Coastal Hydrodynamics and Morphology

Coastal hydrodynamics along tropical coastlines: mangroves and coral reefs

IHE DELFT

What is different relative to the beach in Scheveningen?

What is different relative to the beach at Scheveningen?

Outline

- Coral reefs
  - Characteristics and spatial distribution
  - Morphological characterisation of reef-lined coasts
  - Hydrodynamic processes

- Mangroves
  - Characteristics and spatial distribution
  - Hydrodynamic processes in mangals

Today you will learn…

- …where you can find coral reefs and mangroves
- …what differentiates these environments from clastic (sand/gravel) coasts
- …which concepts from ‘regular’ sandy beach hydrodynamics you can apply in these environments, and which ones you cannot

Coral reefs

Corals

Animals living in symbiosis with algae (zooxanthellae)

- Animal consists of polyps
- Carnivorous suspension feeder
- Builds carbonate housing for protection
- Skeleton remains after polyp dies off

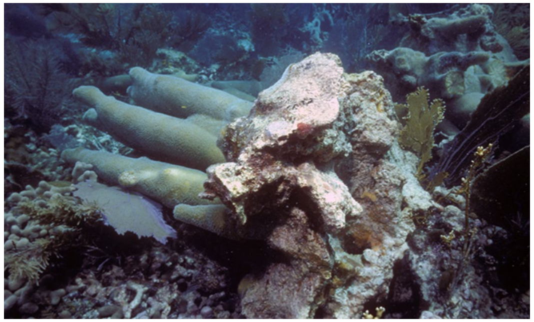
coral polyp with tentacles

What is a “coral reef”

- B
  –
  –
  – other
- G
  –
  –
  –
  –
  –

Building the reef

$CaCo_3$ addition	- $CaCo_3$ loss	=	Accumulation
Biogenic production	Biological erosion		Reef Growth
Sediment Import	Mechanical erosion		
Cementation	Sediment export, dissolution		



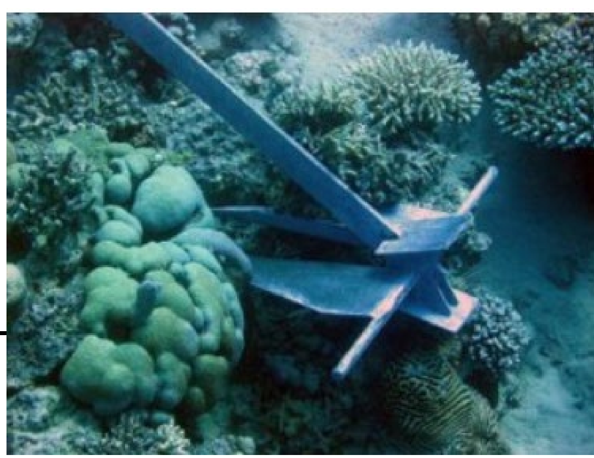
Kleypas et al 2001; pictures NatGeo, NOAA

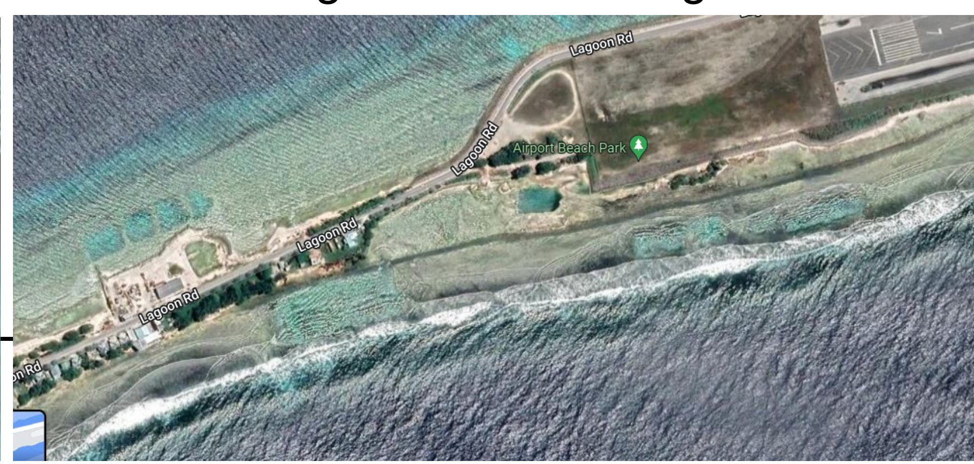
Why are reefs important?

- Coral reefs most biodiverse systems in the world (more so than rain forests)

- Reefs and mangroves offer ecosystem services worth more than 375 billion EUR/yr, such as fisheries, tourism and coastal protection (see next slide)

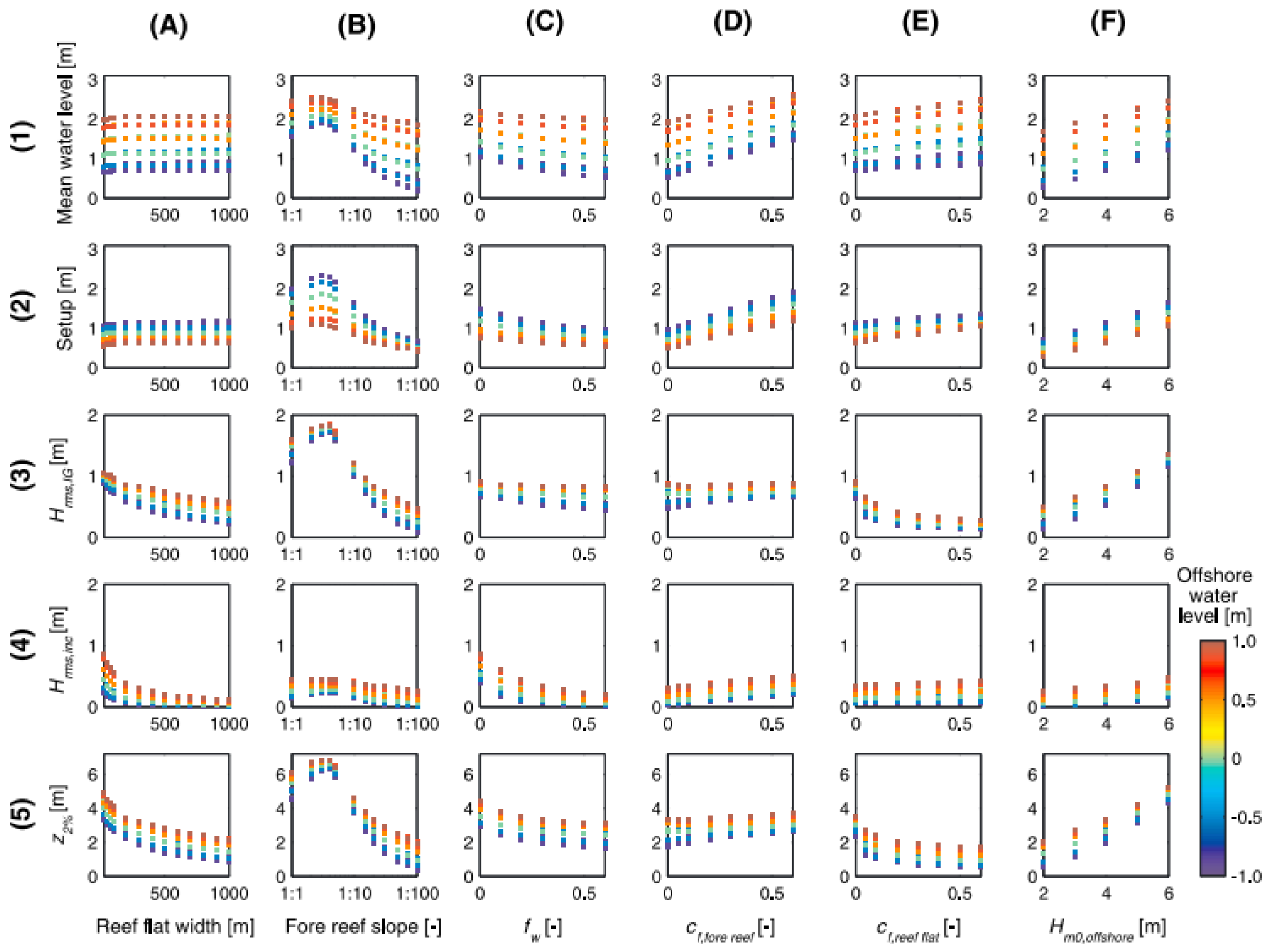
- Threats to coral reefs
  - *Natural*: bleaching, predation, acidification, sea level rise, storms
  - *Anthropogenic*: Pollution, overfishing, destructive fishing practices using dynamite or cyanide, tourism and mining coral for building materials





Why

Response



Reef characteristics

Figure 4. Response of nearshore hydr… …haracteristics (columns a–f) for hourly varying offshore water levels (colors). W… …with steep fore reef slopes and deep, smooth reef flats with low coral coverage. Higher water levels, higher waves, and lower bed roughness—all expected effects of climate change—will therefore result in greater wave runup and, thus, coastal flooding.

Quataert et al 2015

Types of reef

"*Classic*" subdivision: Fringing, Barrier, Atoll, Drowned

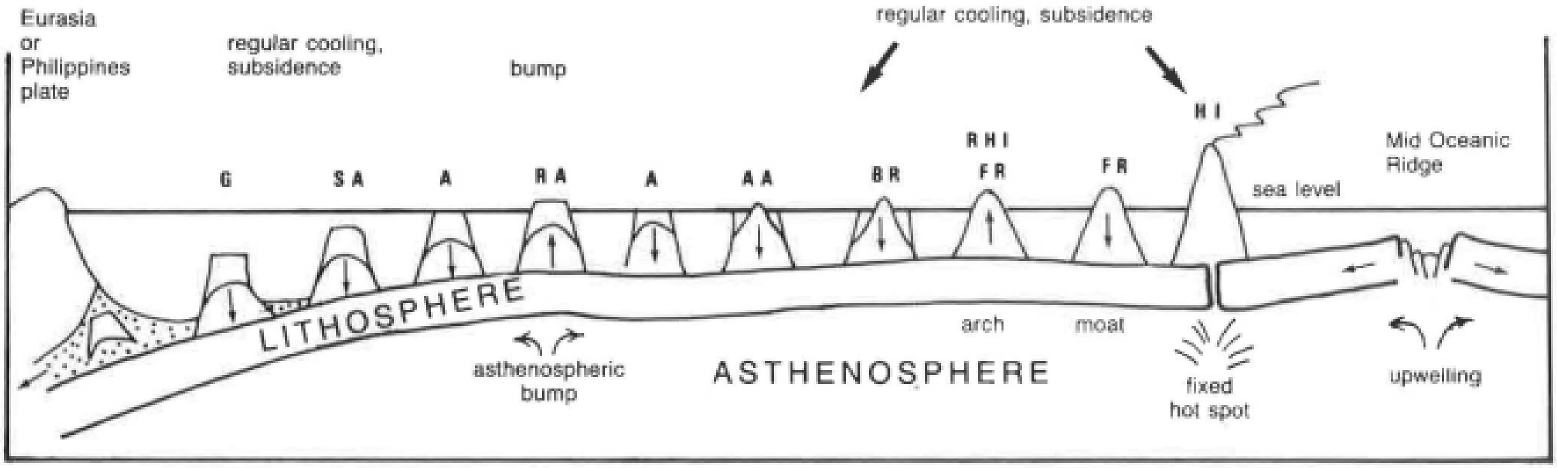


Fig. 59 Proposed model for island development on the Pacific plate. Simplified after Scott and Rotondo (1983). HI: high island; FR: fringing reef; RHI—FR: raised high island with fringing reef; BR: barrier reef; AA: almost-atoll; A: atoll; RA: raised atoll; SA: submerged atoll; G: guyot. Arrows indicate subsidence or emergence

Guilcher 1988

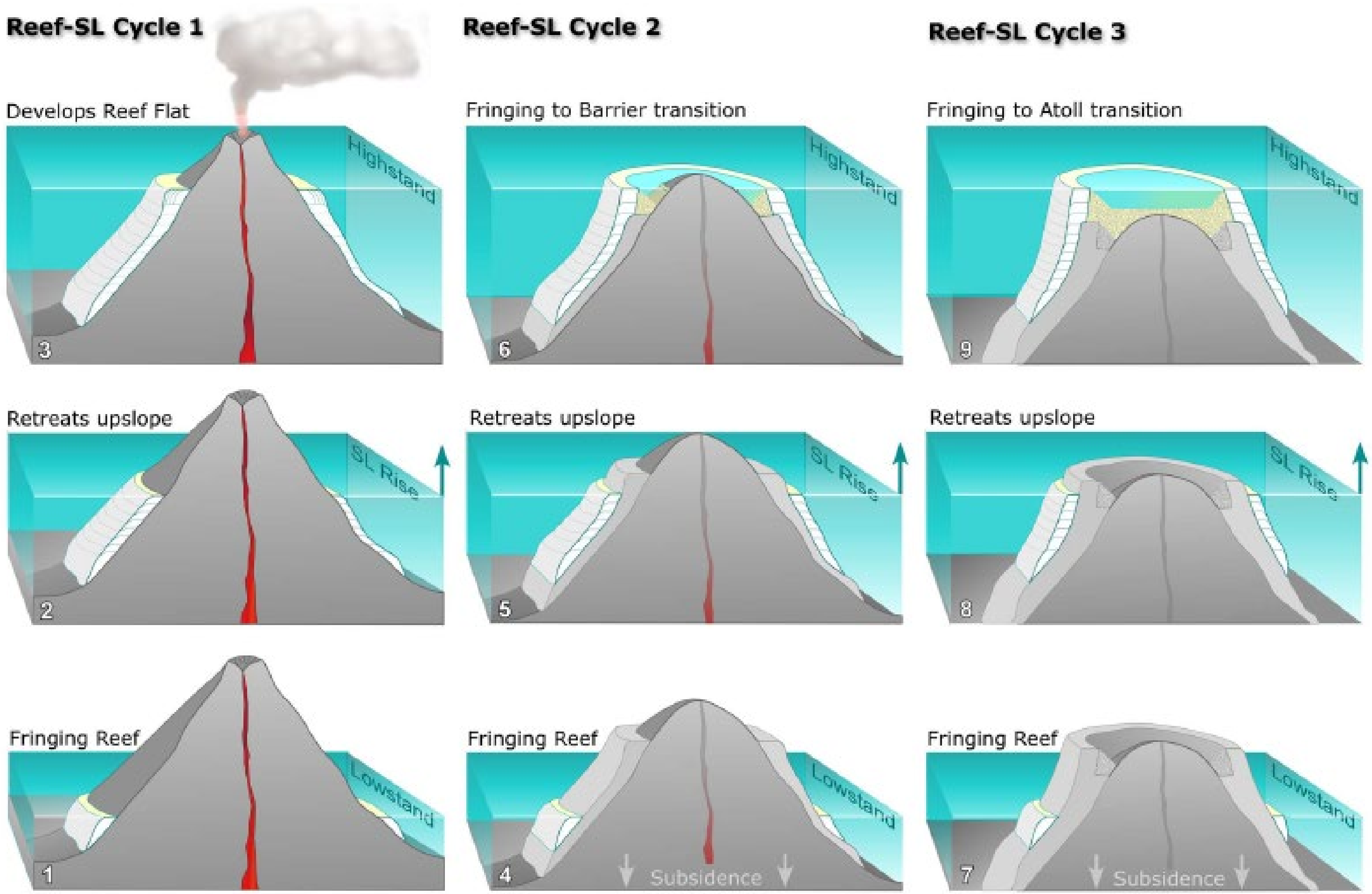
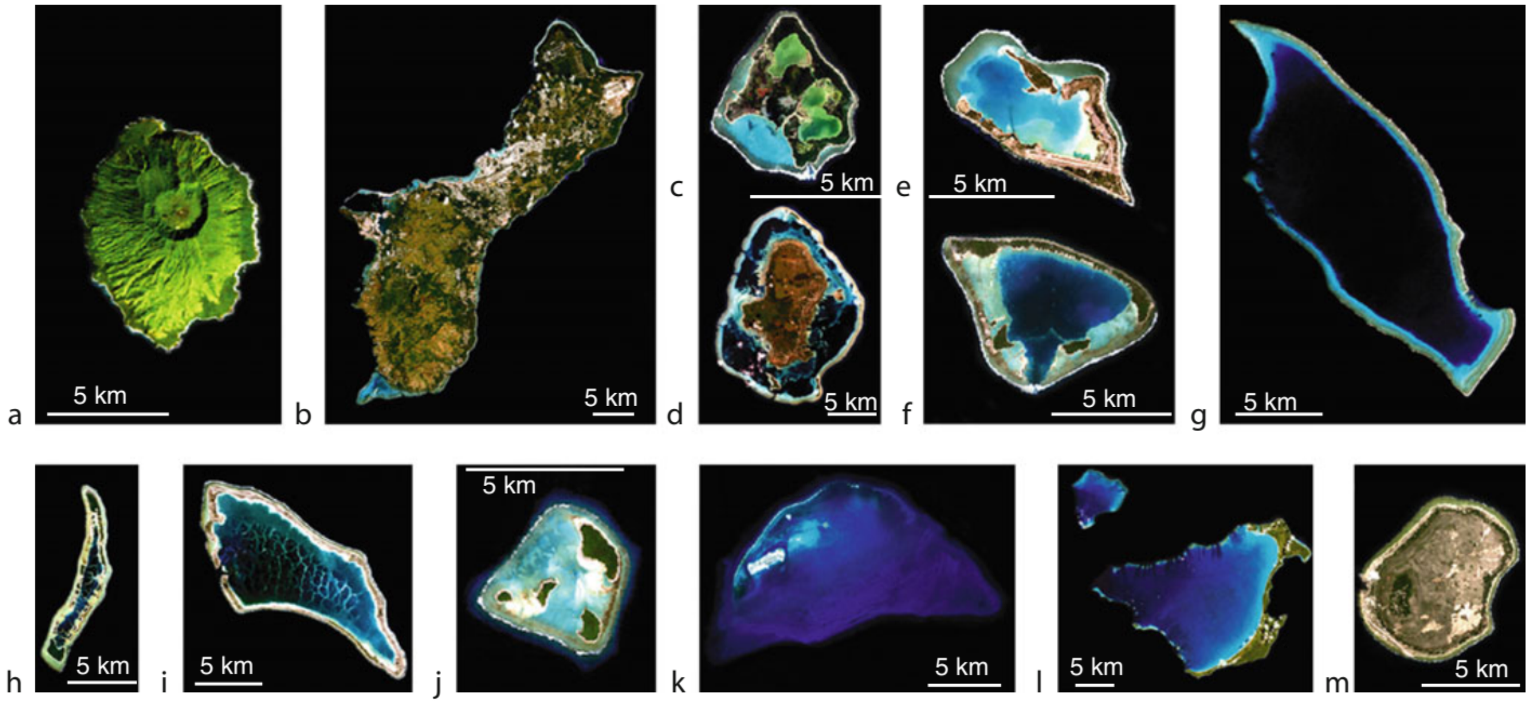


Figure 5 | Fringing-reef retreat controls the transition between reef types during glacio-eustatic SL cycles. The first SL cycle starts with a fringing reef during the glacial lowstand (1). During the rapid postglacial transgression, the reef is forced to retreat upslope due to its low accretion rate (2). Only as SL rise slows into the interglacial, can the fringing reef advance seawards producing a reef flat (3). Following glacial SL fall, the second cycle begins, as before, with a fringing reef retreating upslope with the transgression (4). This time, however, it encounters the former reef-flat platform at a lower elevation due to island subsidence. The slight reverse slope of the platform prevents further upslope retreat and fixes the reef on its rim, producing a lagoon that traps coastal sediment (5). Isolated from sediment, the reef is colonised by fast-growing acroporids which allow it to accrete vertically and keep pace with SL rise, producing a barrier reef (6). In the final cycle, subsidence and erosion displace the volcanic peak below the highstand elevation (7), so that when the fringing reef reaches the rim of the former barrier-reef flat (8), it can accrete vertically and transform into an atoll (9).

