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Field and numerical investigations of wave transformation and inundation on atoll islands

Edward Paul Beetham

2016

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Geography, School of Environment, University of Auckland
Abstract

Field data were collected on Fatato Island, Funafuti Atoll, Tuvalu, to understand contemporary wave transformation processes on a previously unstudied atoll. Subsequently, a fully nonlinear Boussinesq model was used to simulate wave processes on Fatato and other reefs with variable morphology to evaluate the impact of sea level rise (SLR) on shoreline wave energy, runup and inundation within atoll environments. Field data from Fatato Island indicate clear tidal controls on sea swell (SS) waves and setup at the reef flat and shoreline, but identify no tidal influence on infragravity (IG) waves that were consistently amplified towards the shoreline. The open source model Basilisk GN was capable of replicating two months of field data, achieving model skill > 0.96 for SS, IG and setup processes at the outer reef flat and shoreline. Numerical outputs were used to analyse runup elevation at the shoreline and highlighted the importance of setup at low tide, SS waves at high tide, and IG waves at all tidal stages. Simulations of wave transformation on Fatato indicate that 0.3 m of SLR will cause inundation at spring high tide under annual maximum swell and storm wave conditions. Additional simulations show that vertical reef growth with SLR can mitigate the associated increase in shoreline energy but also demonstrate that reef growth has limited potential to protect islands from inundation. Results from Fatato were extended by simulating wave transformation and inundation on 768 idealised reefs with variable morphology under mean, swell and storm conditions. Model outputs were used to develop the island inundation index, using reef width, reef depth and berm height to classify levels of vulnerability to inundation under moderate wave conditions. The index is a simple tool for assessing island vulnerability and was applied to track the trajectory of vulnerability to inundation on a range of studied reef islands in the Pacific Ocean, with SLR up to 1 m. Results from this thesis can be used to assist coastal management on atoll islands facing SLR.
Dear Dr Hiroki Ogawa,

I took it for granted that I could always visit you for an interesting discussion about science and your latest adventures.

You taught me so much as a teacher and friend and helped me with countless data and technical issues through my undergraduate and postgraduate years. You inspired me to undertake a PhD and to pursue a research career. Beyond that, you motivated me to make the most of every day and every opportunity.

Thank you for being an amazing influence in my life and in the lives of so many others. You are deeply missed and continue to inspire everyone who had a chance to meet you.

Rest in peace my friend.

Hiroki Ogawa 1982 – 2013
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<tr>
<td>$H_{ss}$</td>
<td>Significant SS wave height (top 1/3rd)</td>
</tr>
<tr>
<td>$H_{ig}$</td>
<td>Significant IG wave height (top 1/3rd)</td>
</tr>
<tr>
<td>$\overline{\eta}$</td>
<td>Wave setup (mean water level)</td>
</tr>
<tr>
<td>$H_o$</td>
<td>Offshore significant wave height</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Significant wave period</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Peak wave period</td>
</tr>
<tr>
<td>$R_{max}$</td>
<td>Maximum wave runup</td>
</tr>
<tr>
<td>$B$</td>
<td>Free-surface slope threshold</td>
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<tr>
<td>$C_f$</td>
<td>Friction coefficient</td>
</tr>
<tr>
<td>$f_{reef}$</td>
<td>Resonant frequency of a reef</td>
</tr>
<tr>
<td>$f_{ig}$</td>
<td>Frequency of incident IG waves</td>
</tr>
<tr>
<td>$w_r$</td>
<td>Reef width</td>
</tr>
<tr>
<td>$h_r$</td>
<td>Reef depth</td>
</tr>
<tr>
<td>$\beta_r$</td>
<td>Fore-reef slope</td>
</tr>
<tr>
<td>$\beta_{beach}$</td>
<td>Beach slope</td>
</tr>
<tr>
<td>$Z_{berm}$</td>
<td>Berm height above reef flat</td>
</tr>
<tr>
<td>$BE$</td>
<td>Berm height above still water level</td>
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List of publications

Thesis Chapters 4, 5, 6 and 7 are a series of journal articles that are in different stages or preparation and publication. All publications include Paul Kench (primary supervisor), Joanne O'Callaghan (co-supervisor) and Stephane Popinét (advisor) as co-authors. See the following pages for co-author forms. To avoid unnecessary repetition in the thesis, the introduction, field setting and methodology sections of each paper is slightly different in the thesis compared to the journal manuscripts.

- Chapter 4 is in the final stages of preparation for submission.
- Chapter 5 was published in January 2016 with the following citation:
- Chapter 6 is in the final stages of preparation and will be submitted for publication in *Earth Surfaces Processes and Landforms*.
- Chapter 7 is in the final stages of preparation and will be submitted for publication in *Geomorphology*.

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Thesis Chapter 4.
Title: Benchmark evaluations for simulating wave processes on coral reefs using a fully nonlinear Boussinesq solver.
Publication details: The manuscript is currently under review for publication in Journal of Waterway, Port, Coast and Ocean Engineering. Date of submission: 26 November 2015.

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<th>Nature of Contribution</th>
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<tr>
<td>Paul Kench</td>
<td>Dr Kench assisted with developing the manuscript structure and provided three rounds of feedback on figures, data analysis methods, writing style, content and context in thesis.</td>
</tr>
<tr>
<td>Stéphane Popinet</td>
<td>Dr Popinet developed the numerical model that was used in this research and reviewed the manuscript prior to submission to make sure the model was described properly and used appropriately. Comments were also made to improve figures and results descriptions.</td>
</tr>
<tr>
<td>Joanne O'Callaghan</td>
<td>Dr O'Callaghan reviewed the paper prior to submission with comments on understanding model outputs, improving work flow and developing a better writing style.</td>
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**Certification by Co-Authors**

The undersigned hereby certify that:
- the above statement correctly reflects the nature and extent of the PhD candidate’s contribution to this work, and the nature of the contribution of each of the co-authors; and
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<td>Joanne O'Callaghan</td>
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Title: Wave transformation and shoreline water level on Funafuti Atoll, Tuvalu

Published in JGR oceans: Available online January 2016


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<tr>
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</tr>
<tr>
<td>Joanne O'Callaghan</td>
<td>Dr O'Callaghan provided comprehensive feedback on results and data analysis work along with general edits throughout the manuscript</td>
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**Intended date of submission is Feb 2016 to the journal Earth Surface Processes and Landforms**

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<tr>
<td>Joanne O’Callaghan</td>
<td>Dr O’Callaghan provided comprehensive feedback on results, figures, writing and data analysis.</td>
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**Title:** Morphology and sea level controls on wave processes and inundation on atoll islands

**Intended date of submission is March 2016 to the journal Geomorphology**

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Chapter 1: Introduction

1.1 Introduction
This thesis uses a combination of field data and numerical model simulations to examine wave transformation processes on coral reefs in the context of sea level rise (SLR). The study of wave processes on reefs platforms is critical for assessing the future impacts of environmental change on low-lying coral reef islands. Global sea levels are currently rising and are predicted to continue to rising through the 21st century (Becker, et al., 2012, Bindoff, et al., 2007, Church, et al., 2013, Church, et al., 2006). Runup elevation, inundation and morphodynamic change on atoll islands are a function of wave energy available at the shoreline. The magnitude of shoreline wave energy is determined by the rate of incident sea swell (SS) wave dissipation and the transfer of energy to infragravity (IG) wave motions and setup on the reef flat (Merrifield, et al., 2014). There have been few attempts to quantify how these wave transformation processes are influenced by variations in tidal water level or changes in mean sea level on coral reefs. The first aim of this research is to understand how SS waves, IG waves and setup processes operate on coral reefs throughout the contemporary tidal range. The second aim is to examine how SLR will modify wave processes at the shoreline and to assess the implications of SLR on wave runup and inundation on atoll islands.

Coral reef islands are unconsolidated deposits of ecologically derived sediment located on atoll and platform reefs (Kench, et al., 2009c). Small in size and low in elevation (< 5 m above MSL), reef islands are considered among the most vulnerable landforms facing SLR (Nurse, et al., 2014). Arguably, the most at-risk nations facing SLR are Tuvalu, Marshall
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Despite this perceived vulnerability, recent research has revealed that reef islands are physically more resilient than previously assumed, and may not simply wash away or submerge with rising sea levels (Kench, et al., 2005, Kench, et al., 2015, McLean and Kench, 2015, Webb and Kench, 2010). Measurements of shoreline position documented over the last 30 to 100 years demonstrate that the net area of most Pacific Ocean atoll islands has increased or remained stable during a period of measured global and regional SLR (Kench, et al., 2015, Webb and Kench, 2010). Evidence of shoreline change at multi-decadal timescales demonstrates that reef islands are geomorphically dynamic structures that continuously change in size, shape and position on the reef surface in response to environmental boundary conditions (McLean and Kench, 2015). Kench, et al. (2015) highlight that erosion on higher energy (ocean facing) shorelines is often balanced by accretion on lower energy aspects of the same island (lateral or lagoon facing shorelines), often leading to a net increase in island area. Woodroffe (2008) suggests that sediment eroded from the beach face may also be deposited as over-wash material that can increase berm or island elevation. Measurements of shoreline position over shorter timescales further support the idea that reef islands continuously adjust their morphology in response to environmental conditions that operate at: storm event scale (Beetham and Kench, 2014,
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Flood, 1986), seasonal scale (Kench and Brander, 2006a, Kench, et al., 2009b) and intra-decadal scale (Chowdhury, et al., 2007). Redistribution of shoreline sediment highlights a natural potential for islands to adapt to SLR, however concern remains for developed islands with immobile infrastructure (McLean and Kench, 2015). Many atoll islands with dense populations do not have natural shorelines and are instead armoured with sea walls, roads and other structures; preventing any natural adjustment of island morphology to environmental conditions.

Tidal flooding and inundation are additional hazards facing communities living on reef island landforms and are expected to increase in frequency and magnitude with SLR (Mortreux and Barnett, 2009). Fongafale Island on Funafuti Atoll, Tuvalu, currently experiences flooding of low lying central areas during extreme spring (‘king’) tides (Lin, et al., 2014). Tidal flooding of islands is a result of a porous structure a natural central depression that, in some cases, is accentuated by excavation for aggregate material (Woodroffe, 2008, Yamano, et al., 2007). A rise in mean sea level will lower the tidal amplitude required for marine intrusion, resulting in more frequent flooding events each year. Penetration of tidal water through unconsolidated island structures poses a threat to fresh water resources, agriculture, and infrastructure (Chui and Terry, 2013).

An expected consequence of SLR is that the increase in reef depth will allow larger waves to reach island shorelines, increasing the potential for wave over-wash and inundation (Sheppard, et al., 2005). Inundation as a result of ocean waves can cause significant damage to buildings, roads, airports and people on developed islands (Ford, et al., 2013, Hoeke, et al., 2013, Merrifield, et al., 2014, Roeber and Bricker, 2015, Shimozono, et al., 2015). Reports of wave driven inundation on reef coastlines during extreme wave events are often associated with water level surges at infragravity wave frequencies and sediment being transported from the reef flat onto the island surface (Hoeke, et al., 2013, Roeber and
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Bricker, 2015). On developed islands, sediment transported in over-wash flow increases the potential for damage to people and property. However, deposition of sediment during inundation events on natural islands is an essential process for island formation and vertical growth (Kench, et al., 2009c, Woodroffe, 2008). A rise in mean sea level will decrease the wave energy threshold required for inundation, with estimates of frequent wave driven flooding events at low to moderate levels (0.3 – 0.5 m) of SLR (Merrifield, et al., 2014). However, the mechanics of wave runup and inundation on atoll reefs remain poorly understood, limiting any potential to predict how SLR will modify runup processes that result in wave inundation.

1.2 Coral reefs as an eco-morphodynamic system

Reef islands are a product of dynamic interactions between reef morphology, physical processes, reef ecological, and carbonate sediment production. Kench, et al. (2009c) coined the term ‘eco-morphodynamics’ to conceptualise these dynamic interactions across millennial and contemporary timescales (Fig. 1.1). Modern reef islands started forming when Holocene sea level stabilised 5-6 kbp, provided that coral reefs kept-up or caught-up with post glacial SLR (Woodroffe, et al., 1999). Vertical reef growth was constrained once reefs reached sea level, forcing a shift in constructional processes from reef growth to sediment production and island formation (Kench, 2013, Kench, et al., 2009c). In the context of reef platform development and the interplay between sea level and reef growth, modern reef islands are young features that developed during a period of relatively stable sea level during latter stages of the Holocene (McLean and Kench, 2015). Field studies show that island formation can occur under rising sea level, falling sea level (post high-stand) and stable sea level (Kench, 2013, Kench, et al., 2005, Kench, et al., 2012).
Reef islands form when sufficient biologically generated sediment is transported towards a nodal point of deposition (Gourlay, 1988). Therefore, modern islands are in eco-morphodynamic equilibrium with sea level, reef morphology, reef ecology, sediment supply and hydrodynamic processes (Perry, et al., 2011). Kench, et al. (2009c) highlight that the interlinked network of feedbacks in the eco-morphodynamic framework means any change in boundary conditions can flow through the system, and manifest in a forced change to contemporary processes and landforms (Fig. 1.1). Anthropogenic forced climate change and associated SLR is one example of an altered boundary condition that has the potential to change physical processes on coral reefs, forcing reef islands to change in morphology (Woodroffe, 2008). However, a detailed analysis of how island landforms may
adjust in response to SLR is lacking. As recent evidence suggests, islands have the potential to adjust in morphology and their presence on atoll reefs may not simply wash away with SLR (McLean and Kench, 2015). One reason for this is the limited understanding of how SLR will alter wave transformation processes on coral reefs.

1.2.1 Contemporary controls on island morphology

Contemporary elements of the eco-morphodynamic reef system highlight the dynamic interaction between wave driven physical processes, reef carbonate production, and island morphology (Fig. 1.1). Island formation and maintenance require the transportation of reef generated sediment and deposition on the reef surface (Kench, 1997, Kench, 1998a, Kench, 1998b). Sediment transport on coral reefs is primarily associated with wave generated currents, with entrainment forced by instantaneous wave orbitals that are at a maximum at the breakpoint and outer surf-zone (Gourlay, 2011c). Once entrained, sediment transport pathways are dictated by mean currents that are controlled by wave setup gradients across the reef (Gourlay, 2011a). Setup on an atoll rim with no island is maximum at the reef edge and decays across the reef flat generating a flow of water that decreases in velocity towards the lagoon (Hearn, 1999). The influence of wave dissipation, setup and setup driven currents have a primary influence on island deposition and morphology on coral reefs (Fig. 1.2; Kench, 2013). Wave refraction on circular and elongate platform reefs creates a more complex hydrodynamic environment, where island formation and sediment transport are associated with nodal points of wave convergence where refracted wave crests interfere with oncoming wave crests (Gourlay, 1988, Mandlier and Kench, 2012). Reef depth and morphology act as a major control on contemporary wave processes and velocity dynamics on modern coral reefs (Gourlay, 1996a, Kench and Brander, 2006b, Lowe, et al., 2010). Therefore, a rise in mean sea level will likely change the way wave energy is transformed across the reef; resulting in altered energy gradients and circulation patterns that influence
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sediment transport processes and ultimately island morphology (Cowell and Kench, 2001). Therefore, predicting how island morphology will respond to SLR cannot be achieved without an accurate understanding of contemporary hydrodynamics and a confident assessment of how SLR will modify physical processes.

Figure 1.2: Schematic showing a conceptualised understanding of how wave transformation processes influence reef island deposition and morphology. Adapted from Kench (2013).

1.3 Wave processes on coral reefs

Wave processes on tropical coral reef coastlines are fundamentally different from those observed on the comparatively well studied sedimentary shorelines (Roeber and Cheung, 2012b). Atoll and fringing reef morphology is characterised by a steep fore-reef slope which abruptly transitions to a near-horizontal reef flat (Kench, et al., 2009c). The abrupt transition from intermediate to shallow water results in a concentrated zone of energetic wave breaking at the reef edge. Ferrario et al. (2014) demonstrate that, on average, 86% of incident wave energy is dissipated within this transition zone. Dissipation from friction on the reef flat further decreases wave energy, typically resulting in very high rates of dissipation (97%) near the shoreline (Ferrario, et al., 2014). Globally there is a large variation in fore-reef slope, reef flat depth, reef flat width and reef flat roughness (Quataert, et al., 2015). These morphological characteristics, along with incident wave conditions,
determine the amount and mode of wave energy that reaches reef island shorelines (Kench and Brander, 2006b).

A slight fall in sea level following the mid-Holocene high stand has resulted in reef flat elevation being level with or slightly above the low tide level on many Pacific Ocean atolls (Schofield, 1977). The intertidal nature of contemporary atoll reefs results in a pronounced tidal modulation of wave processes at the reef flat and shoreline (Becker, et al., 2014, Ford, et al., 2013, Kench and Brander, 2006b, Merrifield, et al., 2014, Quataert, et al., 2015). Reef depth has an important control on wave breaking, which is understood to occur at a critical depth, and also limits the height of broken and reformed waves (Dean and Dalrymple, 1991). Experimental observations show that the largest wave heights that can propagate across a reef flat are $0.55h_r$ (Massel, 1996), emphasising the strong tidal control on wave energy at island shorelines. Field observations of wave transformation on coral reefs support this, with reef flat and shoreline wave heights in the sea swell (SS) frequency band showing a strong relationship with tidally controlled water level on the reef flat (Kench and Brander, 2006b). Kench and Brander (2006b) show that a ratio between reef depth and reef width can be used to predict the temporal exposure of island shorelines to SS wave activity. Conceptual models, field measurements, and empirical relationships demonstrate that larger waves impact islands at high tide, and suggest SLR will result in even larger waves at the shoreline, for a longer period of time (Becker, et al., 2014, Gourlay, 1994, Kench and Brander, 2006b, Merrifield, et al., 2014, Péquignet, et al., 2011, Vetter, et al., 2010). An example of relative SLR is presented in Sheppard, et al. (2005), where mass mortality and degradation of living coral on reef flats in the Seychelles resulted in deeper reefs which allowed larger waves to reach the shoreline. Sheppard, et al. (2005) explain that some areas of the coast initially accreted as material eroded from the reef was
deposited on the shoreline, however long-term erosion occurred as the coastline adjusted to the larger waves.

It is generally accepted that SLR will result in a linear increase in shoreline wave energy (Ferrario, et al., 2014, Quataert, et al., 2015). However, such an assumption does not account for the impact of SLR on secondary wave processes such as IG wave motions and wave setup. These secondary processes are associated with incident wave breaking and have a strong influence on shoreline water level and runup elevation (Merrifield, et al., 2014). Recent field measurements on coral reefs reveal that much of the incident frequency energy that is dissipated through wave breaking is conserved through the generation of infragravity waves and wave setup (Becker, et al., 2014, Péquignet, et al., 2014, Péquignet, et al., 2011, Vetter, et al., 2010). The combined influence of SS waves, IG waves, and setup determine shoreline water level, maximum wave runup and whether inundation occurs on an atoll island (Merrifield, et al., 2014). These three key surf-zone processes each exhibit a unique relationship with reef depth but also influence the behaviour of each other, creating a complex and nonlinear process regime. SLR is expected to decrease wave attenuation on coral reefs and increase the importance of SS waves at the shoreline (Kench and Brander, 2006b). A change in the rate of SS wave dissipation will alter the transfer of energy to IG motions and setup, leading to fundamentally altered process regime at the shoreline. Wave setup is a function of wave attenuation (Gourlay, 1994) and is likely to decrease with SLR, creating a negative feedback that may offset a rise in mean reef depth. Preliminary analysis from Becker, et al. (2014) show that while setup will decrease with SLR, the feedback will not fully offset increasing water levels on the reef flat. The relationship between IG waves and reef depth is not well understood on contemporary reefs, with limited existing research discussing the across reef behaviour of IG waves (Ford, et al., 2013, Péquignet, et al., 2014, Pomeroy, et al., 2012). Resolving how secondary wave motions are influenced by reef
depth is of critical importance for understanding the impact of SLR on coral reef islands. Understanding the individual characteristics and the combined nature of SS, IG and setup processes is necessary for any assessment of atoll island vulnerability under contemporary conditions or in context of SLR (Merrifield, et al., 2014).
1.4 Research aims and objectives

The overall aim of this research is to understand how sea level controls the wave transformation processes that contribute to wave runup and inundation on atoll island shorelines.

Specific objectives are:

1. To document wave transformation across a coral reef platform on Funafuti Atoll.
2. To resolve contemporary tidal controls on incident wave dissipation and secondary wave processes (IG waves and setup).
3. To evaluate the application of an open-source numerical wave model to coral reef environments using benchmark data to assess model skill for representing SS wave behaviour, IG wave behaviour, setup, spectral wave transformations and wave runup.
4. To evaluate model skill at field scale using measurements from Funafuti Atoll to quantify sensitivity, skill and error for representing SS waves, IG waves and wave setup at the reef flat and shoreline.
5. To apply the numerical model to examine wave runup processes at the field location and identify water level controls on the contribution of SS waves, IG waves and setup on maximum runup.
6. To simulate wave transformation and maximum runup under different wave conditions using controlled sea levels that represent the contemporary tidal range and future scenarios of SLR.
7. To predict SLR thresholds for wave inundation at the Funafuti Atoll field site, under different wave conditions.
8. To apply the evaluated numerical model to resolve how morphological properties of reefs and island shorelines influence shoreline wave processes and island inundation.

