Exploring millennial responses of reefs to climatic forcing, insights from coupled wave and carbonate growth forward stratigraphic model

T. Salles[1], J. Pall[1], J. Webster[1], A. Vila-Concejo[1], S. Duce[1], B. Dechnik[1]

Key Points.

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Abstract. (Type abstract here)

1. Introduction

(Article text here.)

2. Carbonate platform evolution models

3. pyReef model

3.1. Model overview

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3.2. Large-scale forcings

temperature, salinity sea-level tectonics ph

3.3. Wave transformation

SWAN, short for *Simulating WAves Nearshore*, is a third-generation, finite-difference, wave model used to predict wave propagation in coastal areas and estuaries. It is governed by the wave action balance equation [*Bretherton and Garrett*, 1968; *Hasselmann et al.*, 1973; *Holthuijsen et al.*, 1993; *Booij et al.*, 1999]:

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}} \cdot \left[\left(\vec{c_g} + \vec{U} \right) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = \frac{S_{tot}}{\sigma} \quad (1)$$

where $N(\vec{x}, t, \sigma, \theta)$ is the wave action function of geographical space $\vec{x}$, time t, relative frequency σ and wave direction θ. $\nabla_{\vec{x}}$ is the gradient operator in space, $\vec{c_g}$ and $\vec{U}$ are the wave group velocity and ambient current vector respectively and c_θ, c_σ is the propagation velocity in θ and σ domain. Finally S_{tot} is the source term which can include wind, whitecapping, surf breaking and bottom friction [*Booij et al.*, 1999]. In our model, shoaling and refraction are accounted for from a series of deep-water wave conditions through time in the absence of wind forcing. Hence to compute wave field generation, the model requires bathymetric conditions and definitions of offshore significant wave height, characteristic period of the energy spectrum and wave direction and associated spreading angle.

To evaluate reef responses over several hundreds of years, the approach taken here does not examine temporal evolving wave fields, such as those produced during storm events and relies on SWAN stationary mode. In pyReef, the wave transformation model is generally performed for time intervals varying from 0.5 to 10 years. Our aim is to simulate realistic wave fields by imposing a sequence of wave forcing conditions (*e.g.* series of fair-weather and/or storm events). At any given time interval, we define a percentage of activity for each deep-water wave conditions and the bathymetry is used to compute associated wave parameters. Possibility is given to derived these parameters for both low and high tides.

Combined with the climatic forcing described above, two additional wave factors could be adjusted in the model: the breaking parameter and the bottom friction.

In regions where wave height is close to water depth, wave breaking is an important source of energy dissipation on reefs [*Symonds et al.*, 1995; *Becker et al.*, 2014]. This effect is typically approximated with a constant breaking parameter γ_s [*Symonds et al.*, 1995; *Vetter et al.*, 2010] which values have been calibrated for different reef systems [*Apotsos et al.*, 2007; *Vetter et al.*, 2010; *Monismith et al.*, 2013; *Franklin et al.*, 2013; *Rogers el al.*, 2015].

The high rugosity of reefs plays a significant role on wave dynamics by increasing the frictional dissipation of wave energy flux [*Young*, 1989; *Lowe et al.*, 2005; *Lowe and Falter*, 2015]. This dissipation is usually approximated with a wave roughness friction factor f_w which values have been well constrained for sand grain [*Kamphuis*, 1975; *Grant and Madsen*, 1979; *Dean and Dalrymple*, 1991]. In phase-averaged wave action approach like SWAN, this bottom dissipation is parameterised as a function of wave excursion to bottom roughness scale with a maximum value of 0.3 for f_w [*Jonsson*, 1966; *Madsen et al.*, 1988]. Several studies [*Nelson*, 1996; *Lowe et al.*, 2005; *Lentz et al.*, 2015; *Rogers el al.*, 2015; *Monismith et al.*, 2015] indicates that this roughness factor can be much higher for reef systems (*i.e.* up to 5.0 for reef platform in the Red Sea [*Lentz et al.*, 2015]). To better estimate the impact of reef rugosity on frictional dissipation, we have modified the existing formulation for f_w in SWAN and used the proposed parameterisation from *Rogers el al.* [2015] based on *Swart* [1974]:

$$f_w = \begin{cases} exp\left[a_1 \left(A_b/k_N\right)^{a_2} + a_3\right], \ A_b/k_N \geq 0.0369 \\ 50, \ A_b/k_N < 0.0369 \end{cases} \quad (2)$$

[1]School of Geosciences, University of Sydney, Sydney, NSW, Australia.