Blanchon 2014

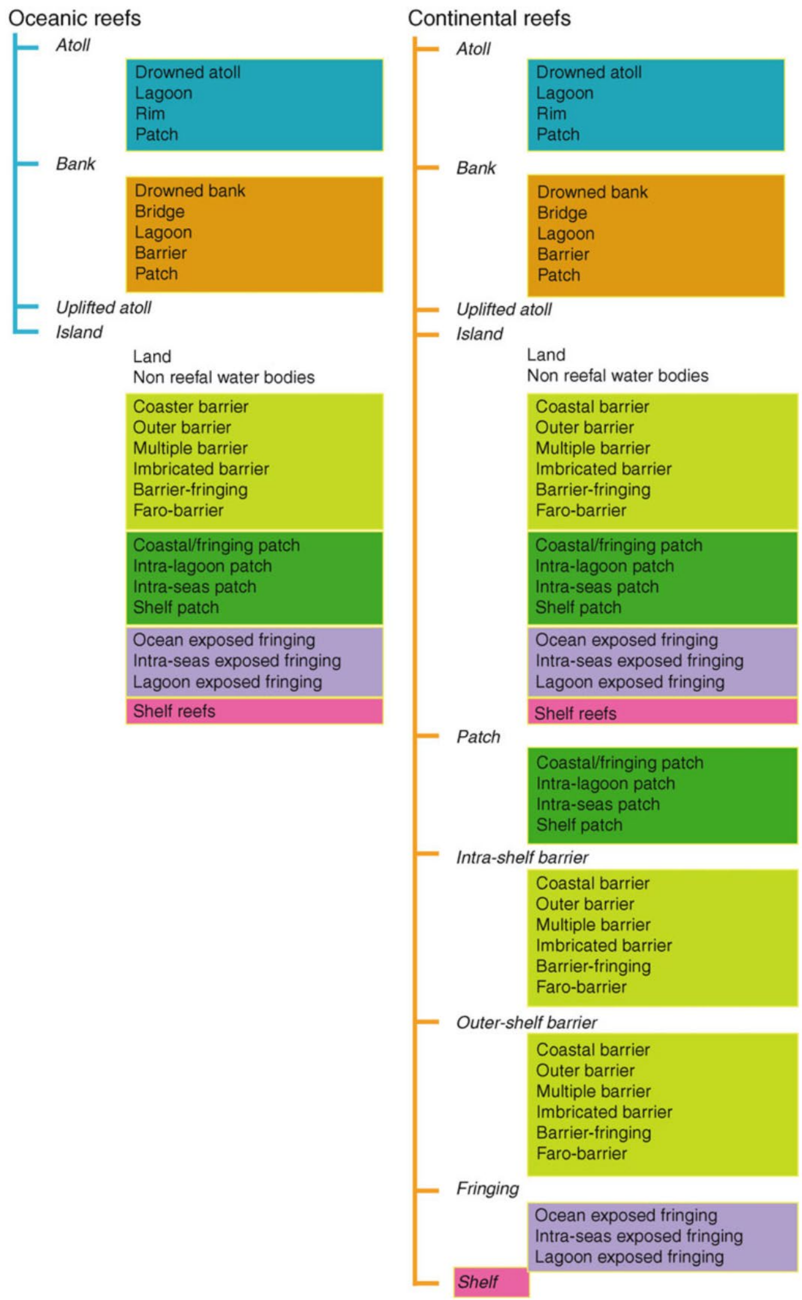
Types of reef



Reef Typology, Figure 1 Examples of the diversity of Pacific Ocean atoll and island types viewed by Landsat 7 satellite. (**a**) Agrihan, an island without fringing reef (Northern Marianas Islands); (**b**) Guam, an island with fringing reef; (**c**) Maiao, an island with widening fringing reefs and shallow lagoons (French Polynesia); (**d**) Wallis Island, an island with a deep lagoon and a barrier reef (Wallis and Futuna, France); (**e**) Wake Island, a shallow lagoon atoll (United States); (**f**) Haraiki atoll, a deep atoll lagoon with a wide pass and reef islands (French Polynesia); (**g**) Osprey Reef, a deep atoll without islands, and narrow reef flats (Coral Sea, Australia); (**h**) Caroline, an atoll with shallow small reticulated basins (Line Island, Kiribati); (**i**) Kanton, an atoll with deep lagoon and reticulated reefs and rim islands (Phoenix Island, Kiribati); (**j**): Maria Ouest, a shallow lagoon atoll with islands (French Polynesia); (**k**) Johnston Atoll, an almost-drowned bank(United States); (**l**) Ouvea Atoll (right side), a raised atoll with deep lagoon (New Caledonia); (**m**) Nauru, a raised atoll without lagoon.

Andrefouet 2011

Types of reef

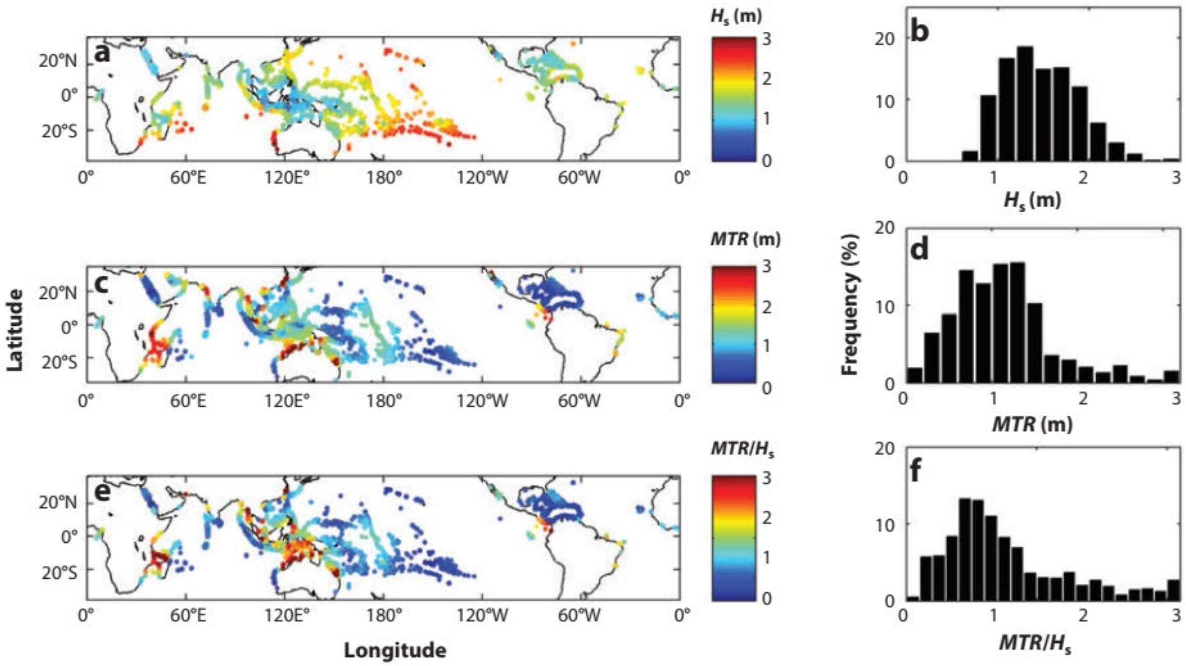


Andrefouet 2011

Environmental requirements

Physical environment

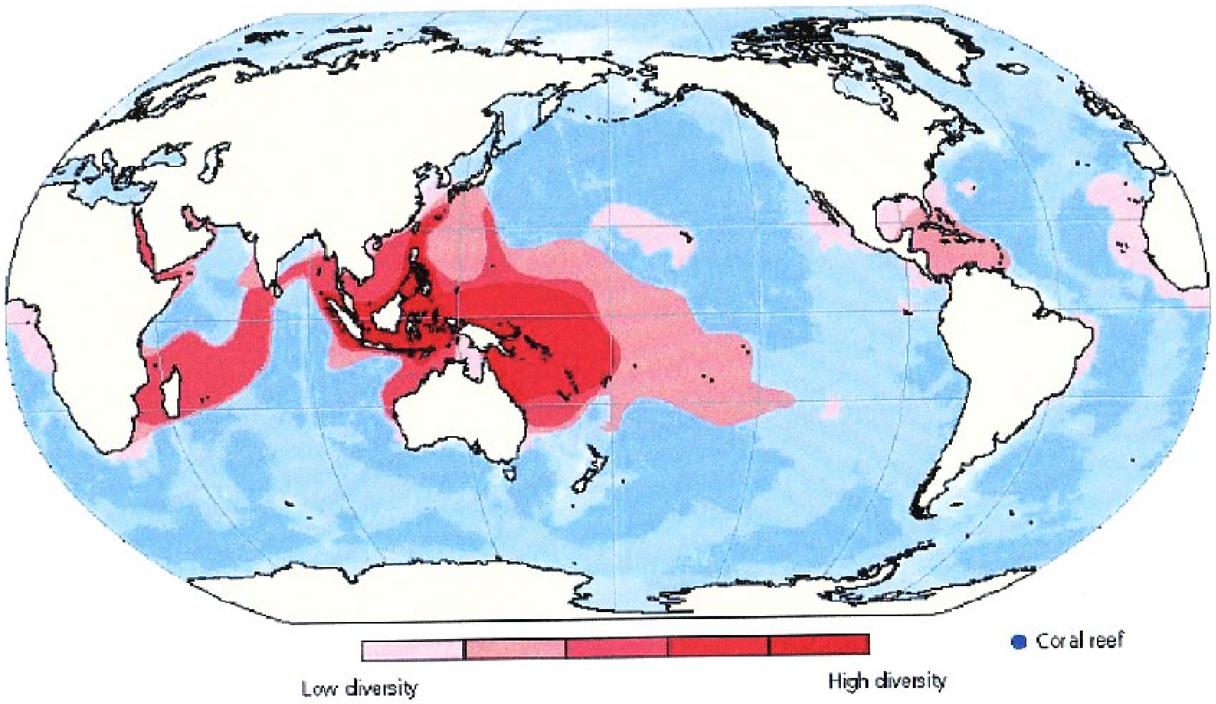
- Water temperature of 25-31^{o}C (limited Northwards by the 18^{o}C minimum isotherm)
- Salinity of 27-40 ppt
- Light level: non-turbid waters, mostly in top 30 m of depth
- Hydrodynamics not important constraint on distribution



Lowe&Falter 2014

Coral distribution and diversity patterns

Indo-Pacific and Caribbean ‘provinces’



- Effect of upwelling of cold water on west coasts
- Decline with latitude

Morphology of reef systems

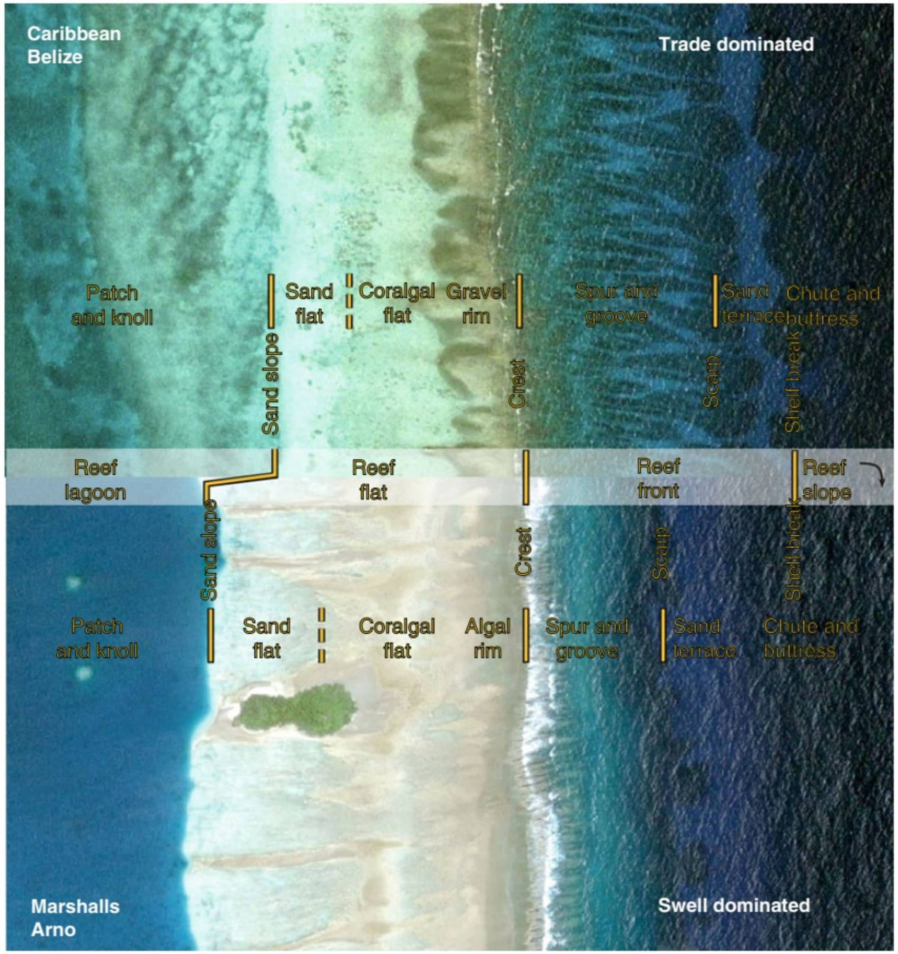
Profoundly different systems than sandy beaches

Steep slopes (~1:20 to 1:1)

Complex 3D morphologies

Large bottom roughness

Morphology of reef systems

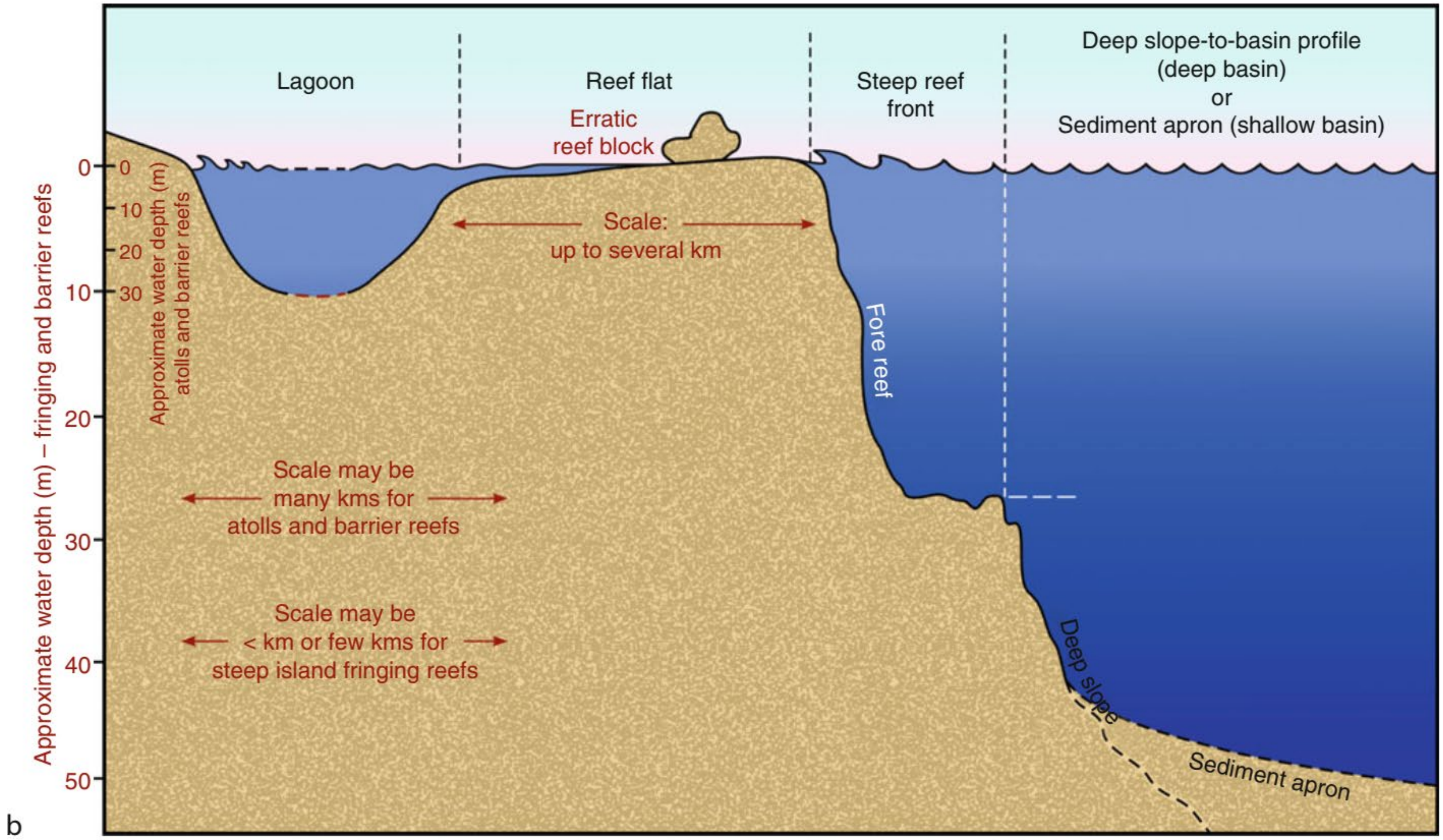


Geomorphic Zonation, Figure 1 Geomorphic zonation of rough-water reefs. Both swell- and trade-wind-dominated reefs develop five standard reef zones: lagoon, reef flat, reef front, reef slope, and fore reef (not shown). These zones are delineated by simple slope breaks: the sand slope between lagoon and reef flat, the reef crest between the reef flat and reef front, the shelf break between the reef front and reef slope, and the break between the subvertical lower slope and the talus cones of the fore-reef sediment. These standard zones are divided into several widely occurring subzones, which vary with respect to margin orientation, area, and region. Images copyright of Google Earth, DigitalGlobe and GeoEye, 2010.

Four ‘standard’ geomorphological zones

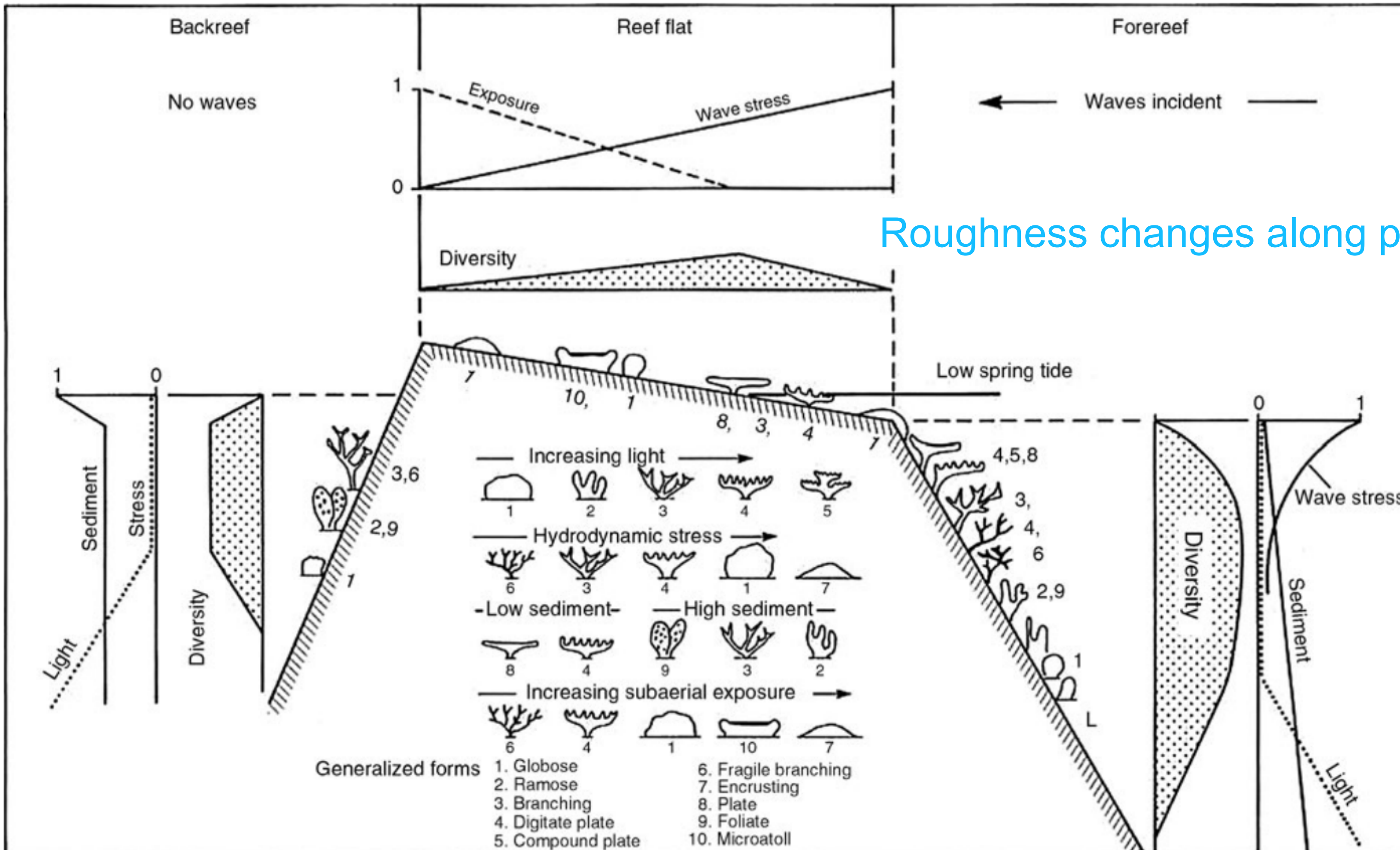
Blanchon 2014

Morphology of reef systems



Lugo-Fernández 2014

Species zonation



Roughness changes along profile!

