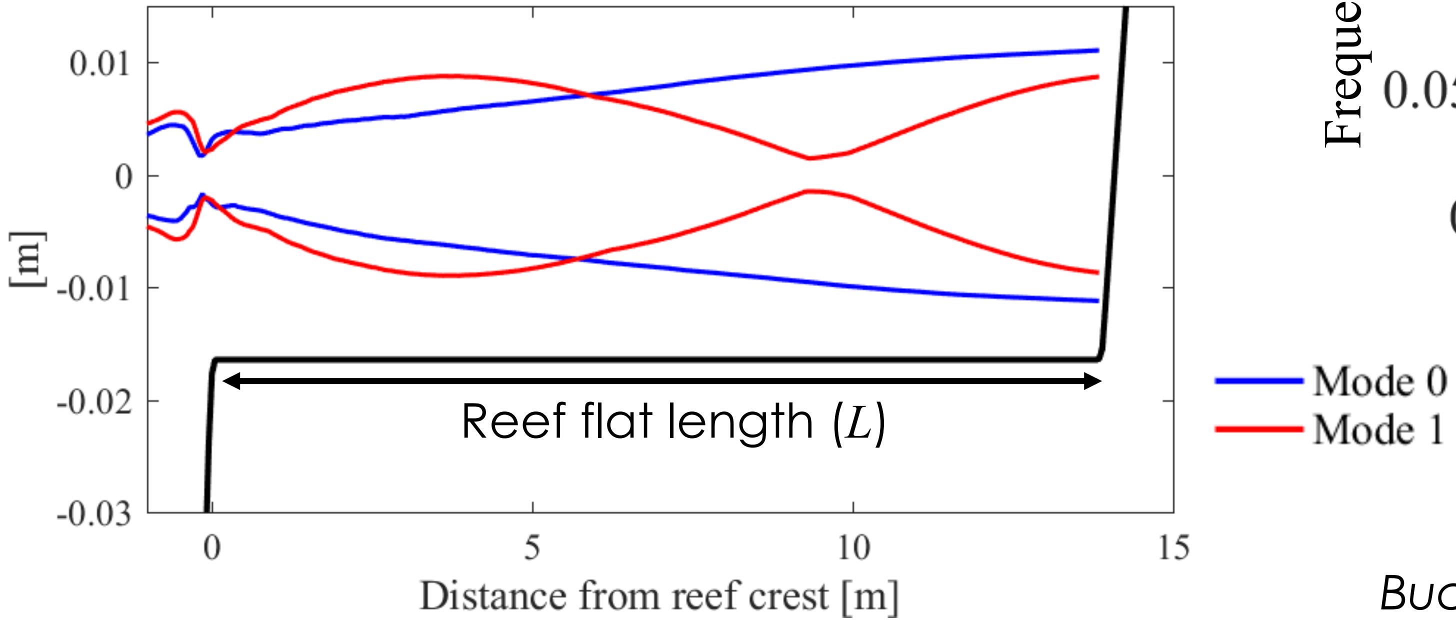
Standing / resonant wave motions (very low frequency IG waves)

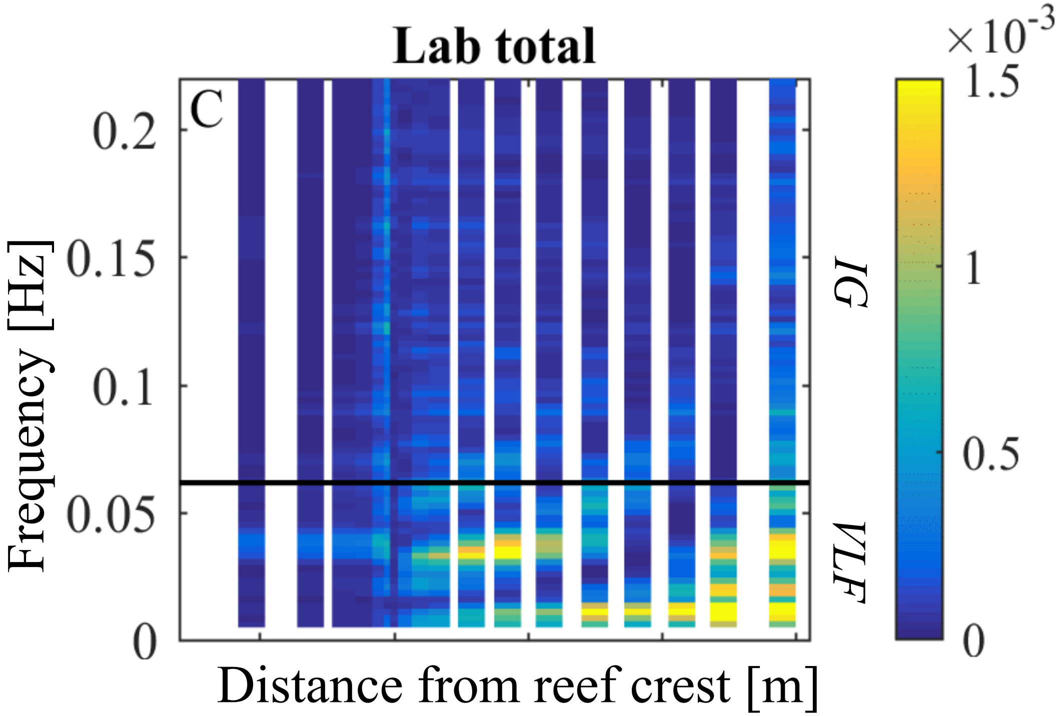
Natural frequencies of the reef flat

$$T_n = \frac{4L}{(2n+1)\sqrt{gh}} \qquad n = 0, 1, \ldots$$

n = mode
L = reef flat length
h = average reef flat depth (including setup)

Water level extremes for natural frequencies (SWASH)