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where A_b is the wave excursion distance, k_N is the bottom roughness scale and the coefficients a_1 =5.213, $a_2 = -0.194$, and $a_3 = -5.977$ have been set based on *Rogers el al.* [2015] Palmyra study. Alternate coefficient from *Nielsen* [1992] can also be used (a_1 =5.5, $a_2 = -0.2$, and $a_3 = -6.3$). For large values of A_b/k_N, this formulation is similar to the one from Madsen et al. [1988] (implemented in SWAN), but extends the parameterisation for lower A_b/k_N. In pyReef, the bottom friction is based on the proposed formulation and requires the definition of the bottom roughness scale (k_N) which values is generally set to 2-3 times the characteristic diameters of the studied region [*Nielsen*, 1992; *Lowe et al.*, 2005; *Rogers el al.*, 2015].
For each forcing conditions, the wave transformation model computes and returns the significant wave height, the mean wave direction and the root-mean-square value of the maxima of the orbital velocity near the bottom. These parameters are subsequently used to evaluate the long-term hydrodynamic forces active over the simulated region.

3.4. Long-term wave-driven circulation

Flow circulation in and around reef platforms depends on the complex interactions between the overlying water motion and the three-dimensional bottom roughness formed by reef organisms. Attempts to numerically simulate flow dynamics around individual coral colonies have been proposed [*Kaandorp et al.*, 2003; *Chang et al.*, 2009; *Chindapol et al.*, 2013] but such models require the flows to be solve down to few millimetres scale and are beyond the scope of our approach. Here we assume that the flow circulation in the reef platform is mainly driven by waves and regional-scale drivers of reefs hydrodynamics such as coastal upwelling or ocean currents are ignored. Numerical studies of wave-driven flow around reef systems commonly use depth-averaged Navier-Stokes equations [*Raupach and Shaw*, 1982; *Symonds et al.*, 1995; *Lowe et al.*, 2005, 2009; *Pomeroy et al.*, 2012; *Taebi et al.*, 2011]. In the context of millennial scale reef platform evolution, these methods however are still computationally prohibitive. In pyReef, the proposed method consists in producing *snapshots* of wave-driven circulation distribution resulting from series of deep-water wave scenarios by computing time-averaged cross-shore and longshore currents.

In nearshore environments, longshore current runs parallel to the shore and is generated by the radiation stresses associated with the breaking process for obliquely incoming waves and by the surplus water which is carried across the breaker zone towards the shoreline [*Longuet-Higgins*, 1970]. This current affect the transport and transfer of mass (loose carbonate sands, nutrients and carbon) in the nearshore reef waters [*Hamner and Wolanski*, 1988; *Monismith*, 2007; *Lowe and Falter*, 2015]. Many empirical formulation of longshore current have been proposed since the initial work from *Longuet-Higgins and Stewart* [1964] [*Komar and Inman*, 1970; *Komar and Miller*, 1975; *Galvin*, 1987; *Reniers and Battjes*, 1997; *Ruessink et al.*, 2001; *Grasmeijer and Ruessink*, 2003]. In pyReef, the approach from *Komar and Miller* [1975] is used to calculate the longshore current velocity ($\vec{v_l}$) in the middle of the breaking zone:

$$\vec{v_l} = \kappa_l u_b cos(\theta) sin(\theta) \vec{k} \tag{3}$$

where u_b is the maximum near-bed orbital velocity obtained from SWAN, θ the angle of incidence of the incoming waves, κ_l a scaling parameter and $\vec{k}$ the unit vector parallel to the breaking depth contour. For wave rays approaching the reef at on oblique angle, the component of wave energy flux parallel to the reef shore will drives this longshore velocity. The calculation of the angle of incidence in pyReef is quite straightforward and requires an estimate of wave breaking depth (defined for each wave scenario) and wave direction (obtained from the wave transformation model).