Chapell 1980

Hydrodynamics of reefs

Hydrodynamic forcing

- Waves
- Tides
- Winds
- Baroclinic pressure gradients: temperature

Physical concepts are essentially the same as on sandy beaches, but:

- Relative importance of processes and time scales differ
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Hydrodynamics of reefs

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Hydrodynamics of reefs - Waves

Over most reefs, wave-driven currents dominate circulation

Wave action balance:

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x}\left(EC_g \cos\left(\vartheta\right)\right) + \frac{\partial}{\partial y}\left(EC_g \sin\left(\vartheta\right)\right) = -D$$

$$E = \rho g < \eta^2 > = \frac{1}{2}\rho g a^2 = \frac{1}{8}\rho g H_{rms}^2$$

Wave energy

Group velocity

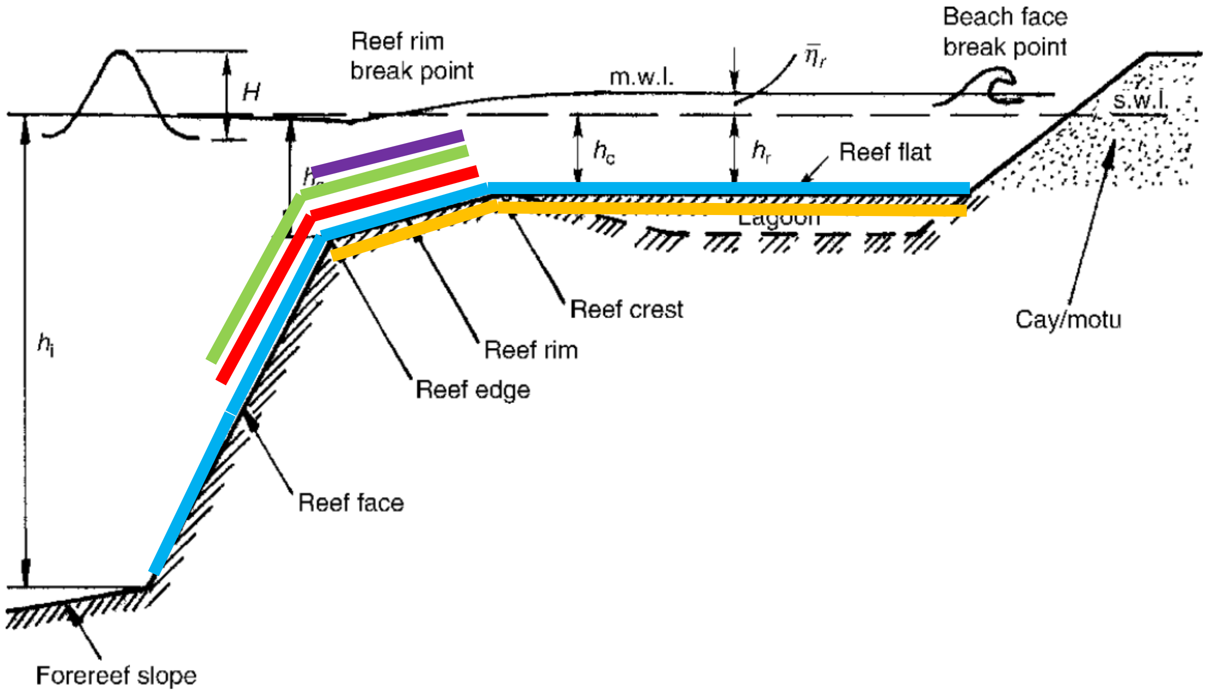
Wave angle

Wave dissipation

Hydrodynamics of reefs - Waves

Wave transformation processes

- *Bottom friction*: wave amplitude decreases
- *Refraction*: wave crests parallel to the reef crest
- *Shoaling*: group velocity decreases, amplitude increases
- *Breaking*: wave amplitude decreases
- *Energy transfers* to super- and subharmonics: generation of long waves



Hydrodynamics of reefs - Waves

$$\frac{\partial E}{\partial t}+\frac{\partial}{\partial x}\left(EC_g\cos(\vartheta)\right)+\frac{\partial}{\partial y}\left(EC_g\sin(\vartheta)\right)=-D$$

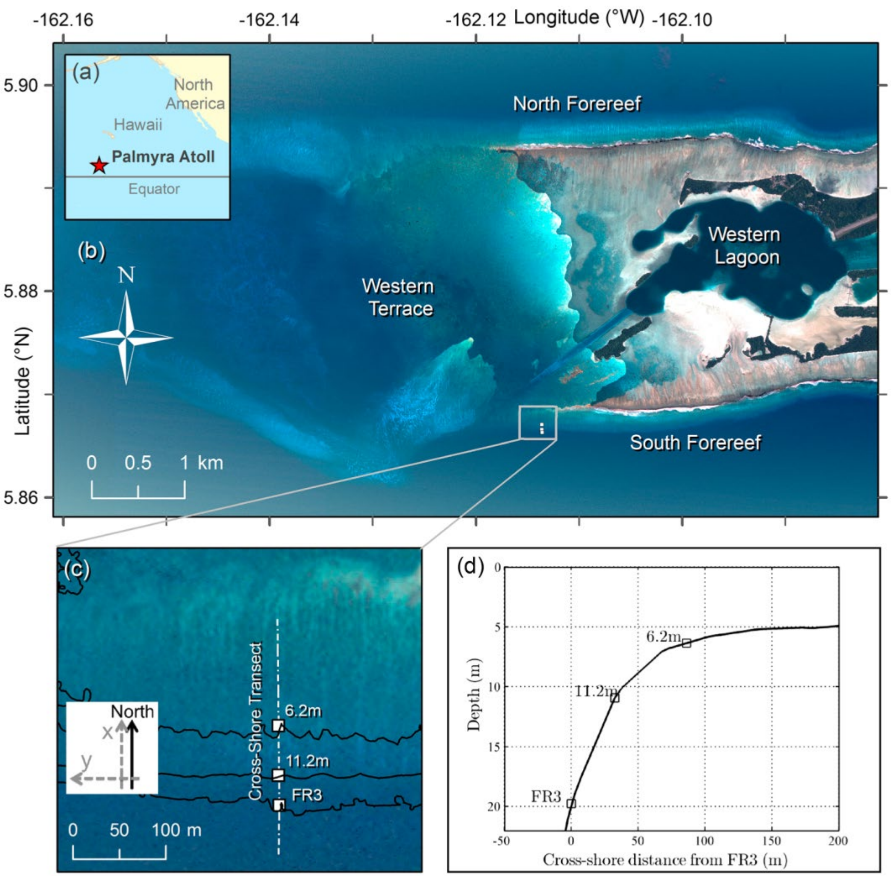
$$E=\rho g<\eta^2>=\frac{1}{2}\rho g a^2=\frac{1}{8}\rho g H_{rms}^2$$

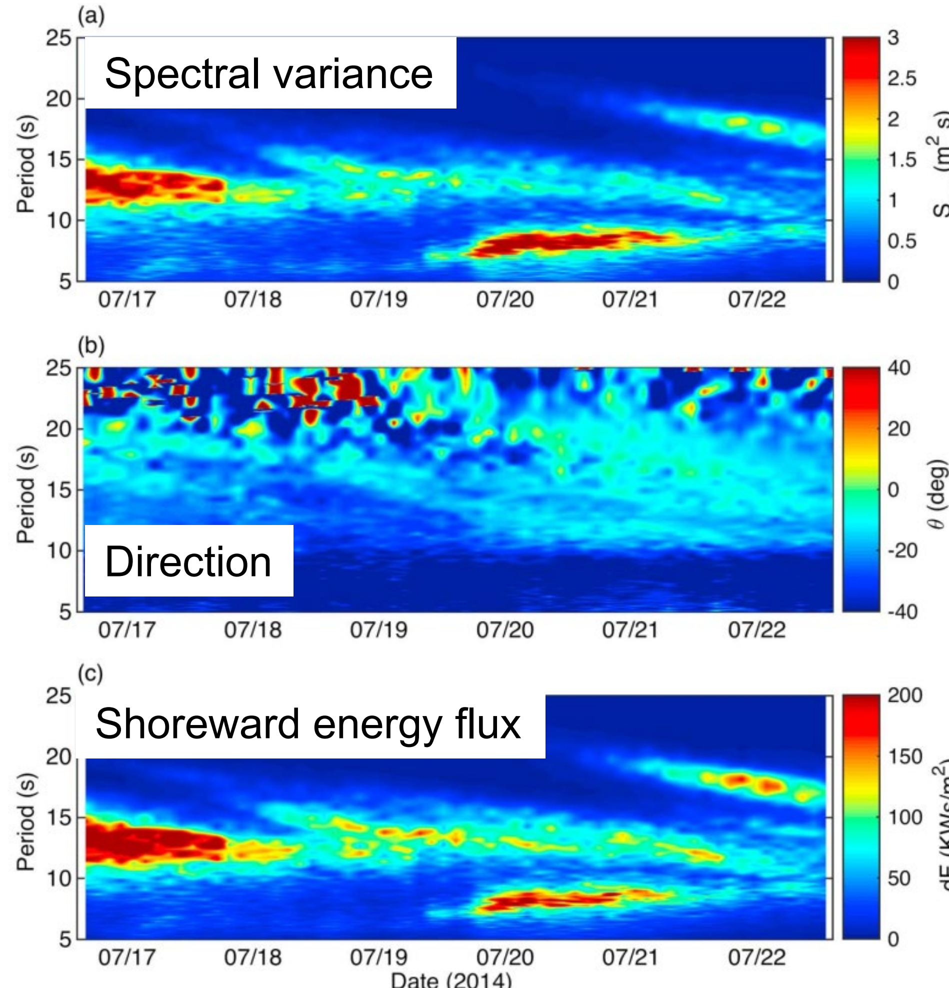
Wave dissipation D has 2 contributions on reefs:

- Wave breaking D_b , see before;
- Bottom friction D_f, averaged over wave group:

$$\left\langle D_f\right\rangle=\left\langle \tau u_{orb}\right\rangle=\frac{2}{3\pi}\rho f_w u_{orb}^3$$

Hydrodynamics of reefs – Frictional wave dissipation

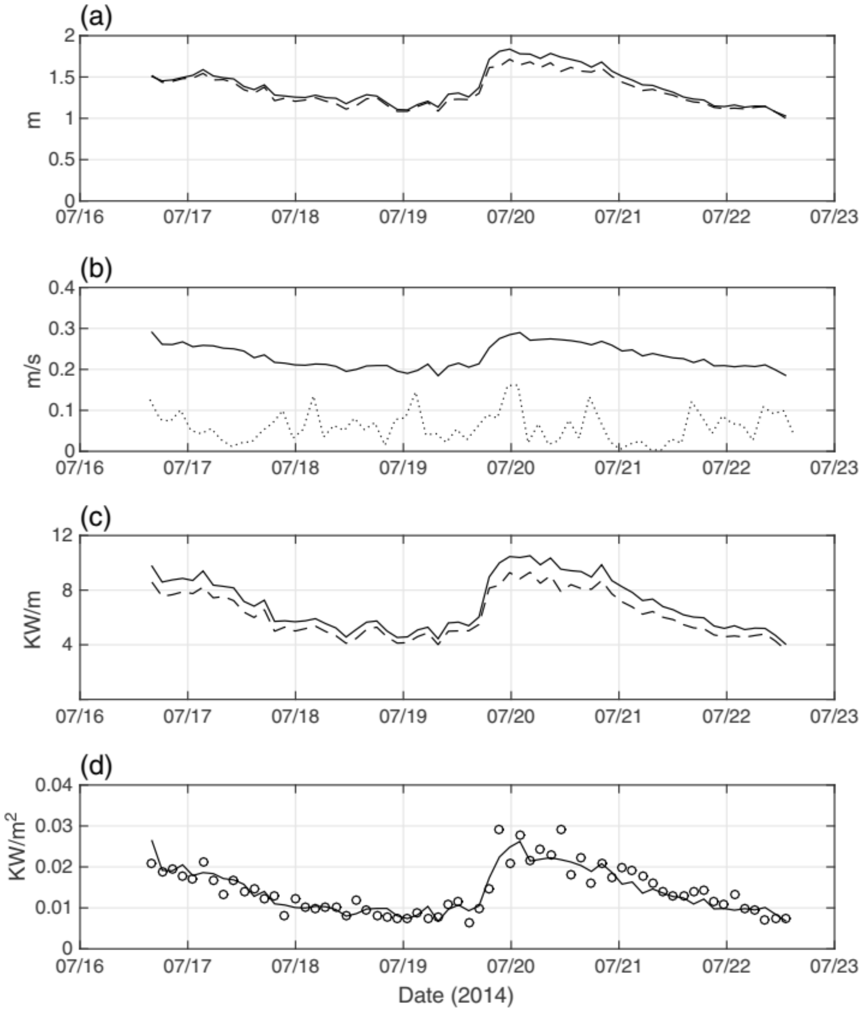




outside the surf zone!

Monismith 2015

Hydrodynamics of reefs – Frictional wave dissipation



wave height 11m (full) and 6m depth (dash)

u_{orb} (full) and u_{mean} (dash)

E*Cg 11m (full) and 6m depth (dash)

Measured dissipation (dots) and calculated friction using

$$\langle D_f \rangle = \langle \tau u_{orb} \rangle = \frac{2}{3\pi} \rho f_w u_{orb}^3$$

Monismith 2015

Hydrodynamics of reefs – Steady wave setup on reefs

- Shoaling under steady wave conditions

$$\frac{\partial(ECg\cos\theta)}{\partial x}=0$$

When the depth decreases, but *before* the breaker depth, Cg decreases. To maintain the constant gradient, E should grow. The waves become higher.

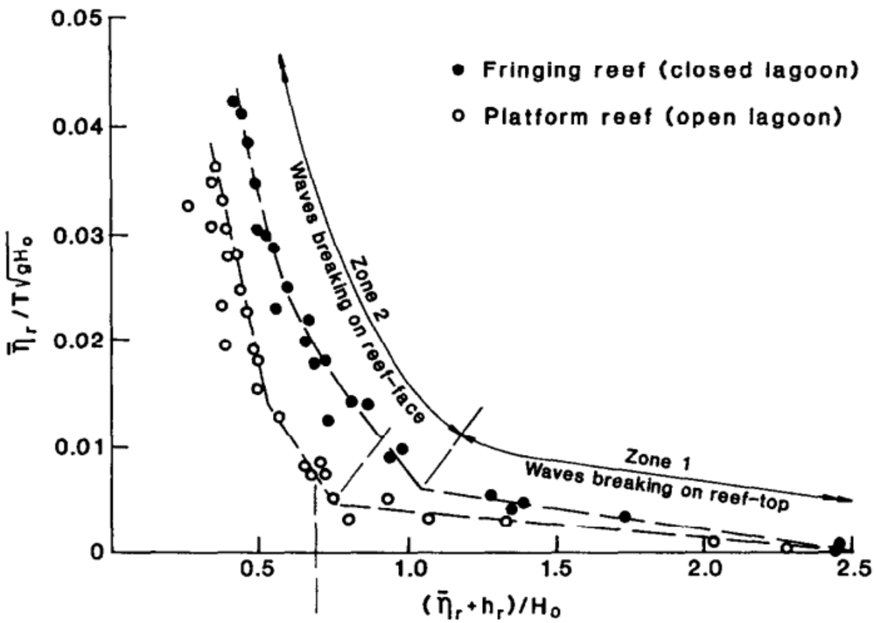
- Wave breaking under steady wave forcing

$$\frac{\partial(ECg\cos\theta)}{\partial x}=-D_b$$

When the depth reaches the breaker depth, waves break and transfer energy to lower frequencies and turbulence (D_b). To maintain the constant gradient (Cg≈C ≈constant), E should decrease. The waves become smaller.

Hydrodynamics of reefs – Steady wave setup on reefs

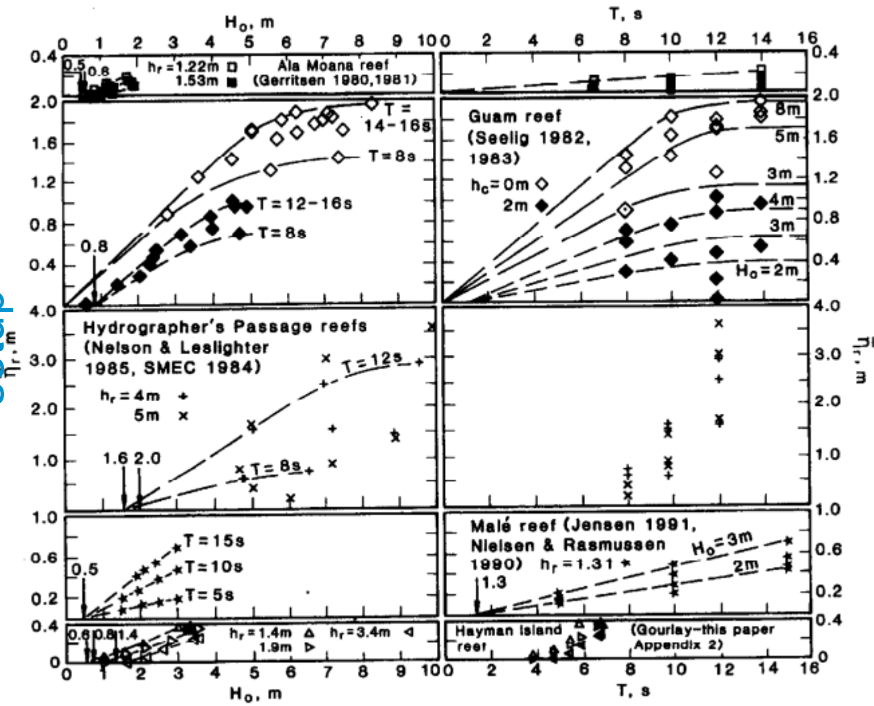
TIDE EFFECT



setup

submergence

WAVE CHARACTERISTICS



setup

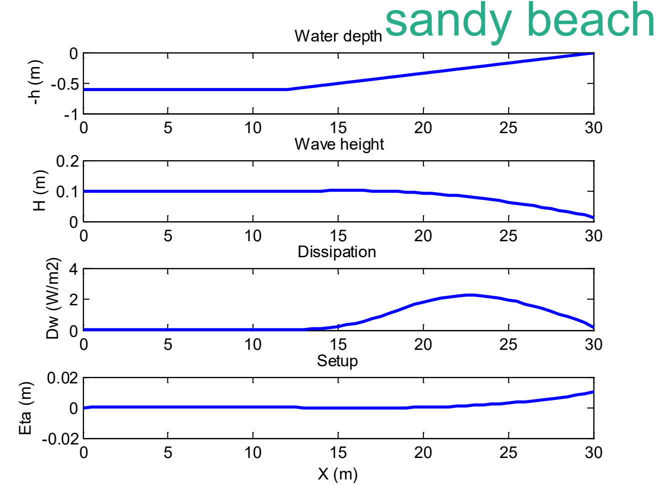
Wave height

Period

$$g\frac{\partial \eta}{\partial x} = \frac{F_x}{\rho h} \Rightarrow \frac{\partial \eta}{\partial x} = \frac{1}{\rho g h}\frac{\partial}{\partial x}\left[\left(2n - \frac{1}{2}\right)E\right]$$

Gourlay 1996a,b

Hydrodynamics of reefs – Steady wa



Setup on reefs (Gourlay 1996a,b)

- Setup increases with wave height and period
- Setup is larger at low tide than at high tide. When the depth over the flat is too great, waves don't break, and setup is zero (disregarding friction).
- Setup is higher for closed reef flats (where water flows back over seaward edge) than for reefs with lagoons or boat channels where the flow exits laterally
- Setup induced flow is small at low tide, and high at higher water levels (as long as waves break!), because of friction effects. If waves do not break, wave driven flow is again weak.
- Breakpoint is highly localised, so radiation stress gradients are almost zero over reef flat: setup almost constant over flat