1.5 Research design

1.5.1 Overview

The goal of this thesis is to explore how sea level controls the physical processes that operate on coral reefs, and to identify how these processes contribute to wave runup and inundation on island shorelines. To achieve this goal, the study uses field data to understand contemporary processes and numerical modeling techniques examine how wave processes will change with SLR. Research findings and the methods used in this research have potential to be adopted by atoll nations to assess island vulnerability to SLR and could assist in developing strategic planning responses to rising sea levels. The research was undertaken in three connected stages: 1) field data collection, 2) numerical model evaluation, and 3) numerical model applications (summarised in Figure 1.3).
Field measurements of contemporary wave transformation were collected on Fatato Island, Funafuti Atoll, Tuvalu (Figure 1.4). Funafuti was selected because the atoll is frequently cited as being highly vulnerable to climate change (Connell, 1999, Connell, 2003, Dickinson, 1999, Farbotko and Lazrus, 2012, Liu, 2004, McNamara and Gibson, 2009, Mortreux and Barnett, 2009, Patel, 2006, Pernetta, 1992, Yamano, et al., 2007). This perception of vulnerability is supported by tide gauge records and satellite data measuring SLR at an average rate of 5.1 mm/yr between 1950 and 2011 (Becker, et al., 2012). Therefore, the current rate of SLR at Funafuti is nearing the average rate of Holocene SLR (5 – 8 mm/yr) in the tropical southwest Pacific Ocean (Marshall and Jacobson, 1985). To date, no field experiments have measured wave transformation processes on Funafuti Atoll and the contemporary interaction between waves and island shorelines is unknown. The Funafuti field campaign is an essential part of this research, with results providing a
baseline understanding of contemporary processes and a means to evaluate numerical model skill. Field measurements of incident waves and wave processes at the outer reef flat and shoreline were collected for 62 days over June and July in 2013. Wave data were analysed to resolve tidal controls on the transformation of SS waves, IG waves and wave setup across the reef flat. Full descriptions of the field campaign and field results are presented in Chapter 5.

Figure 1.4: Arial photo of Fatato Island, Funafuti Atoll, Tuvalu. Photo taken by Professor Paul Kench in February 2013 on a flight form Fongafale Island to Suva.

1.5.3 Numerical model evaluation
Numerical models that represent natural systems can be used to understand how specific processes will respond to expected future boundary conditions (Oreskes, et al., 1994). Therefore, a model that can represent the dynamics of wave transformation across coral reefs can be used to understand how physical processes will respond to SLR. The model evaluation stage of this thesis was designed to demonstrate that the open source numerical model Basilisk GN is capable of representing nonlinear wave transformation processes on coral reefs. Basilisk GN is a fully nonlinear shock-capturing Boussinesq model from Popinet (2015) and is described in Chapter 3. Basilisk GN is a highly capable nonlinear wave solver, as evident when evaluated against benchmark data for wave dispersion, shoaling, breaking and runup (Popinet, 2014, Popinet, 2015). However, this research presents the first application of Basilisk GN to coral reefs and therefore the initial aims of
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this thesis were to evaluate Basilisk GN using reef specific benchmark scenarios and field data.

The first stage of model evaluation involved numerically replicating wave flume measurements from three previously published benchmark experiments. The first wave flume test simulated SS wave attenuation, IG wave motions, setup and runup from the idealised coral reef experiment from Demirbilek and Nwogu (2007). This test was used to assess how sensitive Basilisk GN outputs for SS wave height, IG wave height and setup are to parameters that control dissipation through friction and breaking. The second test was to numerically simulate water level motions associated with a solitary wave shoaling and breaking on an emerged reef crest, with outputs tested against flume measurements form Roeber and Cheung (2012b). The third test used Basilisk GN in 2D and tested water level and velocity outputs against measured data for a solitary wave interacting with a complex three dimensional reef and island morphology Lynett, et al. (2011). Full descriptions of the benchmark model evaluation experiments and results are presented in Chapter 4.

Benchmark model evaluation is an important first step for understanding model behaviour. However, wave flume experiments are also a simplification of natural processes and therefore it was necessary for the model to be evaluated against field data where friction and morphology complicate wave transformation processes. The second model evaluation stage used field data from Fatato Atoll, Funafuti, to assess model predictions of SS wave height, IG wave height, setup and wave spectra at the reef flat and shoreline, using Basilisk GN in 1D. Sensitivity analysis of breaking and friction parameters was undertaken on 10% of the field data, to identify how each surf-zone process responded to parameters that control dissipation. The combination of input parameters that achieved the highest skill was used to replicate the complete field experiment, which was further evaluated for skill and error. Model evaluation results from Funafuti Atoll are presented in Chapter 5.
1.5.4 Numerical model applications

The final stage of this research utilised the evaluated numerical model to examine wave dynamics on atoll reefs in the context of SLR, wave runup and wave inundation. The first application of the evaluated model was a numerical analysis of wave runup on Fatato Island during the field deployment (Chapter 5). Wave runup is not well understood on atoll islands and is logistically difficult to measure in the field but model outputs can provide valuable insight. Model outputs were used to understand the mechanics of wave runup by identifying the contribution of SS waves, IG waves and setup to maximum runup at different stages of the tide. The second model application was to simulate wave transformation on Funafuti Atoll under controlled sea levels from spring low tide to spring high tide with SLR up to 1.5 m (Chapter 6). The purpose of this experiment was to identify the sea level threshold for inundation under different wave conditions and to understand how the processes influencing runup and inundation will change with SLR. The third numerical model application simulated wave transformation on a series of idealised reefs of variable morphology (Chapter 7). This set of simulations explored how reef morphology influences wave processes at the shoreline and identifies how reef morphology can mitigate or enhance the potential for wave inundation and flooding.
1.6 Thesis structure

Chapter 2 provides a review of relevant literature on wave transformation across coral reefs, focusing on the impact that sea level has on the different wave processes that contribute to wave runup and inundation. Chapter 3 describes the numerical model Basilisk GN that is used throughout this research. Thesis results are presented as a series of four journal articles in Chapters 4–7. Chapter 4 presents benchmark model evaluation results. Chapter 5 presents field data from Funafuti Atoll and uses field measurements to evaluate model skill before simulating water level controls on wave runup mechanics. Chapter 6 examines how SLR will alter wave process on Funafuti Atoll, highlighting the SLR thresholds for wave inundation under different incident wave conditions. Chapter 7 extends the results of this thesis beyond Funafuti by simulating sea level controls on wave transformation and inundation using a range of idealised reef morphologies. Chapter 8 outlines the major findings of this research and identifies areas for future work.
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Chapter 2: Literature Review

2.1 Introduction

Waves provide a dominant source of physical energy on coral reef systems and exert a fundamental control on biological and geomorphic processes (Kench, et al., 2009c). Coral reefs naturally dissipate incident waves through a combination of breaking and friction (Hearn, 1999). Wave breaking typically occurs at the reef edge and leads to a rapid decrease in energy across the outer reef flat (Roberts, et al., 1975). Residual wave energy on the inner reef flat is further dissipated through bottom friction, with rates of attenuation determined by roughness on the reef surface (Lowe, et al., 2005). Ferrario, et al. (2014) present an updated analysis of existing field data and highlight that wave breaking and friction on coral reefs dissipate 97% of incident wave energy before the shoreline. However, dissipation of waves in the incident SS band is associated with a transfer of energy into the IG wave band (Péquignet, et al., 2014) and results in a setup water level across the reef flat (Becker, et al., 2014). Consequently, the interaction of waves with reefs and reef islands is a combination of water level motions at incident frequencies (SS waves) and longer period secondary wave motions (IG waves and setup). SS, IG and setup processes combine with tide elevation and sea level to determine water levels on the reef flat and the limit of wave runup at the shoreline (Merrifield, et al., 2014). SS wave attenuation, IG wave behaviour and wave setup also interact with each other on the reef flat, and are each individually influenced by reef morphology, reef depth and incident wave conditions. The nonlinear complexity of different frequency wave processes on the reef flat is poorly understood on contemporary reefs and needs to be resolved before attempting to predict how nearshore processes will respond to a rise in mean sea level.
This literature review first outlines the different reef morphologies that are commonly studied before outlining the existing research on wave transformation processes across coral reefs. Wave transformation is reviewed with the specific aim of understanding sea level controls on SS wave dissipation, IG wave transmission and wave setup. The interaction of wave processes with island shorelines is examined in the context of wave runup, highlighting the conditions and processes that promote wave inundation on atoll islands. The final section outlines different numerical modeling techniques that have been used to simulate wave processes on coral reefs, and emphasises the importance of representing wave processes at all surf-zone frequencies.

2.2 Reef morphology

Coral reef morphology exerts an overall control on wave transformation processes, dictating the rate of incident wave dissipation and the dynamics associated with infragravity waves and wave setup. Fringing, barrier, atoll, and platform reefs are the four main reef morphologies that are referred to in coral reef literature (Kench, et al., 2009c). Fringing reefs are connected to continental landforms and may have a shallow sedimentary back-reef moat. Barrier reefs are separated from continental land by a deep water lagoon. Atoll reefs have no association with continental land and typically form an annular ring of coral with narrow channels that exchange water between the ocean and an internal lagoon basin (Kench, et al., 2009c). Platform reefs can be described as small standalone reefs that are found inside atoll lagoons, in the open ocean or as part of a barrier reef system.

The only landforms that exist on atoll and platform reefs are intertidal sections of the reef flat and sedimentary deposits of calcium carbonate material produced by biological processes on the reef (McLean and Kench, 2015, Woodroffe, 2008). Atoll reefs are characterised by high wave energy on the ocean reef edge and an across reef decay in energy towards the sheltered lagoon reef edge (Kench, 2013). Platform reefs typically have
a circular or elongate structure that results in a process regime controlled by wave refraction and nodal points of low energy wave convergence (Mandliker and Kench, 2012).

The majority of wave transformation studies have been undertaken on fringing reefs because of their proximity to populated shorelines (Péquignet, et al., 2014, Péquignet, et al., 2011, Pomeroy, et al., 2012, Roeber and Cheung, 2012b, Storlazzi, et al., 2011, Storlazzi, et al., 2004, Van Dongeren, et al., 2013, Vetter, et al., 2010). Wave processes have also been studied on platform reefs in the Maldives (Beetham and Kench, 2014, Kench, et al., 2009a, Kench, et al., 2009b) and in the Great Barrier Reef (Brander, et al., 2004, Gourlay and Hacker, 1991, Jago, et al., 2007). Barrier reefs are typically isolated from populated shorelines and have received less research attention (Lowe, et al., 2009b). Research efforts on atoll reefs have recently focused on understanding wave processes and inundation in the Marshall Islands (Becker, et al., 2014, Ford, et al., 2013, Merrifield, et al., 2014, Quataert, et al., 2015). However, no peer reviewed research exists regarding wave transformation on any of the atolls or reef platforms that belong to Tuvalu, Kiribati or Tokelau.

2.3 Wave transformation on coral reefs

2.3.1 Sea swell wave transformation
The first point of interaction for waves approaching a reef is when water depth on the offshore reef-slope is less than half the wave length. At this point waves slow down and become influenced by reef bathymetry as they shoal towards the reef edge. Shoaling is associated with a decrease in wave length and amplification of wave height (Dean and Dalrymple, 1991). Waves reach a maximum height just prior to breaking and given that wave energy is a function of wave height squared (2.1), energy is maximum at the breakpoint.
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\[ E = \frac{1}{8} \rho g H^2 \]  

(2.1)

Alongshore variations in water depth on the reef slope result in uneven propagation speeds that cause waves to refract according to reef bathymetry. Wave refraction can focus wave energy approaching a convex section of reef and diverge wave energy away from channels or concave sections of the alongshore profile (Gourlay, 2011b). These alongshore variations in wave energy influence circulation on the reef flat in a way similar to headlands and pocket beaches or discontinuous bars on sandy beaches (Gourlay, 2011c).

Wave breaking on coral reefs typically occurs at the upper reef slope (reef edge), or on an elevated reef crest at the outer reef flat. However, waves may propagate across the reef edge and break on the reef flat or shoreline when incident wave height is small relative to reef depth. Wave breaking occurs when the wave face steepens to point that it becomes unstable and topples over. In the simplest form, wave breaking is controlled by water depth and can be expressed as a critical breaking ratio (2.2):

\[ \frac{H_b}{h_b} = \gamma_b \]  

(2.2)

Mathematical solutions for \( \gamma_b \) in the context of a shallow water solitary wave can range between 0.73 and 1.03 (Galvin, 1972), with \( \gamma_b = 0.78 \) from McCowan (1894) commonly accepted as a default value for applications of solitary wave theory. In reality \( \gamma_b \) can be anywhere between 0.4 and 1.3 depending on reef slope, wave period and local wind conditions (Nelson and Gonsalves, 1992). More information on breaker type and energy dissipation at the reef edge can be identified using the nonlinearity parameter from Gourlay (1994), (2.3):
where $F_{co} > 150$ results in plunging wave breakers at the reef edge with minimal transfer of energy to the inner reef flat. Less energy is lost at the reef edge when $F_{co} < 150$ and dissipation is associated with spilling breakers that slowly release energy across the reef flat (Gourlay, 1994, Massel and Gourlay, 2000). Once broken, waves on the reef flat are depth limited and experimental results show wave height cannot exceed $0.6h_r$, where $h_r$ is reef depth (Massel, 1996, Nelson, 1996).


$$F_{co} = \frac{g^{1.25} H_r^{0.5} T^{2.5}}{h_r^{1.75}}$$

(2.3)
to between 21% and 76% of the tide, depending on the ratio between reef depth and reef width (Kench and Brander, 2006b):

$$\Psi = \frac{\bar{h}}{w_r}$$

(2.4)

Where $\Psi$ is the non-dimensional reef energy window, $\bar{h}$ is mean reef flat depth at spring high tide and $w_r$ is reef flat width. Kench and Brander (2006b) show that the reef energy window has a strong correlation to the proportion of time island shorelines are geomorphically active.

Collectively, measurements of incident frequency wave transformation across coral reefs show high rates of wave energy attenuation and minimal wave activity at the shoreline (Ferrario, et al., 2014). Further, consistent tidal controls on SS wave breaking and attenuation imply that SLR will result in larger wave heights and greater energy at the shoreline. However, incident wave breaking is associated with a nonlinear transfer of energy to low frequency surf-zone processes that directly influence water level on the reef flat and runup at the shoreline (Péquignet, et al., 2014, Vetter, et al., 2010). Recent analysis of island susceptibility to extreme events and flooding show that infragravity waves and wave setup may be more important than incident frequency waves when assessing island vulnerability (Becker, et al., 2014, Ford, et al., 2013, Hoeke, et al., 2013, Merrifield, et al., 2014, Roeber and Bricker, 2015).

2.3.2 Infragravity wave dynamics on coral reefs

Infragravity waves are characterised by frequencies below 0.04 Hz and above 0.005 Hz with an amplitude 10-40% of incident wave height (Guza and Thornton, 1985). Initial observations of ‘surf beat’ described long period waves in the surf-zone that were approximately 10% of incident wave height (Tucker, 1950). Two main theories explain the
presence of infragravity waves in the surf-zone; the release of group bound long waves (Longuet-Higgins and Stewart, 1962) and dynamic setup from a variable break-point position (Symonds, et al., 1982). Both mechanisms relate IG wave characteristics to the incident wave field and result in free propagating long waves being released at the break-point. Free propagating long waves on sandy beaches have a long wavelength relative to their amplitude and therefore do not break but instead surge through the surf-zone with considerable momentum (Guza, et al., 1984). IG waves generally provide the dominant mode of energy in the swash zone and heavily influence runup elevation on sandy coastlines (Guza and Thornton, 1985). Field measurements on gentle sloping dissipative beaches show a relative and absolute increase in the concentration of wave energy within the IG wave band through the surf-zone, with IG energy maximum at the shoreline (Ruggiero, et al., 2004). Storm conditions on sandy coastlines have been associated with highly energetic IG waves that can significantly elevate runup level, causing flooding and erosion (Roelvink, et al., 2009a).

Compared to sandy beaches, few studies have examined IG wave dynamics on coral reefs and their behaviour on the reef flat is still not well understood (Péquignet, et al., 2014, Pomeroy, et al., 2012). Initial measurements of IG waves on coral reefs were limited to observations of a low frequency peak in spectral density at inner reef flat locations (Kench and Brander, 2006b, Lee and Black, 1978, Lugo-Fernandez, et al., 1998a). More recent work has developed an understanding of across shore variations in IG wave height between the reef edge and shoreline (Ford, et al., 2013, Pomeroy, et al., 2012, Quataert, et al., 2015, Van Dongeren, et al., 2013). Results from these field studies are variable and suggest that IG wave processes are sensitive to incident wave conditions, reef depth and reef morphology. On reefs that have a wide (>300 m), shallow, and topographically variable reef flat, IG wave height and energy has been observed to dissipate through friction,
resulting in a tidally modulated long wave signal on the inner reef flat (Péquignet, et al., 2014, Pomeroy, et al., 2012, Van Dongeren, et al., 2013). Under moderate incident wave conditions ($H_s = 1-2$ m), IG wave energy on these wider reefs was observed to peak within 100 m of the reef edge before dissipating across the inner reef flat to be minimal at the shoreline. On a narrow (<300 m) and relatively smooth reef in the Marshall islands, IG wave height was observed to increase towards the shoreline to heavily influence swash processes and runup (Ford, et al., 2013, Quataert, et al., 2015). Therefore, IG wave processes are potentially more significant on reefs where islands are located close to the reef edge (e.g. Funafuti Atoll).

Shorelines fringed by wide reefs are still vulnerable to energetic IG waves when exposed to extreme incident wave conditions. Large incident waves generated by typhoon Haiyan produced ‘tsunami like’ IG waves that were amplified towards the shoreline on wide (<400 m) and shallow reefs, causing devastating inundation in Hernani, Philippines (Roeber and Bricker, 2015, Shimozono, et al., 2015). The behaviour of IG waves on the reef flat is influenced by the incident wave field and is further complicated by reef configuration. The behaviour of IG waves on contemporary coral reefs is poorly understood and the relationship between reef depth, reef morphology and IG wave dynamics needs to be resolved before predicting the impact of SLR on coral reef landforms.

Other recent work has analysed the mechanics of energy transfer between incident and infragravity frequencies, identifying that IG waves on coral reefs are the result of both group bound incident waves and variable break-point forcing (Péquignet, et al., 2014). However, their analysis indicates that incident wave breaking works against bound IG waves, resulting in limited propagation towards the shoreline (Péquignet, et al., 2014). In contrast, a variable break-point was found to excite IG waves at group frequencies, allowing free long waves to propagate across the reef flat. Measurements on the 450 m
wide reef at Ipan, Guam, also show that IG wave energy peaked within 100 m of the reef edge before dissipating through friction on the reef flat. However, the attenuation of IG energy was associated with an increase in far infragravity (0.001-0.005 Hz) energy that dominated wave spectra at the shoreline.

Measurements of surf-zone dynamics on coral reefs highlight that IG waves are an important component of the contemporary process regime that directly influence reef flat water level, SS wave transmission, runup and inundation. However, the relationship between IG wave transmission and sea level remains poorly understood, with contrasting observations depending on reef width and morphology.

The response of IG wave processes to SLR remains unknown. However, the presence of IG waves on the reef flat relates to incident wave dissipation which suggests a potential for IG wave energy to decrease as SLR reduces the rate of wave attenuation. Therefore, shoreline wave energy within the IG band may decrease with SLR as more energy in concentrated within the SS wave band. This potential shift in shoreline wave spectra complicates the assumption that SLR will be associated with a linear increase in shoreline wave energy. Before understanding the impact of SLR on reef islands, it is necessary to first resolve how sea level, reef morphology and incident waves influence the behaviour of infragravity waves on coral reefs.

2.3.3 Wave setup

Wave setup is the increase in mean water level that is observed through the surf-zone in the presence of breaking waves (Gourlay, 2011a). Wave setup has an important control on reef top circulation patterns (Symonds, et al., 1995) and is one of the main processes that contribute to runup elevation and inundation (Merrifield, et al., 2014). Wave setup can be explained using the radiation stress theory introduced by Longuet-Higgins and Stewart (1964). As a wave shoals prior to breaking, the wave crest becomes higher and steeper and
the trough becomes shallower and flatter (Dean and Dalrymple, 1991). This change in the momentum balance influences the mean hydrostatic pressure by depressing the mean water level seaward of the break point, a process referred to as wave set-down (Longuet-Higgins and Stewart, 1964). Set-down is observed in the shoaling zone and typically reaches a maximum at the break point (Gourlay, 2011a). Wave setup occurs shoreward of the break point and is associated with an increase in mean water level as wave height dissipates through the surf-zone (Symonds, et al., 1995). Decreasing wave energy and momentum in the surf-zone causes hydrostatic pressure to relax, which generates the rise in mean water level (Gourlay, 2011a). Wave setup magnitude is therefore relative to the rate of wave dissipation and on coral reefs can be predicted using the difference between incident wave height and wave height on the reef flat (Becker, et al., 2014).

Initial observations of wave setup on coral reefs were made on Bikini Atoll, where Munk and Sargent (1948) measured an elevated water level on the reef crest up to 0.6 m above the still water level. The setup water level on Bikini Atoll decreased towards the lagoon and was thought to be responsible for generating an across reef current away from the reef edge (Munk and Sargent, 1948). Setup was also observed to have a control on reef ecology and has been associated with assisting the formation of a raised algal rim that is often located at the seaward edge of coral reefs exposed to open ocean waves (Von Arx and Sargent, 1954). Following these initial observations of wave setup on coral reefs, Tait (1972) applied the momentum stress theory from Longuet-Higgins and Stewart (1964) to develop an analytical model for setup on coral reefs, highlighting that setup magnitudes are approximately 20% of incident wave height. Field and wave flume data were utilised by Gerritsen (1981) to further develop analytical representations of setup and wave transformation on coral reefs, revealing that setup is a function of both wave height and reef depth. A detailed understanding of wave setup on coral reefs was achieved through a
series of wave flume experiments using idealised and realistic reef morphologies (Gourlay, 1994, Gourlay, 1996a, Gourlay, 1996b). Flume measurements from Gourlay (1996b) show that wave setup on coral reefs is maximum when the reef is level with still water \((h_r = 0 \text{ m})\), with setup decreasing as reef depth increases under constant wave conditions. Setup is only observed when waves break and is therefore not present when wave height is small relative to reef depth. Gourlay (2011a) shows that setup is theoretically zero when \(H_o < 0.4h_r\). Wave setup was also found to increase proportional to incident wave height and wave period, with maximum setup on coral reefs predicted to occur at low tides during energetic incident wave conditions (Gourlay, 1994, Gourlay, 1996b).