In addition to longshore current, two types of cross-shore velocities are simulated in pyReef. First we estimate the onshore velocity which is essential in predicting the shoreward transport of broken carbonate particles during fair-weather periods [*Elfrink et al.*, 1999; *Ruessink et al.*, 1998]. In our model, we assume a linear dependency between the near-bed orbital velocity and the intensity of this onshore current $\vec{v_o}$:

$$\vec{v_o} = \kappa_o u_b \vec{n} \tag{4}$$

with u_b the maximum near-bed orbital velocity, $\vec{n}$ the unit vector parallel to the incoming wave direction and κ_o a correction factor. κ_o can be derived from local shallow reef water conditions and reflects natural wave skewness and asymmetry which are known to play a central part in cross-shore velocity profile [*Grasmeijer and Ruessink*, 2003; *Crawford and Hay*, 2003]. The onshore velocity ($\vec{v_o}$) is usually associated to the wave crest and is stronger than the one due to the wave trough [*Isobe and Horikawa*, 1982; *Grasmeijer and Ruessink*, 2003].

During strong wave conditions, a second type of wave-induced cross-shore velocity is defined in pyReef and simulates an offshore-directed steady current referred to as undertow. The time-averaged and depth-averaged undertow velocity $\vec{v_u}$ is derived from the mass flux due to the wave motion and surface roller [*Svendsen et al.*, 1987]. Under normal incident periodic waves, *Longuet-Higgins* [1975] showed that the depth- and time-averaged undertow velocity is related to the wave's kinetic energy density and phase speed. Assuming equipartition of kinetic and potential wave energy, the total energy density of the wave is approximately [*Svendsen*, 1984]:

$$E_w = \frac{1}{8} \rho g H^2 \tag{5}$$

with ρ the ocean density and H the root-mean-square wave height returned by SWAN. Following *Cox and Kobayashi* [1998], the undertow velocity is assumed to have the following form in our model:

$$\vec{v_u} = -\kappa_u \frac{\sqrt{gh}}{8} \left(\frac{H}{h}\right)^2 \vec{n} \tag{6}$$

with κ_u an empirical coefficient [*Kobayashi et al.*, 1998], g the gravitational acceleration, h the water depth and $\vec{n}$ the unit vector parallel to the incoming wave direction.

3.5. Calcareous sand transport

A common feature of many reef systems is the presence of diverse marine communities, including seagrasses, coral reef organisms, sponges and mangroves. Simulating the evolution of these communities involves to resolve the details of their individual transport by waves and currents at fine scale and therefore requires very advanced and computationally expensive numerical models [*Lowe and Ghisalberti*, 2016]. The approach proposed here is based on a parametric transport model that consider the main hydrodynamic forces presented in previous section and relies on coral assemblages rather than individual communinities. Coral assemblages are derived from coral composition and comparison with modern coral zonation. In the Southern Great Barrier Reef, from 22 identified fossil coral species, *Dechnik et al.* [2015] was able to define four main coral assemblages and their palaeoenvironments. In pyReef, multiple coral assemblages can be defined and we assume that each assemblage is made of hard and loose corals. The hard coral (*e.g.* living part) can either grow in-situ or be disintegrated in loose particles.

Only the loose particles are subject to transport and we assume that these particles can be represented by a unique diameter and density value.

To our knowledge, transport law for calcareous sand based on their hydraulic characteristics has not been proposed yet. It has been recognised [*Prager et al.*, 1996; *Dai*, 1997; *Smith and Cheung*, 2004] that variations in the hydraulic properties between siliceous and calcareous sand due to both their shapes and fall velocities lead to different transport behaviors. From flume experiments, *Smith and Cheung* [2005] shows that transport models designed for siliceous particles might be applied after a correction factor has been introduced. From their experiment, the model of *Engelund and Hansen* [1967] seems to provide the best fit with their dataset, however they conclude that these corrections are not universally applicable.
Therefore, in pyReef, we have chosen to build our transport model based on a classical approach. Assuming sediment transport induced by waves and currents, our method is derived from Soulsby and Van Rijn formulation [*Soulsby*, 1997]. We compute the total load transport rate resulting from the addition of bed load and suspended load for each type of loose carbonate sands initially set by the user. The model also assumes that each of sand particles are perfectly sorted. The method suits well with our approach as it can be applied in a quasi-steady form. The transport rate is defined by:

$$q_t = (A_{sb} + A_{ss})\bar{v}\left[\sqrt{\bar{v}^2 + \frac{0.018}{C_D}u_b} - \bar{u_{cr}}\right]^{2.4}(1 - 1.6\nabla z) \tag{7}$$

where $\bar{v}$ is the depth-averaged current velocity obtained from the long-term wave driven circulation model defined in previous section, C_D is the drag coefficient (due to current alone) and ∇z the slope. The bed load transport A_{sb} is given by:

$$A_{sb} = \frac{0.005h(d/h)^{1.2}}{(s-1)gd} \tag{8}$$

with s is the relative density of sediments and d is the median grain diameter. The suspended load transport A_{ss} is obtained from the following formula:

$$A_{ss} = \frac{0.012hd_\star^{-0.6}}{(s-1)gd} \tag{9}$$

where $d_\star$ refers to the dimensionless particle diameter.
The threshold current velocity of motion ($\bar{u_{cr}}$) is defined by:

$$\bar{u_{cr}} = \begin{cases} 0.19\, d^{\,0.1}\, log_{10}(4h/d),\ 0.1 \geq d \geq 0.5\,\text{mm} \\ 8.5\, d^{\,0.6}\, log_{10}(4h/d),\quad 0.5 \geq d \geq 2.\,\text{mm} \end{cases} \tag{10}$$

In addition, to the above sediment transport model a multi-lithology non-linear diffusion model has been implemented to simulate secondary gravity-driven transport processes happening over longer temporal scale than wave and current induced ones. Based on *Rivenaes* [1997] and considering n different types of coral assemblages, the following set of nonlinear partial differential equations (PDEs) are used to calculate the proportion of each assemblage a_k:

$$\begin{aligned} &\textstyle\sum_{k=1}^{n} a_k = 1 \\ &\tfrac{\partial z}{\partial t} = \textstyle\sum_{k=1}^{n} \tfrac{1}{c_k}\nabla\cdot(\kappa_k a_k \nabla z) \\ &d_l \tfrac{\partial a_k}{\partial t} + a_k \tfrac{\partial z}{\partial t} = \tfrac{1}{C_k}\nabla\cdot(\kappa_k a_k \nabla z) \end{aligned} \tag{11}$$

where κ_k denotes the diffusion coefficient for sediment k, c_k is the compaction ratio and d_l is a constant representing the thickness of a prescribed top layer, in which sediments are transported. This set of PDEs is solved using a fully explicit schema following the approach from *Clark et al.* [2010].

To simulate bed morphology and stratigraphic evolution a classical multi-level bed framework tracks the distribution of every coral assemblage through time by layers (*Warner et al.* [2008] and reference therein). In pyReef, each layer stores the bulk properties including thickness and percentage of hard and loose coral assemblages. An active layer at the top of the stratigraphic pile is used to calculate the transport of the calcareous sand from both the wave-current driven and diffusion-based models presented above.

3.6. Carbonate growth and disintegration

The fuzzy model simulates the deposition of reefs and carbonate facies through integration of local and global variables. Local-scale factors include basement relief, sea-level change, climate, latitude, water energy, water depth, background sedimentation rate, and substrate conditions. Regional and global-scale changes include relative sea-level change, climate, and latitude.

4. Models setup

5. Results

impact of storms on carbonate evolution (model with fair weather and model with 1 storm and after 2 storms)
impact of sea-level change and thermal subsidence
impact of change in pH and ocean temperature

6. Discussion

7. Conclusions

Acknowledgments. (Text here)

References

Apotsos, A., B. Raubenheimer, S. Elgar, R. T. Guza, and J. A. Smith (2007), Effects of wave rollers and bottom stress on wave setup, *J. Geophys. Res.*, *112*, C02003, doi:10.1029/2006JC003549.

Becker, J. M., M. A. Merrifield, and M. Ford (2014), Water level effects on breaking wave setup for Pacific Island fringing reefs, *J. Geophys. Res. Oceans*, *119*, 914–932, doi:10.1002/2013JC009373.