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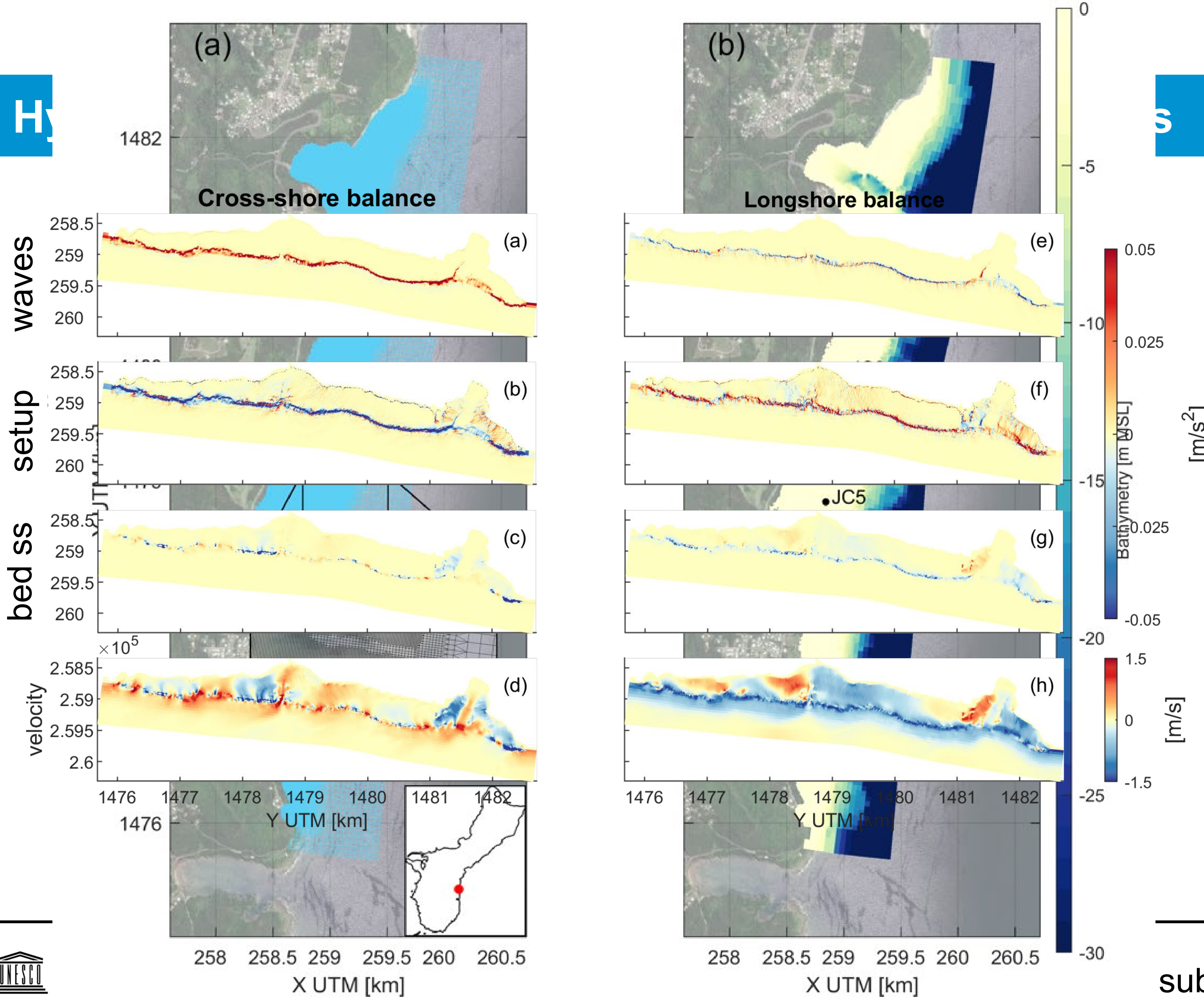


(a)
(b)
Cross-shore balance
Longshore balance
waves
setup
bed ss
velocity
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
258.5
259
259.5
260
×10^5
2.585
2.59
2.595
2.6
1476
1477
1478
1479
1480
1481
1482
Y UTM [km]
X UTM [km]
258
258.5
259
259.5
260
260.5
1482
1476
JC5
Bathymetry [m MSL]
0
-5
-10
-15
-20
-25
-30
0.05
0.025
0
-0.025
-0.05
[m/s^2]
1.5
0
-1.5
[m/s]

subm

Hydrodynamics of reefs – Infragravity waves

Offshore

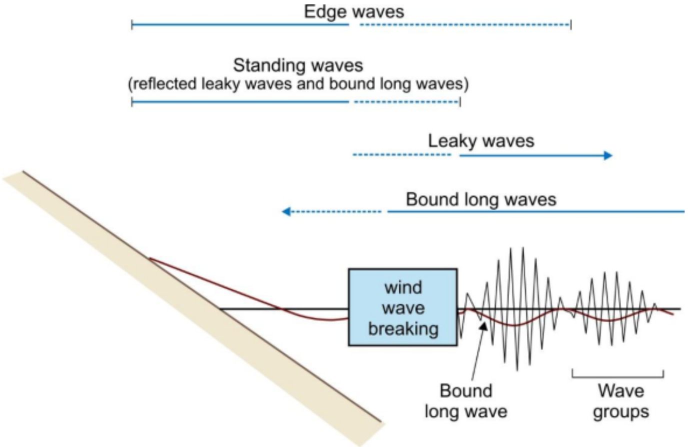
Propagation of waves in groups
Group amplitude "depresses" the mean surface (e.g., Longuet-Higgins and Stewart 1964)
Propagation of this depression is referred to as 'bound wave'

Generation

- *Bound wave release*: Release of bound wave as free IG waves due to short wave breaking (Battjes et al., 2004)
- *Breakpoint forcing*: Periodic forcing by wave groups, steeper slopes (Symonds et al, 1984)

Dissipation

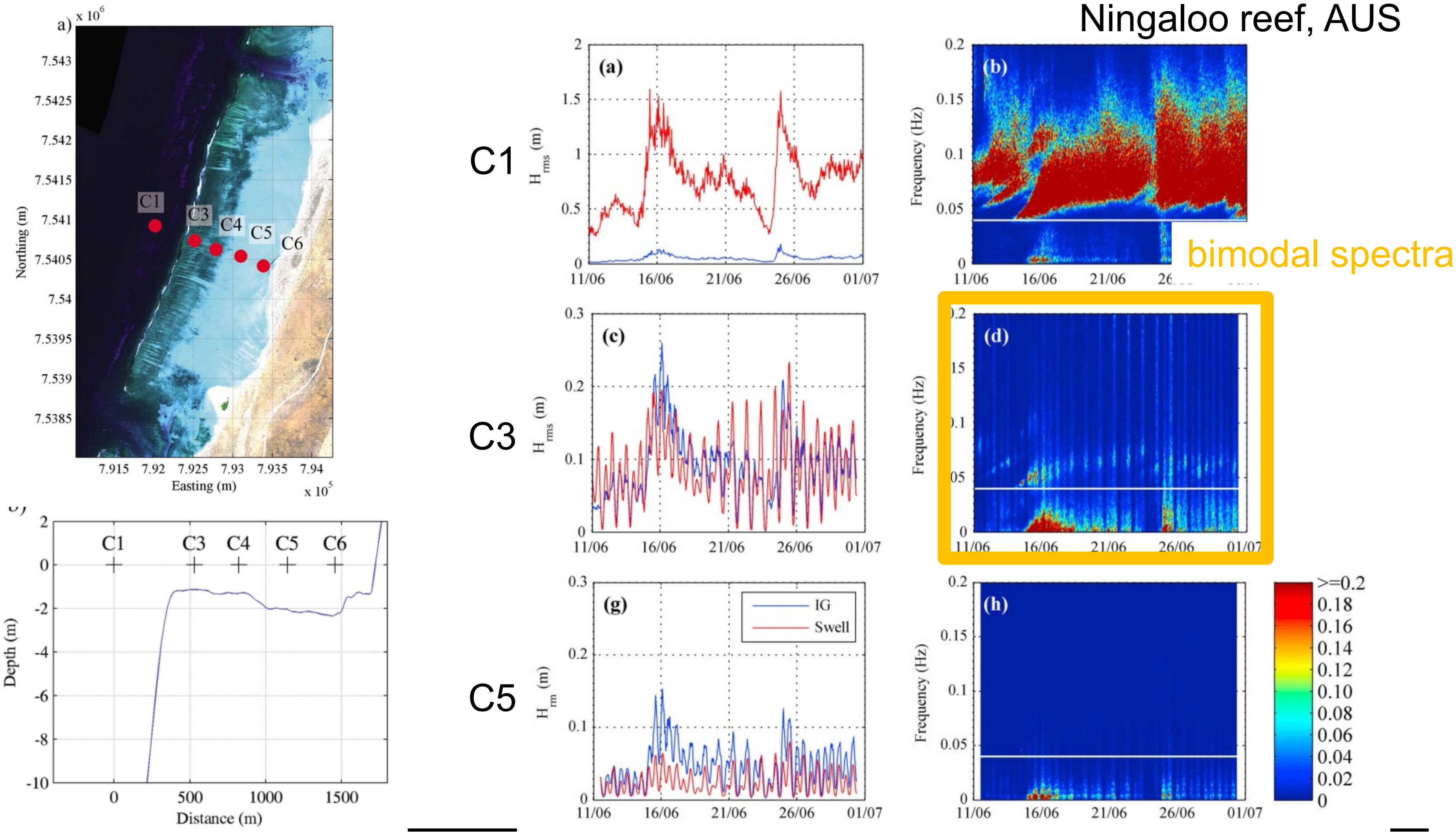
- Interaction with wave groups
- Bottom friction
- IG wave (bore) breaking



Lowe 2017

Hydrodynamics of reefs – Infragravity waves

Ningaloo reef, AUS



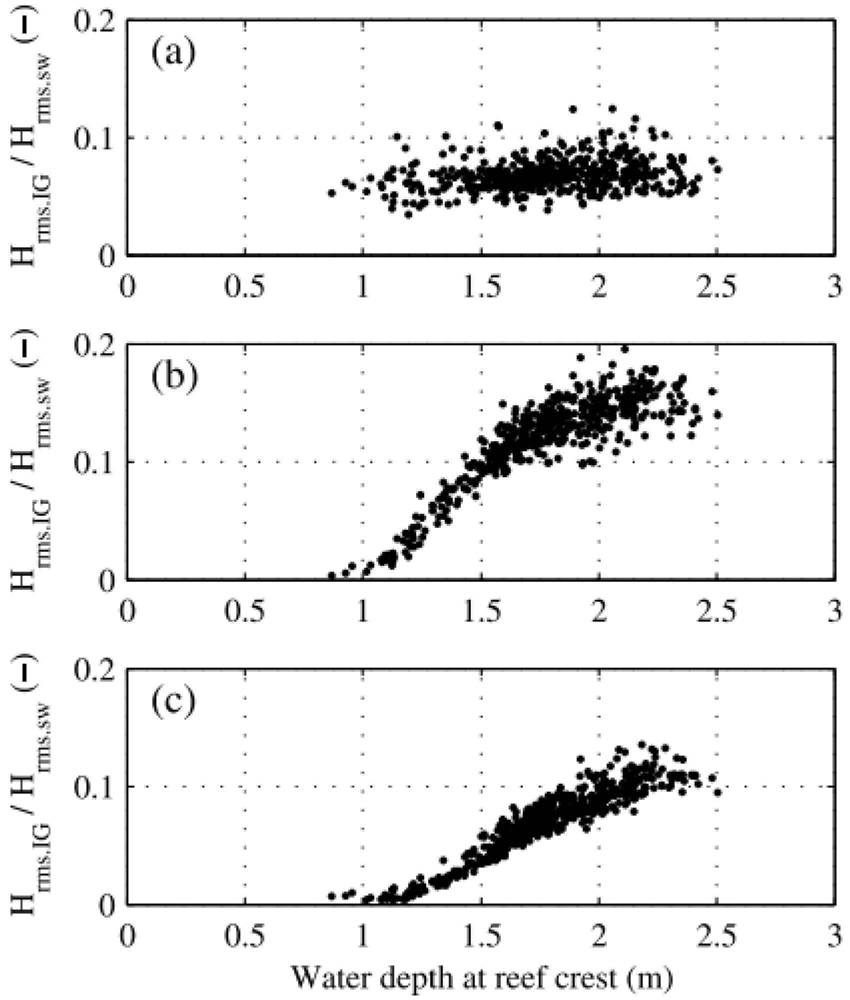
Pomeroy 2012

Hydrodynamics of reefs – Infragravity waves

C1

C3

C5



Offshore:
Outgoing wave + leaky IG

Reef crest:
Breakpoint generated IG

Inshore:
dampened IG by friction (and energy transfers between frequencies, leading to IG bores)

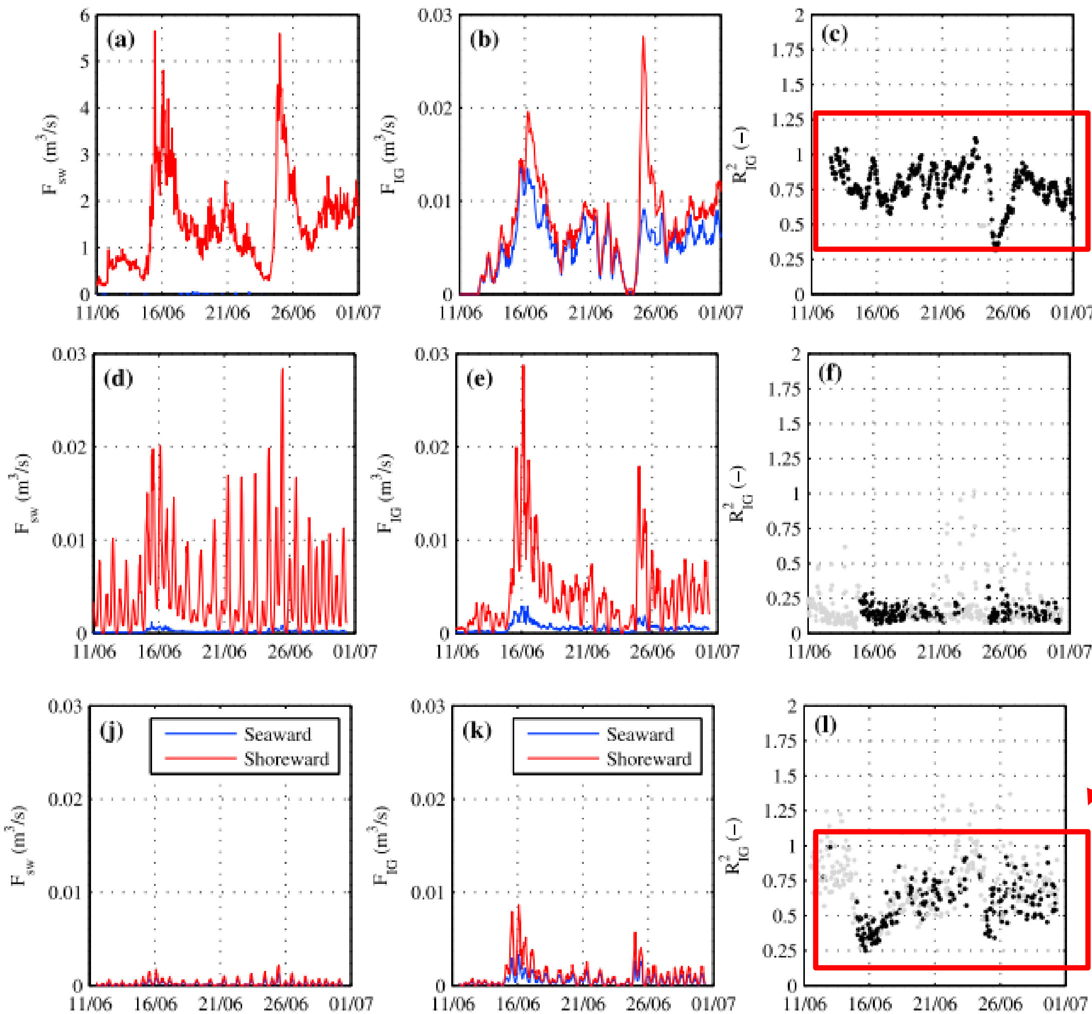
Hydrodynamics of reefs – Infragravity waves

Energy fluxes

C1

C3

C5



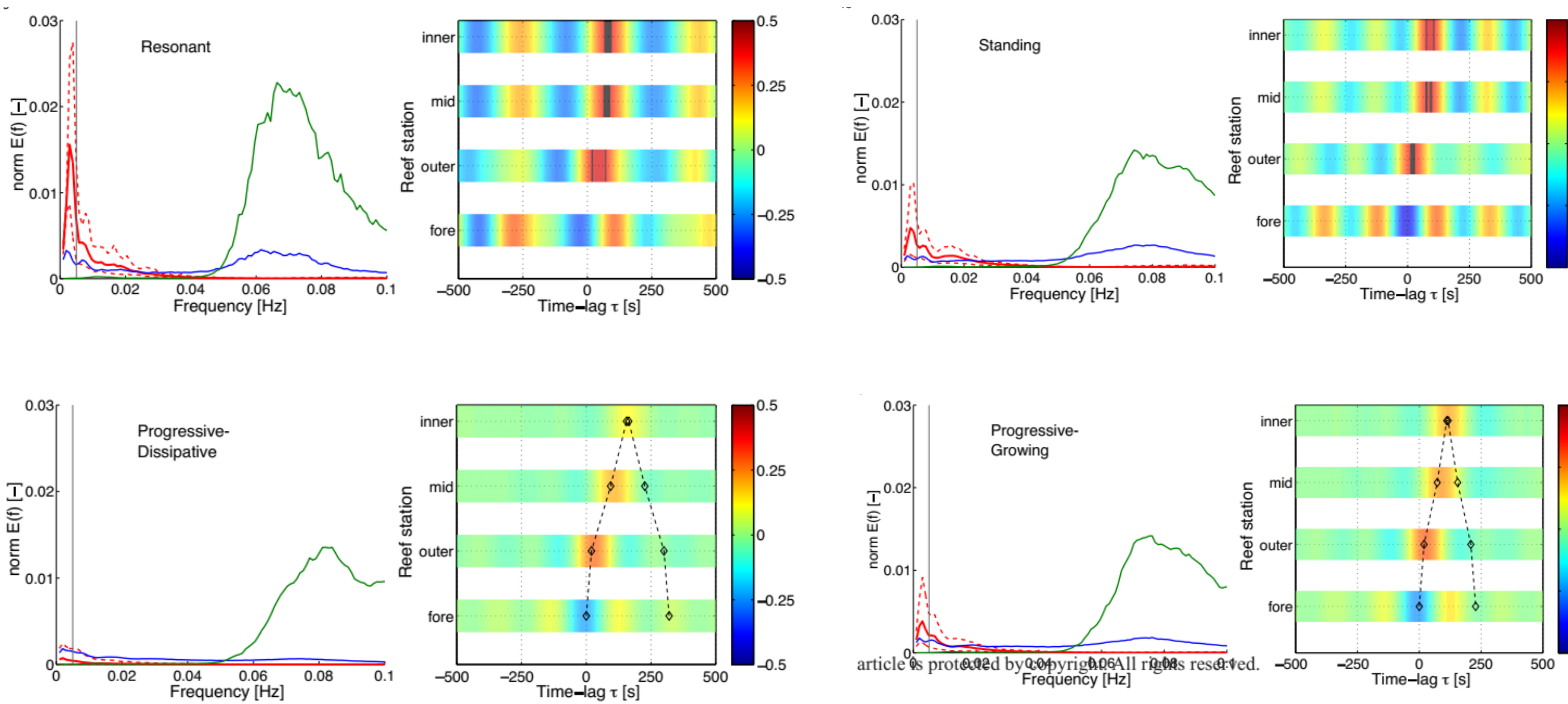
why large reflection?

this one can lead to resonance!