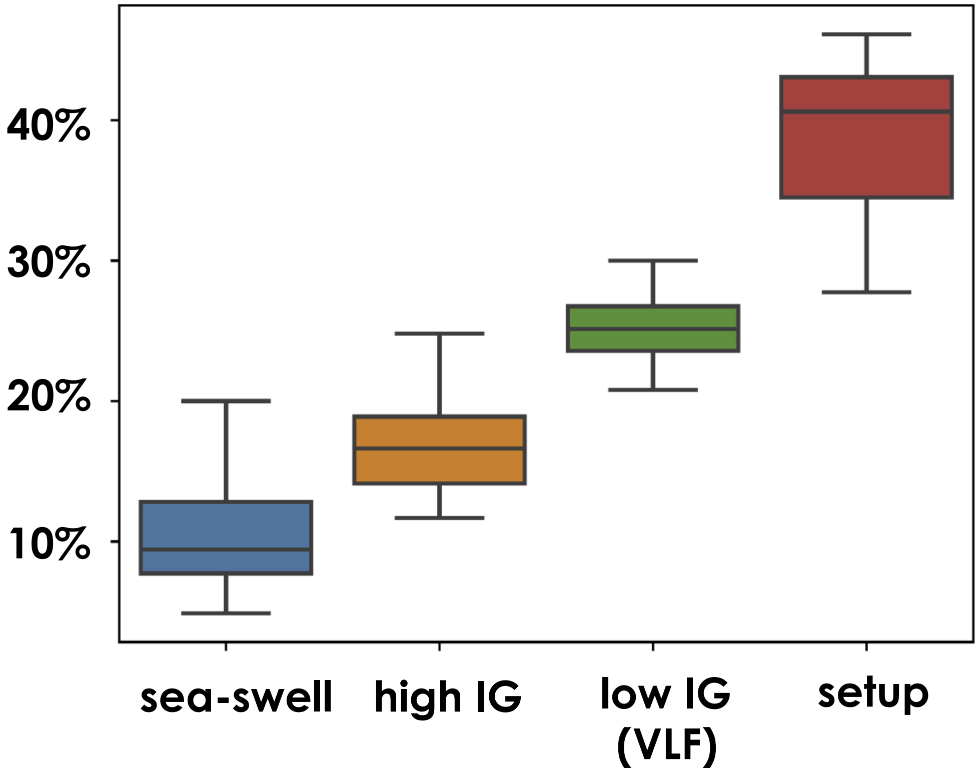
Buckley et al. 2018, JGR

Wave runup contributions and influence of bottom roughness

Buckley et al. 2018, JGR

- Runup dominated by wave setup and low IG (VLF) motions

Percent runup contribution (smooth runs)



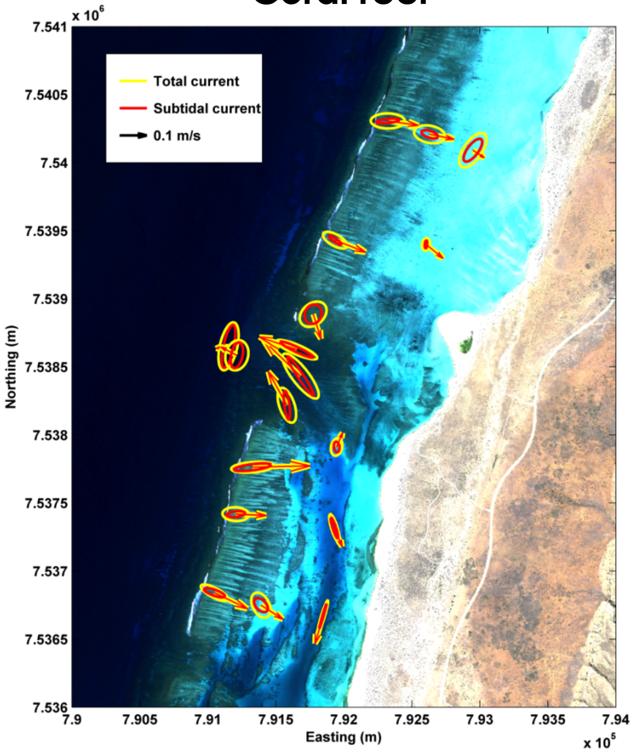
Response to bottom roughness

- Total $R_{2\%}$: -38%
  - *SS*: -32%
  - *IG*: -93%
  - *VLF*: -60%
  - Wave setup: -14% (setup not affected)

Wave-driven mean flows (2DH / 3D effects): implications for shoreline erosion / accretion

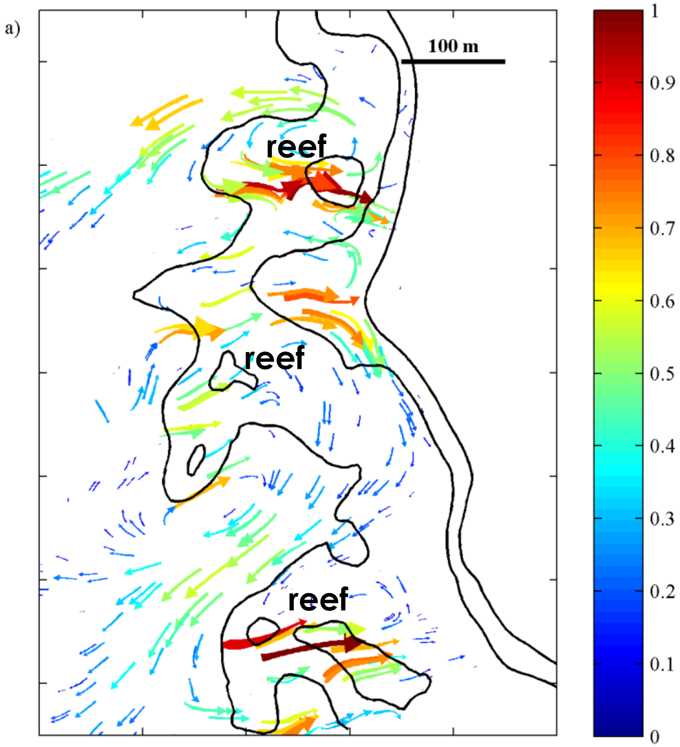
- With alongshore variability in reef morphology, wave breaking drives depth-averaged mean flows that interact with shorelines