Booij N., R. Ris, and L. Holthuijsen (1999), A third-generation wave model for coastal regions. 1. Model description and validation, *J. Geophys. Res.*, *104*,(C4), 7649–7666.

Bretherton, F., and C. Garrett (1968), Wavetrains in inhomogeneous moving media, *Proc. R. Soc. Lond. Ser. A*, *302*, 529–554; doi:10.1098/rspa.1968.0034.

Chang, S., C. Elkins, M. Alley, J. Eaton, and S. G. Monismith (2009), Flow inside a coral colony measured using magnetic resonance velocimetry, *Limnol. Oceanogr.*, *54*, 1819.

Chindapol N., J. A. Kaandorp, C. Cronemberger, T. Mass, and A. Genin (2013), Modelling growth and form of the scleractinian coral Pocillopora verrucosa and the influence of hydrodynamics, *PLoS Comput. Biol.*, *9*, e1002849

Clark, S. R., W. Wei, and X. Cai (2010), Numerical analysis of a dual-sediment transport model applied to Lake Okeechobee, Florida, *in: Proceedings of the 9th International Symposium on Parallel and Distributed Computing, IEEE Computer Society Press*, pp. 189–194.

Cox, D. T. and N. Kobayashi (1998), Application of an Undertow Model to Irregular Waves on Plane and Barred Beaches, *J. Coast. Res.*, *14*, 4, 1314–1324.

Crawford, A. M., and A. E. Hay (2003), Wave orbital velocity skewness and linear transition ripple migration: Comparison with weakly nonlinear theory, *J. Geophys. Res.*, *108*, 3091, doi:10.1029/2001JC001254.

Dai, J. (1997), Engineering Characteristics of Tropical Island Beaches. Master's Thesis, Department of Ocean Engineering, University of Hawaii, Honolulu, Hawaii.

Dean, R. G., and R. A. Dalrymple (1991), Water wave mechanics for engineers and scientists, *Advanced Series on Ocean Engineering*, vol. 2, World Sci., Hackensack, N. J.

Dechnik, B., J. M. Webster, P. J. Davies, J.-C. Braga, and P. J., Reimer (2015), Holocene 'turn-on' and evolution of the Southern Great Barrier Reef: revisiting reef cores from the Capricorn Bunker Group, *Marine Geology*, *363*, 174–190.

Elfrink, B., K. A. Rakha, R. Deigaard, and I. Brøker (1999), Effect of near-bed velocity skewness on cross-shore sediment transport, *Proceedings Coastal Sediments. ASCE, Reston, VA, USA*, pp. 33–47.

Engelund, F., and E. Hansen (1967), A Monograph on Sediment Transport. Technisk Forlag, Copenhagen, Denmark.

Franklin, G., I. Marin o-Tapia, and A. Torres-Freyermuth (2013), Effects of reef roughness on wave setup and surf zone currents, *J. Coastal Res.*, *Special Issue 65*, 2005–2010.

Galvin, C. (1987), The continuity equation for long shore current velocity with breaker angle adjusted for a wave-current interaction, *Coast. Eng.*, *11(2)*, 115–129.

Grant, W. D., and O. S. Madsen (1979), Combined wave and current interaction with a rough bottom, *J. Geophys. Res.*, *84(C4)*, 1797–1808, doi:10.1029/JC084iC04p01797.

Grasmeijer, B. T., and B. G.Ruessink (2003), Modeling of waves and currents in the nearshore: parametric vs. probabilistic approach, *Coastal Engineering*, *49*, 185–207.

Hamner, W., and E. Wolanski (1988), Hydrodynamic forcing functions and biological processes on coral reefs: a status review, *In Proceedings of the 6th International Coral Reef Symposium, Vol. 1: Plenary Addresses and Status Review, ed. JH Choat, D Barnes, MA Borowitzka, JC Coll, PJ Davies, et al.*, pp. 103–13. Townsville, Aust.: Int. Coral Reef Symp. Exec. Comm.

Hasselmann, K., et al. (1973), Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP), *Dtsch. HydrogrZ. 2*, Suppl., 1 (A8), 1–95.

Holthuijsen L. H, N. Booij, and R. C. Ris (1993), A spectral wave model for the coastal zone, *Proceedings of the 2nd international symposium on ocean wave measurement and analysis, New Orleans, LA*, pp. 630–641.