Pomeroy 2012

Hydrodynamics of reefs – Infragravity waves

Types of VLF/farIG (0.001<f<0.005) motions on reef flats



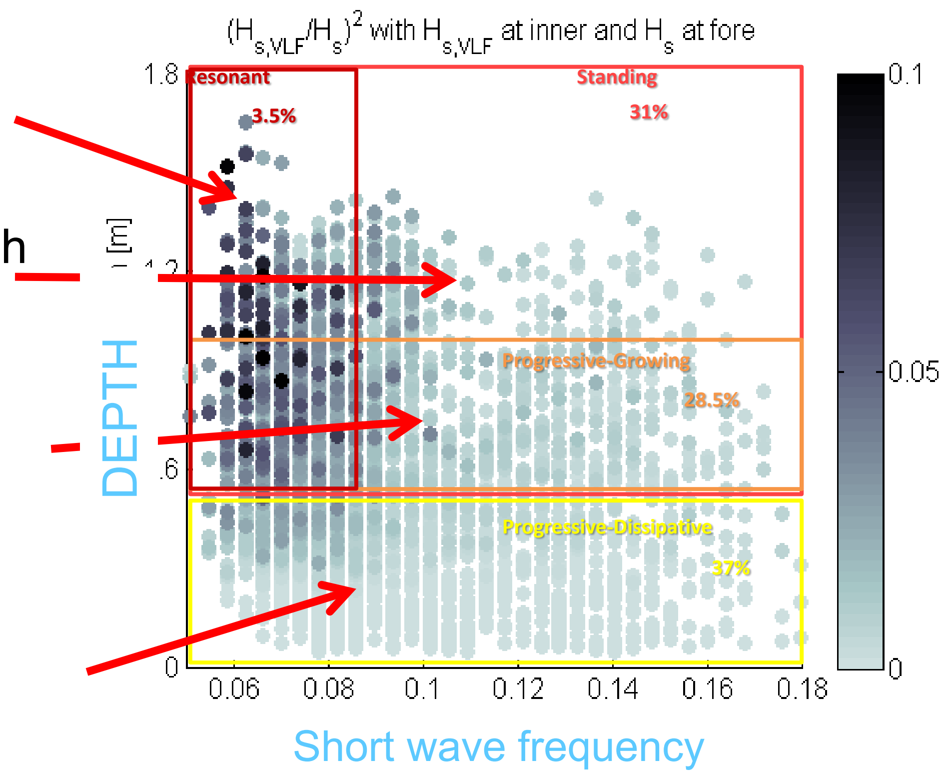
Normalized, ensemble-averaged inner (red) and outer (blue) reef flat and fore reef (green) spectra

Gawehn 2016

IHE DELFT

Hydrodynamics of reefs – Infragravity waves

- Resonant waves at high water level and low peak frequencies
- Standing waves at intermediate to high water levels
- Progressive-growing at intermediate water levels
- Progressive-dissipative at low water levels.



Gawehn et al. JGR 2016

Hydrodynamics of reefs

Hydrodynamic forcing

- Waves
- Tides
- Winds
- Baroclinic pressure gradients: temperature

Physical concepts are essentially the same as on sandy beaches, but:

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Hydrodynamics of reefs - Tides

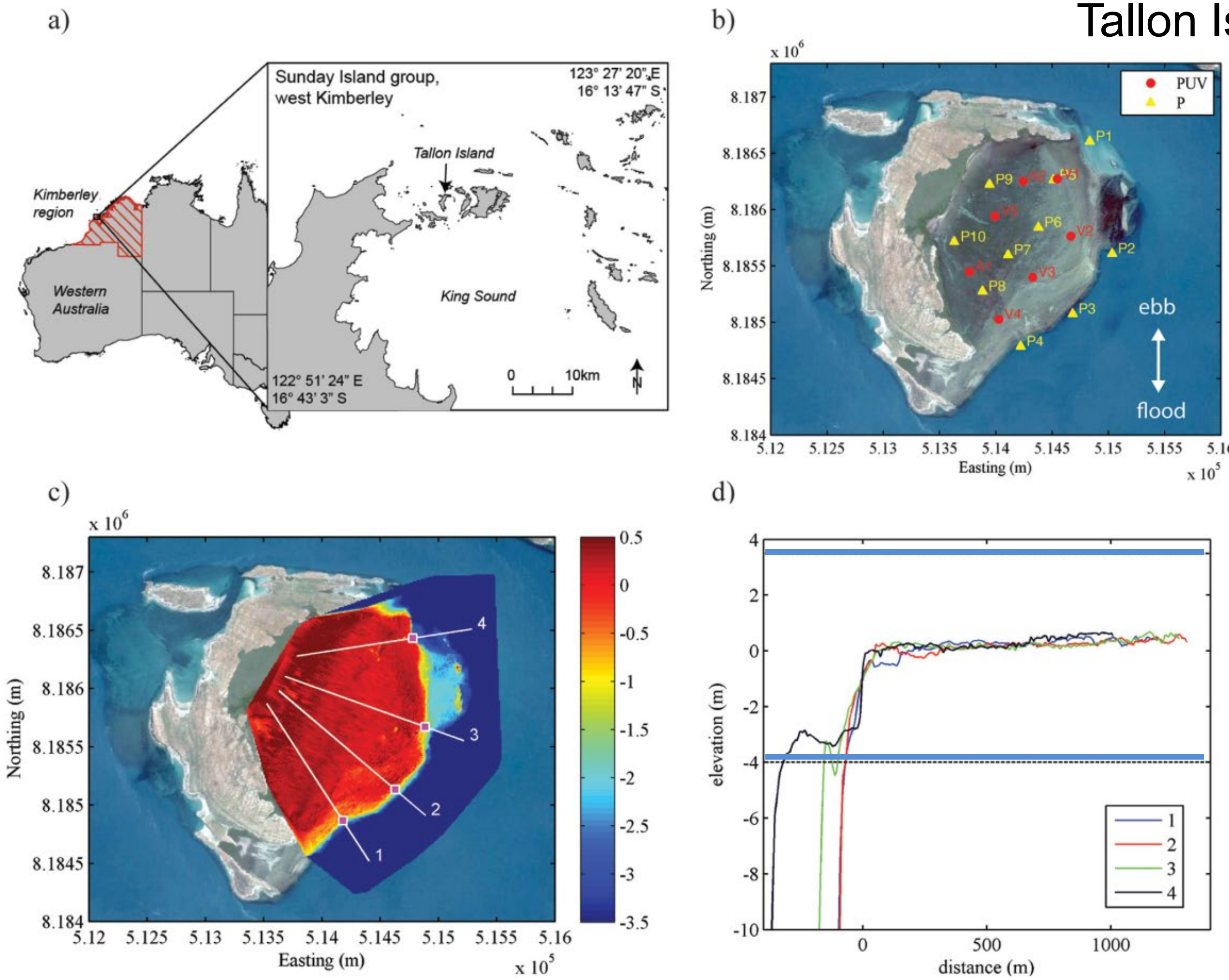
Effects of tides on reef hydrodynamics

- Modulates water level on reef flat, regulating wave processes (wave heights, setup, bottom drag)
- Circulation and flushing of lagoons: bring in nutrients, flush out excess heat
- Residual wake circulation around reefs and islands

- See **The Tidal Regimes of Three Indian Ocean Atolls and some Ecological Implications** (Pugh&Rayner 1981) for examples

Hydrodynamics of reefs - Tides

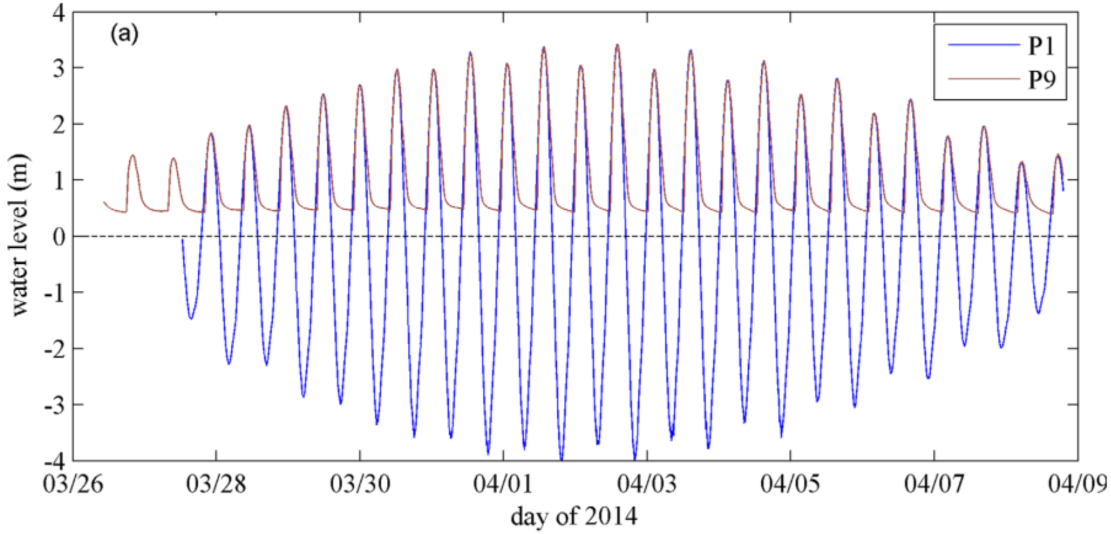
Tallon Island, AUS



tidal range

Lowe 2015

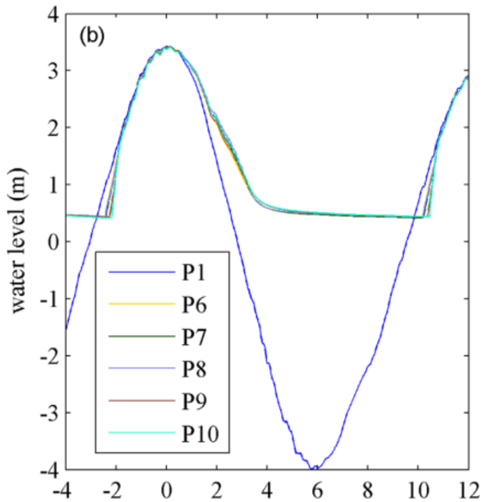
Hydrodynamics of reefs - Tides



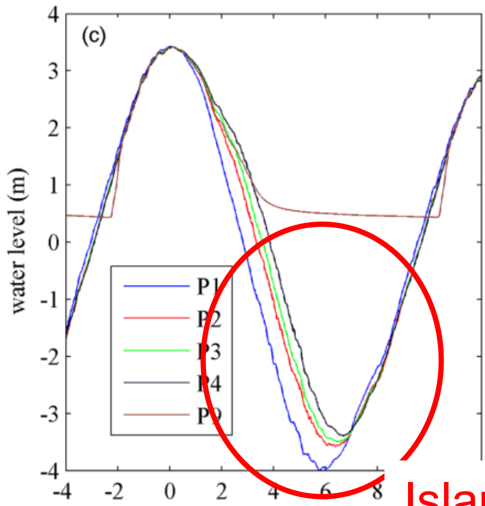
P1: offshore station
P9: reef flat

Tidal range ~ 8m

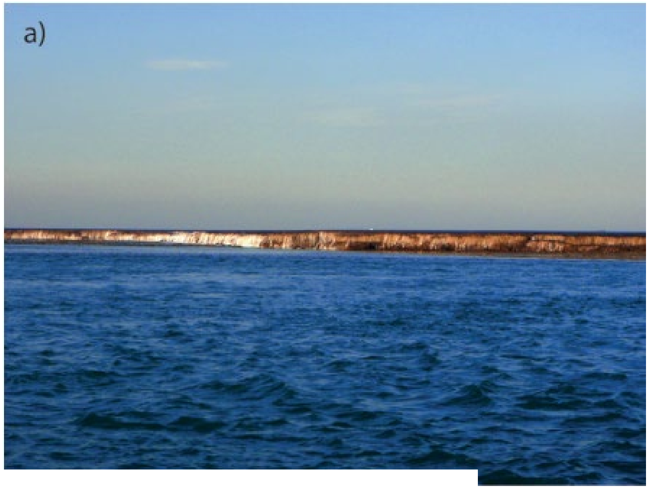
Flow over reef flat and reef edge to ocean at low tide



Reef flat

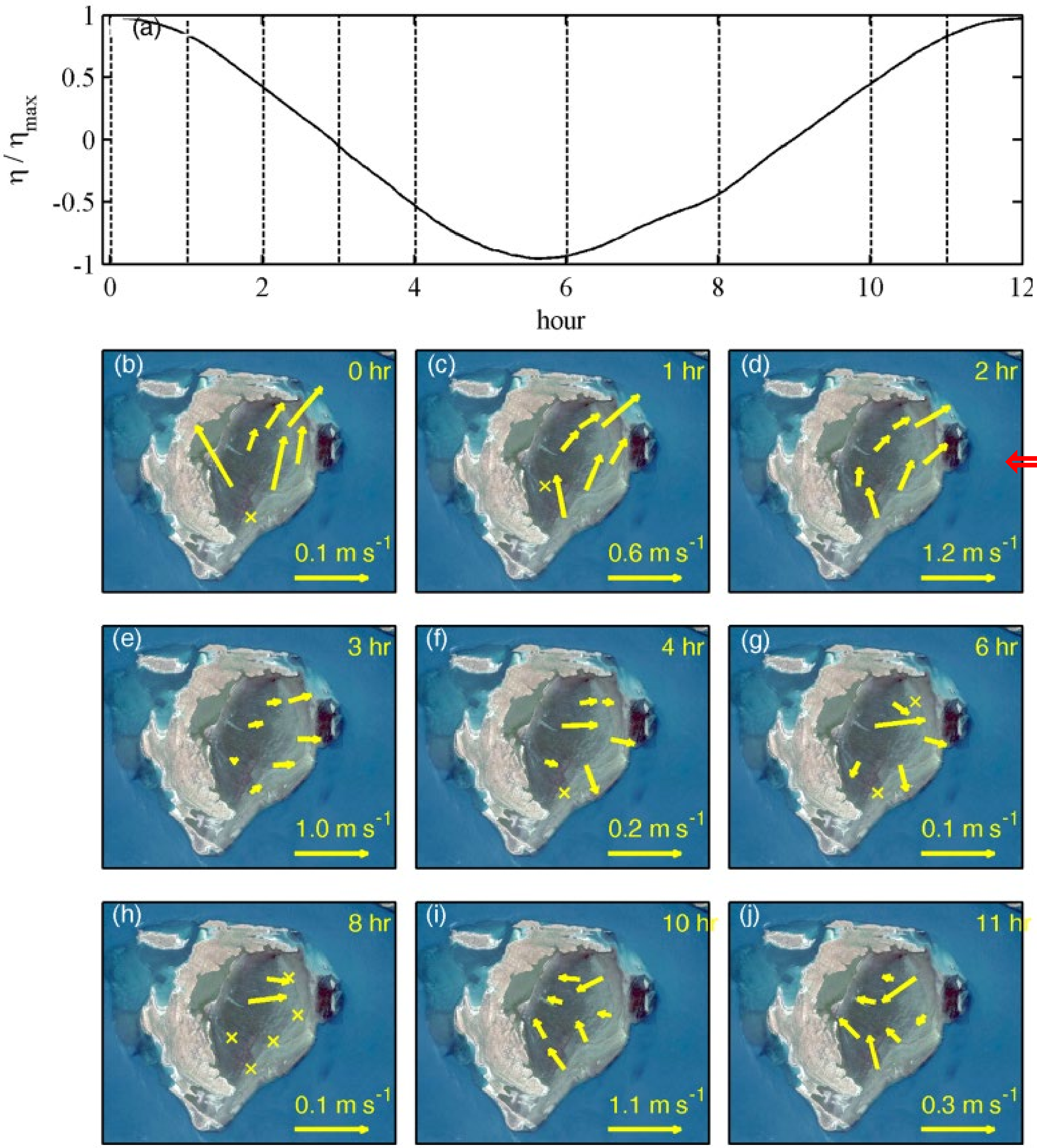


Offshore

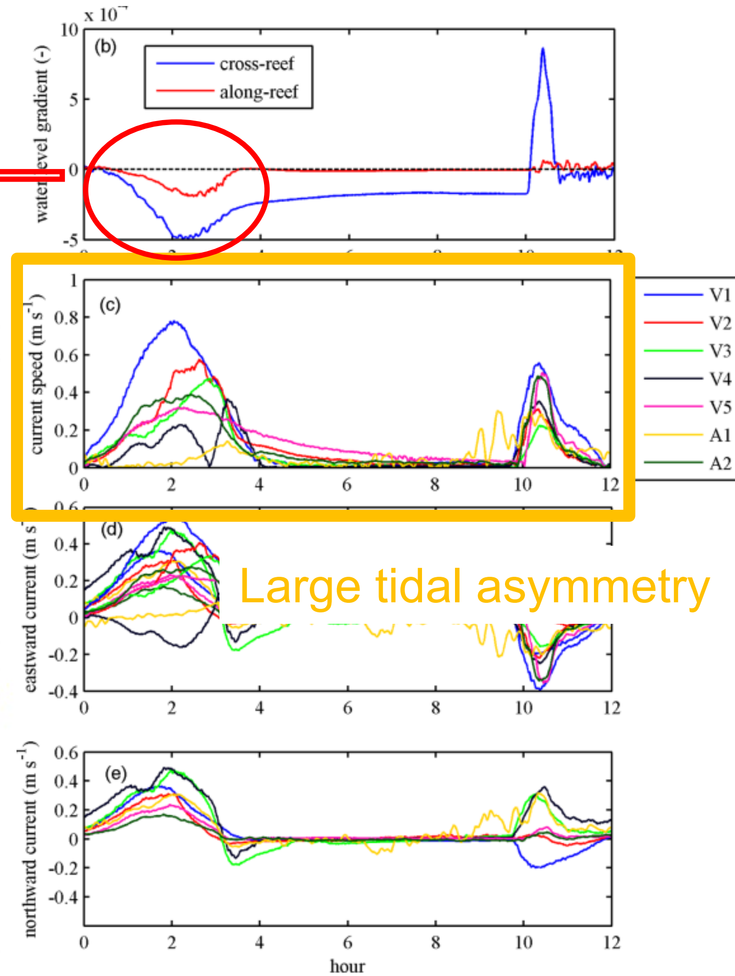


Island blocking during ebb flow

Lowe 2015



Note the difference in scales for vectors



Hydrodynamics of reefs

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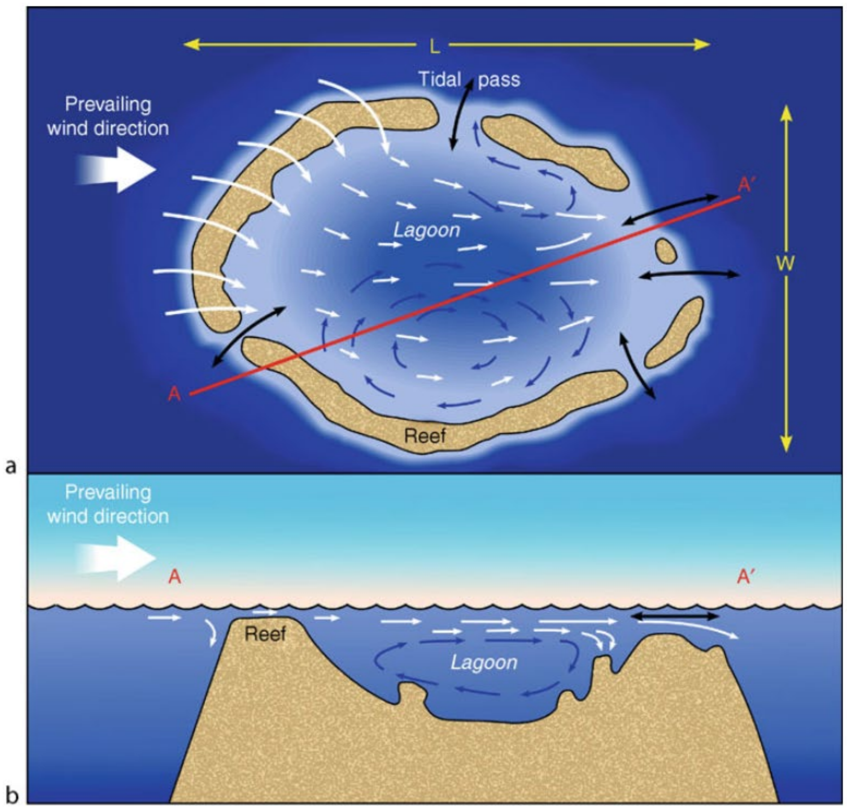
Hydrodynamics of reefs - Wind

Effects of wind on reef hydrodynamics

- Modulates water level in fringing reef lagoons and on reef flats (wind setup)
- Complex 3D circulation of countercurrents in atoll lagoons
- Generates *wind waves* in atoll lagoons

Hydrodynamics of reefs - Wind



Lagoon Circulation, Figure 2 (**a**) A schematic plan view representation of two-layer circulation in an atoll lagoon. White arrows represent surface currents, blue arrows are deep counter currents, and black arrows are tidal currents concentrated in the tidal passes. (**b**) This cross-sectional view of the atoll lagoon along line A–A′ in panel A shows the surface current (white arrows) forced by wave-driven cross-reef flow plus wind stress and a counter current in the deep part of the lagoon.