The next stage of setup research focused on understanding how setup influences wave driven flow across coral reefs (Gourlay, 1996a, Hearn, 1999, Symonds, et al., 1995). Field measurements of wave setup and velocity over a 1 month period on John Brewer Reef in the Great Barrier Reef identified a strong correlation between incident \(H_{rms}\) and mean velocity on the reef flat (Symonds, et al., 1995). An analytical solution was developed to explain that the pressure gradient created by wave setup was responsible for controlling the direction and magnitude of velocity across the reef flat (Symonds, et al., 1995). Hearn (1999) continued to developed an analytical model of setup driven flow and emphasised the influence of tide level in modulating setup magnitude and therefore velocity. It is now widely accepted that across-shore and alongshore differences in wave setup have a strong influence on reef top circulation (Gourlay and Colleter, 2005, Lowe, et al., 2009b, Lowe, et al., 2010, Massel, et al., 2001, Massel and Gourlay, 2000, Monismith, et al., 2013). Therefore, setup also has a fundamental control on coral larvae distribution and sediment transport (Gourlay, 2011c). Recent analysis by Monismith, et al. (2013) highlights that setup decreases towards the lagoon when there is no island, but remains more constant across the reef flat when an island is located on the reef flat. Therefore, the across reef flow
associated with lagoon-ward sediment transport on an atoll reef may breakdown when an island forms, blocking water flow into the lagoon.

Recent field measurements have continued to develop an understanding of wave setup on coral reefs. Data obtained using stilling wells on Lady Elliot Island have revealed a tidal control on setup position on the reef flat, with setup focused on the reef flat at low tide shifting to the beach face at high tide (Jago, et al., 2007). Jago, et al. (2007) also noted a dual setup system at mid-tides, characterised by a seaward zone of setup at the reef flat and second setup zone at the island shoreline. Maximum wave setup on Lady Elliot Island was found to be 0.14 m above still water level in the presence of 0.4 m incident waves with setup approximately 25% of incident $H_s$, on average. One of the first field measurements of wave setup during energetic wave conditions was undertaken on Ipan Reef, Guam, where 1.3 m of setup was generated by 4.6 m high incident waves (Vetter, et al., 2010). Setup on Ipan reef was identified to slightly increase towards the shoreline and was on average 25% of incident $H_s$. Becker, et al. (2014) present a comprehensive field assessment of how tide level influences setup. Becker, et al. (2014) show that setup on coral reefs peaks at low tide (40-50% of incident $H_{rms}$) and is reduced at high tide (10-20% of incident $H_{rms}$). Field measurements from Becker, et al. (2014) were used to show setup can be confidently predicted using the difference in incident wave height and wave height on the reef flat:

$$\hat{\eta}_i = \frac{5}{16} \hat{\gamma}_b \left( H_b - 1.2 H_i \right)$$

(2.5)

Where $\hat{\eta}_i$ represents wave setup at a given location on the reef flat, $\hat{\gamma}_b$ is a representative ratio between wave height and water depth at the break-point, $H_b$ is wave height at the break-point and $H_i$ is wave height on the reef flat where setup is being predicted. This method for predicting setup accounts for the tidal modulation of setup because wave heights on the reef flat are naturally influenced by tidal water level. One of the key feedbacks
associated with SLR is that wave setup levels may decrease on the reef flat as less wave attenuation occurs through the breaking process. Becker, et al. (2014) use an empirical formula to show that setup will indeed decrease with SLR, and suggest that the decrease in setup will not fully offset a net increase in reef flat water level. Recent wave flume experiments emphasise the importance of both incident wave height and reef depth when predicting setup, which can be achieved using linear wave theory with a wave-roller based correction for kinetic energy (Buckley, et al., 2015). Further quantification of the response in wave setup to sea level is important for understanding island vulnerability under various wave conditions and reef morphologies.

2.4 Wave runup and inundation

One of the most commonly emphasised points of vulnerability for coral reef islands facing SLR is an increase in wave inundation that may damage agriculture, fresh water supplies and infrastructure (Ferrario, et al., 2014, Nicholls and Cazenave, 2010, Nicholls, et al., 2011, Patel, 2006). Wave runup has been well studied on sandy beach shorelines and is a function of tide level, setup and swash from SS and IG waves (Guza and Thornton, 1985, Guza, et al., 1984, Stockdon, et al., 2006). Less research has investigated wave runup on atoll islands or other reef associated shorelines. The most detailed assessment of wave processes impacting the shoreline on atoll reefs was a recent investigation of maximum water level observed ~10 m seaward of the shoreline on reefs in the Marshall Islands (Merrifield, et al., 2014). Using field data for the 2% exceeded maximum water level ($\hat{\eta}_i$) on the reef flat, Merrifield et al. (2014) deconstructed the relative importance of SS waves, IG waves and setup near the shoreline. Their results emphasised that $\hat{\eta}_i$ was not strongly dependent on tidal elevation, even though each of the contributing processes ($H_{ss}$, $H_{ig}$, setup) are individually influenced by tide levels. Merrifield, et al. (2014) show that $\hat{\eta}_i$ at their two field sites was approximately ~32% of incident wave height. On average, 48% of
\( \tilde{\eta} \) was attributed to SS and IG waves, with the remaining 52% associated with wave setup (Merrifield, et al., 2014). The empirical relationship identified in Merrifield, et al. (2014) was used to predict historic inundation events using hind-cast wave data, estimating that \( \tilde{\eta} \) + tide level + sea level breached the 2 m overtopping threshold approximately 11 times over the last 30 years. These overtopping events were typically associated with a combination of high tide and large incident wave conditions. Merrifield, et al. (2014) also predicted the annual occurrence of inundation with SLR, showing that a 0.5 m rise in sea level will result in 5 inundations per year and a 1 m rise in mean sea level will result in 50 inundation events each year.

Reports of wave inundation in the literature are associated with extreme super-typhoon generated waves (Roeber and Bricker, 2015, Shimozono, et al., 2015), high energy swell waves (Hoeke, et al., 2013) and moderate energy swell waves (Ford, et al., 2013). All of these publications comment on the importance of swash motions at infragravity wave frequencies. Super-typhoon Haiyan generated extreme incident waves offshore of the Philippines in 2013 and resulted in significant wave inundation 3-6 m above mean sea level in the Hernani region (Shimozono, et al., 2015). This region is sheltered by a 400 - 600 m wide shallow coral reef and local reports described the flooding was caused by a series of tsunami-like waves (Roeber and Bricker, 2015). Numerical investigations have revealed that these tsunami-like waves were actually energetic infragravity waves that were excited at the reef edge and amplified towards the shoreline (Roeber and Bricker, 2015, Shimozono, et al., 2015).

Long period waves generated by a distant source storm in December 2008 caused inundation on a number of reef fringed Pacific Islands. No local measurements were available to quantify wave transformation, but the event was simulated in a numerical
model and results support local reports of overtopping swash at infragravity frequencies (Hoeke, et al., 2013). A small overtopping event was measured when instruments were deployed across a reef on Majuro Atoll, when incident swell waves \(H_s = 2\, \text{m}, T_p = 15\, \text{s}\) impacted the reef at high tide (Ford, et al., 2013). The shoreline on Majuro was elevated 2 m above the reef flat and inundation was primarily associated with 0.8 m high IG waves \((40\%\, H_o)\) at the shoreline, with 0.4 m high SS waves and approximately 0.2 m of setup (Ford, et al., 2013).

While this literature clearly identifies the role of IG frequency waves in over-topping events, the mechanics of wave runup on atoll islands and the processes associated with inundation at present and future sea levels remain an important and relatively unexplored area of research.

2.5 Sea level rise and wave transformation

Limited research has specifically attempted to understand how SLR will influence wave processes on coral reef environments, however relationships between processes and water level under contemporary conditions provide a key insight. Measured tidal controls on SS wave height (Brander, et al., 2004, Kench and Brander, 2006b, Lugo-Fernandez, et al., 1998b, Péquignet, et al., 2011) and setup (Becker, et al., 2014, Gourlay, 1994, Vetter, et al., 2010) suggest that SLR will be associated with higher waves at the shoreline and lower setup across the reef flat. The impact of SLR was indirectly measured by Sheppard, et al. (2005) when coral reefs in the Seychelles decreased in elevation following an El Nino generated bleaching event and mass coral mortality. The deeper reef flat effectively doubled wave energy at the shoreline and corals eroded from the reef were deposited on the beach as sediment, causing pockets of short term accretion (Sheppard, 2011). However, the beach soon responded to the larger waves and long-term coastal erosion was observed (Sheppard, et al., 2005). Despite this preliminary understanding of SLR implications for
coral reef coast, little research has been done to predict the rate at which SS wave heights will increase with SLR, or to understand the rate that setup will decrease with SLR. Therefore, it is not clear how SLR will influence island vulnerability for different reef morphologies and incident wave conditions.

Field measurements of IG wave dynamics on coral reefs remain inconsistent regarding tidal controls (Ford, et al., 2013, Van Dongeren, et al., 2013), shoreward amplification (Ford, et al., 2013, Quataert, et al., 2015) and across reef attenuation (Péquignet, et al., 2014, Pomeroy, et al., 2012, Van Dongeren, et al., 2013). Therefore, a conceptual understanding of how IG wave behaviour will respond to SLR remains unestablished. Resolving the contemporary behaviour of IG waves on coral reefs and predicting their response to SLR is a key element of this thesis.

Numerical models have been used to understand how wave processes respond to variations in contemporary sea level (Quataert, et al., 2015) and predicted future sea levels (Storlazzi, et al., 2011). Quataert, et al. (2015) used the XBeach model to systematically analyse how reef morphology and incident wave conditions impact wave processes at the shoreline under a contemporary 2 m tidal range. However, they did not extend their analysis to consider how wave processes will respond to future sea levels and are limited to a 2 m reef depth. Results from Quataert, et al. (2015) highlight that reefs with a steep fore-reef slope, a narrow reef flat and low roughness receive greater wave energy at the shoreline and are therefore more vulnerable to inundation and erosion with SLR. Model results in Quataert, et al. (2015) also reveal the behaviour of SS waves, IG waves and setup in response to different reef morphologies, sea levels and incident wave heights. SS wave heights at the shoreline were modeled to increase proportional to incident wave height, sea level and reef slope, with a decrease in shoreline wave height associated with increasing reef width and friction. Setup was predicted to increase proportional to incident wave height and fore-reef
slope with a decrease in setup associated with increasing sea level. IG wave heights at the shoreline were modeled to increase proportional to incident wave height, sea level and fore-reef slope, with a decrease in shoreline IG wave height associated with increasing reef width and friction. Interestingly, results in Quataert, et al. (2015) did not identify a sea level threshold where IG wave heights began to decrease with SLR as more energy remains concentrated within the SS wave band due to a decrease in wave attenuation (Péquignet, et al., 2014). Therefore, further research is needed to resolve how sea level controls the balance between SS and IG wave energy at the shoreline. Results from Quataert, et al. (2015) highlight the importance of accounting for reef morphology when considering wave dynamics on coral reefs and suggest that field results from a narrow or rough reef may not apply to a wide or smooth reef.

Storlazzi, et al. (2011) used a coupled Delft 3D wave, flow and morphology model to simulate how nearshore processes on a fringing reef in Molokai Island, Hawaii, operate at present and under different magnitudes of SLR. Model outputs in Storlazzi, et al. (2011) show that the SLR associated increase in wave height will increase velocity on the reef flat and amplify sedimentation rates. Storlazzi, et al. (2011) highlight that this SLR associated increase in sedimentation will be detrimental to coral productivity and suggest that the higher waves and stronger currents will result in coastal erosion that will add further sediment to the reef system.

These existing numerical model based studies provide a preliminary understanding of how SLR will impact coastal environments on coral reefs and encourage further use of numerical modeling techniques to explore the response of wave processes in greater detail. Further understanding of reef island vulnerability to SLR can be achieved using high resolution simulations of SS waves, IG waves, setup, runup and inundation under a range of present and future sea level, and on a range of reef morphologies.
2.6 Numerical modeling of wave processes on coral reefs

The most accurate way to understand natural processes is to collect and analyse field data (Reyns, et al., 2013, Woodroffe and Murray-Wallace, 2012). However, field measurements are limited to contemporary conditions and are not always suitable for predicting how processes will respond to environmental change. Numerical models have the potential to assist in developing an understanding of how contemporary environmental processes operate and can be used to predict future change (Oreskes, 2003). However, it is important that models provide a reasonable representation of individual processes and interactions between processes and it is essential that outputs are evaluated for sensitivity and accuracy (Oreskes, et al., 1994).

Numerical models for representing waves in coastal and nearshore environments are solved using either phase-averaging or phase-resolving techniques (Buckley, et al., 2014). Phase-averaging models do not simulate individual waves but represent the average energy of a wave group using spectral wave transformation theory (Hoeke, et al., 2013, Hoeke, et al., 2011). Phase-averaging models (e.g. SWAN; Simulating WAVes Nearshore) are solved using a stochastic method and were traditionally used to represent spectral wave transformation at incident (gravity wave) frequencies across regional areas outside of the surf-zone (Booij, et al., 1999). Phase-resolving models represent the free-surface behaviour of individual waves by solving equations of momentum and can be applied to nearshore and surf-zone areas but need to be solved at a high spatial resolution, making them much more computationally expensive (Zijlema, 2012). The following review of existing modeling work is focused on understanding the model requirements for simulating SS waves, IG waves, setup, runup and inundation coral reef environments.
2.6.1 Phase-averaging models

Traditional phase-averaging models (e.g. SWAN) were developed to simulate spectral transformation of gravity waves and do not represent surf-zone processes such as IG waves and setup (Booij, et al., 1999). Phase-averaging models can be used with a coarse spatial resolution and are often used to efficiently simulate regional scale processes in two horizontal dimensions (2D). Buckley, et al. (2014) suggest that common phase-averaging spectral models are not suitable for simulating the wave processes coral reef shorelines because IG wave processes are omitted. An exception to this is the XBeach model that was specifically developed for surf-zone applications, with a focus on representing infragravity wave motions (Roelvink, et al., 2009a). XBeach represents SS frequency wave processes using a phase-averaging spectral model but simulates the behaviour of IG waves using a phase-resolving solver for the nonlinear shallow water equations. XBeach was initially developed for gentle sloping environments with a sedimentary nearshore and has become a popular tool for coastal management and research on sandy beach systems. Recent applications of XBeach to coral reef environments have successfully replicated flume and field scale measurements of wave transformation (Buckley, et al., 2014, Pomeroy, et al., 2012, Quataert, et al., 2015, Van Dongeren, et al., 2013). At the wave flume scale, Buckley, et al. (2014) tested model results against data collected from experiments presented in Demirbilek, et al. (2007) to show that XBeach can accurately predict SS wave height, IG wave height and setup across the reef flat and shoreline. XBeach has also been used to accurately replicate field measurements of SS waves, IG waves and setup on a fringing reef in Western Australia (Pomeroy, et al., 2012, Van Dongeren, et al., 2013) and on an atoll reef in the Marshall Islands (Quataert, et al., 2015). A strength of XBeach is that it is computationally efficient and can be run using a relatively coarse domain in 1D and 2D (Buckley, et al., 2014). XBeach can also simulate sediment transport and morphodynamic
adjustments of coastal landforms (Roelvink, et al., 2009a). One limitation of XBeach is that only a single incident frequency can be represented through the surf-zone, limiting the potential to simulate nonlinear feedbacks between water level oscillations that operate at different timescales in the surf-zone (Quataert, et al., 2015). The ability to simulate multiple incident wave frequencies and the nonlinear interactions between SS waves, IG waves and setup is important for accurately representing processes on the reef flat and swash motions at the shoreline. Such analysis can be undertaken using a fully nonlinear phase-resolving model (Roeber and Bricker, 2015).

2.6.2 Phase-resolving models
High resolution representations of incident frequency waves, IG waves, setup and the dynamic feedbacks between each of these processes can be achieved using a phase-resolving free-surface model based on equations for momentum and conservation (Roeber and Cheung, 2012b). Phase-resolving models for nearshore application are usually either based on nonlinear shallow water equations (NSWEs) or Boussinesq-type equations (Brocchini and Dodd, 2008). Phase-resolving models offer a high resolution representation of wave processes in coastal environments but are limited by high computation demands and are often applied to local scale areas or are limited to one horizontal dimension (1D).

2.6.2.1 Boussinesq equations
Boussinesq models represent the shape, velocity and propagation of waves through the nearshore and shoaling zone and have become an indispensable tool for coastal engineering and research (Kennedy, et al., 2000, Kirby, 2003, Madsen, et al., 1997, Nwogu, 1993, Schaffer, et al., 1992). Boussinesq equations were developed as an approximation of the Euler equations (Boussinesq, 1872, Peregrine, 1967). The Euler equations accurately describe the behaviour of ocean surface waves but require an approximate solution for integration into a numerical model structure (Popinet, 2015). A key element of Boussinesq
equations is the representation of wave shape and the propagation of different wave frequencies in the nearshore and shoaling zone (Kirby, 2003). Without additional terms, the Boussinesq equations have a theoretical landward limit where wave height remains less than water depth, $\delta = \frac{H}{h} < 1$ and a seaward limit where water depth is less than the wave length, $\mu = \frac{h}{L} < 1$, and are suitable for environments characterised by an Ursell number near 1, $Ur = \frac{H (\frac{h}{L})^2}{h} \approx 1$ (Huntley, 2013). However, developments have been made to apply Boussinesq equations to represent dispersive wave behaviour for relatively low amplitude waves in deep water (Lynett and Liu, 2004) and for relatively large amplitude waves in very shallow water (Bonneton, et al., 2010b, Green and Naghdi, 1976). A key strength of the Boussinesq approach is that the nonlinear transformation of a wave shape is represented by replicating the asymmetrical skewness that is observed when waves enter the shoaling zone. This shape is characterised by a steeper wave crest with higher velocities and a flatter wave trough with lower velocities (Dean and Dalrymple, 1991). The dispersive function conserves the shape of a propagating conidial or solitary wave and prevents the wave crests from over steepening prior to the breakpoint (Huntley, 2013).

A key limitation to Boussinesq models is the need for artificial terms to represent wave breaking and dissipation through the surf-zone (Bonneton, et al., 2011b, Huntley, 2013, Roeber and Cheung, 2012b). Wave breaking in Boussinesq-type models is typically forced using an empirical eddy viscosity term (Kennedy, et al., 2000). Wave breaking has also been implemented by adding a roller term to the momentum equation (Svendsen, 1984) or using an analytical vorticity function (Musumeci, et al., 2005). An area of developing research is focused on applying the shock-capturing ability of NSWEs to represent wave breaking and dissipation in Boussinesq-type models, limiting the need to include artificial
or empirical terms (Fang, et al., 2013, Ma, et al., 2012, Roeber and Cheung, 2012b, Tissier, et al., 2012a). Shock-capturing is a term used to describe the characteristic saw-tooth wave shape generated by NSWEs when wave steepness become unstable and highly nonlinear (Roeber, et al., 2010). This representation of waves and shocks provides a reasonable description of wave shape during and after the breakpoint, including dissipation through the surf-zone (Bonneton, et al., 2011a). This new breed of shock-capturing Boussinesq-type models also provides a suitable solution for wave runup motions in the swash-zone where equations for wave dispersion are unsuitable (Bonneton, et al., 2010a, Bonneton, et al., 2011a, Bonneton, et al., 2011b). Application of shock capturing Boussinesq models is especially suitable to coral reef environments where wave processes rapidly transition from dispersive to dissipative (Roeber and Cheung, 2012b, Yao, et al., 2012).

2.6.2.2 Nonlinear shallow water equations

Nonlinear shallow water equations are based on equations for momentum and continuity but omit wave dispersion and are more appropriate for representing wave dissipation through the surf-zone and runup at the shoreline (Brocchini and Dodd, 2008). NSWEs become suitable when relative wave height ($\delta$) is more important than relative wave length ($\mu$) and dissipation becomes more important than conservation of momentum (Huntley, 2013). The NSWEs were initially applied to ocean waves by Stoker (1957) but resulted in an ever steepening wave face due to velocity at the crest exceeding velocity at the wave base, eventually forming a vertical shock. The development of a vertical wave face was found to represent the shape of a wave bore and subsequent research focused on developing the NSWEs to treat these vertical shocks in a way that represents wave breaking and dissipation through the surf-zone (Brocchini and Dodd, 2008, Huntley, 2013). These shock discontinuities were initially treated artificially using ‘shock-fitting’ techniques that required a separate set of equations (Brocchini and Dodd, 2008). More recent developments
use a ‘shock-capturing’ form of the NSWEs that can apply the same set of equations to broken and non-broken waves using a finite-volume solution (Brocchini and Dodd, 2008, Hibberd and Peregrine, 1979, LeVeque and George, 2008). Modern NSWEs therefore provide an intuitive representation for unstable wave breaking and nonlinear dissipation through the surf-zone. Another development of the NSWEs has focused on retaining numerical stability and accuracy with a moving shoreline, where the swash-zone irregularly changes between wet and dry (Audusse, et al., 2004, Bonneton, et al., 2011b). The ability of NSWEs to represent wave breaking and shoreline interaction mean they are particularly suited to examining surf-zone processes, wave runup and wave inundation (Brocchini and Dodd, 2008). A drawback of the NSWEs is that they do not represent wave dispersion and therefore have a limited potential to represent wave behaviour seaward of the breakpoint. This is a key limitation in applying NSWEs to nearshore environments because representing processes in the surf-zone relies on understanding how waves behave in the shoaling zone (Bonneton, et al., 2011b). One method used to overcome traditional limitations to the NSWEs is by representing wave dispersion by applying a non-hydrostatic pressure correction. Non-hydrostatic pressure corrections are implemented in the SWASH model (Simulating WAves until SHore) and in XBeach-NH and have proven capable of simulating nonlinear wave transformation processes on coral reefs (Ma, et al., 2014, Zijlema, 2012).

2.6.2.3 Shock capturing Boussinesq-type models

Since Boussinesq-type models work best seaward of the break-point and NSWE models work best shoreward of the break-point, it was inevitable that the two techniques would eventually be combined (Bonneton, et al., 2011b). This was initially achieved by defining a break-point location and applying a dispersive solution to the seaward zone and a shock-capturing solution to the shoreward zone. However, without a natural and dynamic break-
point this type of application had limited practicality (Tissier, et al., 2012a). A new class of shock-capturing Boussinesq-type models was established when dispersive and shock-capturing source terms were coupled in a dynamic way that did not require horizontal domain splitting (Bonneton, et al., 2010a). A threshold for splitting between dispersive and shock-capturing source terms has been applied using a local wave height to water depth criteria (Tonelli and Petti, 2010), a local free-surface slope threshold (Bonneton, et al., 2011a, Popinet, 2015, Tissier, et al., 2012a) and a local momentum gradient (Roeber and Cheung, 2012b). Application of such models to surf-zone environments has resulted in accurately representing the shoaling and dissipation of irregular SS waves, the generation and behaviour of IG waves, wave setup and wave runup (Bonneton, et al., 2010a, Bonneton, et al., 2011b, Roeber and Cheung, 2012b, Tissier, et al., 2012b).