Coral reef



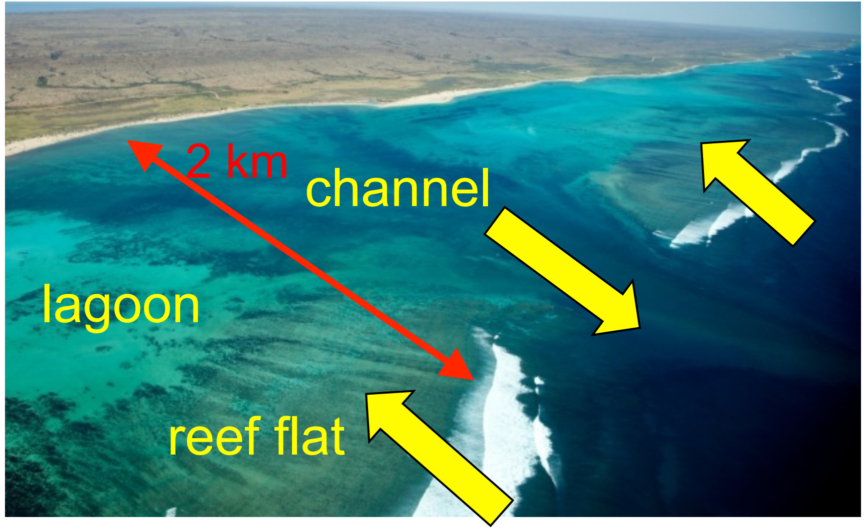
Taebi et al. *(2011), JGR*

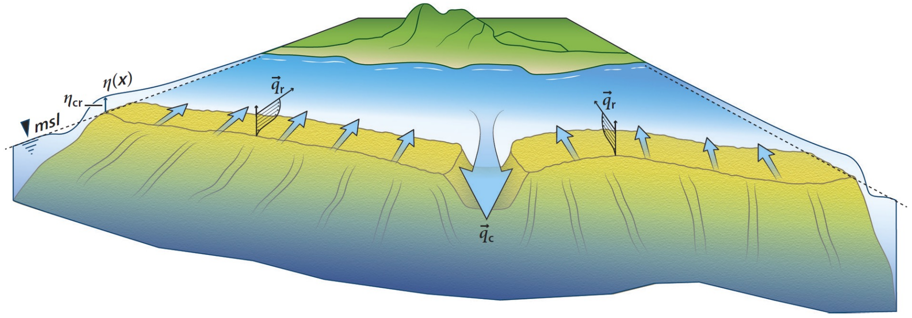
Rocky reef reef (drifter tracks)



Winter et al. (2020), CSR

Ningaloo Reef





Lowe et al. (2015), ARMS

Contrasting shoreline responses from submerged breakwaters / artificial reefs

Example highlighting knowledge gaps…

7 of 10 sites reviewed experienced <u>erosion</u>

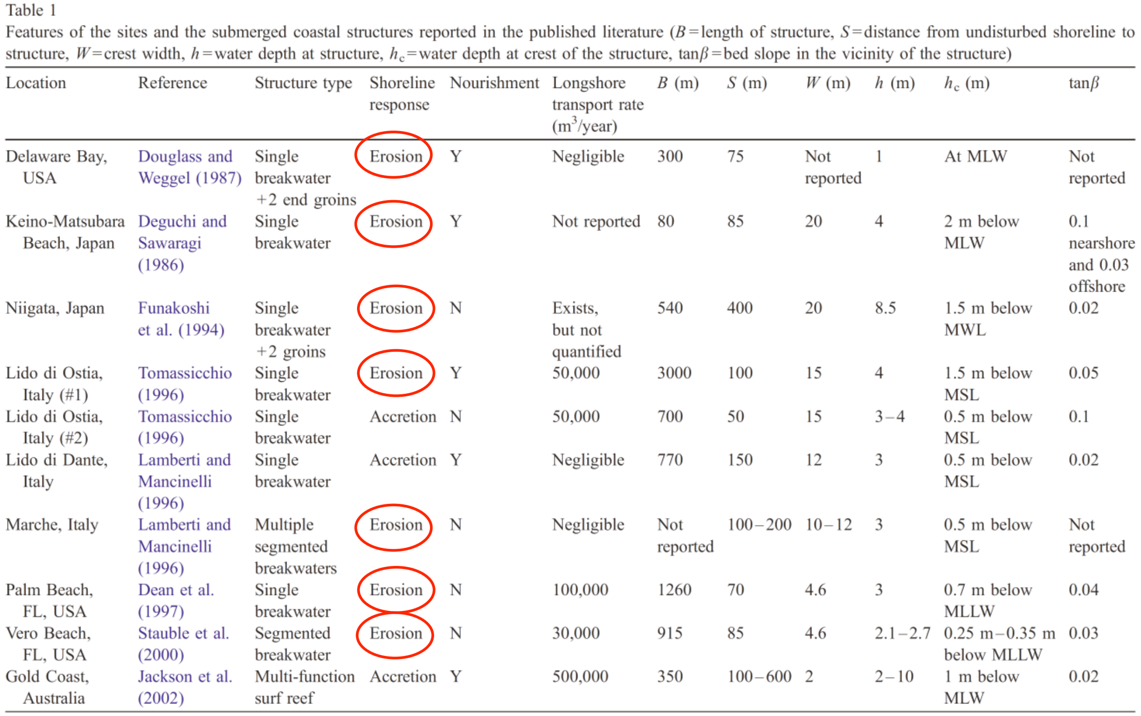
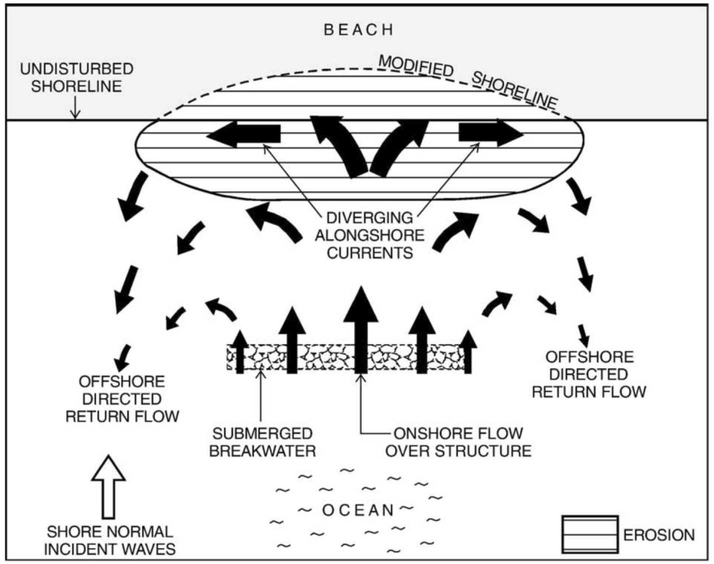