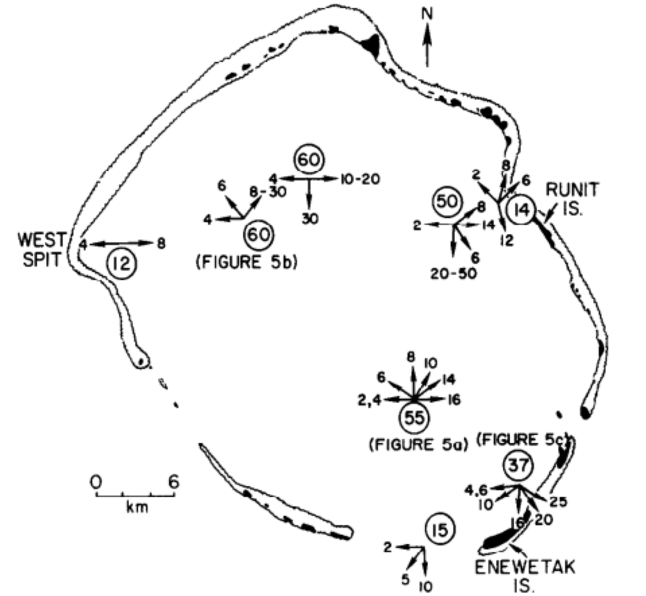
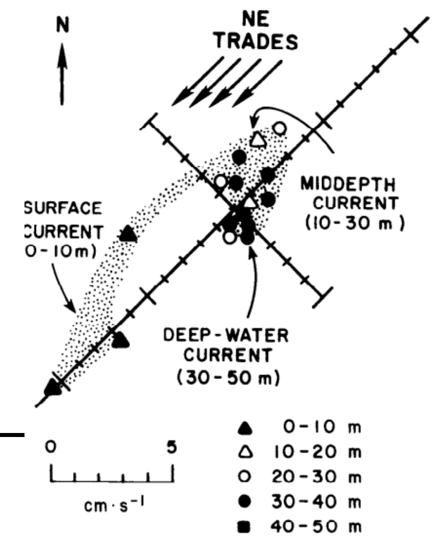


Fig. 6. Vertical flow profiles using dye dispensers suspended on a vertical line. Arrow shows direction of flow and number at end of arrow gives depth in meters. Circled number is bottom depth in meters. Winds blew from the east when these measurements were made.



Atkinson 1981; Roberts 2014

Hydrodynamics of reefs

Hydrodynamic forcing

- Waves
- Tides
- Winds
- Buoyancy forcing by temperature gradients

Physical concepts are essentially the same as on sandy beaches, but:

- Relative importance of processes and time scales differ
- Will illustrate every category with case study

Hydrodynamics of reefs - Buoyancy

- Steep reef topography can lead to baroclinic flow exchange due to differential heating or cooling
- Shallow reef waters respond quicker to heating or cooler than deep offshore waters
- Generated *baroclinic flow ~ (bottom slope, depth, surface heat flux, heat capacity)*

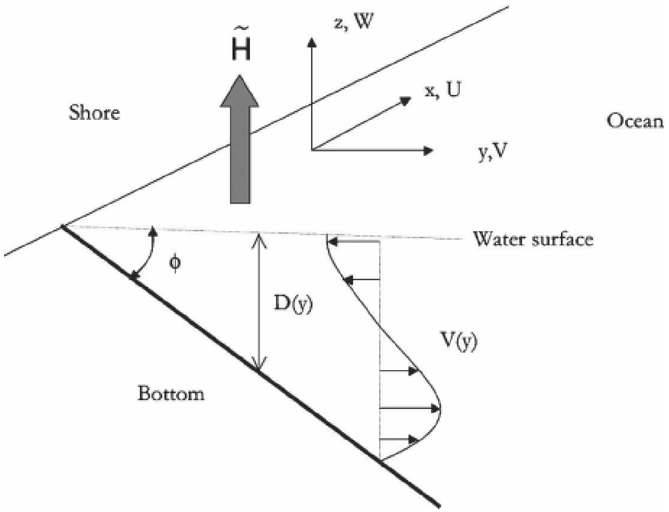
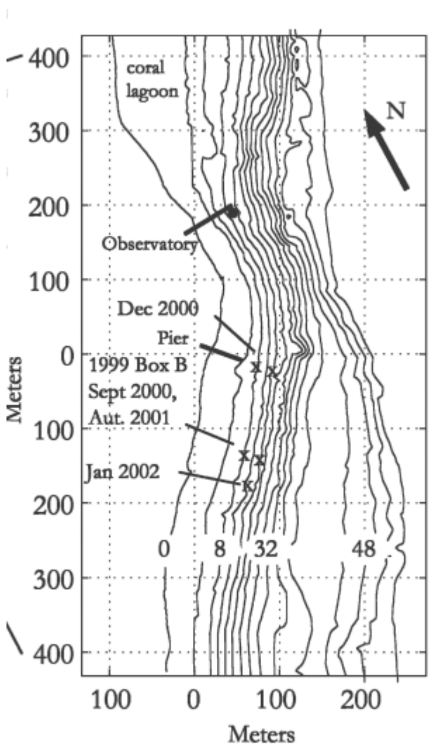


FIG. 1. Sketch of problem geometry for heating and cooling flows in a wedge.

Monismith 2006

Hydrodynamics of reefs - Buoyancy



Bathymetry off Steinitz Marine Laboratory (depth in m)

Eilat, Israel

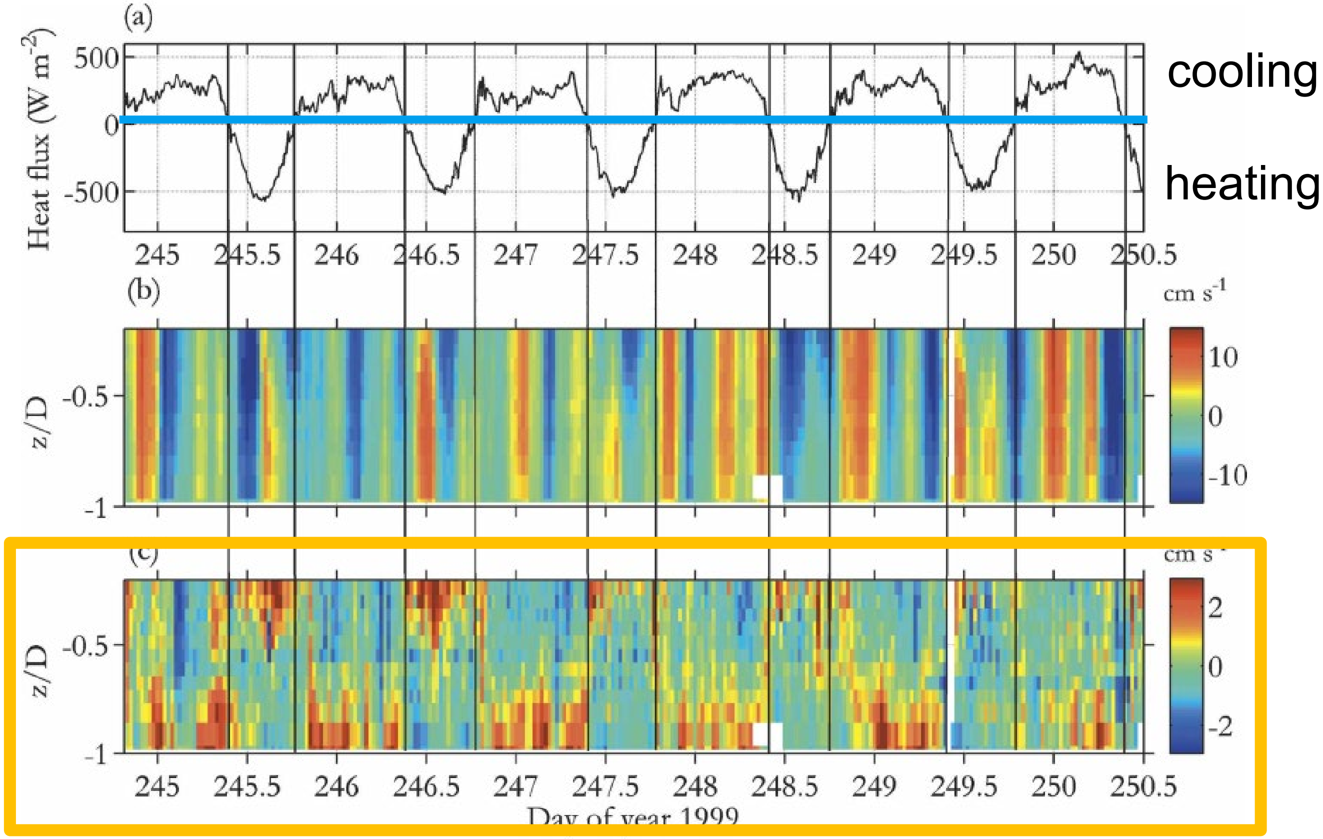


FIG. 4. Box-B observations: (a) surface heat flux, (b) longshore flow on the 8-m isobath, and (c) cross-shore flow on the 8-m isobath. The vertical lines mark the transitions from heating to cooling and vice versa.

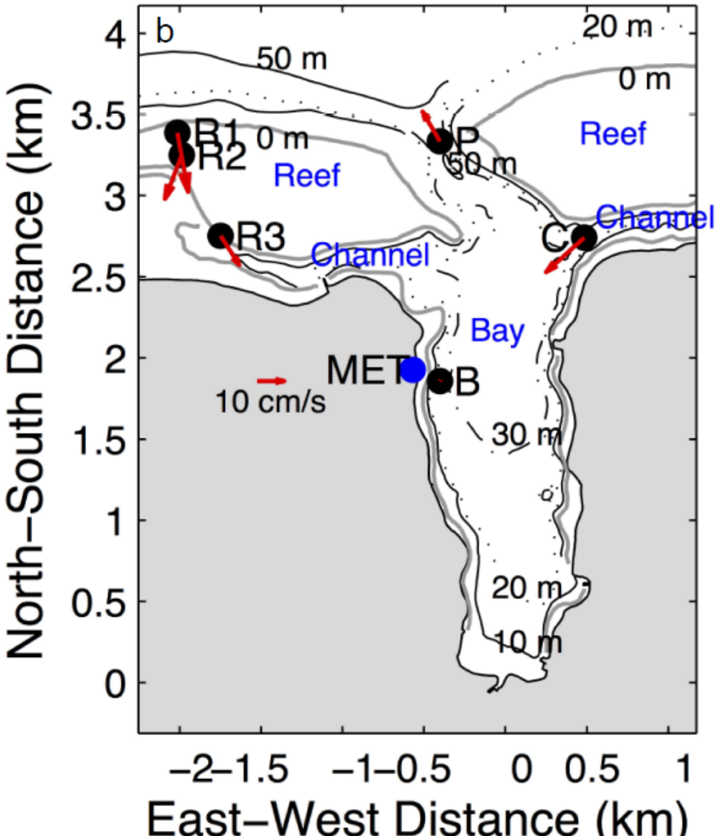
Inversion of 3D sheared cross-shore flow during heating/cooling

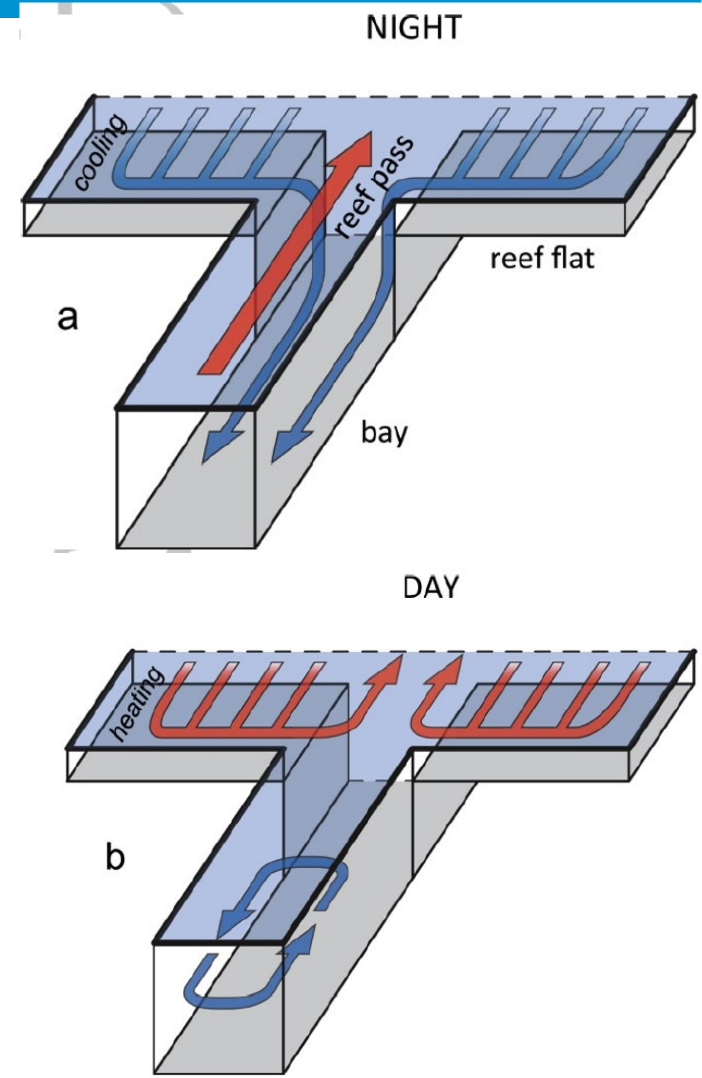
Red=offshore

Monismith 2006

Hydrodynamics of reefs - Buoyancy

Paopao Bay, Moorea





Herdman 2015

Mangroves

Mangroves and mangals

Mangal: a tropical shoreline community in which various species of mangrove are the dominant plant species

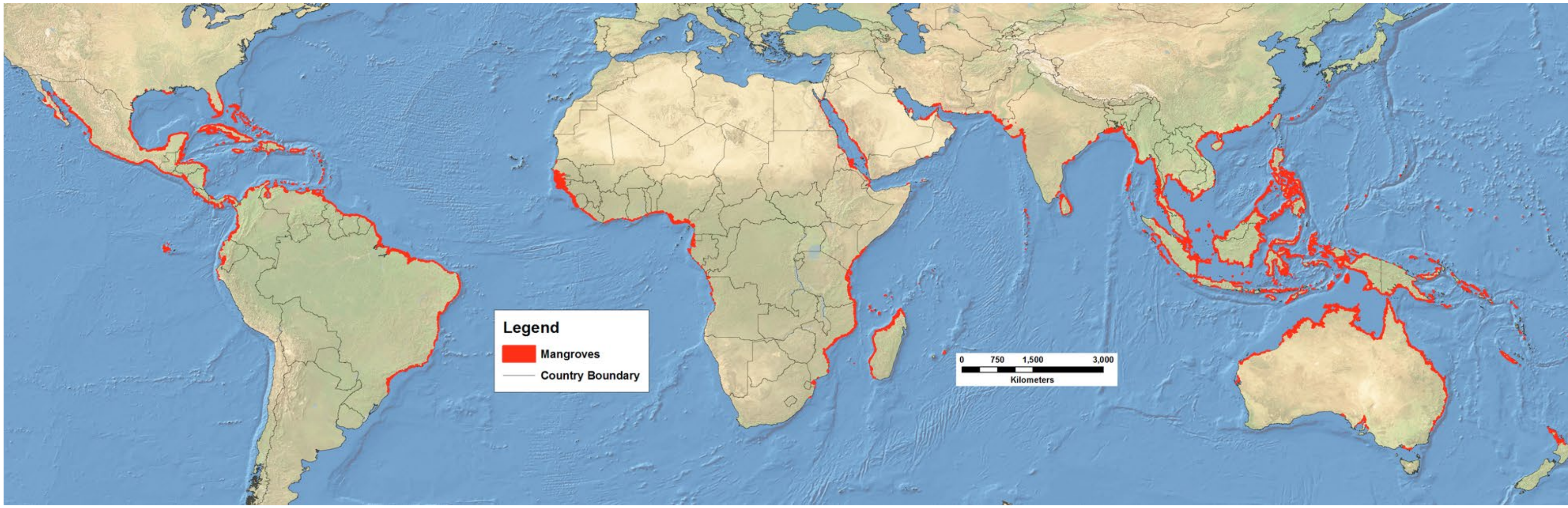
Conditions for mangal formation:

- Protection from strong wave action
- Availability and accumulation of sediment
- Periodic flooding by salt water
- (Sub) tropical climate

Threats to mangals:

- Clearing of forests for wood and agriculture
- Climate change (droughts, salinisation)
- Sea level rise, if forests cannot keep up
- Increased storminess; tsunami

Global distribution



Found on coastlines between 25° N and 25°S latitude, dependent on temperature

- Rhizophora - survive 2-4° C for 24 hrs
- Avicennia – survives 2-4° C for several days

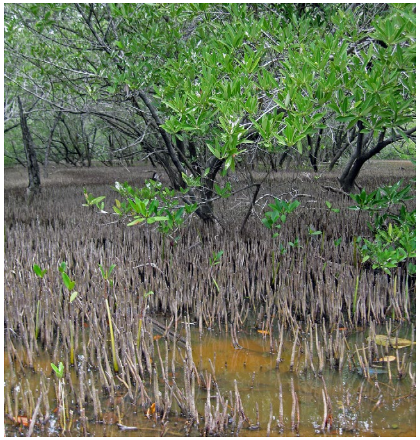
Salinity is not a requirement, just gives competition advantage

UNEP (https://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=103)

Zonation and succession

Main genera

Rhizophora
(red mangroves)

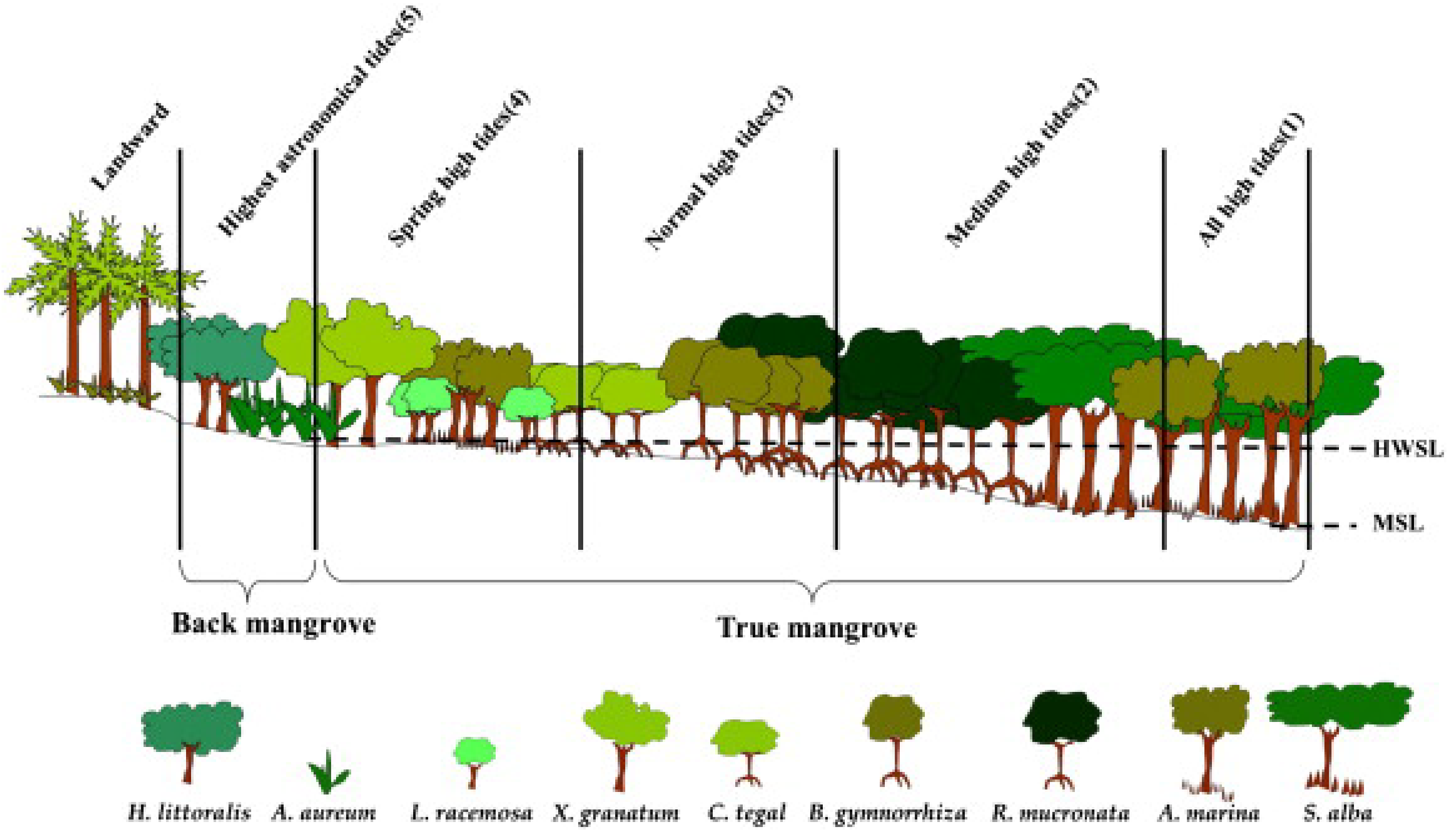


Avicennia
(black mangroves)

Laguncularia
(white mangroves)

Sonneratia
(apple mangroves)

Zonation and succession



Distribution depends on salt and sedimentation tolerance

Mangroves

- Five types hydrodynamic settings
  - Fringe type only one subject to important wave action, next to tides
  - Riverine type forms flood plains along rivers and tidal channels where waves have dissipated. Highly sinuous creeks circulate water and nutrients;
  - Basin type local depressions in coastal/river plains. Basin forests are associated with partially impounded depressions that are rarely flooded at high tide during the dry season but inundated by spring high tides during the rainy season. This swamp type is significantly affected by groundwater level differences with the sea.
  - Overwash type: Low islands and small peninsulas, which are completely overwashed on all high tides
  - Dwarf forest: Topographic flats above mean high water, which are tidally inundated only during wet season, and are dry for most of year.