2.6.2.4 Applications of phase-resolving models to coral reefs

The potential to numerically represent free-surface wave dynamics on coral reefs has improved with the development of nonlinear shock-capturing Boussinesq models, allowing a highly dynamic representation of nearshore, surf-zone and shoreline processes (Roeber and Cheung, 2012b). A major strength of this technique is avoiding the need for cumbersome eddy viscosity terms to represent energetic wave breaking (Roeber and Cheung, 2012b). Recent applications of free-surface models that combine shock-capturing representations of wave breaking with a dispersive source term have accurately simulated SS waves, IG waves, setup and runup on reef fringing coastlines (Demirbilek and Nwogu, 2007, Nwogu and Demirbilek, 2010, Shimozono, et al., 2015, Su, et al., 2015, Zijlema, 2012). The primary source for testing the accuracy of these models is the wave flume data presented in Demirbilek, et al. (2007) which is freely available online. Only a few Boussinesq-type models have been evaluated using field data from coral reefs (Demirbilek and Nwogu, 2007, Roeber and Cheung, 2012b). To date, no phase-resolving model work
has focused on atoll reef environments that are characterised by a sedimentary island or flow into a lagoon basin. Applying a shock-capturing Boussinesq model to an atoll environment has significant potential to develop an understanding of how wave driven hydrodynamics will respond to SLR. However, it is important that model results are evaluated to provide a skilful representation of natural processes before they can be used for research or management purposes.

2.6.3 Using models to simulate wave processes with sea level rise

It is argued that a fully nonlinear shock-capturing Boussinesq model is the best way to numerically represent the dynamic wave processes that impact coral reef landforms (Roeber and Bricker, 2015). The research presented in this thesis uses the shock-capturing fully nonlinear Boussinesq model, Basilisk GN, from Popinet (2015) to simulate wave processes on coral reefs. The motivation for using a numerical model is based on developing a simulation environment for skilfully representing nonlinear physical processes that can be used to examine the impact of SLR on shoreline wave energy and inundation.

The response of different frequency wave processes to SLR may not be linear and therefore a fully nonlinear model will produce more accurate results than extrapolating contemporary field measurements to higher sea levels. Therefore, it is essential to ensure that the model represents the nonlinear behaviour of different wave processes and the interactions between different wave processes. Numerical models are beneficial because they can be used to understand physical processes at a spatial resolution that cannot be achieved using field data. However, a model must be established as a skilful representation of the real world before outputs can be trusted (Oreskes, et al., 1994). Model skill is a quantifiable assessment of how accurately a model represents a natural process and is based on error and linear regression (Buckley, et al., 2014, Hoeke, et al., 2011, Lowe, et al., 2009a). Model
sensitivity is a measure of how variable a model output is when an input parameter value is changed (e.g. friction coefficient). Therefore, the first step towards using a model as a research tool is establishing that the model produces a skilful representation of natural processes (Oreskes, 2000). This can be done by numerically replicating results from a physical model (wave flume) or measured field data (Roeber and Cheung, 2012b). Models that are based on a robust representation of physical processes, and are evaluated to provide a skilful representation of contemporary processes, can be used as a tool to simulate natural processes under predicted future boundary conditions.

2.7 Summary

Sedimentary islands on coral reefs are potentially susceptible to increased erosion, inundation and flooding as a result of SLR (Hoeke, et al., 2013, Merrifield, et al., 2014, Quataert, et al., 2015). Field measurements of wave transformation across coral reefs show that SS wave height at the shoreline is a function of reef depth. Therefore, waves of geomorphic significance are typically limited to high tide (Kench and Brander, 2006b) or extreme events (Péquignet, et al., 2011). Field data have also been used to understand sea level controls on wave setup on coral reefs, and show maximum water level at low tide and minimal setup at high tide (Becker, et al., 2014). Empirical calculations of wave setup reveal that the decrease in setup associated with SLR will not offset a net increase in reef flat water level, especially at high tide (Becker, et al., 2014). Reports of inundation on atoll and fringing reefs are typically associated with wave energy concentrated in the infragravity wave band, with field and model data showing that maximum IG wave height can occur at the shoreline (Ford, et al., 2013, Hoeke, et al., 2013, Quataert, et al., 2015, Roeber and Bricker, 2015, Shimozono, et al., 2015). However, field measurements of infragravity wave behaviour on reefs have shown inconsistent results and the response of IG waves to SLR remains unknown. The combined influence of SS waves, IG waves and
setup determine reef flat water level above the still water level and collectively determine runup level (Merrifield, et al., 2014). However, a number of fundamental questions remain regarding wave processes on coral reef environments:

- How do tide elevation and mean sea level influence infragravity wave behaviour on coral reefs?
- What is the contribution of SS waves, IG waves and setup on total runup elevation at different tide stages?
- How will SLR change the balance of wave processes at the shoreline?
- How does reef morphology influence wave processes at the shoreline?
- How does island morphology influence the potential for inundation?

Recent advances in numerical wave modeling for nearshore and surf-zone applications (Lannes and Marche, 2015, Popinet, 2015, Roeber and Cheung, 2012b) have significantly increased the potential to study wave processes on atoll reefs and assist answering these questions. However, the dynamic nature of wave processes that operate at different frequencies within the surf-zone require high resolution simulations that accurately represent each process and the interactions between processes (Roeber and Bricker, 2015). Further, model results must be understood in terms of sensitivity and accuracy when compared with contemporary field measurements (Oreskes, 2000). Only then can model outputs be used to explore wave transformation under future boundary conditions.
3.1 Model background

The Green-Naghdi (GN) solver from Popinet (2015) is used throughout this thesis to simulate wave processes on coral reefs. The GN solver is available open source as part of the Basilisk software package (basilisk.fr). The Green-Naghdi model in Basilisk (herein referred to as Basilisk GN) is a fully nonlinear Boussinesq solver that utilises a shock-capturing NSWE source term to handle wave breaking and runup (Popinet, 2015). Basilisk GN has proven to be a skilful and robust model for simulating shallow water wave dynamics (Popinet, 2014, Popinet, 2015) but has not yet been applied to a coral reef environment.

Basilisk GN can be distinguished from other shock-capturing Boussinesq models because the GN equations (Green and Naghdi, 1976) were specifically developed to simulate relatively large amplitude waves ($\delta \sim 1$) in shallow water ($\mu \ll 1$), with variable bathymetry (Bonneton, et al., 2011b, Lannes and Marche, 2015, Popinet, 2015, Tissier, et al., 2012a). The trade-off for representing relatively large amplitude waves is that the GN equations are weakly dispersive, and are therefore not ideal for simulating waves seaward of the shoaling zone (Lannes and Marche, 2015). As explained in Chapter 2.6.2, equations for wave dispersion rely on conserving momentum and are therefore not naturally capable of simulating wave dissipation or runup at the shoreline (Bonneton, et al., 2011b). Recent numerical developments have focused on extending the GN equations to include a NSWE source term for representing wave breaking, surf-zone dynamics and shoreline interaction.
Chapter 3: The Basilisk Green-Naghdi Solver


Shock-capturing GN formulations were initially developed for solving 1D scenarios, establishing the characteristic ‘saw tooth’ shape (Fig. 3.1) for representing the vertical face of a wave bore in the surf-zone (Bonneton, et al., 2011b, Tissier, et al., 2012a). These 1D formulations were also found to skilfully replicate the generation and propagation of IG waves through the surf-zone (Tissier, et al., 2012b) and have been used to accurately replicate flume scale measurements of wave runup (Bonneton, et al., 2011a). More recent research has developed shock-capturing GN models for solving shallow water wave behaviour in 2D (Lannes and Marche, 2015, Popinet, 2015). The approach by Popinet (2015) reformulates the hyperbolic finite-volume system from Popinet (2011) to include a finite-difference GN source term. Following Bonneton, et al. (2011b) and Tissier, et al. (2012a) a free-surface slope threshold was implemented in Basilisk GN to locally remove the dispersive source term when the wave face becomes highly unstable (Popinet, 2015). The finite-volume NSWEs are activated at this point and control the rate of dissipation and wave shape in the surf-zone. Basilisk GN can be used in 1D and 2D with either quadtree-adaptive mesh or a Cartesian grid.

3.2 Model equations

3.2.1 Numerical scheme

An outline of the key equations implemented in Basilisk GN are presented here, the reader may refer to Popinet (2015) for a full description of the numerical scheme. Further information can also be obtained by viewing the documented source-code and examples on the basilisk website (Popinet, 2014).
Chapter 3: The Basilisk Green-Naghdi Solver

In integral form, the GN equation set is:

\[
\partial_t \int_{\Omega} q \, d\Omega = \int_{\Omega} f(q) \cdot n \, d\Omega + \int_{\partial \Omega} S \, d\Omega
\]  

(3.1)

where \( \Omega \) is a given subset of space, \( \partial \Omega \) is the boundary of \( \Omega \) and \( n \) is the unit normal vector of \( \Omega \). For conservation of mass and momentum in shallow water \( q \) and \( f(q) \) are taken from the NSW system outlined in Popinet (2011), and are written as:

\[
q = \begin{pmatrix} h \\ h \, u_x \\ h \, u_y \end{pmatrix}, \quad f(q) = \begin{pmatrix} h \, u_x \\ h \, u_y \\ h \, u_x^2 + \frac{1}{2} gh^2 \\ h \, u_x \, u_y \\ h \, u_y^2 + \frac{1}{2} gh^2 \end{pmatrix}
\]  

(3.2)

where \( u \) is the velocity vector and \( h \) is water depth.

The weakly dispersive source term in (3.1) is \( S \), defined as:

\[
S = \begin{pmatrix} 0 \\ -h g \nabla z_b + h \left( \frac{g}{\alpha} \nabla \eta - D \right) \end{pmatrix}
\]  

(3.3)

where \( z_b \) is bathymetry elevation, \( \eta \) is free surface elevation, and \( \alpha \) is a dispersion constant.

The default value of \( \alpha = 1.153 \) was used for all simulations in this thesis. The second part of (3.3), \( h \left( (g/\alpha) \nabla \eta - D \right) \), is the dispersive term that is added to the original NSW system (Popinet, 2015). If this second term is removed or equal to zero the system reduces to a non-dispersive NSW model. See Popinet (2015) for a description of how vector field \( D \) is solved by inverting the linear system.
3.2.2 Wave breaking

An accurate representation of surf-zone dynamics relies on having a realistic method for identifying when a wave is about to break. Once this critical threshold is reached in Basilisk GN, the dispersive source term is locally removed and the shock-capturing NSWEs are utilised to represent wave shape and dissipation through the surf-zone. Existing shock-capturing Boussinesq models have implemented the wave breaking procedure using a local free-surface slope (wave face) threshold (Bonneton, et al., 2011b, Tissier, et al., 2012a), a wave height to water depth criteria (Tonelli and Petti, 2010) and a threshold momentum gradient (Roeber and Cheung, 2012b). Basilisk GN uses the free surface slope threshold (B) technique to locally remove the dispersive finite-difference source term when the wave face becomes highly nonlinear and numerically unstable. The threshold slope for locally applying the NSWEs is implemented as a user defined parameter in Basilisk GN, with a default value of $B = 1$ (45°). Therefore, the finite-volume NSWEs are used in areas of high instability and represent wave bores through the formation of shocks (Bonneton, et al., 2011a, Bonneton, et al., 2011b, Popinet, 2015, Tissier, et al., 2012b).

Runup on an otherwise dry shoreline is another challenge when applying a dispersive solver to a surf-zone environment (Bonneton, et al., 2011a). This is managed in Basilisk GN by turning off the dispersive term when a cell has a ‘dry’ neighbour (dry default is $h < 10^{-10}$ m). Therefore, wet-dry interactions are handled using the NSWEs that include a hydrostatic reconstruction technique from Audusse, et al. (2004) to guarantee positivity of water depth (Popinet, 2011, Popinet, 2012). Sensitivity analysis is presented in Chapters 4 (flume scale) and Chapter 5 (field scale) to quantify how variations in $B$ influence model outputs for different wave processes.
3.2.3 Friction

Wave dissipation through friction is an important process in the surf-zone and can be especially high on coral reefs, compared to a relatively smooth sandy beach environment (Hearn, 1999, Lowe, et al., 2005). Implicit quadratic bottom friction (3.4) was included in all the simulations presented in this thesis, to account for the effect of friction in the surf-zone. The rate of dissipation through friction is controlled by a non-dimensional coefficient, $C_f$ (3.4):

$$S_f = -C_f \| u \| u$$  \hspace{1cm} (3.4)

The value of $C_f$ can therefore be adjusted to represent the effect of micro-scale roughness on the reef surface that is not accounted for at the bathymetry scale. Chapter 4 presents a detailed analysis of how different wave processes on the reef flat respond to high and low $C_f$ values and Chapter 5 identifies the $C_f$ value that provides the most accurate representative of measured processes on Funafuti Atoll.

3.3 Benchmark validations

The basilisk website includes a series of validation scenarios, using benchmark data, for 1D simulations of solitary waves propagation, solitary wave runup on a beach, solitary wave over-topping a sea wall and sinusoidal wave propagation over a submerged bar (Popinet, 2014). Benchmark validations in 2D include solitary wave runup on a conical island and wave refraction over an elongate shoal. These test case scenarios and simulation files are available online and in Popinet (2015). Popinet (2015) also simulated the 2011 Tohoku tsunami on the east coast of Japan and compares outputs to tide gauge data and runup measurements.
3.4 Application to coral reefs

To date, Basilisk GN has not been applied to reef-fringed coasts. However, existing Boussinesq-type models have utilised similar shock-capturing techniques to successfully represent SS waves, IG waves and setup on coral reefs (Roeber and Cheung, 2012b, Shimozono, et al., 2015). The ability of Basilisk GN to simulate the behaviour of relatively large amplitude waves across a variable bathymetry is highly suited to coral reef environments and is a key reason why Basilisk GN was selected for this research. Coral reefs are characterised by a relatively steep offshore reef slope and a rapid transition to a shallow and near-horizontal reef flat (Kench, 2013). This rapid transition creates a highly nonlinear environment for wave breaking and dissipation that is a challenge for traditional models to replicate (Roeber and Cheung, 2012b). The implementation of a shock-capturing scheme for wave breaking in Basilisk GN is therefore an important attribute that is highly suited to coral reefs. NSWEs are capable of simulating energetic wave dissipation in shallow water where existing eddy viscosity terms have proven to be cumbersome and unsuitable for use on reef environments (Roeber and Cheung, 2012b). Wave runup and inundation remain poorly studied on atoll environments but are of critical importance when considering the impacts of SLR (Quataert, 2015). Numerical simulations of wave runup and inundation require a phase-resolving model that can represent the water level dynamics associated with incident wave dissipation, IG waves and wave setup (Lannes and Marche, 2015, Roeber and Bricker, 2015). Figure 3.1 shows that the equations implemented in Basilisk GN have the potential to simulate the transformation of an irregular wave field across coral reefs, while accounting for IG wave motions, setup and swash behaviour.
Chapter 3: The Basilisk Green-Naghdi Solver

Figure 3.1: Example output from Basilisk GN showing across reef changes in the wave profile and the presence of setup (green) and IG wave motions (red). a) Across reef profile showing the change in wave shape and the setup zone on the reef flat. Insets show the raw water level time series overlaid with a low pass filtered (0.04 Hz) signal to show waves in the IG band at, a) offshore, b) reef edge and c) shoreline locations.

3.4.1 Applications of Basilisk GN in this thesis

Chapters 5 and 6 present detailed evaluations of model performance and sensitivity at flume scale and field scale, respectively. Sensitivity analysis was undertaken to explore and evaluate how different frequency wave processes (SS, IG, setup, runup) are influenced by the breaking slope ($B$) value and the friction coefficient value ($C_f$). All of the simulations presented in this thesis used a measured wave field as the boundary conditions. This was done by importing offshore water level data from flume measurements or field data. Using a realistic wave field is important for achieving a realistic and natural representation for IG wave dynamics, setup and runup. Model accuracy at field and flume scale were quantified using calculations for mean absolute error (MAE, Eq. 3.5) and model skill (Eq. 3.6). Skill and MAE were calculated separately for SS wave height, IG wave height and wave setup. MAE and skill are based the residual value, where the observed value ($O_i$) from flume or field measurements was subtracted from the modeled value ($P_i$). Model skill is based on
the method used in Lowe, et al. (2009a), with skill equal to one when \( P_i = O_i \). Therefore, skill values closer to one identify a better representation of measured processes.

\[
MAE = |P_i - O_i|
\]  
(3.5)

\[
\text{Skill} = 1 - \frac{\sum |(P_i - O_i)^2|}{\sum (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}
\]  
(3.6)

Vertical bars in (3.5) and (3.6) represent the absolute mean of enclosed values.

Once model skill and sensitivity were understood, the model was first used to investigate wave runup dynamics on Fatato Island, Funafuti (Chapter 5). The second application of Basilisk GN (Chapter 6) was to simulate how wave processes, runup and inundation on Funafuti Atoll are influenced by contemporary sea level and SLR. The final application of Basilisk GN (Chapter 7) was an investigation of wave transformation, runup and inundation on a series of coral reefs of variable morphology.
4.1 Introduction
Coral reefs play an important role in modulating wave generated processes that impact low lying sedimentary landforms on tropical coastlines (Ferrario, et al., 2014). Reef systems are unique in that they are characterised by a sharp transition from a steep fore-reef slope to a shallow reef flat and are often exposed to energetic ocean waves (Jago, et al., 2007, Kench, et al., 2009c). These properties create a hydrodynamic regime that is challenging to represent in numerical models due to the highly nonlinear nature of wave breaking and dissipation (Roeber and Cheung, 2012b). However, reliable modeling techniques are critical for assessing island vulnerability to wave driven inundation and flooding associated with environmental change and SLR.

Traditional numerical models used to simulate nearshore wave processes utilise phase-averaging techniques to resolve spectral transformation at sea swell (SS) frequencies, without attempting to represent the transfer of energy to infragravity (IG) waves (Hoeke, et al., 2013). This is a significant omission because IG frequency waves have a considerable influence on surf-zone processes, runup and inundation (Roeber and Bricker, 2015). To account for this, nonlinear phase-averaging models have been specifically developed in order to represent IG waves (Roelvink, et al., 2009b). IG specific models have been verified using field data from coral reefs, revealing new insight regarding the tidal controls on IG waves at the shoreline (Pomeroy, et al., 2012, Quataert, et al., 2015, Van Dongeren, et al.,
Chapter 4: Benchmark model evaluation results

2013). However, such models only represent a single incident wave frequency and therefore do not capture all of the processes that influence wave runup. A complete representation of nearshore and surf-zone processes requires numerical solutions for incident wave propagation, shoaling, wave breaking and the transfer of energy to IG motions and setup (Roeber and Cheung, 2012b). This can be achieved using a phase-resolving free-surface solver that combines a source term for wave dispersion with a shock-capturing scheme to handle unstable wave breaking (Bonneton, et al., 2011b, Lannes and Marche, 2015, Tissier, et al., 2012a). A recent analysis by Roeber and Bricker (2015) explains how the damaging long-period waves observed in Hernani, Philippines during Typhoon Haiyan could have been predicted if phase-resolving models were utilised in assessments of wave inundation.

As noted in Chapter 2, recent advances in numerical modeling have combined dispersive and shock-capturing equations to provide a fully nonlinear representation of wave processes in the nearshore and surf-zone (Bonneton, et al., 2011b, Lannes and Marche, 2015, Tissier, et al., 2012a, Tonelli and Petti, 2010). Shock-capturing Boussinesq-type models have been applied to coral reef environments and results show potential for simulating SS waves, IG waves, setup, runup and inundation (Roeber and Bricker, 2015, Roeber and Cheung, 2012b, Shimozono, et al., 2015, Su, et al., 2015).

Despite these advances, there is a limited understanding of how the breaking and friction parameters used in these type of models influence the surf-zone processes that operate at different frequencies. This chapter evaluates the ability of Basilisk GN, from Popinet (2015) to simulate wave processes on coral reefs. A range of free-surface slope thresholds ($B$) are tested, identifying how SS waves, IG waves, setup and runup respond to the slope threshold for locally switching between dispersive and shock-capturing schemes.
Chapter 4: Benchmark model evaluation results

Sensitivity analysis is also undertaken to identify how different wave processes respond to
the friction coefficient ($C_f$) used in eq. (3.4).

This study utilises existing wave flume data to evaluate Basilisk GN in the context of
simulating wave transformation on coral reefs. Benchmark experiment 1 (BM1) considers
1D wave transformation associated with SS waves, IG waves, setup and runup and uses
data from the University of Michigan (UM) wave flume to evaluate model outputs
(Demirbilek and Nwogu, 2007). BM1 assesses model sensitivity to breaking and friction
parameters, and highlights how different frequency wave processes respond to the
parameters that control dissipation. Benchmark experiment 2 (BM2) uses the model in 1D
to simulate a solitary wave shoaling across a reef slope before breaking on an emerged reef
crest and compares water level outputs to flume data from Roeber and Cheung (2012).
Benchmark experiment 3 (BM3) uses the model in 2D to simulate the interaction of a
solitary wave with a complex reef structure that has a triangular shelf and an emerged
island. Water level and velocity outputs are compared to flume data from Lynett, et al.
(2011). BM2 and BM3 are simulated using the breaking and friction values that achieved
the highest model skill from BM1. The approach utilised is a necessary first step for using
the model as a research tool that can support coastal management on coral reef coastlines.