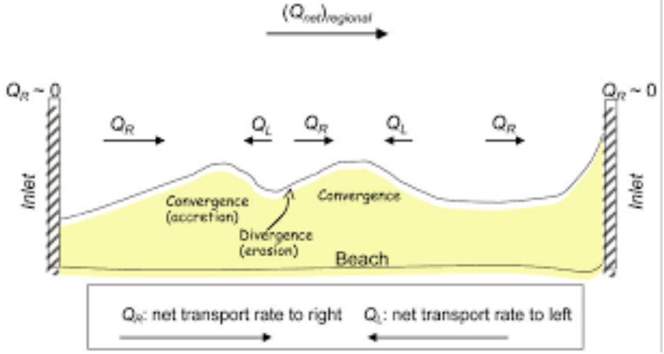
Table 1
Features of the sites and the submerged coastal structures reported in the published literature (B=length of structure, S=distance from undisturbed shoreline to structure, W=crest width, h=water depth at structure, h_c=water depth at crest of the structure, $\tan\beta$=bed slope in the vicinity of the structure)

Location	Reference	Structure type	Shoreline response	Nourishment	Longshore transport rate (m^3/year)	B (m)	S (m)	W (m)	h (m)	h_c (m)	$\tan\beta$
Delaware Bay, USA	Douglass and Weggel (1987)	Single breakwater +2 end groins	Erosion	Y	Negligible	300	75	Not reported	1	At MLW	Not reported
Keino-Matsubara Beach, Japan	Deguchi and Sawaragi (1986)	Single breakwater	Erosion	Y	Not reported	80	85	20	4	2 m below MLW	0.1 nearshore and 0.03 offshore
Niigata, Japan	Funakoshi et al. (1994)	Single breakwater +2 groins	Erosion	N	Exists, but not quantified	540	400	20	8.5	1.5 m below MWL	0.02
Lido di Ostia, Italy (#1)	Tomassicchio (1996)	Single breakwater	Erosion	Y	50,000	3000	100	15	4	1.5 m below MSL	0.05
Lido di Ostia, Italy (#2)	Tomassicchio (1996)	Single breakwater	Accretion	N	50,000	700	50	15	3–4	0.5 m below MSL	0.1
Lido di Dante, Italy	Lamberti and Mancinelli (1996)	Single breakwater	Accretion	Y	Negligible	770	150	12	3	0.5 m below MSL	0.02
Marche, Italy	Lamberti and Mancinelli (1996)	Multiple segmented breakwaters	Erosion	N	Negligible	Not reported	100–200	10–12	3	0.5 m below MSL	Not reported
Palm Beach, FL, USA	Dean et al. (1997)	Single breakwater	Erosion	N	100,000	1260	70	4.6	3	0.7 m below MLLW	0.04
Vero Beach, FL, USA	Stauble et al. (2000)	Segmented breakwater	Erosion	N	30,000	915	85	4.6	2.1–2.7	0.25 m–0.35 m below MLLW	0.03
Gold Coast, Australia	Jackson et al. (2002)	Multi-function surf reef	Accretion	Y	500,000	350	100–600	2	2–10	1 m below MLW	0.02

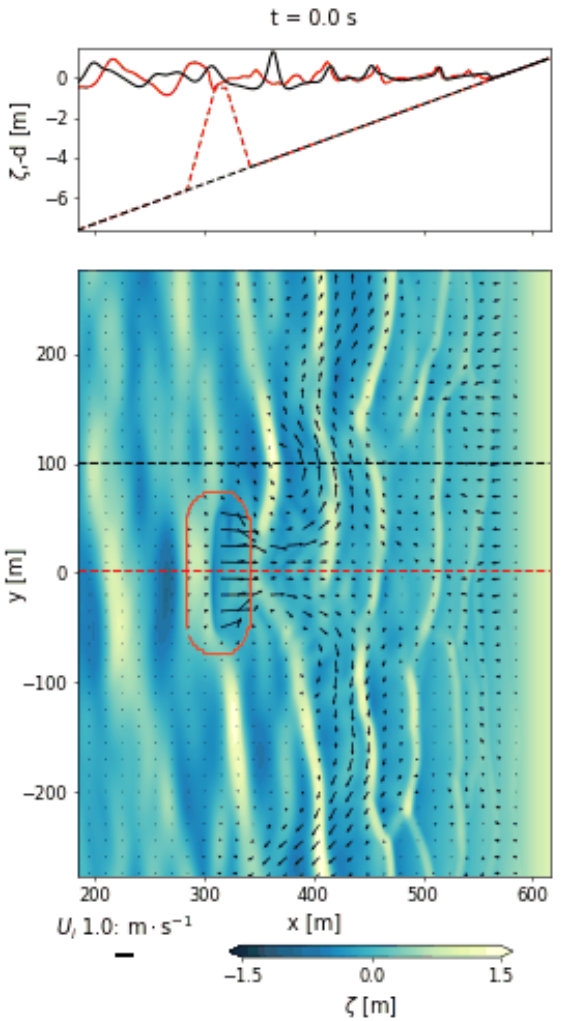
Ranasinghe and Turner (2006)