Isobe, M., and K. Horikawa (1982), Study on water particle velocities of shoaling and breaking waves, *Coast. Eng. in Japan*, *25*, 109–123.

Jonsson, I. G. (1966), Wave boundary layer and friction factors. *Coastal Eng. Conf.*, *1(10)*, 125–148.

Kaandorp, J.A., E. A. Koopman, P. M. Sloot, R. P. Bak, M. J. Vermeij, and L. E. Lampmann, (2003), Simulation and analysis of flow patterns around the scleractinian coral Madracis mirabilis (Duchassaing and Michelotti), *Philos. Trans. R. Soc. Lond. B 358*, 1551–57

Kobayashi, N., M. N. Herrman, B. D. Johnson, and M. D. Orzech (1998), Probability distribution of surface elevations in surf and swash zones, *J. Waterway, Port, Coastal, and Ocean Eng.*, *124*, (3), 99–107.

Kamphuis, J. (1975), Friction factor under oscillatory waves, *J. Waterw. Harbors Coastal Eng. Div. ASCE*, *101*, 135–144.

Komar, P. D., and D. L. Inman (1970), Long-shore sand transport on beaches, *J. Geophys. Res.*, *75(30)*, 5914–5927.

Komar , P. D., and M. C. Miller (1975),The initiation of oscillatory ripple marks and the development of plane-bed at high shear stresses under waves, *J. Sed. Res.*, *45(3)*, 697–703.

Lentz, S. J., J. H. Churchill, K. A. Davis, and J. T. Farrar (2015). Surface gravity wave transformation across a platform coral reef in the Red Sea, *J. Geophys. Res.*, doi:10.1002/2015JC011142.

Longuet-Higgins, M. S., 1970. Longshore currents generated by obliquely incident sea waves, *J. Geophys. Res.*, *75(33)*, 1–35.

Longuet-Higgins, M.S. (1975), Integral properties of periodic gravity waves of finite amplitude, *Proceedings of the Royal Society of London A*, *342*(1629), 157–174

Longuet-Higgins, M. S., and R. W. Stewart (1964), Radiation stresses in water waves; a physical discussion, with applications, *Deep-Sea Research*, *11*, 529–562.

Lowe, R. J., J. L. Falter, M. D. Bandet, G. Pawlak, M. J. Atkinson, S. G. Monismith, and J. R. Koseff (2005), Spectral wave dissipation over a barrier reef, *J. Geophys. Res.*, *110*, C04001, doi:10.1029/2004JC002711.

Lowe, R.J., J. L. Falter, S. G. Monismith SG, and M. J. Atkinson (2009), A numerical study of circulation in a coastal reef-lagoon system, *J. Geophys. Res.*, *114*, C06022.

Lowe, R. J., and J. L. Falter (2015), Sediment transport processes within coral reef and vegetated coastal ecosystems: a review, *WAMSI Dredging Science Node, Report Theme 3, Project 3.1.2*, 19 p.

Lowe, R. J., and M. Ghisalberti (2016), Oceanic forcing of coral reefs, *Annu. Rev. Mar. Sci.*, *7*, 43–66, doi:10.1146/annurev-marine-010814-015834.

Madsen, O. S., Y. Poon, and H. C. Graber (1988), Spectral wave attenuation by bottom friction: Theory, *Coastal Eng. Conf.*, *1(21)*, 492–504.

Monismith, S. G. (2007), Hydrodynamics of coral reefs, *Annu. Rev. Fluid Mech.*, *39*, 37–55.

Monismith, S. G., L. Herdman, S. Ahmerkamp, and J. Hench (2013), Wave transformation and wave-driven flow across a steep coral reef, *J. Phys. Oceanogr.*, *43*, 1356–1379, doi:10.1175/JPO-D-12-0164.1.

Monismith, S. G., J. S. Rogers, D. Koweek, and R. B. Dunbar (2015), Frictional wave dissipation on a remarkably rough reef, *Geophys. Res. Lett.*, *42*, 4063–4071, doi:10.1002/2015GL063804.

Nelson, R. C. (1996), Hydraulic roughness of coral reef platforms, *Appl. Ocean Res.*, *18(5)*, 265–274.