4.1.1 Outline of test cases

BM1 simulates wave transformation across a ‘typical’ Guam reef (Fig. 4.1a) from the UM
wind wave flume experiment presented by Demirbilek, et al. (2007). UM data was initially
used to evaluate a Boussinesq model by Demirbilek and Nwogu (2007), and has
subsequently become a standard benchmark for applying wave models to coral reef
environments (Buckley, et al., 2014, Demirbilek and Nwogu, 2007, Demirbilek, et al.,
Shimozono, et al., 2015, Su, et al., 2011, Zijlema, 2012). Basilisk GN was evaluated using
fifteen incident scenarios from the UM dataset. The model was run in 1D using measured water level from wave gauge 1 (WG1) as the wave field. Model outputs for SS wave height ($H_{ss}$), IG wave height ($H_{ig}$), wave setup ($\bar{\eta}$) and maximum runup ($R_{max}$) were compared with flume data to assess model skill and sensitivity. A comprehensive sensitivity analysis was undertaken to identify how systematic variations in $B$ and $C_f$ influence each output parameter ($H_{ss}$, $H_{ig}$, $\bar{\eta}$ and $R_{max}$). In addition, the $B$ and $C_f$ combination that best represents the range of processes across the surf and swash zone were identified. Fourteen $C_f$ values were tested with 8 $B$ values (112 combinations) using the 15 incident conditions, resulting in a total of 1680 simulations. A wide range of friction values was simulated to understand model behaviour and sensitivity, not just to identify the value that best represents wave flume conditions. Pressure sensor data from the wave flume experiments were downloaded from http://cirp.usace.army.mil/pubs/techreports.php.

BM2 uses the $B$ and $C_f$ combination that produced the highest model skill from BM1 and simulates a solitary wave breaking on an emerged 1D reef crest. Data obtained during the Hawaii reef (HI reef) experiment from the O.H. Hinsdale Wave Research Laboratory at Oregon State University presented in Roeber and Cheung (2012) were used to evaluate model results. The HI reef test simulates a 0.75 m solitary wave being released in 2.5 m of water to shoal across a steep reef face before breaking on an emerged reef crest and plunging onto a shallow reef flat (Fig. 4.1b). BM2 required solutions for dispersion, nonlinearity, wave breaking and dry to wet dynamics (Roeber and Cheung, 2012b). Bathymetry and wave flume data from the HI reef experiment were downloaded from http://hydraulic.lab.irides.tohoku.ac.jp/app-def/S-102/2014/?page_id=56.

BM3 data comprise part of the National Tsunami Hazard Mitigation Program (NTHMP, 2012) benchmarking repository. BM3 considers a solitary wave interacting with a complex 3D shelf that has a triangular extension and an emerged conical island, from the flume
experiments by Lynett, et al. (2011). BM3 used Basilisk GN in 2D (depth averaged) and required solutions for dispersion, shoaling, refraction, diffraction, breaking, and wet/dry dynamics. The 3D shelf experiment has become a popular Boussinesq model benchmark scenario (Fang, et al., 2013, Roeber and Cheung, 2012a, Shi, et al., 2012, Yamazaki, et al., 2012) with bathymetry and wave gauge data available online (http://coastal.usc.edu/currents_workshop/problems.html). Again, $C_f$ and $B$ values from BM1 were used, evaluating the application of tuned parameters in 2D.

![Model bathymetry for each of the benchmark experiments. a) Benchmark 1 is the idealised Guam reef from a series of flume experiments undertaken in the University of Michigan wave laboratory. b) Benchmark 2 is the Hawaii Reef (HI reef) bathymetry used in the O.H. Hinsdale Wave Flume. c) Benchmark 3 uses the model in 2D with a complex reef bathymetry that has a steep slope, a triangular shelf and a conical island. Wave gauge (WG) locations used for measured and modeled data comparison are also shown for each bathymetry.](image-url)
4.2 Benchmark experiment 1: University of Michigan wave flume experiment

4.2.1 Bathymetry and boundary conditions

To establish the bathymetry in Basilisk, the topography used in Demirbilek and Nwogu (2007) was interpolated to a 1D grid with $\Delta x = 0.05$ m. Offshore depth was 0.5 m at the wave maker, 15.5 m from the reef slope (Fig. 4.1a). The fore-reef was characterised by three sections, a steep seaward slope (1:5), a mild mid slope (1:18.8) and a steep upper slope (1:10.6). The 4.8 m wide reef flat was made of smooth PVC pipe and the beach face had a 1:12 slope (Fig. 4.1). Wave flume data were collected using 9 capacitance wave gauges (WG) measuring free-surface elevation at 20 Hz (Fig. 4.1a). WG2 and WG3 were close to WG1 and WG4 was found to be faulty, therefore only six of the gauges were used to compare model and flume data. Runup data were collected in the wave flume using a capacitance wire on the beach face. The UM wind wave flume generated a JONSWAP wave field with peak enhancement factor of $\gamma = 3.3$. The GN model was run using the wave field measured at WG1 as a water level boundary condition. Each simulation ran for 900 s, with mean reef depth stabilising at approximately 100 s.

4.2.2 Data analysis

Water level data from the UM flume and Basilisk GN were collected at 20 Hz at each wave gauge location and were analysed using the same techniques. Data were trimmed to include only the final 700 s of wave activity, when mean depth was stable. A spectral filter with a 0.25 Hz (4 s) cut-off was used to separate SS and IG wave components. The 0.25 Hz separation is approximately double the peak incident period used in most UM simulations. Significant wave heights for SS ($H_{ss}$) and IG ($H_{ig}$) components were then calculated using a zero down-crossing routine in Matlab. Wave setup ($\bar{\eta}$) was calculated as the mean free-
surface displacement. Wave spectra were calculated from the raw pressure signal using the first 8192 samples from \( t = 200 \text{ s} \) (409.5 s) with an overlapping Hamming window and 16 degrees of freedom. Maximum runup (\( R_{\text{max}} \)) was calculated from model results using profile data for maximum water level across the model domain. UM values for \( R_{\text{max}} \) reported in Demirbilek and Nwogu (2007) were used to evaluate Basilisk GN outputs.

Model skill (eq. 3.5) was calculated separately at each wave gauge for \( H_{\text{ss}}, H_{\text{lg}}, \overline{\eta} \) and \( R_{\text{max}} \) to quantify model accuracy for each combination of \( B \) and \( C_f \). The skill value for each output variable \( (H_{\text{ss}}, H_{\text{lg}}, \overline{\eta}) \) was then averaged to quantify model performance across the range of surf-zone processes.

### 4.2.3 Sensitivity analysis results

Results show that each wave process exhibits a different sensitivity to breaking and friction parameters, resulting in a confined number of \( C_f \) and \( B \) combinations that produce high model skill for \( H_{\text{ss}}, H_{\text{lg}} \) and \( \overline{\eta} \) across the reef. Model sensitivity is first discussed based on the skill value associated with each output parameter at each wave gauge. Mean skill is then discussed based on \( H_{\text{ss}}, H_{\text{lg}} \) and \( \overline{\eta} \) at each wave gauge. Finally, \( R_{\text{max}} \) skill is presented, and mean skill at the beach toe is calculated based on \( H_{\text{ss}}, H_{\text{lg}} \) and \( \overline{\eta} \) at WG9, combined with \( R_{\text{max}} \) skill. Mean skill at the shoreline provides a quantitative assessment of the \( B \) and \( C_f \) parameters that best represent processes impacting the shoreline.

#### 4.2.3.1 SS waves

Model skill for \( H_{\text{ss}} \) at WG5 and WG7 was above 0.95 when using \( C_f < 0.01 \) combined with \( B > 0.6 \), offering a range of combinations that achieve skilful representations of incident wave behaviour near the reef edge (Fig. 4.2a-b). Model accuracy decreased slightly towards the shoreline, with maximum skill 0.93 and 0.90 at WG7 and WG9, respectively. The best prediction of \( H_{\text{ss}} \) at WG9 was achieved using \( B = 0.4 \) and \( C_f = 0.004 \), achieving a skill value
of 0.90 (Fig. 4.2d). However, \( H_{ss} \) predictions also recorded high skill and minimal sensitivity using \( C_f < 0.005 \); regardless of the \( B \) value. Model skill at WG9 decreased significantly for each \( C_f \) value above 0.007, especially with higher \( B \) values. \( H_{ss} \) at WG9 was slightly over-predicted by low \( C_f \) values and was under-predicted by high \( C_f \) values (Fig. 4.3d). This is a sensible response to increasing and decreasing the rate of dissipation due to friction on the reef flat. SS wave heights also demonstrate a subtle response to changes in the breaking slope. Each \( C_f \) value produced slightly higher shoreline wave heights when using lower \( B \) values compared to the higher \( B \) values (Fig. 4.3d). Low \( B \) values resulted in the dispersive source term being deactivated further offshore of the reef edge, effectively initiating the breaking procedure in deeper water. This led to gradual dissipation, characteristic of spilling waves, and resulted in slightly higher waves at the shoreline. Initiating the breaking procedure with a higher slope threshold allowed a slightly longer shoaling time which led to larger waves breaking in shallower water. This resulted in a relatively high \( H_b/h_b \) ratio leading to rapid dissipation shoreward of the breakpoint and slightly smaller waves at the shoreline. The rapid dissipation associated with higher \( B \) values is characteristic of the plunging breaker type (Nelson and Gonsalves, 1992). Low \( B \) values produced a better fit with flume data at WG9 when high \( C_f \) values were used; otherwise \( H_{ss} \) at the shoreline had minimal sensitivity to \( B \) (Fig. 4.2).
Figure 4.2: Model sensitivity results from BM1 showing how responsive model skill is to breaking ($B$) and friction ($C_f$) values. Model skill is calculated individually for $H_{ss}$, $H_{ig}$ and $\eta$ (columns 1 to 3) and combined skill is the mean of these skill values (column 4). Text at the bottom of each subplot indicates the $B$ and $C_f$ combination with the highest skill, with skill values closer to 1 indicating a better representation of the measured process. Note: x-axis is a log scale.
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Figure 4.3: Comparison of numerical and wave flume outputs using different breaking (increasing left to right) and friction (increasing top to bottom) combinations. Basilisk GN outputs for $H_{ss}$ (black), $H_{ig}$ (red) and setup (blue) at the shoreline (WG9) using different breaking ($B$, left to right) and friction ($C_f$, top to bottom) values are compared to wave flume measurements from the University of Michigan experiment in benchmark test 1.
4.2.3.2 IG waves
Infragravity wave heights at WG5 and WG7 were over-predicted using $C_f < 0.01$, leading to skill values < 0.8. However, skill > 0.9 was achieved using $B = 0.4$ and $C_f = 0.04$ (Fig. 4.2e-f). Basilisk GN was better at predicting $H_{ig}$ on the reef flat, with maximum skill > 0.96 at WG9 and skill > 0.9 recorded across a range of friction and breaking combinations (Fig. 4.2h). Maximum skill at WG9 was achieved using $B = 0.5$ and $C_f = 0.006$, with high skill associated with $C_f$ between 0.002 and 0.008 and any $B$ value above 0.4 (Fig. 4.2h). Model values for $H_{ig}$ at the shoreline were highly sensitive to friction. $H_{ig}$ at WG9 was typically under-predicted using high $C_f$ values (>0.01) and over-predicted using low $C_f$ values (<0.003). Therefore, friction evidently had a strong control on the transmission of long wave motions across the reef flat (Fig. 4.3). IG wave heights at the shoreline were less sensitive to $C_f$ when a higher $B$ value was used. Model runs using $B = 0.4$ were associated with slightly higher IG wave heights at the shoreline; over-predicting $H_{ig}$ when used with $C_f < 0.007$. Using $B = 1$ produced lower IG wave heights at the shoreline that were under-predicted when combined with $C_f > 0.008$ (Fig 4.3). It is possible that the larger IG waves associated with low $B$ values represent the amplification of long-waves when they are released seaward of the reef edge as a result of SS wave breaking being induced in deeper water. Overall, $C_f$ values between 0.004 and 0.007 produced high skill at the shoreline (>0.93), with minimal sensitivity to $B$ value above 0.4.

4.2.3.3 Wave Setup
Basilisk GN outputs for wave setup at the offshore gauges (WG1 - WG5) were nearly equal to zero. However, wave flume data showed a slightly negative mean water level between WG1 and WG5 which is not a true set-down reading. The difference between flume and numerical water levels offshore was minute (MAE = 0.002 m), but the relative difference resulted in model skill values below 0.1 (Fig. 4.2i). However, the numerical model was
capable of matching the magnitude of wave setup across the reef flat, with skill > 0.95 at WG7, WG8 and WG9. Wave setup at the reef edge, reef flat, and shoreline were well represented using most combinations of $C_f$ and $B$, with a relatively lower model skill associated solely with $B = 0.4$, and characterised by an over-predicted setup value (Fig. 4.2, Fig 4.3). The highest model skill at the shoreline was achieved using $B = 1$ and $C_f = 0.001$, yet any friction value combined with $B > 0.6$ produced exceptional model skill (>0.97). Wave setup predictions on the reef flat and shoreline demonstrated no sensitivity to $C_f$ when using any $B$ value above 0.6.

4.2.3.4 Mean skill for SS waves, IG waves and setup

Mean skill associated with $H_{ss}$, $H_{ig}$ and $\eta$ was calculated at each wave gauge to identify the $C_f$ and $B$ combination that best represented the range of processes observed across the reef (Fig. 4.2m-p). Mean skill at WG5 was low ~0.5 due to the disproportionately low setup skill observed seaward of the reef edge. Mean skill dramatically improved at WG7 due to strong predictions of SS wave height and wave setup, with $C_f$ values above 0.01 achieving the highest skill due to IG wave predictions. Mean skill at WG8 and WG9 exhibited similar sensitivities to breaking and friction, with skill > 0.93 across a range of $C_f$ and $B$ combinations (Fig. 4.2o-p). Mean skill at WG9 was highly sensitive to all $B$ values when combined with high friction ($C_f > 0.01$), due to under-predicted SS and IG wave heights. Mean skill at the shoreline was also sensitive to low $B$ values when a low $C_f$ value was used, due to an over-predicted $H_{ig}$ and setup (Fig. 4.2o). The best combination for predicting processes at the shoreline was $B = 0.8$ and $C_f = 0.003$ with high skill achieved using any $B$ value above 0.6, combined with any $C_f$ value between 0.001 and 0.007 (Fig. 4.2o).
4.2.3.5 Runup

The $C_f$ and $B$ combination that achieved the best prediction of surf-zone processes at WG9 continued to produce a reasonable match with $R_{max}$ (Fig. 4.4a), but tended to slightly over-predict flume measurements (skill = 0.84). The best prediction of $R_{max}$ was made using $B = 0.7$ and $C_f = 0.01$ (skill = 0.941). Model skill above 0.9 was also achieved using $B$ values between 0.6 and 1 combined with a $C_f$ value between 0.004 and 0.01 (Fig. 4.4a). Larger SS and IG waves at the shoreline, associated with lower friction ($C_f < 0.005$), resulted in over-predicted runup levels (Fig. 4.5). Model outputs for $R_{max}$ decreased with increased friction as SS and IG wave heights were more accurately predicted. Maximum skill for each $C_f$ value was associated with $B = 0.7$, however there was a slight decrease in skill as the breaking slope increased towards $B = 1.2$. Lower breaking values ($B < 0.5$) resulted in an over-predicted runup due to the exaggeration of IG waves and, to a lesser extent, over-predicted setup and SS wave heights at the shoreline (Fig. 4.5).

![Figure 4.4](image_url)

**Figure 4.4:** Model sensitivity at the shoreline. a) Skill value (colour) for wave runup under each combination of $B$ and $C_f$. b) Mean ToB skill (colour) is the average skill from $H_{ss}$, $H_{ig}$, $\eta$ at the toe of beach (WG9), including $R_{max}$. The data for ToB skill is presented in Table 4.1. The $B$ and $C_f$ combination that produced the highest skill is noted inside each plot.
Figure 4.5: Scatter plots for wave runup results from Basilisk GN compared to flume measurements for BM1. Maximum wave runup ($R_{\text{max}}$) output comparisons are presented for each combination of $B$ (left to right) and $C_f$ (top to bottom).
4.2.3.6 Mean skill at WG9 with runup

Processes occurring at the toe of beach (WG9) are the product of incident wave transformation across the reef flat, and represent the energy that interacts with reef island landforms. Wave processes at the beach toe and $R_{\text{max}}$ are the most important variables to accurately predict when using a model to study shoreline processes or wave driven inundation. Mean skill at the toe of beach (ToB skill) is presented in Figure 4.4b, with the data presented in Table 4.1. The highest ToB skill was 0.93, achieved using using $B = 0.7$ and $C_f = 0.005$ (Fig. 4.4b, Table 4.1). ToB skill was highly sensitive to low friction ($C_f < 0.003$) due to the over-prediction of IG waves and runup. Shoreline skill was also highly sensitive to high friction ($C_f < 0.01$) because of under-predicted SS and IG wave heights. High ToB skill was achieved using $B$ values between 0.6 and 1, with $C_f$ values between 0.004 and 0.008 (Fig. 4.4b).

Table 4.1: Mean model skill based on $H_{\text{ss}}, H_{\text{ig}}, \langle \eta \rangle$ (WG9) and $R_{\text{max}}$, based on the 15 test conditions, for each combination of $C_f$ and $B$. This data is also presented in Figure 4.4b.

<table>
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<th>$C_f$</th>
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<th>B=0.5</th>
<th>B=0.6</th>
<th>B=0.7</th>
<th>B=0.8</th>
<th>B=0.9</th>
<th>B=1</th>
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<td>0.856</td>
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<tr>
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<td>0.853</td>
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<tr>
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</tr>
</tbody>
</table>
Based on this analysis, the most accurate representation of wave processes at the shoreline were achieved using $B = 0.7$ and $C_f = 0.005$. Consequently, these values were used for the solitary wave tests in BM2 and BM3.

### 4.2.4 Across reef wave transformation

Use of the tuned input parameters, $B = 0.7$ and $C_f = 0.005$ to simulate across reef wave transformation resulted in model outputs for $H_{ss}$, $H_{ig}$ and $\bar{\eta}$ closely matching UM wave flume data across the reef flat (Fig. 4.6). $H_{ss}$ was generally well represented between the model boundary and the reef edge, indicating that the weakly dispersive GN solver was capable of skilfully propagating the irregular wave field. Modeled wave heights at WG5 and WG6 were slightly under-predicted for some of the smaller and shorter period incident wave conditions. SS attenuation between the reef edge and shoreline were generally consistent with flume data, however model results for $H_{ss}$ were slightly over-predicted at WG9 when $h_r$ was 0.51 m.

On average, IG wave heights were generally over-predicted between the model boundary and the reef edge, by 0.007 m (Fig. 4.6). Over predicted IG wave heights at WG6 and WG7 were associated with longer period SS waves that shoaled across the outer reef slope, with an associated increase in $H_{ss}$ between WG1 and the break point (WG5 – WG6). Given that SS waves began to interact with reef topography prior to breaking, it appears that the model is sensitive to the development or release of IG oscillations. This may have been exaggerated by using water level data from WG1 as an input wave field because the developing IG signal in the flume was further exaggerated between the numerical boundary and reef edge. The model skilfully predicted $H_{ig}$ between the reef edge and shoreline (Fig. 4.6); with the highest skill observed at the mid reef flat (WG8) and shoreline (WG9).
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Model predictions of wave setup were consistent with wave flume data at each WG location across the profile (Fig. 4.6). Flume data suggest that setup was typically initiated between WG6 (upper reef slope) and WG7 (reef edge), slightly increasing across the outer reef, remaining consistent across the inner reef and peaking at the shoreline. Model data matched this spatial trend and also generated setup of the same magnitude, relative to reef depth and incident wave conditions (Fig. 4.6).

![Figure 4.6](image)

Figure 4.6: Across reef variations in $H_{ss}$, $H_{ig}$ and $\bar{H}$ for the 15 UM test conditions, using the same UM ID from Demirbilek and Nwogu (2007) with $x = 0$ at the reef edge and $x = 5$ at the shoreline. Model results using $C_f = 0.005$ and $B = 0.7$ are compared to flume measurements (x markers) for the three variables.
4.2.5 Wave spectra

Model wave spectra at WG1 matched flume measurements for energy at frequencies below 1 Hz (Fig. 4.7). Higher frequency oscillations (> 1 Hz) were under-predicted at WG1 but not at WG5 and WG7, where UM flume and Basilisk GN data both indicated an increase in high frequency energy. Again, the model under predicted high frequency energy at WG9, and indicated a higher rate of attenuation associated with very short period waves (Fig. 4.7). However, the primary mode of spectral transformation across coral reefs is the transfer of energy from the peak incident SS frequency to IG wave motions, which are released at the reef edge and can dominate spectra on the reef flat and at the shoreline (Ford, et al., 2013, Péquignet, et al., 2014). The attenuation of SS frequency wave energy and the shoreward increase in IG energy observed in the wave flume were skilfully replicated in numerical model results (Fig. 4.7).
4.3 Benchmark experiment 2: solitary wave breaking on a complex 1D reef

4.3.1 Outline
The first benchmark experiment (BM1) shows that Basilisk GN can skilfully represent across reef wave transformation and accounts for the three key surf-zone processes that contribute to wave runup (SS waves, IG waves and setup). The second benchmark experiment (BM2) tests the models ability to replicate the free surface behaviour of a single
solitary wave interacting with an emerged reef crest. Instead of surf-zone processes, BM2 tests if the model can skilfully represent the changes in the profile observed throughout the shoaling, breaking and bore formation process.

4.3.2 Bathymetry and boundary conditions

The wave flume bathymetry used in Roeber and Cheung (2012b) is an 87.3 m wide idealised fringing reef that was interpolated into 1024 cells ($\Delta x = 0.0817$ m) for use in Basilisk. Offshore depth was 2.5 m, with the reef characterised by a 1:12 reef slope, a narrow reef crest 0.065 m above still water level, and a 0.14 m deep reef flat (Fig. 4.1b). Wave flume data were collected by 14 wave gauges across the scaled reef and were used to evaluate numerical model outputs (Fig. 4.1b). A 0.75 m solitary wave was released at the left boundary ($H/h = 0.3$) to interact with the 1D reef profile. $B = 0.7$ was combined with $C_f = 0.005$ to further evaluate the tuned values from BM1 using a different bathymetry and wave condition.