Assumes diverging wave-driven mean flows lead to erosion



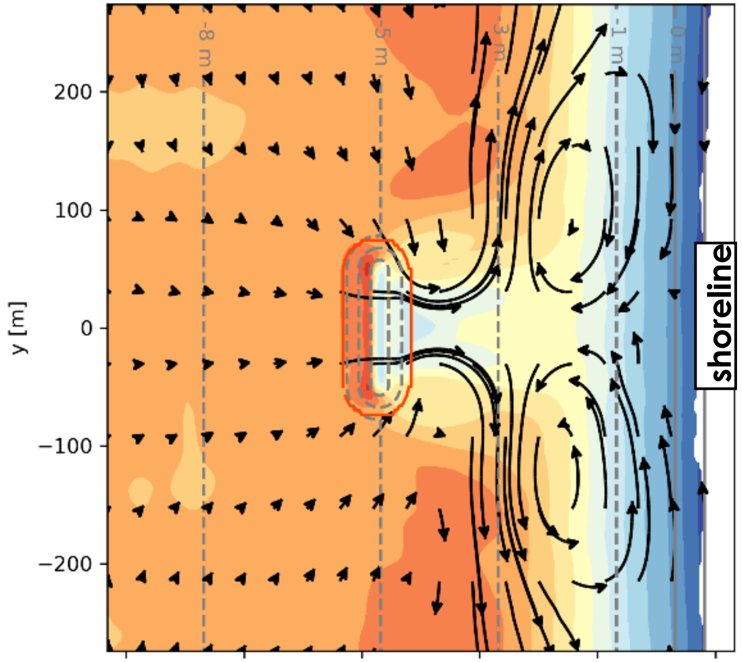


Wave-driven flows over 2DH reefs: implications for shoreline erosion / accretion

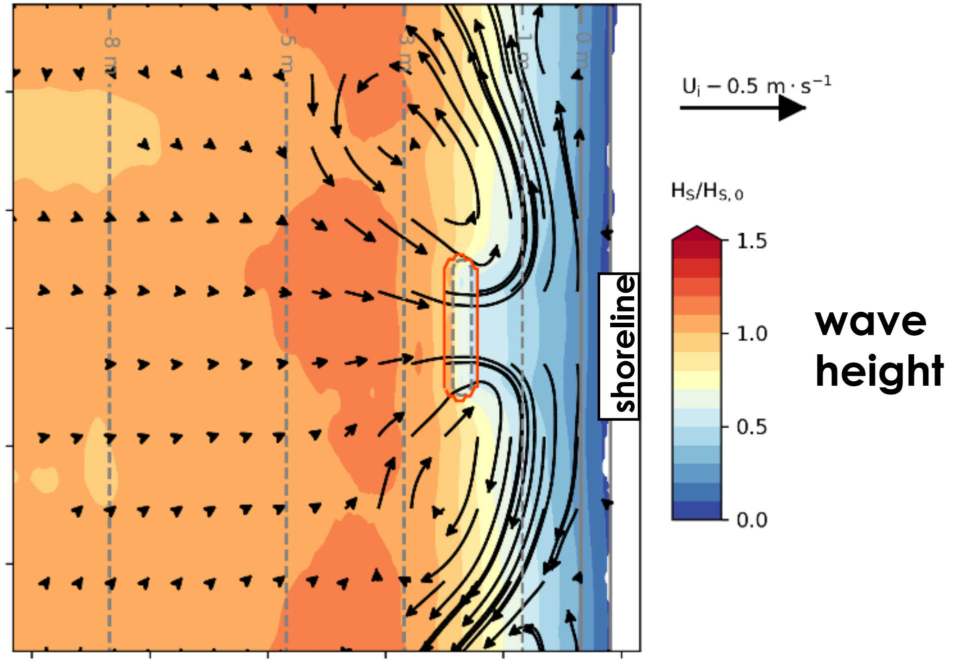


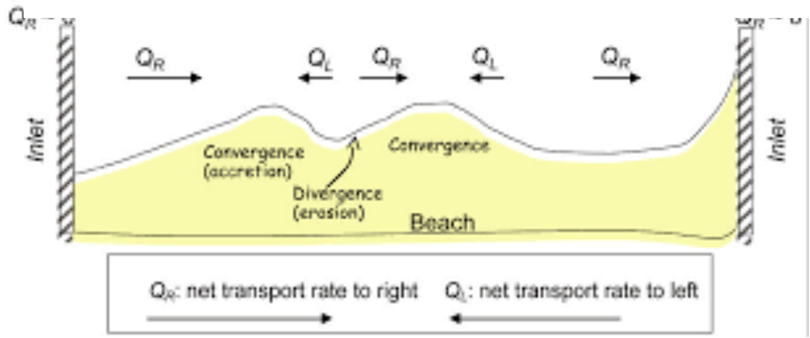
da Silva et al. (2020)

"Four-cell" – shoreline convergence (favours accretion)



"Two-cell" – shoreline divergence (favours erosion)