Tides, waves, and river discharge important hydrodynamic drivers

Mangroves

Fringe type

Riverine type

Why are mangroves important?

- Mangroves cover some 130000km^2, and they are quickly disappearing (1%-2% per yr) (Giri 2011)

- Highly valuable ecosystems providing services such as:
  - CO_2 sink;
  - Support for terrestrial as well as marine food webs
  - Supports mangrove-dependent fauna with their complex habitat linkages
  - Buffering of seagrass beds and coral reefs against the impacts of river-borne siltation,
  - Protection of coastal communities from sea-level rise, storm surges, cyclone waves and tsunamis.
  - Human communities living in or near mangroves have access to sources of essential food, fibers, timber, chemicals, and medicines.

Hydrodynamics of mangroves

Hydrodynamic forcing

- Currents
- Waves

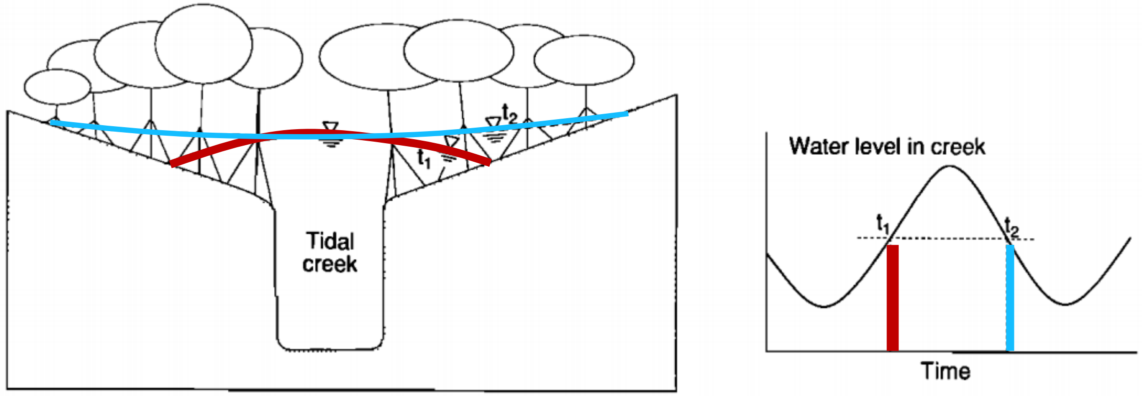
Hydrodynamics of mangroves

Hydrodynamic forcing

- Currents
- Waves

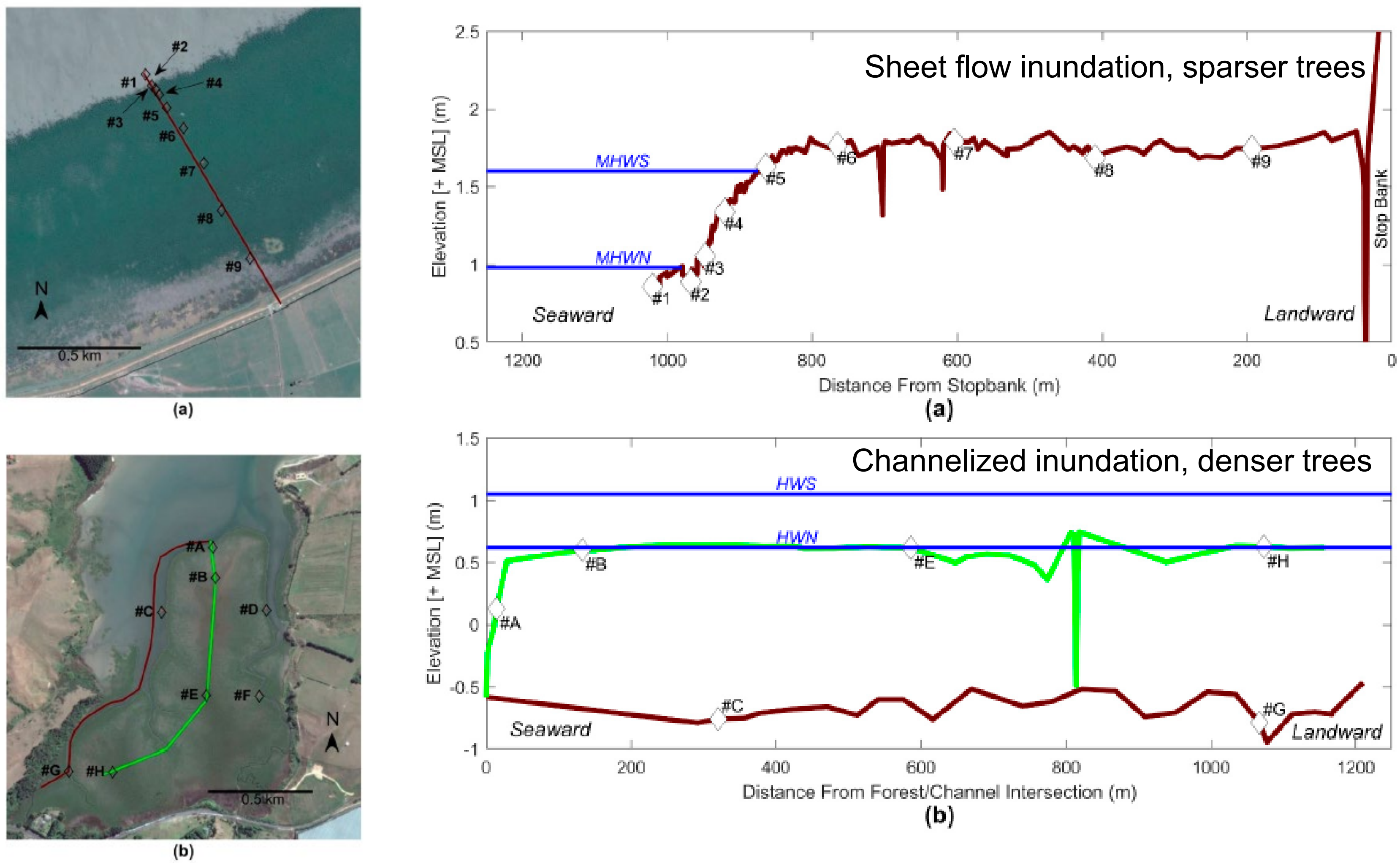
Tidal circulation in mangroves

- Tidal flow in creeks in mangals is asymmetric, and ebb-dominated due to the delayed discharge from the hydraulically rough vegetated areas.
- Current velocities in swamps are order of magnitude smaller than in the creeks, due to high friction;
- Mangal flooding can happen through creek flow (through creek) or sheet flow (over bank), depending on topography and water levels
- Creeks maintain depth by selfscouring through enhanced ebb tidal outflows;
- When creeks have freshwater runoff, density driven currents can arise, inducing 3D circulation



Wolanski 1993

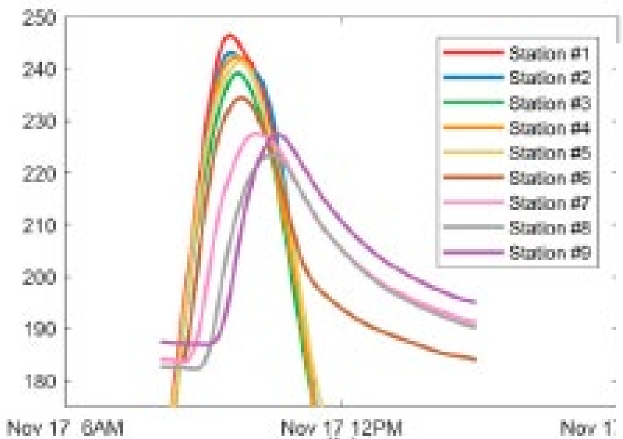
Tidal circulation in mangroves



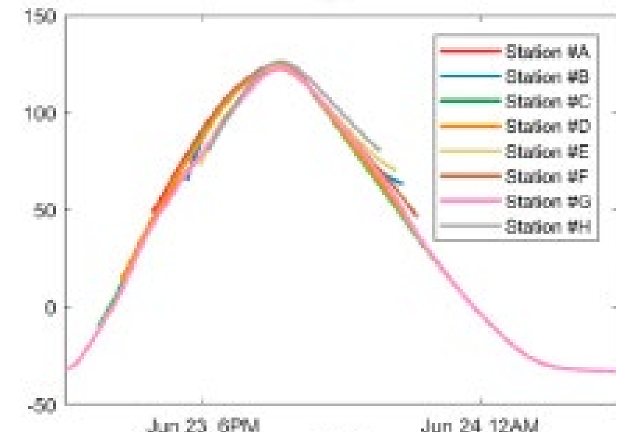
Montgomery 2018

Tidal circulation in mangroves

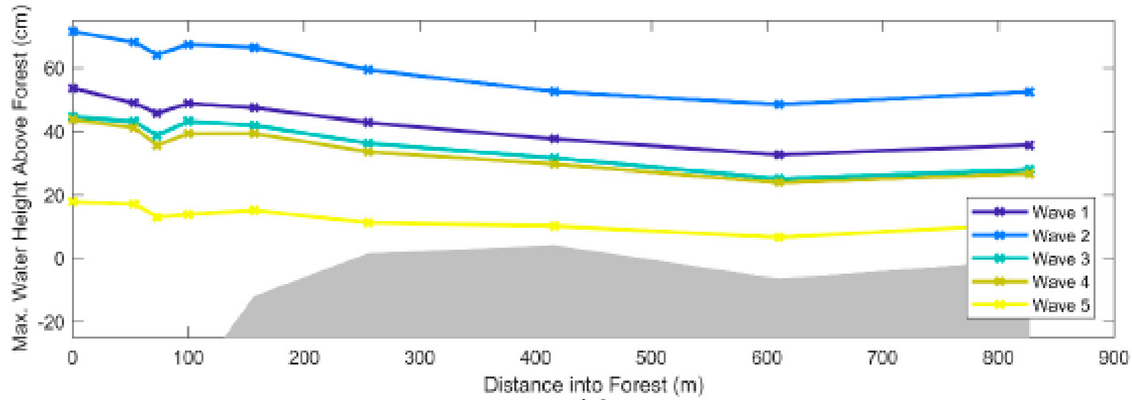
Water level



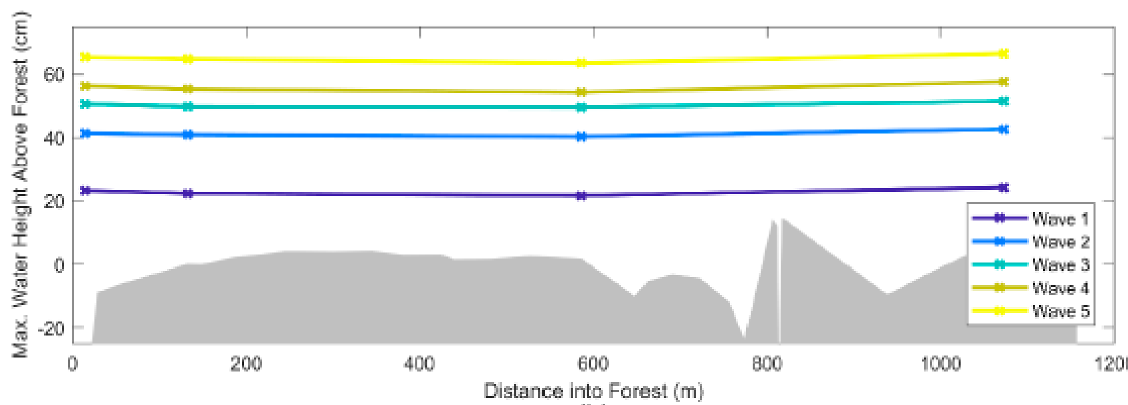
(b)



(d)



(a)



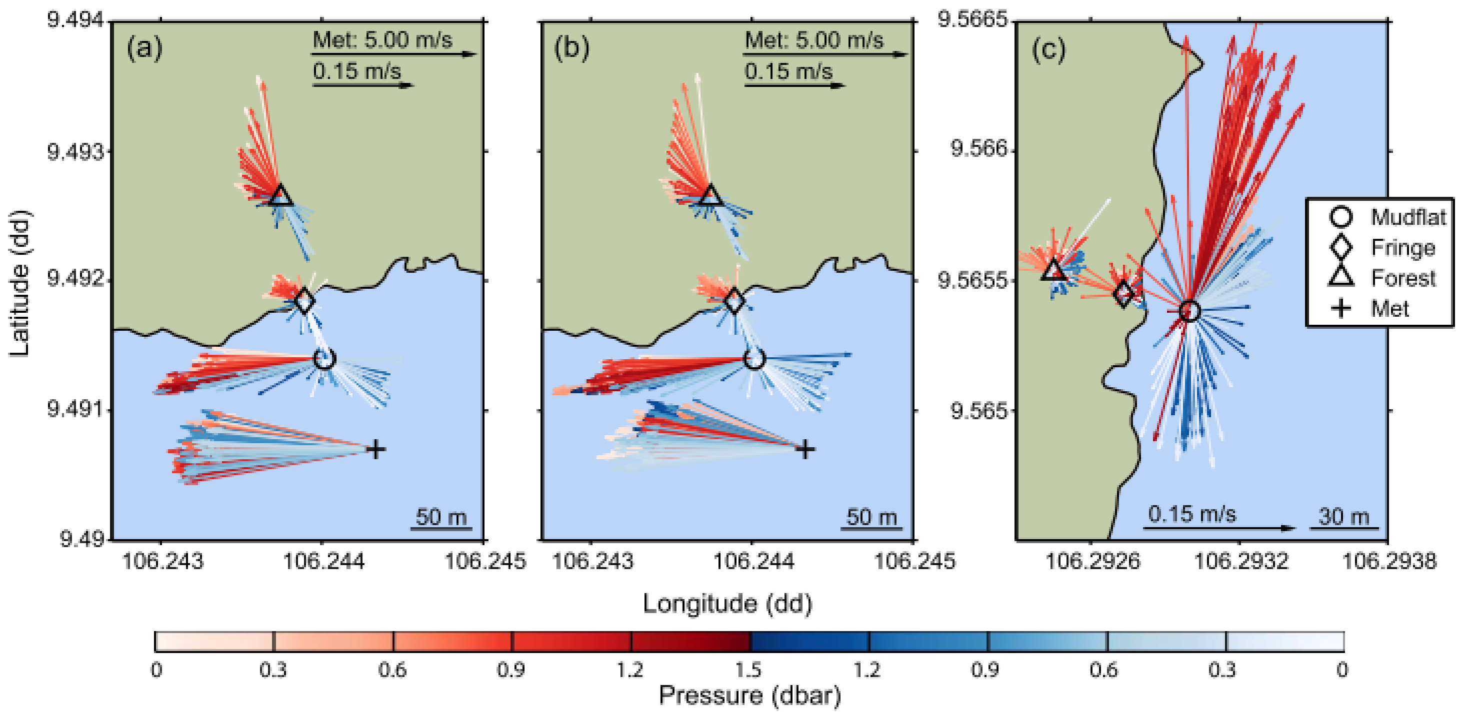
(b)

'wave'=tidal inundation phase

Montgomery 2018

Tidal circulation in mangroves

- Flow rotation: due to frictional effects and turbulence the current direction changes from parallel to the creek axis near the fringe to perpendicular to the creek inside the forest

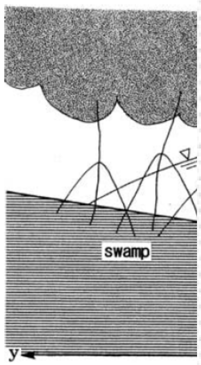


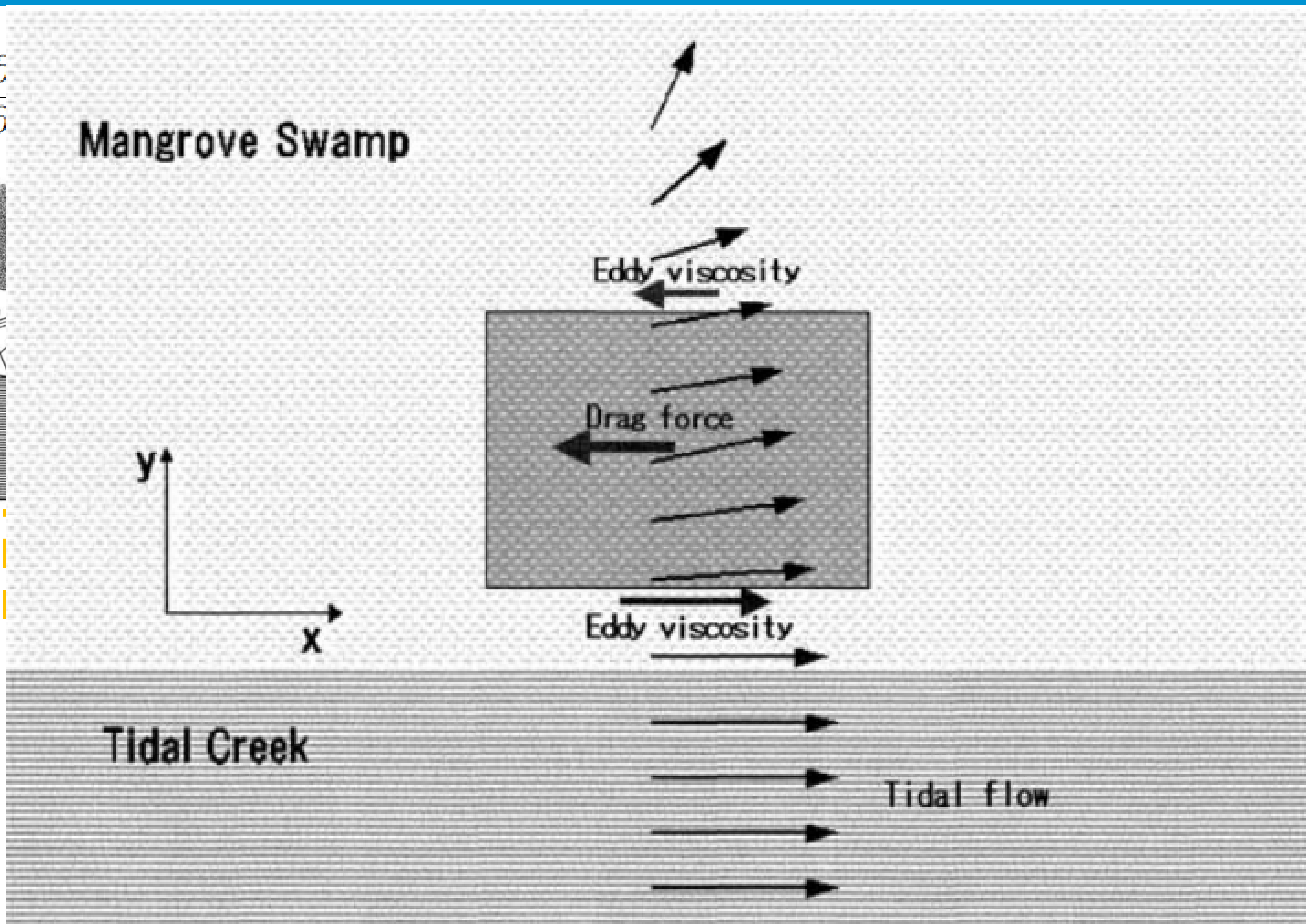
Cu Lao Dung, Vietnam

Mullarney et al. 2017

Tidal circulation in mangroves

$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial}$





$f\frac{\partial^2 u}{\partial y^2}$

			(+)
Ebb tide	(−)	(+)	(−)

Kobashi & Mazda 2005

Hydrodynamics of mangroves

Hydrodynamic forcing

- Currents
- Waves

Wave propagation through mangrove forests

- Mangroves very efficient in dissipating wave energy
- Wave height decreases exponentially with distance in forest
- Wave attenuation is depth dependent, as the tree morphology changes in height above the forest floor (prop roots, pneumatophores, stems, foliage)

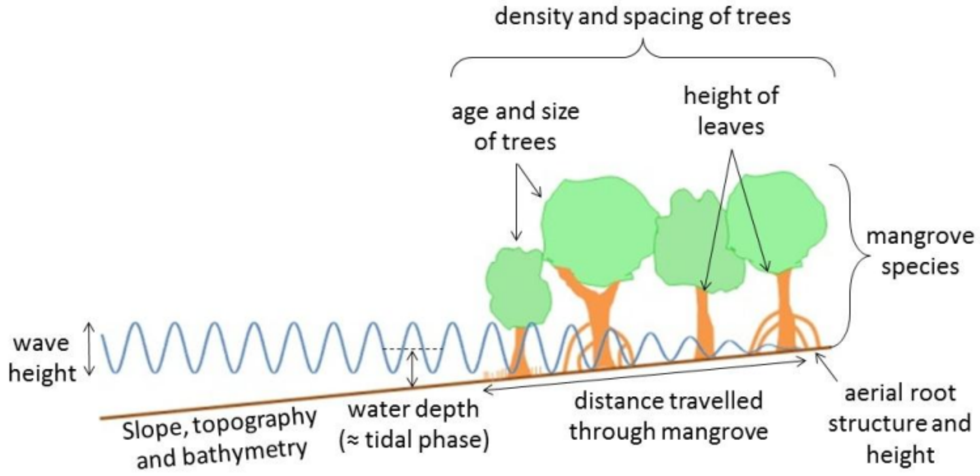


Figure 3. Factors affecting wave attenuation in mangroves.