4.3.3 Measured and modeled water level

The numerical wave dispersed from the model boundary and retained a 0.75 m amplitude and solitary wave shape until interacting with the reef slope (Fig. 4.8a-c). The wave face in Basilisk steepened when shoaling up the reef slope, and became vertical just before the reef crest. Using $B = 0.7$ meant the dispersive source term was turned off locally when the wave face exceeded 35°. This allowed the NSWEs to handle the nonlinear wave breaking action as a vertical shock, and created a bore shape that propagated across the reef flat from $t = 12$ to 15 s (Fig. 4.8d-h). Free surface elevation matched wave flume measurements throughout propagation, shoaling and most of the breaking phase (Fig. 4.8). The depth averaged model did not simulate the three dimensional nature of a plunging wave over-turning, leading to some misrepresentation between numerical and flume data as the wave plunged onto the
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reef flat at \( t = 13 \) to \( 14 \) s in Figure 4.8. The generation of a bore that propagated across the reef flat was represented reasonably well by the GN model, matching the width and amplitude of flume measurements between 14 and 20 seconds. The dispersive function attempted to decouple the bore by generating a narrow wave crest at the tail edge, seen at \( t = 25 \) s (Fig. 4.8k). This peak was not observed in flume data but did not change the overall behaviour of the plunge generated bore. In addition, the model was able to compute how the plunge reflected off the right boundary to propagate back over the reef crest, eventually forming a hydraulic jump on the seaward side of the reef crest between \( t = 36 \) and 40 s (Fig. 4.8n,o).
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Figure 4.8: Water level output data from BM2 at different snapshot times for the 1D solitary wave experiment. Numerical water level (black line, grey shade) is compared with flume measurements (black circles) with the reef bathymetry shown in black shade.

Water level data from Basilisk GN closely matched wave flume measurements, with skill values above 0.9 at each of the 14 wave gauges (Fig. 4.9). Solitary wave propagation and shoaling were well represented numerically between WG1 and WG9, and were characterised by skill > 0.98 (Fig. 4.9a-i). After the solitary wave broke and reflected off the right boundary it propagated back over the reef edge towards the left boundary ($t > 30$).
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Model results replicated the rise in water level and series of short period oscillations that propagated from WG9 to WG1 as the reflected surge re-entered deep water (Fig. 4.9). However, the numerical solution shows that the short period waves reached each gauge left of WG4 slightly earlier in time compared to flume measurements (Fig. 4.9). High skill (>0.9) was also retained through the breaking and surge processes between WG10 and WG14. WG10 recorded the initial and reflected surge of water over the reef crest. Model timing at WG10 matched flume timing, but the water level was higher than flume data for the initial and reflected surge (Fig. 4.9j). Model data at WG11 show that the reef flat became dry near the reef crest as the surging bore reached the right boundary, around $t = 25$ s. This is inconsistent with flume measurements, where no drying was observed. Model outputs for the initial bore propagating past WG12 match the sharp rise in water level but not the rapid decrease in water level at the tail edge. Model outputs show a gradual decrease in water level as the bore passed WG12, instead of a rapid decrease. However, model outputs match flume measured water level when the reflected wave passed back over WG12 after reflecting off the right boundary. The highest skill (>0.97) values on the reef flat were recorded at WG13 and WG14, closely replicating flume measurements (Fig. 4.9m-n).
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4.4 Benchmark experiment 3: solitary wave breaking on a complex 2D reef

4.4.1 Outline

The first two test scenarios show that Basilisk GN can simulate surf-zone dynamics and free-surface wave behaviour using one horizontal dimension. These results are encouraging, but omit the hydrodynamic complexity associated with refraction, diffraction and convergence that are key processes on coral reefs. The final test case used Basilisk GN in 2DH (two horizontal dimensions, depth averaged) to simulate a solitary wave refracting,
dиффрагмирующего и сургающегося через сложную 3D батиметрию рифа. Оптические данные для уровня воды и скорости были использованы для оценки моделирования навыков в серии волновых гаuges.

4.4.2 Bathymetry and boundary conditions

The wave flume used in Lynett, et al. (2011) was 43.74 m long and 26.55 m wide, with an offshore depth of 0.78 m (Fig. 4.1c). The reef slope rose from h=0.78 m (at x = 10 m) to h = 0 m (at x= 27 m) and a triangular point extended towards the left boundary at y = 0 m, with a conical island centred on x = 17 and y = 0 (Fig. 4.1c). The 0.39 m solitary wave was released at the left boundary (H/h = 0.5) to interact with the complex reef structure. The experiment was replicated in Basilisk using $C_f = 0.005$ and $B = 0.7$ (from BM1) with $\Delta x$ and $\Delta y = 0.0855$ m. Model outputs were tested against water level data extracted at nine wave gauge locations (WG1 to WG9) and velocity data from three gauges (WG2, WG3, WG10), as shown in Figure 4.1c.

4.4.3 Water level results

Basilisk GN was capable of reproducing water level measurements from BM3 with skill between 0.717 and 0.969 (mean = 0.88) across the 9 wave gauges (Fig. 4.10). WG1 and WG4 demonstrated that the numerical solitary wave height and shape matched flume data when the wave propagated from the boundary (Fig. 4.10a,d). Model results from WG2 and WG5 replicated the steepening wave face observed in the flume as the wave interacted with the outer reef slope (Fig. 4.10b,e). The initial wave propagated past the first four gauges between $t = 1 - 10$ s (Fig. 4.11) with reflected waves reaching WG2 from $t = 15$ s (Fig. 4.10b). Model results identified the initial reflection well, but failed to identify the subsequent oscillations observed in the flume, lowering the skill value at WG2 to 0.86 (Fig. 4.10b). The other seaward instruments recorded a reflected signal consistent with flume data (WG1, WG4, WG5), and skill values above 0.95 (Fig. 4.10).
The solitary wave surged over and diffracted past the conical island between $t = 6$ s and $t = 10$ s (Fig. 4.11b-d). WG3 was positioned directly behind the island and recorded water level dynamics associated with overwash and convergence (Fig. 4.10c). Numerical water level at WG3 matched the onset of the bore at $t = 7.5$ s, but at a higher amplitude when compared with flume measurements (Fig. 4.10c). Flume data also identified a trough before a second increase in water level at $t = 9.5$ s that was not captured by the model (Fig. 4.10c). The initial surge of water up the beach face (behind and adjacent to the island) was replicated well in the model at WG7 and WG8, respectively (Fig. 4.10g,h). As the bore surged up the beach face some water overtopped the berm at $x = 30$ m and travelled towards the right boundary (Fig. 4.11g,h). However, a significant amount of runup was reflected and propagated towards the left boundary, identified by water level oscillations from $t = 15$ s (Fig. 4.10). In the flume data, this reflection was primarily observed as a second bore at $t = 22$ s on WG3 (Fig. 4.10c). The model replicated the reflection but in the form of a wider bore shape that arrived slightly earlier with a lower elevation (Fig. 4.10c). Overall, the water level dynamics at each wave gauge were replicated well in the model, with some variation in amplitude and shape in areas of shadowing and reflection.
Figure 4.10: Time-series comparison of measured and numerical free-surface elevation at the 9 wave guage locations used in BM3. Wave gauge locations are shown in Figure 4.1c.
Figure 4.11: Surface plots of the model free-surface as the solitary wave interacts with the conical island and surges up the beach face.

4.4.4 Velocity results

Velocity data were recorded by WG2 and WG3, capturing flow dynamics on the exposed and leeward side of the island (Fig. 4.12). In front of the island, WG2 recorded the velocity signal of the steepening solitary wave, with $U_x$ recording a close match to flume measurements (Fig. 4.12a). WG2 also recorded a similar $U_x$ signal associated with reflected water level between $t = 7$ and $18$ s. Leeward of the island, flume measurements recorded a sharp increase in $U_x$ as the wave surged over the island at $t = 7.5$ s (Fig. 4.12b). Model results for $U_x$ at WG3 demonstrated the same plunge, followed by a similar trough, between $t = 8.5$ and $22$ s. Modeled $U_y$ data at WG2 and WG3 produced low velocities and did not
identify the minor oscillations observed in the flume until \( t > 22 \) s (Fig. 4.12d,e). Data from WG10 measured velocity at the upper reef slope away from the island, with numerical outputs for \( U_x \) and the more significant variations in \( U_y \) showing a good agreement with flume data (Fig. 4.12c,f). Note, skill was not calculated for velocity outputs due to missing sections of data from each of the wave flume sensors.

![Figure 4.12: Model velocity (\( U_x \) on left, \( U_y \) on right) at three wave gauge locations compared to flume measurements for BM3.](image)

### 4.5 Summary and conclusion

The three benchmark experiments presented in this chapter highlight that Basilisk GN can skilfully represent surf-zone processes, water level variations and velocity dynamics on coral reef environments. Of the three benchmark experiments, BM1 is most the appropriate test for how Basilisk will be applied to simulate surf-zone dynamics and wave runup in the following chapters of this thesis. Physical phenomenon that contribute to wave runup and inundation on atoll islands include: SS waves, IG waves and setup (Merrifield, et al., 2014). Field measurements demonstrate how each of these processes respond differently to incident wave conditions and reef depth (Becker, et al., 2014, Ford, et al., 2013, Kench and...
Chapter 4: Benchmark model evaluation results

Brander, 2006b, Pomeroy, et al., 2012). Further, these processes influence the behaviour of each other, complicating a conceptual understanding of how environmental conditions influence runup on atoll islands (Merrifield, et al., 2014). Recent developments in numerical modeling allow these nonlinear interactions to be simulated under controlled boundary conditions, and provide a unique tool for exploring how these physical processes will respond to environmental change (Popinet, 2015, Roeber and Cheung, 2012b, Su, et al., 2015). However, an appropriate application of such models requires an understanding of how numerical outputs respond to parameters that control dissipation.

The systematic sensitivity analysis presented in BM1 highlights that SS attenuation, IG transmission, setup and runup all exhibit an individual sensitivity to breaking and friction parameters. However each output variable had a range of $B$ and $C_f$ values that produced a close match with measured data. Identifying where this range overlaps between different wave processes is critical for achieving the best representation of surf-zone dynamics. Therefore, a combined assessment of all parameters is required to achieve a realistic representation of processes that impact the shoreline. In general, outputs were more sensitive to the friction coefficient ($C_f$) than to the slope threshold used for locally removing dispersion ($B$). However, $B=0.4$ (21.8°) was found to initiate breaking further offshore, and resulted in over-predicted values for IG waves and setup. Buckley, et al. (2014) found that a higher breaking slope (~55°) gave the best representation of the Demirbilek, et al. (2007) experiment (BM1), when using the nonlinear phase-resolving model SWASH (SWASH default is 25°). Using a high breaking slope can be explained physically on coral reefs due to the narrow transition from deep to shallow water typically producing plunging breakers.
that are characterised by a steep wave face. Using Basilisk GN, minimal sensitivity and higher skill were observed using a slope threshold between $B=0.7$ ($35^\circ$) and $B=1.2$ ($-50^\circ$).

Higher friction values were associated with both SS and IG waves being under-predicted at the shoreline. IG waves were highly sensitive to friction and were over-predicted at WG9 when using low friction and were dramatically under-predicted using high friction. However, good IG predictions were achieved using a $C_f$ range between 0.002 and 0.008. Model results highlight the role of friction on the reef flat as a primary control for long-wave behaviour on coral reefs. Wave setup was consistently well predicted, with minimal sensitivity to friction, unless $B=0.4$ was used. Accounting for $R_{max}$, added another level of complexity when trying to achieve a skilful prediction of the processes impacting the shoreline. $R_{max}$ was highly sensitive to SS and IG dynamics, leading to over-predicted values when using low friction and under-predicted values using high friction. However, good predictions were achieved using midrange friction values between 0.005 and 0.01, with any breaking slope above 0.6. The best representation of all processes was found using $C_f = 0.005$ and $B=0.7$. Shimozono, et al. (2015) also used $C_f = 0.005$ when replicating the UM experiment, and achieved good representations for $H_{ss}$, $H_{ig}$, $\bar{\eta}$ and $R_{max}$ using a different fully nonlinear Boussinesq model. The calibrated Basilisk model was further tested at a flume scale in 1D and was able to closely replicate the nonlinear transformation of a solitary wave on complex bathymetry. Using the model in 2D, free-surface water level was again replicated well, however a decrease in model skill was observed in comparison to 1D outputs. Collectively, the three benchmark scenarios show that Basilisk GN is capable of simulating the range of wave frequencies and nonlinear dynamics associated with wave transformation on coral reef systems.

A benefit of fully nonlinear free-surface models is the direct feedback between wave processes that operate at different frequencies (Shimozono, et al., 2015). For example the
attenuation of irregular SS waves resulted in IG motions and setup that in turn influenced the transmission of reformed SS waves across the reef flat. This is important and necessary for skilful simulations of the processes that promote elevated sea level and coastal flooding, as recently highlighted by Roeber and Bricker (2015). However, the interlinked nature of these models also means that the sensitivity of each process needs to be carefully understood before being applied to real world scenarios. Simulations presented here are the first step taken in applying Basilisk GN to study the complex interplay of the processes associated with wave transformation on coral reef coastlines. Results suggest that the combination of weakly dispersive Green-Naghdi equations and nonlinear shallow water equations implemented in Basilisk have significant potential for simulating detailed wave processes on reef environments. Consequently, the model could provide a powerful research tool to explore wave dynamics on reef systems and act as an insightful resource for supporting coastal management decisions in the face of SLR. Results from the series of benchmark scenarios encourage further model testing at the field scale, where bathymetry is much more complex and friction can be orders of magnitude higher. Once evaluated with field data, Basilisk GN has potential to be used as an exploratory tool for simulating wave transformation in the context of environmental change and SLR.
Chapter 5: Wave transformation and shoreline water level on Funafuti Atoll, Tuvalu

5.1 Introduction
Coral reef islands on Funafuti Atoll, Tuvalu, are frequently being classified as highly vulnerable to SLR, with increasing concern that coastal erosion and flooding will make the atoll uninhabitable within the next hundred years (Connell, 1999, Connell, 2003, Dickinson, 1999, Farbotko and Lazrus, 2012, Patel, 2006). However, no field data have been collected to understand the wave driven process that impact islands on Funafuti Atoll. This chapter presents field data from a two month field experiment on Fatato Island, Funafuti Atoll, and examines tidal controls on the different wave processes that impact the island shoreline. Field data from Fatato were also used to evaluate model skill and sensitivity to different breaking and friction values, before the entire field experiment was replicated in the numerical model.

The most frequently cited cause of inundation in Tuvalu is when extreme spring tides, also referred to as king tides, submerge low lying areas Fongafale Island on the eastern rim of Funafuti Atoll (Lin, et al., 2014, Yamano, et al., 2007). However, recent research has predicted that wave overtopping will become the most frequent cause of island flooding as sea levels rise (Hoeke, et al., 2013, Merrifield, et al., 2014). Runup generated from distant source swell waves or locally generated storm waves can overtop and flood atoll islands causing significant damage to infrastructure (Ford, et al., 2013, Hoeke, et al., 2013, Shimozono, et al., 2015). Notwithstanding the concerns raised by such episodic events,
geomorphic change can also occur under regular conditions when waves interact with sediment on the beach face (Kench and Brander, 2006b). To date, few studies have examined the temporal exposure of reef island shorelines to different frequency wave processes.

Maximum runup elevation on an atoll island is primarily influenced by sea swell (SS) waves, infragravity waves (IG), wave setup, and tidal elevation (Merrifield, et al., 2014). Incident SS wave energy (> 0.04 Hz) is dissipated through wave breaking at the reef edge and by friction across the reef flat (Hearn, 1999, Péquignet, et al., 2011). Field experiments have demonstrated a strong tidal control on SS wave transmission across the reef, with attenuation between 70% at high tide and 100% at low tide (Ford, et al., 2013, Kench and Brander, 2006b, Péquignet, et al., 2011). Consequently, field results indicate that the potential for SS wave driven geomorphic change at the island shoreline is typically constrained to high tide (Brander, et al., 2004, Kench and Brander, 2006b). Despite these findings, few studies have extended the analysis of wave transformation beyond a near shoreline instrument to include runup limits on the beach face.

IG frequency waves (< 0.04 Hz) are released when SS wave groups interact with the reef edge (Péquignet, et al., 2014, Pomeroy, et al., 2012). Field measurements across narrow atoll reefs (~100 m) indicate that IG waves contribute the main form of shoreline energy under mean and swell wave conditions (Ford, et al., 2013). During a long period swell event, runup at IG frequencies was reported to overwash berm elevation on a number of Pacific atolls (Hoeke, et al., 2013). However, measurements on wide fringing reefs indicate that IG waves generated under mean wave conditions will peak near the reef edge (~100 m) and be dissipated by friction across the reef flat (Péquignet, et al., 2014, Pomeroy, et al., 2012, Van Dongeren, et al., 2013). Numerical analysis of wave transformation under extreme typhoon conditions show the potential for IG waves to damage the shoreline on
wide and shallow fringing reefs (Shimozono, et al., 2015). Wave breaking at the reef edge also generates a setup water level across the reef flat (Gourlay, 1996a). On average, setup on coral reefs has been measured to be 25% of incident $H_s$ (Jago, et al., 2007, Vetter, et al., 2010). However, Becker, et al. (2014) identify a strong tidal control on setup; with higher setup at low tide exceeding 40% of incident $H_s$, and a relatively small setup at high tide (<10% of $H_s$). Large setup results in less attenuation from friction on the reef flat, allowing larger wave heights at the shoreline and an elevated point of interaction for SS and IG waves on the beach face.

Recent research on wave transformation on across atoll reefs have suggested that wave overtopping will become increasingly common with SLR (Hoeke, et al., 2013, Merrifield, et al., 2014, Quataert, et al., 2015), without considering the character of wave processes on the beach face. Sea level, tidal oscillations, setup, IG waves, and SS waves combine to determine reef flat water level and the point of maximum runup at the shoreline (Merrifield, et al., 2014). In turn, reef flat water level and runup influence the temporal window for geomorphic activity at the shoreline. Therefore it is necessary to investigate wave transformation in the context of the resultant model of processes that impact shoreline water level in order to understand the key drivers of geomorphic change on atoll landforms.

This research considers how SS waves, IG waves and wave setup influence shoreline water level on atoll islands. Wave transformation data is presented from field measurements taken over a 62 day period on Fatato Island, Funafuti Atoll. Funafuti is often cited as being especially vulnerable to SLR, with spring tides frequently flooding island infrastructure (Lin, et al., 2014, Yamano, et al., 2007). An analysis of sea level records also suggests that Funafuti is currently experiencing a rise in mean sea level of 5 mm/yr, three times the global average (Becker, et al., 2012). Despite this vulnerability, no attempt has been made to quantify the wave processes that impact island shorelines on Funafuti Atoll. Field results
are presented first to understand how tide level and incident wave conditions influence SS waves, IG waves and setup on the reef flat. Basilisk GN is then used to replicate field conditions and estimate maximum wave runup at the shoreline. Model results for maximum runup are deconstructed to understand the influence that SS waves, IG waves and setup have on elevating water level at the shoreline. A thorough review of model performance and sensitivity is presented before numerical results are used to extend field measurements from a near shoreline instrument to the runup limit.

5.2 Field Setting

Funafuti Atoll hosts 32 sedimentary islands across a series of 10 shallow coral reef platforms that form an annular ring around an internal lagoon (h ~ 50 m). Funafuti atoll stretches 18 km east to west, 25 km north to south and is part of Tuvalu, located in the tropical south west Pacific Ocean (8°30’ S, 179°06’ E) between Fiji and Kiribati (Fig. 5.1a). The atoll reef on the east side of Funafuti is narrow (mean width of 300 m) and has a series of vegetated sand and gravel islands (Kench, et al., 2015). Field data were collected on the ocean-facing reef flat near Fatato Island on eastern rim of Funafuti Atoll, directly south of the main population on Fongafale Island. Fatato Island faces to the southeast (143°) and is directly exposed to waves approaching between 60° and 213°. Mean $H_s$ near Funafuti is 1.2 m in summer and 1.4 m in winter (30 year Wave Watch 3 data), with mean peak direction ($D_p$) shifting from 145° in summer to 135° in winter (Durrant, et al., 2014).

Fatato is an uninhabited island, approximately 87 m wide and 860 m long, comprised of coarse coral gravel. The island is located on a 300 m wide reef flat with an ocean side reef width of 100 m and an average fore-reef slope of 23.5° (Fig. 5.1). A discontinuous cemented rubble bank is located on the inner reef flat (Fig. 5.1d). The cemented bank is the remains of a rubble rampart that was deposited 30 m from the reef edge during Tropical Cyclone Bebe in October 1972 (Maragos and Beveridge, 1973). A ~10 m wide
conglomerate platform is located between the area of cemented rubble and the beach face, with the seaward edge 0.3 m below mean sea level (MSL). The island beach is located from 0.39 m above MSL and forms a steep beach face (12.2°), with a berm elevated 3.5 m above MSL (Fig. 5.1d). Sediment on the ocean-facing beach is predominantly gravel sized (-4.2 to -6.4 phi) with some sand sized sediment from 1.15 to -0.32 phi (Ryan, 2012).

Figure 5.1: a) Location of Funafuti Atoll in the Pacific Ocean. b) Funafuti Atoll with contour lines at -500, -200 m and -2 m, islands are black and the reef flat (h>3 m) is grey. c) Bathymetry around Fatato Island with field instrument positions and contours at -100 m, -20 m and -2 m. d) Profile of the reef flat and Fatato Island, highlighting geomorphic features and instrument locations. e) photo of the reef flat and instrument profile at high tide and f) at low tide.
5.3 Field campaign

5.3.1 Wave data

Over a 62 day field deployment waves were measured by three separate wave and tide instruments located: offshore, on the outer reef flat, and adjacent to the island shoreline (Fig. 5.1d). The instruments were deployed to record pressure (water level) at 1 Hz for 2048 s (~34 min) every 3 hours. Data collection started at 12 pm on 4 June 2013 and ended at 9 pm on 5 August 2013, resulting in 500 synchronised bursts. In order to measure incident waves, a Nortek AWAC was deployed at a depth of 19 m on the fore-reef slope. In addition, two RBR Tide and Wave recorders (TWRs) were deployed on the reef flat. The outer reef flat TWR was deployed 70.4 m seaward of the island beach (32 m shoreward of the reef edge) at an average depth of 0.9 m below MSL. The shoreline TWR was positioned at the seaward edge of the conglomerate platform (MSL - 0.38 m); 11.6 m seaward of the beach sediment (Fig. 5.1d). Both TWRs were bolted to the reef with sensors 0.05 m above the bed. The 62 day long field measurement duration covered a mixture of spring and neap tidal conditions and captured a range of incident wave conditions that were deemed sufficient for understanding wave transformation processes under non-extreme conditions.