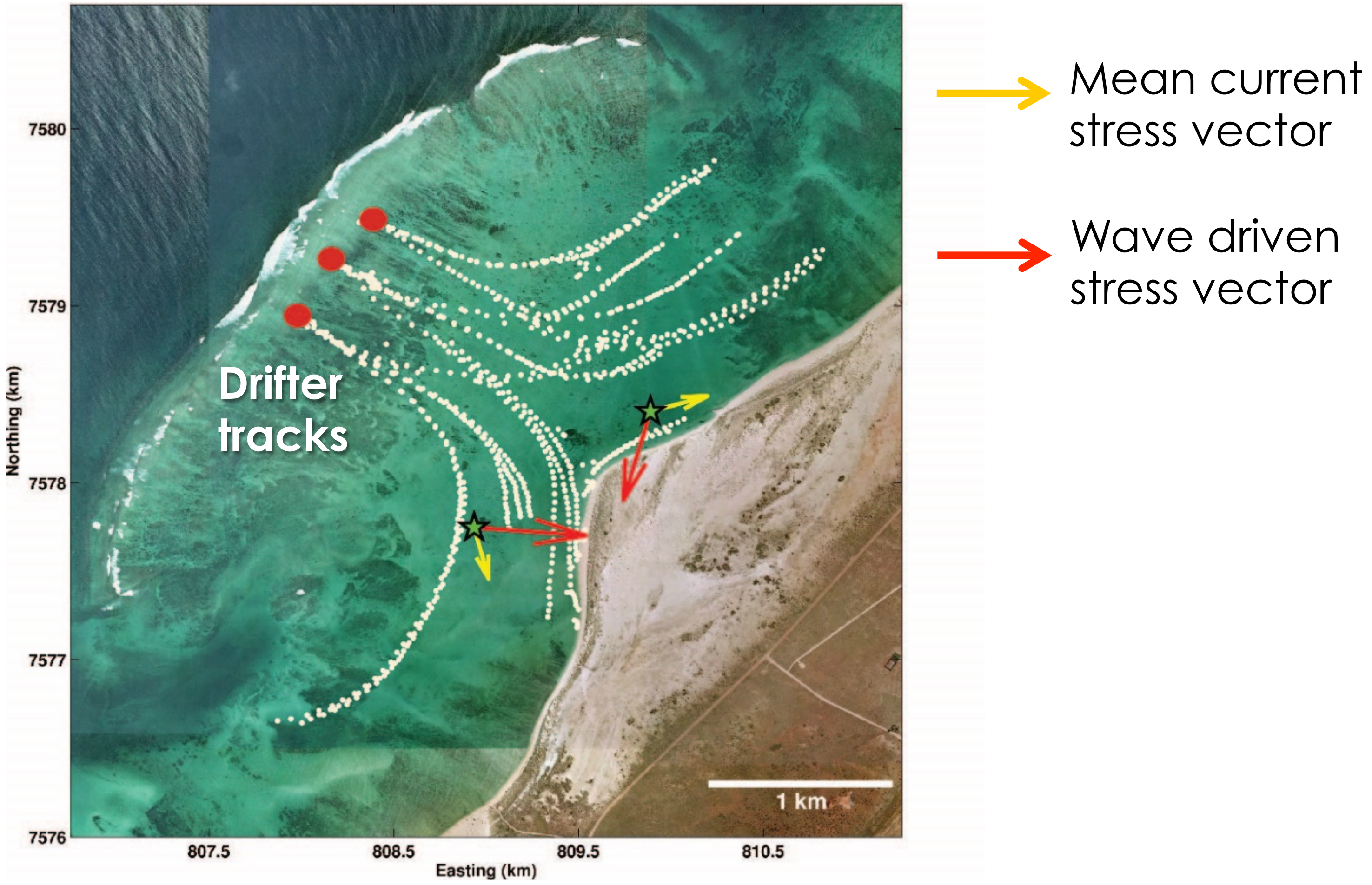




- The shoreline response to submerged reefs (and breakwaters) is influenced by converging / diverging mean current patterns generated by reefs

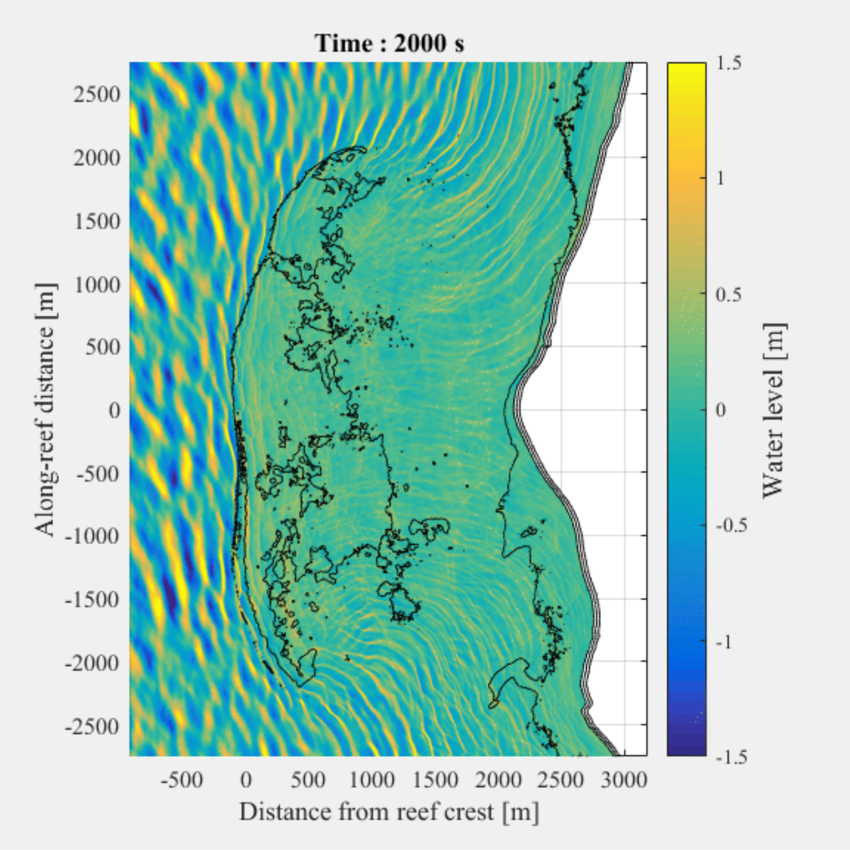
Mechanisms of sediment transport behind reefs (example from Ningaloo Reef)

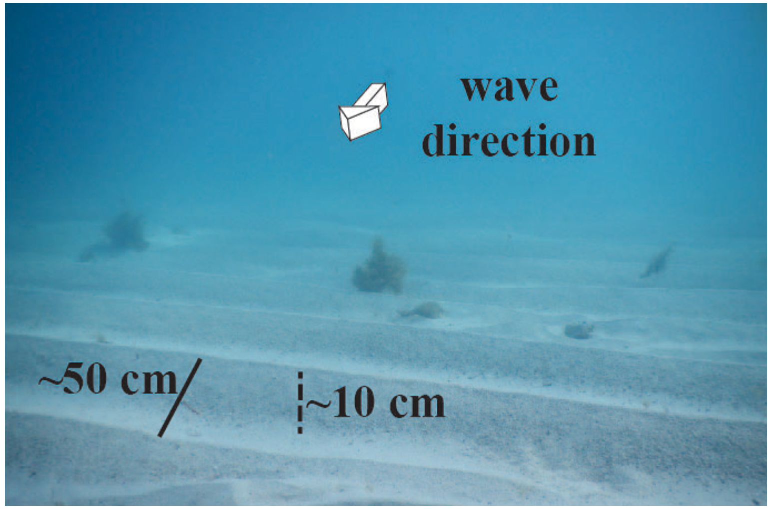
- Large salients extending 10s-100s m seaward are common onshore of fringing coral reefs
- What are the mechanisms that form and maintain these features?