Nielsen, P. (1992), *Coastal Bottom Boundary Layers and Sediment Transport, Advanced Series on Ocean Engineering*, vol. 4, World Sci., Hackensack, N. J.

Pomeroy A., R. J. Lowe, G. Symonds, A. van Dongeren, and C. Moore (2012), The dynamics of infragravity wave transformation over a fringing reef, *J. Geophys. Res.*, *117*, C11022.

Prager, E. J., J. B. Southard, and E. R. Vivoni-Gallart (1996), Experiments on the entrainment threshold of well-sorted and poorly sorted carbonate sands, *Sedimentology*, *43*, 33–40.

Raupach, M. R., and R. H. Shaw (1982), Averaging procedures for flow within vegetation canopies, *Bound. Layer Me- teorol.*, *22*, 79–90.

Reniers, A. J. H. M., and J. A. Battjes, (1997), A laboratory study of long shore currents over barred and non-barred beaches, *Coast. Eng.*, *30(1-2)*, 1–21.

Rivenaes, J. C. (1997), Application of a dual-lithology, depth-dependent diffusion equation in stratigraphic simulation, *Basin Research*, *4*, 2, 133–146.

Rogers, J. S., S. G. Monismith, D. A. Koweek, and R. B. Dunbar (2015), Wave dynamics of a Pacific Atoll with high frictional effects, *J. Geophys. Res. Oceans*, *120*, doi:10.1002/2015JC011170.

Ruessink, B. G., K. T. Houwman, and P. Hoekstra (1998), The systematic contribution of transporting mechanisms to the cross-shore sediment transport in water depth of 3 to 9 m, *Marine Geology*, *152*, 295–324.

Ruessink, B. G., J. R. Miles, F. Feddersen, R. T. Guza, and S. Elgar (2001), Modeling the alongshore current on barred beaches. *J. Geophys. Res.*, *106*, 22451–22464.

Smith, D. A., and K. F. Cheung (2004), Initiation of motion of calcareous sand, *J. Hydraul. Eng., ASCE*, *130*, 467–472.

Smith, D. A., and K. F. Cheung (2005), Transport rate of calcareous sand in unidirectional flow, *Sedimentology*, *52*, 1009-1020.

Soulsby, R. (1997) Dynamics of marine sand: A manual for practical applications. Thomas Telford Publications, London, 249 pp.

Symonds, G., K. P. Black, and I. R. Young (1995), Wave-driven flow over shallow reefs, *J. Geophys. Res.*, *100(C2)*, 2639–2648, doi:10.1029/94JC02736.

Svendsen, L. A. (1984), Mass flux and undertow in a surf zone, *Coastal Eng.*, *8*, 247–365.

Svendsen, L. A., H. A. Schaffer, and J. B. Hansen (1987), The interaction between the undertow and the boundary layer flow on a beach, *J. Geophys. Res.*, *92*, C11, 11845–11856.

Swart, D. H. (1974), Offshore sediment transport and equilibrium beach profiles, PhD Dissertation, TU Delft, Delft University of Technology, Delft, Netherlands.
Taebi, S., R. J. Lowe, C. B. Pattiaratchi, G. N. Ivey, G. Symonds, and R. Brinkman (2011), Nearshore circulation in a tropical fringing reef system, *J. Geophys. Res.*, *116*, C02016.
Vetter, O., J. M. Becker, M. A. Merrifield, A.-C. Péquignet, J. Aucan, S. J. Boc, and C. E. Pollock (2010), Wave setup over a Pacific Island fringing reef, *J. Geophys. Res.*, *115*, C12066, doi:10.1029/2010JC006455.
Warner, J. C., C. R. Sherwood, R. P. Signell, C. Harris, and H. G. Arango (2008), Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model, *Computers and Geosciences*, *34*, 1284–1306.
Young, I. R. (1989), Wave transformation over coral reefs, *J. Geophys. Res.*, *94(C7)*, 9779–9789, doi:10.1029/JC094iC07p09779.

Corresponding author: Tristan Salles, School of Geosciences, University of Sydney, Madsen Building, Sydney, NSW 2006, Australia. (tristan.salles@sydney.edu.au)