Pressure data from the AWAC was corrected for signal attenuation using the method described in Tucker and Pitt (2001). Pressure data from the AWAC were used in favour of acoustic surface tracking to maintain a consistent data analysis method with the reef flat pressure sensors. Zero-down crossing analysis of the 1 Hz pressure data from each burst, from each instrument, was undertaken to calculate wave height and period. Following Ford, et al. (2013) and Pomeroy, et al. (2012) a 0.04 Hz spectral band-pass filter was used to separate water level oscillations into SS and IG frequencies before calculating the significant wave height associated with SS \( H_{ss} \) and IG \( H_{ig} \) waves. Power spectral density was calculated from the unfiltered water level data using a Fast Fourier Transform with 8
degrees of freedom and an overlapping Hamming window Welch (1967). Wave setup ($\eta_i$) at each reef flat sensor was calculated by identifying the difference in mean depth between the reef sensor and the offshore sensor, relative to the difference in topographic elevation:

\[
\eta_i = \bar{h}_i - (\bar{h}_o + \Delta h),
\]

where $\bar{h}_i$ is the burst average depth at the reef flat sensor, $\bar{h}_o$ is the burst average water depth at the offshore sensor, and $\Delta h$ is the difference in elevation between the offshore sensor and the reef flat ($\Delta h = 18.33$) and shoreline ($\Delta h = 18.82$) sensors. This method assumes no setup or set-down at the offshore sensor.

### 5.3.2 Topography

A laser level total station was used to measure reef and island topography on 10 across reef transects including the instrument profile. The profiles were combined with RTK-GPS survey points from the reef flat to create a terrain model of the reef flat and shoreline. Shallow water topography data was combined with satellite imagery and single beam echosounding data from Hoeke, et al. (2014) to create a bathymetry map of the atoll reef flat near Fatato Island (Fig. 5.1c). All references to topography used in field and model analysis are relative to $\text{MSL} = 0$.

The 1D model transect used for wave simulations was a composite of the total station measured profile across the instrument transect and the composite atoll bathymetry form Hoeke, et al. (2014). The total station profile provided coverage of Fatato Island until the outer reef flat with a seaward limit 1.2 m below MSL, 90 m from the beach toe. The instrument profile was extended seaward by overlapping and stitching a profile sliced from the atoll bathymetry that provided 10 m resolution coverage of the outer reef flat, the reef edge and reef slope (Fig. 5.2). Total station and bathymetry data were both referenced to $x = 0$ m at the toe of beach and interpolated to 1 m resolution for numerical simulations.
5.4 Model experiments

Field conditions from each burst were simulated using Basilisk GN to understand model sensitivity and simulate runup at the shoreline. Sensitivity analysis was undertaken to identify the appropriate $C_f$ (friction coefficient) and $B$ (breaking slope threshold) values to use on Funafuti. Four $B$ slopes (0.4, 0.6, 0.8 and 1) and 8 $C_f$ values (0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08 and 0.1) were tested using 10% of the field data (50 bursts). Each $B$ value was simulated with each $C_f$ value using the 50 test bursts totalling 1600 simulations. The 50 consecutive bursts used to test model sensitivity encompassed a range of incident conditions between 23 June and 29 June 2013, and notably included a swell event that coincided with spring tides. Model outputs for $H_{ss}$, $H_{ig}$, and $\bar{\eta}$ at the shoreline were compared with field measurements to identify the $C_f$ and $B$ combination that best represents conditions on Funafuti. All 500 bursts from the field campaign were then simulated using the $B$ and $C_f$ combination that produced the lowest combined error for $H_{ss}$, $H_{ig}$, and $\bar{\eta}$ at the shoreline. Basilisk GN outputs for $H_{ss}$, $H_{ig}$, $\bar{\eta}$, and wave spectra from the 500 bursts were then compared with field data at the reef flat and shoreline, before model outputs were used to analyse maximum water level on the beach face.

5.4.1 Model inputs

Measured water level from the offshore instrument was interpolated to 10 Hz to use as the boundary wave field for each simulation (Fig. 5.3a). The Basilisk GN solver was used with a 1D grid to simulate wave transformation across the atoll reef. Reef bathymetry was interpolated to a uniform 1D transect with $\Delta x=1$ m, and still water level was offset according to the tide level of each burst. To reduce boundary reflection, imported waves were propagated across a flat shelf (100 m deep) for 650 m before interacting with the atoll reef slope (Fig. 5.3b). Wave statistics were calculated at the AWAC location to make sure the model wave field matched field measurements.
5.4.2 Output data analysis

Each test burst simulated 2048 s of wave activity. It took \(~100\) s for waves to reach the shoreline and \(~300\) s for mean water level to stabilise on the reef. Therefore, only output data between 512 s and 2048 s was considered for analysis. To compare model results with field results time-series water level was extracted at 10 Hz at each of the three instrument positions (Fig. 5.1d). \(H_{ss}, H_{lg}, \bar{\eta}\) and wave spectra were calculated from each model instrument using the same methods applied to field data.

5.4.3 Maximum runup analysis

Maximum water level data were extracted at the end of each model run and used to identify maximum wave runup \((R_{max})\) for each simulation. Of note, field data were unable to be collected for runup, and consequently all \(R_{max}\) results are based on model outputs. \(R_{max}\) was calculated relative to the still water tide level and then separated into SS, IG, and setup components using model data for \(H_{ss}, H_{lg}, \bar{\eta}\) from the shoreline field instrument position (Fig. 5.1d). First, the difference between tide level and \(R_{max}\) was calculated.
Second, the setup contribution was identified (equal to $\eta$ at the shoreline), and subtracted to determine the combined SS and IG contribution. The remaining $R_{\text{max}}$ value was split into SS and IG components proportional to the values of $H_{ss}$ and $H_{ig}$ at the shoreline. Note, this method calculates maximum runup to the nearest horizontal meter ($\Delta x = 1$ m) and does not account for the influence that wave period has on swash elevation.

5.4.4 Model performance
Mean absolute error (MAE) and model skill were used to quantify how well the model predicted $H_{ss}$, $H_{ig}$ and $\eta$ at the reef flat and shoreline.

5.5 Field Observations
5.5.1 Tide and wave conditions
Two semi-diurnal spring tides were recorded during the 62 day data collection period. A spring tidal range of $\sim$2.1 m was observed, where the maximum high tide was + 1.08 m relative to MSL = 0, and the minimum low tide was -1.0 m, relative to MSL = 0. Two neap tides were also recorded, with a larger diurnal range between +0.45 m -0.35 m and a lower semi-diurnal oscillation (Fig. 5.3a). On average, offshore significant wave height ($H_o$) was 1.17 m, and $H_{\text{max}}$ was 2.0 m (Fig. 5.3c,d; Table 5.1).
Chapter 5: Field and model results from Funafuti Atoll

Table 5.1: Summary of field wave statistics for different tide stages at the three instrument locations.

<table>
<thead>
<tr>
<th></th>
<th>Offshore</th>
<th>Reef</th>
<th>Shore</th>
<th>Offshore</th>
<th>Reef</th>
<th>Shore</th>
<th>Offshore</th>
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<td>$H_{o}$ (m)</td>
<td>$H_{o}$ attenuation (%)</td>
<td>$H_{g}$ (m)</td>
<td>Setup (m)</td>
<td>$H_{o}$ (m)</td>
<td>$H_{o}$ attenuation (%)</td>
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<td>$H_{g}$ (m)</td>
<td>Setup (m)</td>
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<tr>
<td>Maximum</td>
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<td>1.17</td>
<td>0.61</td>
<td>81.98</td>
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<td>0.52</td>
<td>0.77</td>
<td>0.81</td>
<td>0.89</td>
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<tr>
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<td>49.98</td>
<td>78.18</td>
<td>0.20</td>
<td>0.30</td>
<td>0.18</td>
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<td>-5.26</td>
<td>29.26</td>
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<tr>
<td>Mean</td>
<td>1.14</td>
<td>0.72</td>
<td>0.39</td>
<td>34.50</td>
<td>64.55</td>
<td>0.20</td>
<td>0.31</td>
<td>0.07</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>0.68</td>
<td>0.53</td>
<td>0.26</td>
<td>-5.26</td>
<td>29.26</td>
<td>0.09</td>
<td>0.14</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Four moderate swell events were measured during the deployment (where $H_{o} \geq 1.9$ m and $T_{s} > 10.5$ s). The largest swell event started on June 23$^{rd}$ and peaked at $H_{o} = 2.1$ m; with $H_{max} = 3.7$ m and $T_{s} = 15.5$ s. The swell arrived during a spring tide, and a number of bursts coincided with spring high tide. Between swell events $H_{o}$ occasionally dropped below 1 m but remained above 0.68 m (Fig. 5.3).
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Figure 5.3: Summary wave conditions from the offshore instrument (blue), outer reef flat instrument (green) and shoreline instrument (red) from the 62 day deployment in 2013. $H_s$ and $H_g$ are significant wave heights in the SS and IG band, respectively. $\bar{\eta}$ is wave setup.
5.5.2 Sea swell waves

On average, incident wave height decreased by 50% between the offshore instrument and the outer reef. On the reef flat, wave height was tidally modulated, especially under low and moderate incident wave conditions (Fig. 5.4a). Mean attenuation was lowest at high tide (35%) compared to mid (51%) and low tides (65%). All bursts recorded wave activity at the outer reef flat; with $H_{ss}$ falling between a minimum of 0.22 m and a maximum of 1.17 m (mean = 0.56 m, Table 5.1).

$H_{ss}$ was significantly lower at the shoreline relative to the reef flat; with a mean of 0.25 m and a range of 0 m to 0.61 m. On average, offshore waves attenuated by 78% at the shoreline. Results show that $H_{ss}$ was tidally modulated across all incident heights. Average attenuation was again greater at low tides (90%), compared to mid (80%) and high (64.5%) tides. Wave height was smallest at low tide (mean = 0.12 m), with 20 bursts recording no wave activity. Larger incident waves (>1.5 m) exhibited less attenuation at low tide, but were significantly attenuated at high tide (Fig. 5.4g). In comparison, smaller incident waves (<1.5 m) were rapidly attenuated at low tide but underwent minimal dissipation at high tide.
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Figure 5.4: Tidal controls on wave processes on the reef flat (left) and at the shoreline (right) from field measurements. Tide is relative to MSL = 0, $H_s$ attenuation is the percentage difference in $H_{ss}$ between the offshore sensor and respective reef flat sensors, $\bar{\eta}$ is wave setup and $\bar{h}$ is mean depth (tide + setup). j) Points outside the small box show that mean depth is above the beach toe (MSL + 0.39m).
5.5.3 **Infragravity waves**

At the outer reef, $H_{lg}$ was primarily controlled by incident waves and only minimally affected by the tide (Fig. 5.4c). On average, $H_{lg}$ at the outer reef ranged from 10% to 29% of $H_o$ (mean = 17%). $H_{lg}$ increased across the reef flat, and at the shoreline, mean $H_{lg}$ was 25% of $H_o$. At the shoreline there was a slight tidal influence on small IG waves ($H_{lg} < 0.5m$); with the largest IG waves observed at mid tide (Fig. 5.4h). At low tide $H_{lg}$ was smaller; possibly due to higher friction on the shallow reef flat. At high tide $H_{lg}$ was also relatively smaller; perhaps as a result of decreased SS wave breaking and attenuation. During large incident conditions, results show that $H_{lg}$ was not tidally modulated and was often larger than $H_{so}$ at the shoreline (Fig. 5.4).

5.5.4 **Wave setup**

Mean setup was 0.18 m (16% of $H_o$) at the outer reef and at the shoreline (Table 5.1). Setup at the outer reef was greater at low tide, with a mean of 0.32 m (26% of $H_o$). At high tide, mean setup on the reef flat was 0.07 m (6% of $H_o$). Mean setup at the shoreline was 0.3 m at low tide, inclusive of the 20 bursts that recorded no wave activity. Wave setup at the reef and shoreline was strongly correlated to tidal level and incident wave height, with maximum setup generated by large waves at low tide (Fig. 5.4). The largest setup observed during the deployment was 0.81 m (38.6% of $H_o$) at the outer reef and 0.89 m (42% of $H_o$) at the shoreline. This observation was associated with $H_o = 2.1$ m and $T_o = 15.5$ s at low tide (-0.73 m) at the peak of the 23 June swell event.

5.5.5 **Shoreline exposure**

The island beach was situated 0.39 m above MSL. Consequently, waves had the potential to directly interact with the beach face when the tide exceeded +0.39 m. From the offshore instrument, it is apparent that tidal elevation exceeded 0.39 m on 112 of the 500 bursts (22.4% of the experiment period). The shoreline instrument was located 0.77 m below the
beach face. Mean depth at the shoreline instrument (tide + setup) exceeded 0.77 m on 125 of the 500 bursts (25% of the experiment period). This data suggests that any interaction between oceanic processes and the beach face was confined to 25% of the field deployment period. However, this figure does not account for runup above still water level caused by SS or IG waves. The connection between wave processes and island sediment is further investigated numerically based on maximum runup outputs.

5.6 Model Results

5.6.1 Sensitivity to breaking and friction parameters
Modeled wave heights at the shoreline sensor were sensitive to changes in $C_f$ (friction coefficient) and $B$ (slope threshold used to turn off the dispersive term to handle wave breaking using the NSW equations). Lower $C_f$ values ($< 0.03$) resulted in an over-predicted shoreline wave height; with mean error between 0.03 m and 0.057 m (Fig. 5.5). Higher $C_f$ ($> 0.06$) resulted in under-predicted shoreline wave heights, with mean error between 0.04 m and 0.06 m (Fig. 5.6). The lowest error was found with $C_f = 0.04$. Each friction value had a stronger correlation and lower error with $B = 0.8$ or $B = 1$. Lower $B$ values (0.6 and 0.4) often resulted in slightly over predicted wave heights at high tide. The lowest mean error (0.02 m), highest model skill (0.994) and the strongest correlation ($R^2 = 0.985$) was achieved using $C_f = 0.04$ and $B = 1$ (Fig. 5.5).
IG wave height was more sensitive to $C_f$ and $B$ values. Lower friction values resulted in significantly over-predicted $H_{ig}$ at the shoreline, with mean error between 0.06 m and 0.15 m for $C_f \leq 0.02$ (Fig. 5.5). $C_f > 0.06$ resulted in under predicted IG wave heights with mean error between 0.07 and 0.12 m (Fig. 5.6). Higher $B$ values (0.8 and 1) gave a much better prediction of field conditions compared to low slopes (0.6 and 0.4). The best representation of $H_{ig}$ at the shoreline was achieved using $C_f = 0.04$ and $B \geq 0.8$. IG error was slightly lower with $B = 0.8$ compared to $B = 1$ (Fig. 5.5).

Model values for wave setup were close to field measurements for most $B$ and $C_f$ combinations (Fig. 5.6). The only deviation from a near perfect prediction was found using $B = 0.4$ or $C_f > 0.06$ (Fig. 5.5). For each friction value, $B = 1$ achieved the best prediction of wave setup. $C_f = 0.01$ and $B = 1$ gave the best representation of wave setup; however any


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$C_f$ value between 0.01 and 0.05 produced a very good match with field data where $B = 1$ (Fig. 5.5).

Figure 5.6: Model sensitivity to friction ($C_f$) and breaking ($B$) parameters based on the 50 test simulations. Model outputs for $H_{ss}, H_{ig}$ and wave setup at the shoreline are compared to field measurements from the shoreline instrument.

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5.6.2 Combined error

The smallest error and greatest model skill were achieved using $C_f = 0.04$. When applied to the steep sloping, rough and shallow atoll reef at Funafuti, the model gave the best prediction of $H_{ss}$, $H_{ig}$ and $ar{n}$ when a breaking slope of 0.8 or 1 was combined with $C_f = 0.04$. Using $C_f = 0.04$ the sum MAE from $H_{ss}$, $H_{ig}$ and $ar{n}$ for both $B = 1$ and $B = 0.8$ was 0.084 m (Table 5.2). $B = 1$ gave a better prediction for $H_{ss}$ and setup but $B = 0.8$ gave a slightly better prediction for $H_{ig}$. However, there was minimal sensitivity between $B = 1$ and $B = 0.8$. Therefore, the values used to simulate the entire field deployment and investigate $R_{max}$ were $C_f = 0.04$ and the default slope threshold, $B = 1$. Using a $B$ value of 1 means the dispersive source term is removed locally on any cell where the free-surface slope (e.g. wave face or back) exceeds 45°, resulting in the onset of wave breaking. This is a simplification of other thresholds used to implement breaking in phase-resolving models, where mean depth is also considered when removing the dispersive terms (e.g. SWASH).

<table>
<thead>
<tr>
<th></th>
<th>$B = 1$</th>
<th>$B = 0.8$</th>
<th>$B = 0.6$</th>
<th>$B = 0.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_f = 0.01$</td>
<td>0.152</td>
<td>0.156</td>
<td>0.176</td>
<td>0.251</td>
</tr>
<tr>
<td>$C_f = 0.02$</td>
<td>0.109</td>
<td>0.112</td>
<td>0.126</td>
<td>0.188</td>
</tr>
<tr>
<td>$C_f = 0.03$</td>
<td>0.086</td>
<td>0.088</td>
<td>0.098</td>
<td>0.144</td>
</tr>
<tr>
<td>$C_f = 0.04$</td>
<td>0.084*</td>
<td>0.084*</td>
<td>0.089</td>
<td>0.116</td>
</tr>
<tr>
<td>$C_f = 0.05$</td>
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<td>0.094</td>
<td>0.096</td>
<td>0.113</td>
</tr>
<tr>
<td>$C_f = 0.06$</td>
<td>0.118</td>
<td>0.116</td>
<td>0.112</td>
<td>0.118</td>
</tr>
<tr>
<td>$C_f = 0.08$</td>
<td>0.155</td>
<td>0.153</td>
<td>0.148</td>
<td>0.144</td>
</tr>
<tr>
<td>$C_f = 0.1$</td>
<td>0.227</td>
<td>0.226</td>
<td>0.222</td>
<td>0.211</td>
</tr>
</tbody>
</table>
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5.6.3 Numerical simulation of wave processes for the entire field deployment

5.6.3.1 Model performance
A comparison between model outputs and field data for the entire experiment using $C_f = 0.04$ and $B = 1$ are presented in Figure 5.7. Model performance across the 500 simulations was characterised by Skill $> 0.91$, MAE $< 0.045$ and $R^2 >= 0.8$, based on outputs for $H_{ss}$, $H_{ig}$ and $\bar{h}$ at the reef flat and shoreline.

Field results show that $H_{ss}$ at the reef and shoreline is primarily a function of tide level and incident wave height. The high skill (>0.97) associated with modeled $H_{ss}$ at the reef and shoreline indicate that tidal controls and incident forcing were numerically replicated very well (Fig. 5.7). $H_{ss}$ at the outer reef flat was generally over-predicted (MAE = 0.045 m), especially during energetic conditions (Fig. 5.7i). Modeled $H_{ss}$ at the shoreline had less error (MAE = 0.023 m), but the smaller wave heights observed at low tide were slightly under-predicted (Fig. 5.7l).

Model results show the same general pattern as measured $H_{ig}$ at the reef flat and shoreline (Fig. 5.7c,f). Numerical simulations also reflect the increase in $H_{ig}$ between the reef flat and shoreline. Compared to $H_{ss}$ and $\bar{h}$, model predictions of $H_{ig}$ demonstrated greater error, lower skill, and a weaker correlation to field results. The weaker prediction is possibly associated with the observation that IG waves have no pronounced tidal modulation. Despite the deviation from a perfect fit, IG wave dynamics across the reef flat were captured reasonably well in the numerical model (Fig. 5.7).
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Figure 5.7: Comparison between field measurements (red) and numerical model outputs (black) for wave statistics at different locations for the 62 day field deployment. a) Incident $H_s$ as measured and modeled at the AWAC location. d-b) $H_{to}$, $H_{ig}$ and $\tilde{\eta}$ at the outer reef and e-g) at the shoreline. X-axis in plots a-g is the date in 2013, in day/month format. Plots h-n) present the same data contained in a-g, in a measured verse modeled scatter plot format, with colour representing tide level (scale bar at top right).

Modeled wave setup followed the same tidal modulation as field results with similar scaling between incident wave height and setup magnitude relative to tide level (Fig. 5.7). Figure 5d shows how the setup peaks at low tide were slightly under-predicted at the reef flat, but
well predicted at the shoreline. However, the low setup values at high tide were slightly over-predicted at the shoreline (Fig. 5.7g).

5.6.3.2 Field and model wave spectra
Measured wave data was used to run model simulations. Consequently, at the offshore sensor, model spectra were almost identical to field measurements (Fig. 5.8a,d). Field based spectra depicted a bimodal peak in incident wave energy during the study period (Fig. 5.9). A shorter period peak at 0.094 Hz (10.6 s) was associated with mean wave conditions and the latter two swell events. A longer period peak at 0.065 Hz (15.4 s) was associated with the first two swell events (Fig. 5.8a,d). Modeled spectra illustrated a similar bimodal peak in incident wave spectra.

![Figure 5.8: Field wave spectra (left) form the offshore instrument (a), outer reef flat (b) and shoreline (c) compared to wave spectra calculated using model outputs (right) at the offshore location (d), outer reef flat (e) and shoreline (f). Note, offshore plots have different y-axis and colour limits. Also, a log scale was used on the y-axis of all plots to highlight spectra within the IG wave band.](image-url)
On the reef flat, the presence of energy at incident wave frequencies was limited to high tide, with greater spectral density occurring during energetic conditions (Fig. 5.8b). Spectra on the reef flat peaked in the IG band at 0.0049 Hz (204 s), with a secondary peak in the swell frequency band (0.072 Hz) during larger incident conditions (Fig. 5.8b). At the outer reef flat, modeled wave spectra identified a clear IG wave signal. However, peak energy occurred at a lower frequency (0.037 Hz, 270 s). The presence of swell wave energy on the reef flat at high tide was evident in model spectra, with peak energy at 0.072 Hz; the same as field measurements.

Figure 5.9: Mean PSD for each frequency across the 500 bursts. Mean PSD from field measurements (top) are compared to mean PSD from model outputs (bottom) at the offshore location, reef sensor and shoreline instrument.