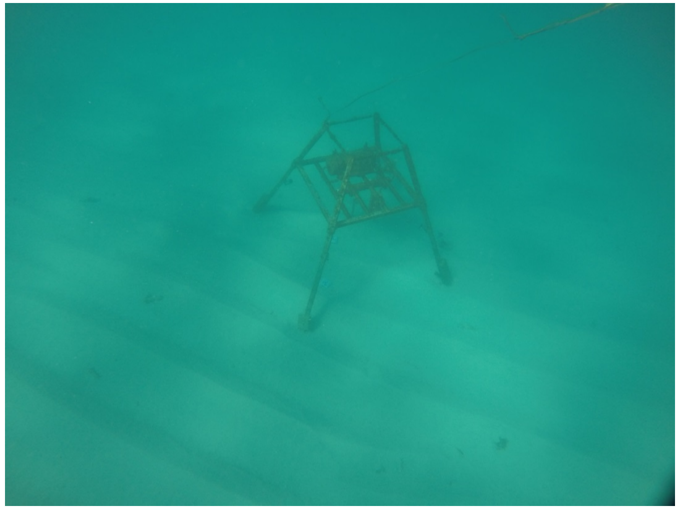


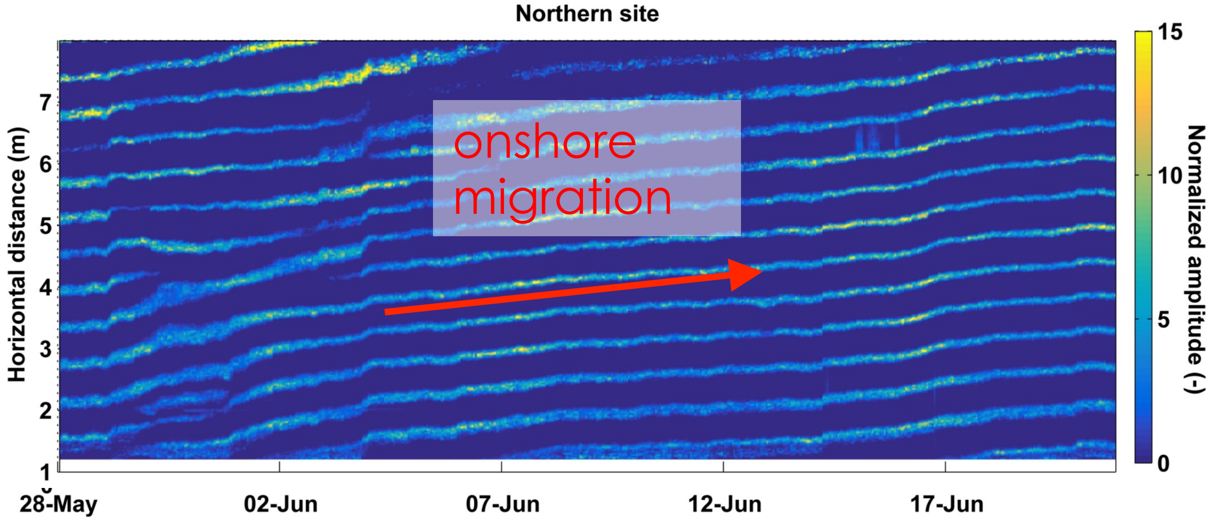
Bedload transport by nonlinear waves

Onshore sediment supply from ripple migration by skewed / asymmetric waves propagating through the channel





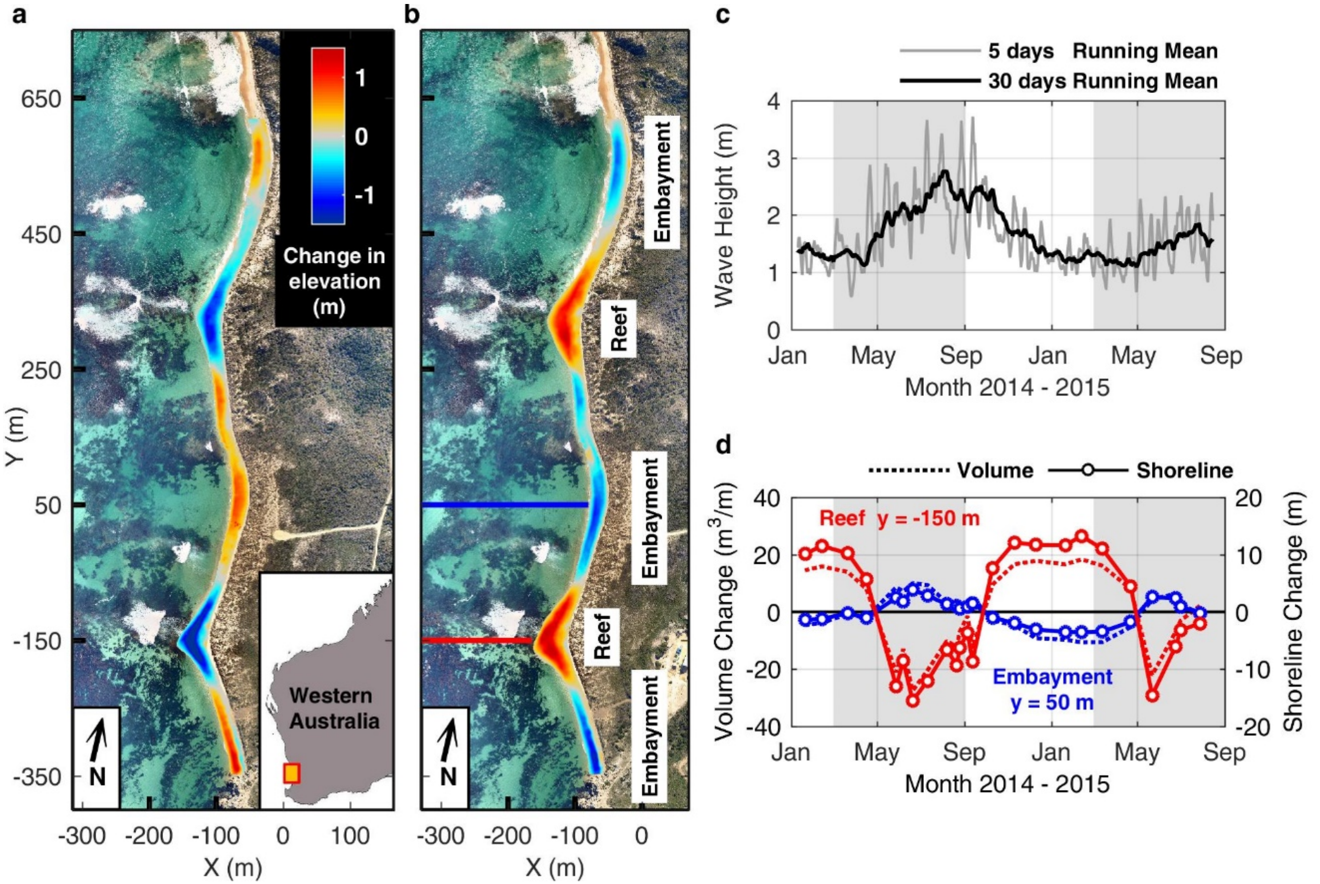




Influence of rocky reefs on seasonal beach erosion and accretion

Beach behaviour along reef fringed coasts can be entirely different than sandy beaches