McIvor 2016

Wave p

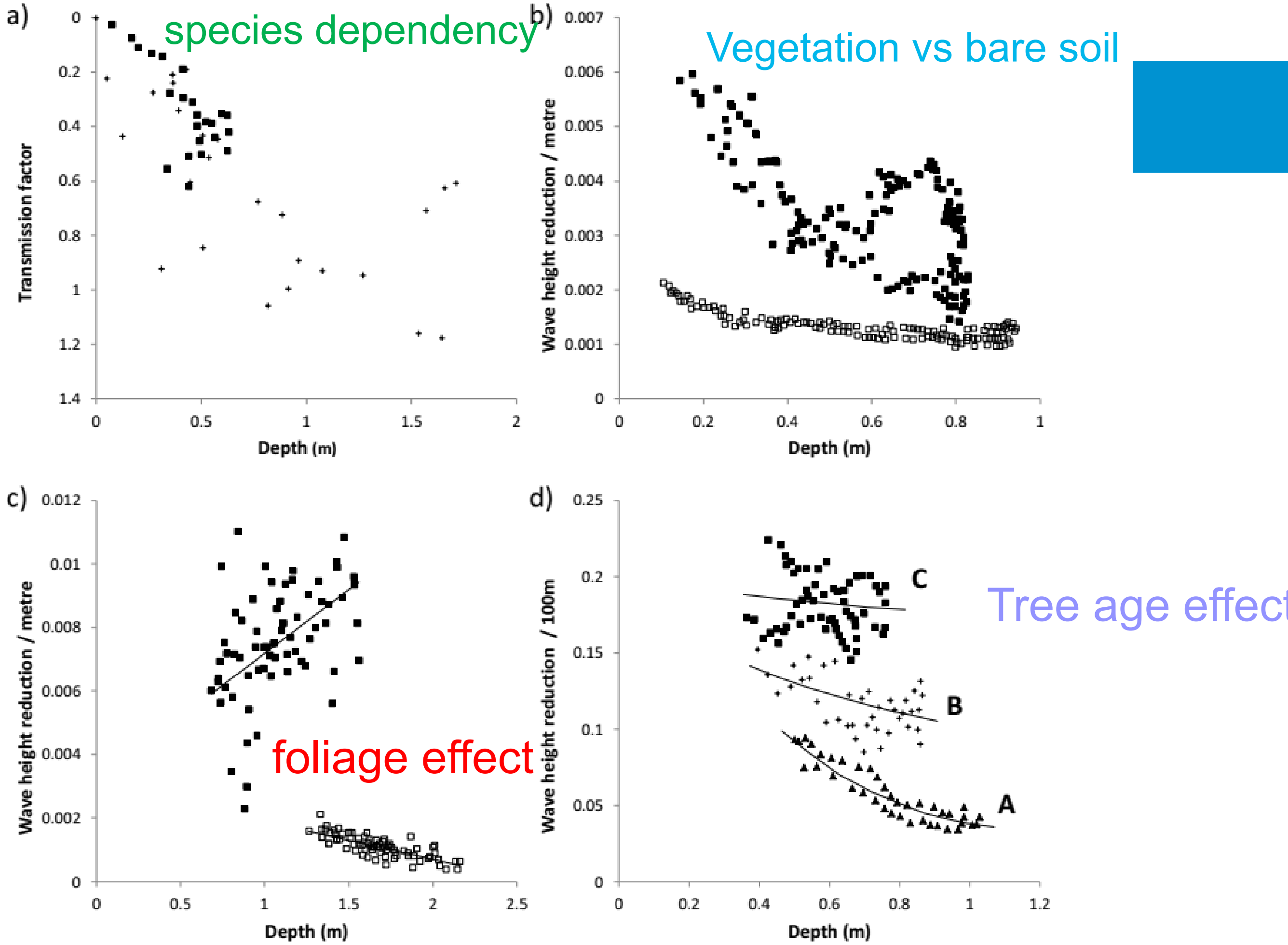


Figure 6. (a) The transmission of wave energy plotted against water depth in a mangrove forest dominated by *Bruguiera* sp. on Iriomote Island (■) and by *Rhizophora stylosa* at Cocoa Creek (+) from Brinkman *et al.* (1997); a low transmission factor shows high wave attenuation (note that the y-axis has been reversed so that the pattern can be compared with the other graphs). (b) Wave height reduction plotted against depth in a mangrove forest dominated by *Sonneratia* sp. (mangrove forest (■) and area without mangroves (□), data from Mazda *et al.* 2006). (c) Wave height reduction in a forest dominated by *Kandelia candel* (mangrove forest (■) and area without mangroves (□), data from Quartel *et al.* 2007). (d) Wave height reduction in an area recently planted with *Kandelia candel*, showing reduction through 6-month-old saplings (▲, area A), 3-4 year-old trees (+, area B) and 5-6 year-old trees (■, area C) (data from Mazda *et al.*, 1997a). See also Table 2, which gives more details about these studies.

McIvor 2012

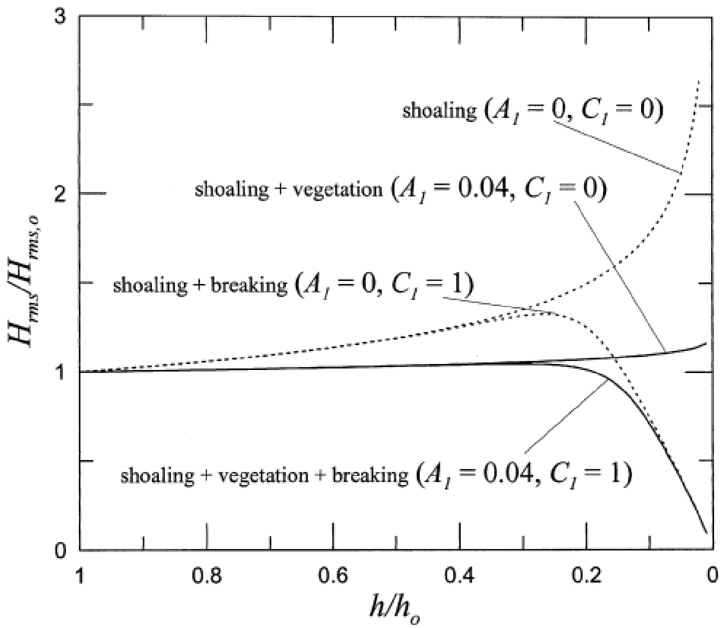
Wave propagation through mangrove forests

- Vegetation effects on sea-swell and infragravity waves
  - Attenuation of wave heights (e.g. Mendez&Losada 2004)
  - Influence on wave setup

Wave propagation through mangrove forests

- Vegetation effects on sea-swell and infragravity waves
  - Attenuation of wave heights (e.g. Mendez&Losada 2004)

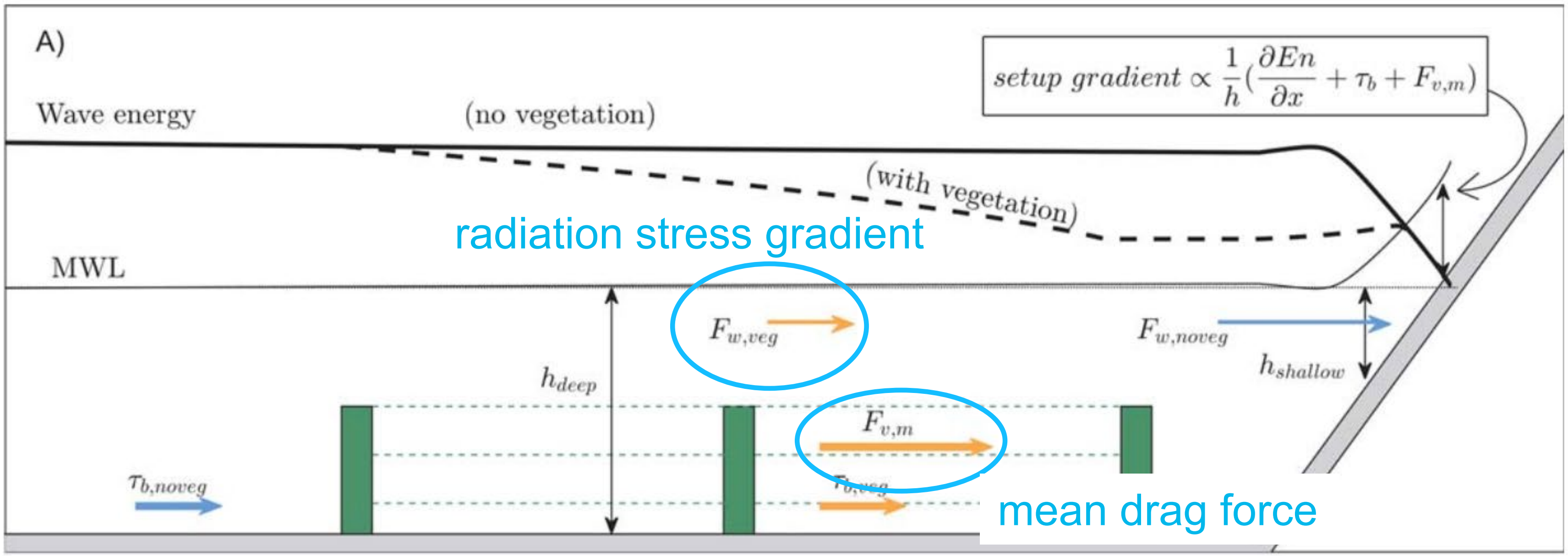
$$D_v = \left(\frac{kg}{2\sigma}\right)^3 \frac{\rho C_D b_v N_v}{2\sqrt{\pi}} \frac{\sinh^3 kh_v + 3\sinh kh_v}{3k\cosh^3 kh} H_{rms}^{\ 3}$$



Plane sloping beach with vegetation

Wave propagation through mangrove forests

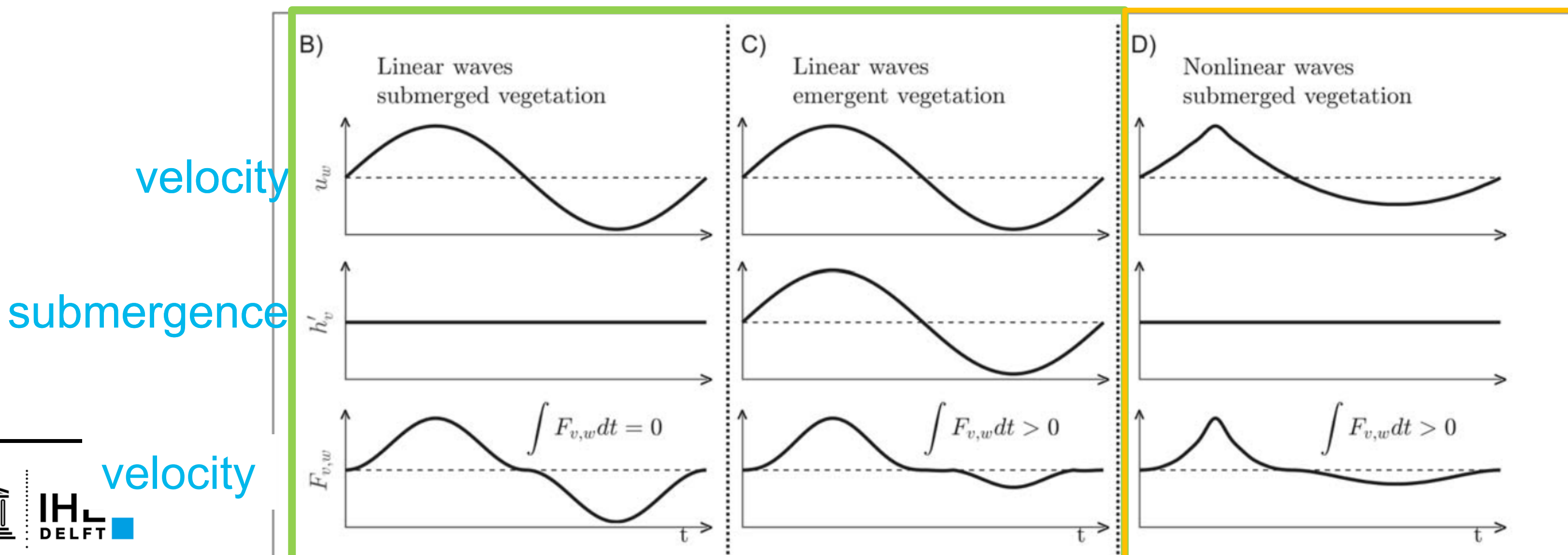
- Vegetation effects on sea-swell and infragravity waves
  - Attenuation of wave heights (e.g. Mendez&Losada 2004)
  - Influence on wave setup by:
    - Radiation stress gradient decrease because of gradual attenuation: decrease
    - Mean drag force by stems on flow: increase



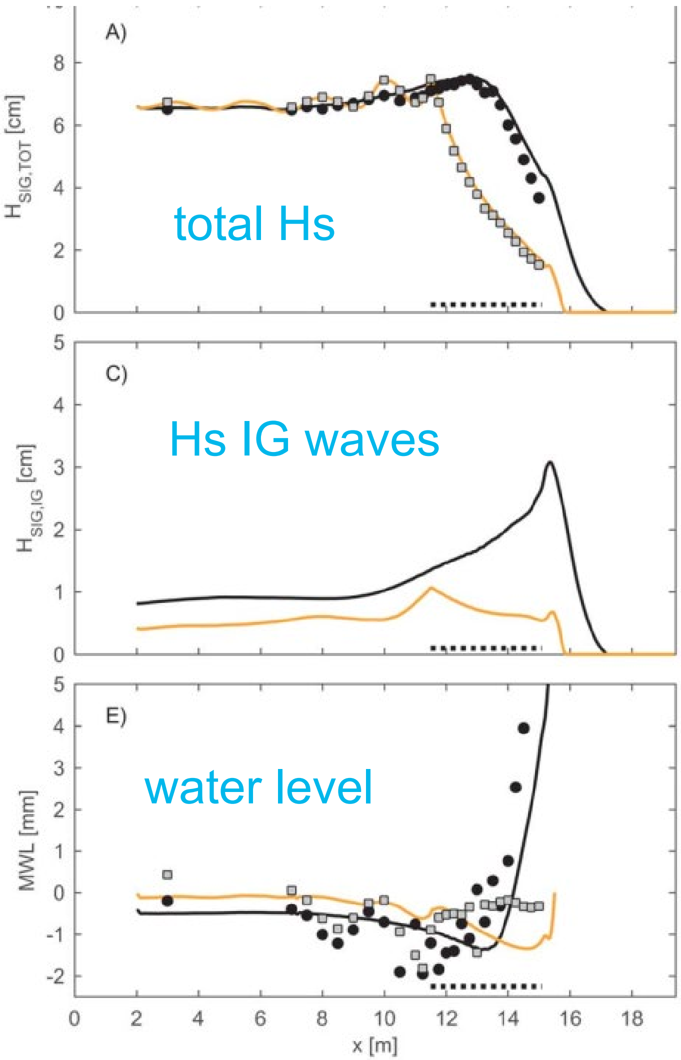
Wave propagation through mangrove forests

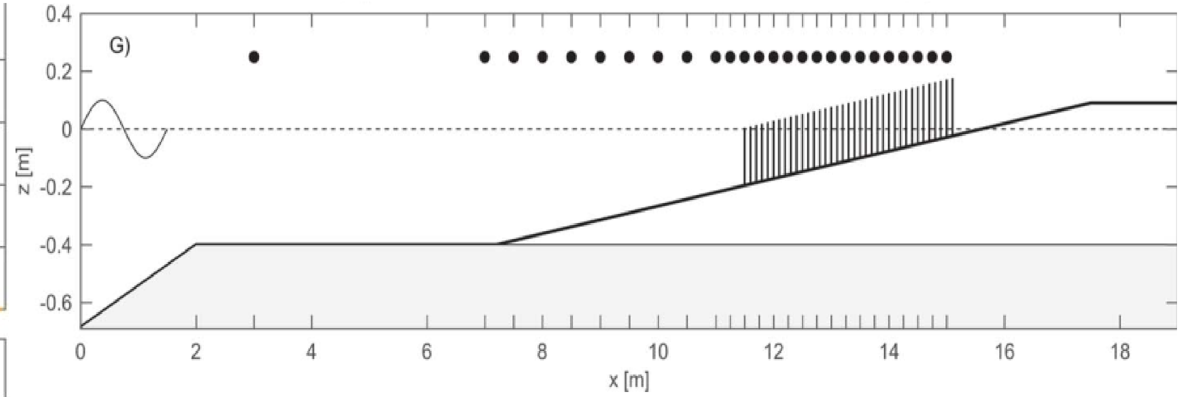
- Vegetation effects on sea-swell and infragravity waves
  - Attenuation of wave heights (e.g. Mendez&Losada 2004)
  - Influence on wave setup by:
    - Radiation stress gradient decrease because of attenuation: decrease
    - Mean drag force by stems on flow: increase
    - Wave induced force on emerged vegetation: decrease
    - Wave non-linearities: decrease

$$F_{v,w} \propto u_w |u_w| \cdot h'_v$$



Wave propagation through mangrove forests





Model-data comparison:

yellow + *grey dots*: with vegetation
black + *black dots*: no vegetation

Van Rooijen 2016

Take home message…

Today you learned…

- …where you can find coral reefs and mangroves
- …what differentiates these environments from clastic (sand/gravel) coasts
- …which concepts from ‘regular’ sandy beach hydrodynamics you can apply in these environments, and which ones not