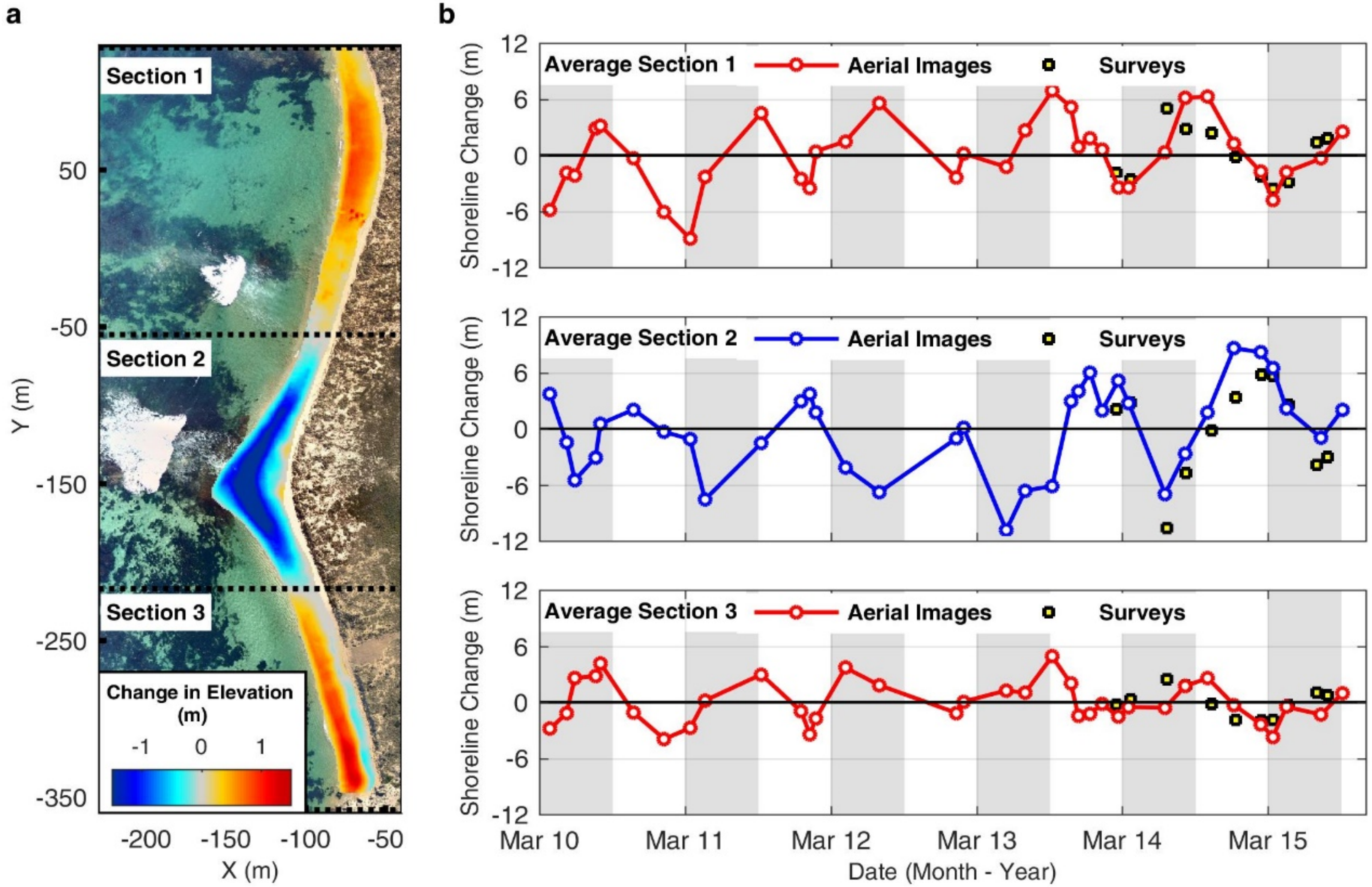
- Seasonal erosion/accretion out of phase between reef-fronted and adjacent embayed beaches (no net sub-aerial volume change)
- This behaviour not reproducible by any conventional coastal morphodynamic model!

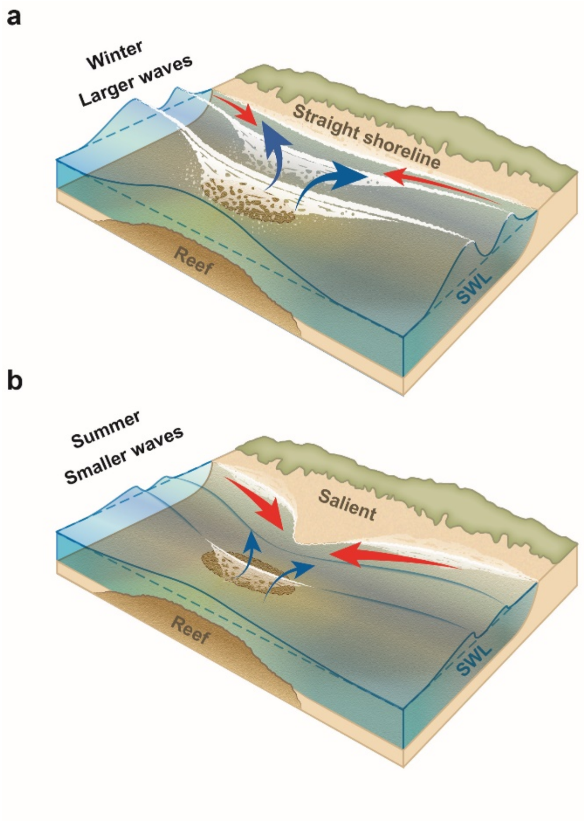


Segura et al., 2016, JGR

Influence of rocky reefs on seasonal beach erosion and accretion

Shoreline variability (5 years)





Summary

- Ecosystems shape nearshore processes by dissipating wave energy by ***drag forces*** and ***wave breaking***
- Prediction of **drag dissipation** requires robust descriptions of how flows interact with the complex geometries and material properties of habitat-forming organisms
- **Wave breaking** over steep, shallow ecosystems (e.g. reefs) effectively dissipates sea-swell energy but can be converted to other forms (i.e. enhanced setup, low-frequency waves and mean currents) that contribute to flooding and erosion

Australian Government
Australian Research Council