Field based spectra demonstrate that SS waves were nearly fully dissipated at the shoreline, with energy concentrated at IG frequencies (Fig. 5.8c). However, some incident frequency energy was present at the shoreline at high tide or during swell events. IG wave energy was present at the shoreline during mean wave conditions at high tide but was amplified throughout the tide cycle when larger incident waves were present. Field data shows that IG wave energy increased between the reef flat and shoreline where spectral density peaked...
at 0.0068 Hz (146 s). Modeled spectra at the shoreline demonstrated a similar spectral density to field results, however identified a slightly higher peak frequency of 0.0061 Hz (163 s). The over-predicted IG period may be a result of using the model in 1D, and therefore omitting the alongshore processes that influence long-wave behaviour.

5.6.4 Maximum runup

Basilisk GN was able to replicate water level variations on the reef flat associated with SS waves, IG waves, and wave setup. Combined, these processes influenced shoreline water level and the maximum runup point that was reached under a particular set of incident conditions. Model results were analysed to identify $R_{\text{max}}$ for each burst. Across all simulations $R_{\text{max}}$ was located between the inner reef flat and upper beach face (Fig. 5.10a). The elevation of $R_{\text{max}}$ relative to MSL was primarily a function of incident wave height and tide level (Fig. 5.10b). Large waves at low tide produced an elevated setup and energetic IG waves that resulted in the same runup elevation as small waves at high tide (Fig. 5.10). During 67 bursts (13.4%), $R_{\text{max}}$ reached the top of the conglomerate platform and was level with the toe of beach (MSL + 0.39 m). Wave interaction with the mid beach face ($R_{\text{max}} > 0.5$ m) occurred during 287 bursts; accounting for 57.4% of the experiment (Fig. 5.10c). Collectively, waves reached or exceeded the beach toe for 70.8% of the experiment (354 bursts). Numerical runup results indicate that the geomorphic window of interaction between waves and island sediment is open for a much longer period of time than was estimated using mean water level.

Table 5.3: Percentage of $R_{\text{max}}$ associated with SS waves, IG waves and setup at different tide stages.

<table>
<thead>
<tr>
<th></th>
<th>High tide</th>
<th>Mid tide</th>
<th>Low tide</th>
<th>All tides</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS (%)</td>
<td>48.7</td>
<td>29.2</td>
<td>14.9</td>
<td>31.6</td>
</tr>
<tr>
<td>IG (%)</td>
<td>39.3</td>
<td>44.7</td>
<td>38.8</td>
<td>41.0</td>
</tr>
<tr>
<td>Setup (%)</td>
<td>12.0</td>
<td>26.1</td>
<td>46.3</td>
<td>27.4</td>
</tr>
</tbody>
</table>
The processes that contributed to $R_{\text{max}}$ varied through the tide cycle (Fig. 5.10d). At low tide ($< -0.4$ m), wave setup was the primary mechanism contributing to shoreline water level. At mid tide stages ($-0.4$ m > $+0.3$ m), the influence of setup decreased significantly and IG waves became the dominant contribution to runup level (Fig. 5.10d). As tide level increased there was a linear increase in the portion of runup associated with SS waves. SS waves became the dominant runup mechanism at tides above $+0.65$ m. However, at tides between $-0.4$ m and $+1$ m, IG waves remained a significant contributor to $R_{\text{max}}$. Overall, wave setup was important at low tide, SS waves were important at high tide, and IG waves contributed a consistently high percentage of $R_{\text{max}}$ at all tide stages (Fig. 5.10d, Table 5.3).

Figure 5.10: $R_{\text{max}}$ analysis using model data. a) $R_{\text{max}}$ location from each burst, highlighting the toe of beach (TOB) threshold for wave interaction with island sediment. b) Tidal controls on $R_{\text{max}}$ above MSL under different incident wave conditions. c) $R_{\text{max}}$ frequency at different elevations, relative to MSL=0. d) The contribution of wave setup (dots), IG waves (+) and SS waves (x) in $R_{\text{max}}$ above tide level.
5.6.5 Swell driven shoreline exposure on June 23

The largest waves measured during the field experiment ($H_o = 2.10 \text{ m}, T_o = 15\text{s}$) coincided with spring tides on June 23, 2013. The swell event generated significant wave setup and IG activity, and model results indicate the presence of waves on the beach face throughout the tide cycle (Fig. 5.11). The swell peaked at low tide (-0.73 m), when a 0.9 m setup resulted in a mean shoreline depth 0.05 m above MSL (Fig. 5.11a). Model results show that the combined runup from IG and SS waves was able to surge over the conglomerate platform and impact the beach face to an elevation of 1.05 m. Runup was primarily associated with wave setup (51.1%), and IG waves (31.9%), but there was also a small SS wave contribution (17%).
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Figure 5.11: Model outputs for instant, mean and maximum water level (WL) on the reef and shoreline during the spring tide swell on June 23. a) Setup dominant $R_{max}$ at low tide. b) IG dominant $R_{max}$ at high tide. c) SS dominant $R_{max}$ at high tide. Bar plots on the right highlight the contribution of tide level, setup, IG waves and SS waves in runup, relative to MSL = 0.

At high tide (+0.61 m), the swell event generated a runup of 2.03 m above tide level and an $R_{max}$ elevation of 2.64 m above MSL (Fig. 5.11b). The deeper reef flat resulted in significantly less wave setup that accounted for 15% of $R_{max}$. Large IG waves at the shoreline ($H_{ig} = 0.72$ m) accounted for 48% of $R_{max}$ and therefore acted as the main control on runup elevation. SS waves were also able to propagate across the reef to account for 37% of $R_{max}$. The highest runup above MSL occurred during a spring high tide (MSL + 0.98 m), when the swell was decreasing (Fig. 5.11c). The combined influence of setup
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(10.5%), IG waves (43%), and SS waves (46.5%) resulted in $R_{max}$ 2.82 m above MSL which is 0.68 m below the berm elevation. Note that under large incident conditions waves do reflect off the shoreline at high tide and interfere with the oncoming wave field, resulting in the peaks observed in the maximum water level line from Figure 5.11b,c.

5.7 Discussion

5.7.1 Tidal modulation of reef flat processes

Field observations from Funafuti show that $H_{ss}$ is strongly modulated by water depth across the reef, a function of tide level and setup (Fig. 5.4). Tidal modulation of shoreline wave height has been well documented on a range of fringing, atoll, and platform reefs (Ford, et al., 2013, Kench and Brander, 2006b, Lugo-Fernandez, et al., 1998b, Péquignet, et al., 2011). The majority of these studies present a strong relationship between wave height and mean reef depth, concluding that SS activity at the shoreline is limited to high tide. Few studies have recorded shoreline wave activity at low tide. Field results from Funafuti emphasise how large setup at low tide can submerge the reef flat and enhance the potential for waves to impact the shoreline throughout the tidal cycle. Compared to other field studies, the narrow reef and consistent exposure to moderate or high energy waves create a relatively active shoreline wave regime. As a result, SS and IG waves are almost always present at the shoreline during low and high tide.

Tidal modulation of wave setup has been identified on coral reefs (Becker, et al., 2014, Gourlay, 1996a). The results from this study support the observations of Becker, et al. (2014), which identified the presence of maximum setup at low tide, and a lower setup at high tide. Field measurements from a high energy fringing reef (Vetter, et al., 2010) and low energy reef platform (Jago, et al., 2007) have found that, on average, setup is 25% of $H_o$ (incident $H_s$). Mean setup at the shoreline on Funafuti was 15.6% of $H_o$ across all tides. However, setup at low tide ranged from 16.8% to 42% of $H_o$ (mean = 28%), and at high
tide setup ranged from 0% to 16.2% of $H_o$ (mean = 6.2%). Similar tidal controls and incident wave height scaling were observed on atoll reefs in the Marshall Islands (Becker, et al., 2014).

Field results from Funafuti indicate that there is minimal tidal influence on IG wave activity on the reef flat or at the shoreline (Fig. 5.4). Results show that $H_{ig}$ increases between the reef flat and shoreline and suggest that IG waves are primarily a function of incident wave conditions; not reef flat water level. At Funafuti, $H_{ig}$ at the shoreline scales between 10% and 43% of $H_o$ (mean = 26%), with no clear tidal control (Fig. 5.4). Results from Majuro Atoll, on a reef with similar morphology and wave exposure to Funafuti, also show $H_{ig}$ at the shoreline to be between 10% and 40% of $H_o$ (Ford, et al., 2013). On the narrow reefs (~100 m) at Funafuti and Majuro, IG wave height was measured to increase across the reef flat and peak at the shoreline. IG waves were also measured to increase in height across a wider (~250 m) and relatively smooth reef on Kwajalein Atoll (Quataert, et al., 2015). However, measurements on wide fringing reefs (+400 m) typically show IG wave height and energy peaks within ~100 m of the reef edge before dissipating across the reef flat to be minimal at the shoreline (Péquignet, et al., 2014, Pomeroy, et al., 2012). Pronounced tidal controls on IG wave height have also been observed on wider fringing reefs, due to frictional dissipation across the inner reef flat (Van Dongeren, et al., 2013). Given the location of Fatato Island relative to the reef edge, IG waves are able to impact the shoreline before any dissipation is observed.

5.7.2 Model capability
The majority of phase-resolving model work on reefs has focused on continental fringing reefs, not atoll reefs that host low lying sedimentary islands (Demirbilek and Nwogu, 2007, Nwogu and Demirbilek, 2010, Shimozono, et al., 2015, Yao, et al., 2012, Zijlema, 2012). Such Boussinesq-type models have been shown to accurately replicate wave attenuation,
wave setup, and IG wave dynamics when evaluated against wave flume data. Few phase-resolving models have been evaluated using field data from fringing or atoll reefs (Demirbilek and Nwogu, 2007, Roeber and Cheung, 2012b). This paper presents the first field evaluation of the ability of a phase-resolving model to simulate wave transformation on an atoll reef. Model results from Funafuti show that Basilisk GN is capable of representing the key processes that contribute to elevated water depth at the shoreline. Water level dynamics associated with SS wave attenuation and wave setup were represented with skill > 0.97 and mean error <0.045 m. IG wave dynamics were also represented reasonably well, with skill = 0.91. Wave height and setup predictions were slightly sensitive to breaking and friction parameters, whereas IG wave heights were highly sensitive to low B values and high friction.

Limitations of the model results cannot be overlooked. While wave transformation results were tested against field data, no data was available to confirm model predictions of $R_{max}$. However, Basilisk GN has been tested against benchmark runup scenarios (Popinet, 2015), that gives some confidence to $R_{max}$ values. Maximum wave runup was also simulated with reasonable accuracy on the wave flume simulations presented in Chapter 4, under a range of breaking and friction values. Beach porosity and percolation were also not accounted for in runup estimations, possibly resulting in over-predicted runup levels. Further, as the model was used in 1D, alongshore processes that influence wave transformation and runup (e.g. refraction, wave convergence, alongshore currents and edge waves) were omitted.

5.7.3 Maximum shoreline runup

The unconsolidated sedimentary structure and low elevation make atoll islands susceptible to wave over-topping and erosion during high energy wave events or periods of elevated sea level (Hoeye, et al., 2013). An understanding of the processes that contribute to increased wave interactions with the shoreline is critical for coastal management, and to
mitigate the potentially adverse effects of future SLR on atoll landforms (Ferrario, et al., 2014). Recent research has highlighted how wave driven flooding can be caused by long period swell waves which are generated by distant weather systems (Hoeke, et al., 2013). However, large waves typically need to coincide with high tide for overtopping to occur. Merrifield, et al. (2014) show that overtopping events happen every 2 – 5 years in the Marshall Islands but will occur multiple times per year with any rise in mean sea level greater than 0.4 m. Results from Merrifield, et al. (2014) indicate that, on average, 52% of non-tidal water level is caused by wave setup, with a further 48% associated with SS or IG waves. An overtopping event was also measured by Ford, et al. (2013) on Majuro Atoll, where land elevation was 2 m above the reef flat. Overwash was generated by 2 m incident waves at high tide and was primarily driven by energetic IG waves at the shoreline ($H_{ig} = 0.8$ m), with a low contribution from SS waves and setup ($H_{ss} = 0.4$ m, $\eta \approx 0.2$ m).

The analysis presented here extends the current understanding of wave interactions with atoll islands by focusing on the processes that promote wave interaction with the beach face. Results provide the first assessment of wave processes impacting islands on Funafuti Atoll, where sea level is currently rising at three times the global average rate (Becker, et al., 2012). Funafuti Atoll is also characterised by a narrow reef flat and steep fore-reef slope (23.5°), which according to Quataert, et al. (2015) increases the risk of wave driven flooding when exposed to a rise in mean sea level. The elevated ocean berm on Fatato prevented any overtopping events during this study, but results do highlight the temporal nature of wave processes that operate on the beach face. Significantly, IG waves are identified as having the dominant influence on runup elevation (41%), compared to wave setup (27.4%) and SS waves (31.6%). However, it is apparent that contribution of different runup generating processes changes through the tide cycle. At low tide, SS wave height is significantly dissipated (78%), and IG wave activity is slightly limited by spring low tides.
and higher friction. Wave setup is at a maximum at low tide and provides the main control on shoreline water level, along with a significant presence of IG wave height. At mid-tide, larger SS waves propagate across the reef flat, setup decreases, and IG waves control runup elevation. At high tide, wave runup is driven by a combination of SS and IG waves, with a small contribution from wave setup.

5.7.4 Island exposure to wave processes

The beach face on Fatato Island is located 0.39 m above MSL. Using field measurements, tide level exceeded the beach toe elevation for 22.4% of the experiment. Tide station data from the atoll lagoon also shows that tides above +0.39 m occur for 23% of the year. Mean water depth at the shoreline (tide + setup) exceeded beach toe elevation for 25% of the experiment. These results suggest the beach face was directly exposed to wave activity for a quarter of the experimental period. However, model analysis of maximum runup as a function of SS waves, IG waves, setup and tide level reveals that waves actually reached or exceeded the beach toe for 70.8% of the deployment, with wave activity on the mid beach face for 57.4% of the experiment.

Modeled $R_{max}$ results show that islands on the south-eastern rim of Funafuti are much more connected to ocean processes than topographic and tide measurements suggest. Geomorphic change on atoll islands is limited to the temporal window of island exposure to wave activity (Kench and Brander, 2006b). By measuring depth controls on SS wave propagation across different reef flats Kench and Brander (2006b) show that interaction between wave processes and island shorelines is limited to a small temporal window at high tide. Results from Funafuti highlight the importance of accounting for water level oscillations at all surf-zone frequencies when assessing wave impacts at the shoreline. Accounting for $R_{max}$ significantly increases the temporal window of connectivity between wave processes and island sediment on Fatato. Under typical wave conditions, sediment
Chapter 5: Field and model results from Funafuti Atoll

transport between the reef flat and island beach can occur for the majority of the tide cycle (71%). However, when exposed to higher wave energy, the island can be connected to wave activity for the entire tide cycle. The enhanced interaction between waves and the island is attributed to the large setup at low tide that results in IG wave activity on the reef flat at all tide stages. The narrow reef flat also results in IG waves impacting the island without any dissipation or tidal forcing being observed in field or model data. Results suggest that even a small rise in sea level may result in 100% interaction between wave processes and island shorelines, significantly increasing the period of time when geomorphic change can occur on the beach face.

5.8 Summary
Field data collected from a 62 day deployment were examined to understand wave transformation on Fatato Island, Funafuti Atoll and evaluate a numerical models capability of simulating SS wave attenuation, IG wave behaviour and wave setup. Research from Fatato indicates that the island shoreline is highly connected to wave processes, despite sitting 0.39 m above MSL and only being submerged for 23% of the tide cycle. Tidal level is a strong control on SS waves and wave setup at the shoreline on Fatato Island. Therefore, SS waves are the primary influence on runup elevation at high tide and wave setup largely determines runup elevation at low tide. Field and model results indicate that infragravity wave activity is not tidally modulated on the eastern rim of Funafuti, and runup analysis shows that IG waves are capable of elevating shoreline water level throughout the tide cycle. Tide level and setup, combined with runup from SS and IG waves, result in island sediment being impacted by wave activity for 71% of the time, on average. The increase in setup and IG wave activity during swell events means that waves can interact with the beach face for a complete spring tide cycle. These results imply that any rise in sea level will further increase the temporal window of interaction between waves and island
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sediment, with SS and IG waves becoming the dominant processes influencing shoreline water level.
Chapter 6: Changing wave processes on Funafuti Atoll in response to rising sea level

6.1 Introduction
As evident in Chapter 5 and Beetham, et al. (2016), Basilisk GN can skilfully represent SS wave attenuation, IG wave propagation and wave setup on coral reefs. This chapter extends the application of Basilisk GN by simulating the response of wave processes and wave runup to systematic SLR that encompasses the contemporary tidal range and still water level 1.5 m above spring high tide. Wave transformation simulations were repeated using different incident wave conditions and two hypothetical reef growth morphologies to identify sea level thresholds for wave inundation.

Low elevation and sedimentary structure make reef islands especially vulnerable to flooding and erosion from energetic waves and SLR (Church, et al., 2006, Dickinson, 2009, Lazrus, 2012, Nurse, et al., 2014). Despite being frequently cited as vulnerable to inundation, few scientific studies have attempted to understand how SLR will alter the physical processes that impact reef islands (Becker, et al., 2014, Merrifield, et al., 2014, Quataert, et al., 2015). Wave heights on coral reefs are limited by reef flat water depth, leading to a tidally modulated process regime at the shoreline (Brander, et al., 2004, Kench and Brander, 2006b, Massel, 1996), Therefore, a common assumption is that SLR will decrease SS wave attenuation rates, resulting in greater wave energy at the shoreline (Quataert, et al., 2015, Storlazzi, et al., 2011). However, SS wave breaking and dissipation also influence the magnitude and behaviour of IG waves and wave setup that significantly
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Contribute to shoreline water levels (Becker, et al., 2014, Beetham, et al., 2016). This study seeks to examine how the key surf-zone processes that influence wave runup (SS waves, IG waves, wave setup) will respond to SLR.

It is not well understood how SLR will modify surf-zone processes on coral reef surfaces, however recent studies provide some critical insights into wave behaviour. Energetic wave breaking on coral reefs produces a setup water level that can exceed 1 m (Vetter, et al., 2010); similar in magnitude to the tidal amplitude in many tropical settings. Wave setup decreases with increasing reef depth (Becker, et al., 2014, Beetham, et al., 2016) and becomes negligible when waves do not break (Gourlay, 1996b). Becker, et al. (2014) demonstrate that setup will significantly decrease with SLR but note that this decrease will not offset a net increase in reef flat water level. The response of IG wave behaviour to SLR is less certain. Field measurements on wide fringing reefs have identified maximum IG wave energy on the central reef flat at high tide, and observe strong dissipation from friction at low tide (Pomeroy, et al., 2012, Van Dongerren, et al., 2013). On narrow or smooth reefs, IG waves have been measured to increase across the reef flat and exhibit less dependence on tidal elevation (Beetham, et al., 2016, Ford, et al., 2013, Quataert, et al., 2015). Systematic modeling results from Quataert, et al. (2015) suggest SLR will be associated with an increase in SS and IG wave height at the shoreline and a decrease in setup across the reef flat. Results in Quataert, et al. (2015) are associated with a maximum sea level representing spring high tide ($h_r \sim 2$ m), with energetic incident wave conditions ($H_{mo} = 2$ - 6 m, $T_p = 14$ s), and therefore do not reveal how SLR will alter physical processes under regular conditions when the surf-zone may not be saturated. SLR under regular and non-extreme wave events may limit incident wave breaking and decrease the generation of IG wave motions that are typically excited at the reef edge (Péquignet, et al., 2014). The first
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aim of this chapter is to analyse how SS waves, IG waves, setup, spectra and maximum runup on an atoll reef respond to systematic SLR under non-extreme wave conditions.

A possible feedback from SLR and climate change is physical change to reef morphology. An increased low tide level will allow corals to re-colonise currently emergent reef flats; potentially growing reef elevation to keep up with SLR (Brown, et al., 2011, Saunders, et al., 2015, Scopélitis, et al., 2011). However, an increase in ocean acidity and temperature associated with anthropogenic CO$_2$ emissions may significantly limit coral growth, potentially causing widespread degradation of reef ecology and preventing vertical reef accretion (Hoegh-Guldberg, et al., 2007). For colonised reef flats, coral mortality can result in reef erosion, causing a relative rise in sea level across a reef surface that compounds the impact of climate change (Sheppard, et al., 2005). The impact of reef degradation was not considered in this research but wave processes were simulated using two different ‘keep-up’ reef growth morphologies.

This study uses a field verified numerical model (Basilisk GN) to investigate wave transformation in the context of present and future sea levels, accounting for SS waves, IG waves, setup and reef morphology. Wave transformation was investigated on Fatato Island, Funafuti Atoll, where field data was collected to quantify the contemporary process regime and verify numerical skill (Chapter 5; Beetham et al., 2016). Funafuti was established as the study location for this work because the atoll is currently experiencing SLR at a rate of 5.1 mm/yr, three times the global average (Becker, et al., 2012) with islands on the atoll highlighted as being highly vulnerability to the impacts of SLR (Connell, 2003, Dickinson, 1999, Farbotko and Lazrus, 2012, Patel, 2006). However, few attempts have been made to understand contemporary wave processes at the shoreline or to assess what wave processes promote wave inundation (Beetham, et al., 2016). Model results presented in this chapter quantify how wave processes at the shoreline respond to systematic SLR and identify sea
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level thresholds for inundation under annual-mean and annual-maximum incident wave conditions. Model results using different reef growth morphologies are also presented to identify if vertical reef accretion can mitigate the potential for wave inundation, assuming no change in island morphology.

6.2 Field setting

The physical setting for Fatato Island and Funafuti Atoll are described in Chapter 5.2 and presented in Figure 5.1.

6.2.1 Sea level at Funafuti Atoll

Records of SLR in the tropical pacific north of Funafuti (Tarawa, Kiribati) indicate that sea level increased by 5 – 8 mm/yr during the Holocene (Marshall and Jacobson, 1985). Funafuti Atoll reef either kept-up or caught-up with SLR, accreting by 26.4 m over ~5,000 years, at an average rate of 5 mm/yr (Ohde, et al., 2002). The modern atoll has an intertidal reef flat, with the reef edge close to level with spring low tide. Using tide gauge data combined with satellite altimetry, Becker, et al. (2012) reconstructed sea level at Funafuti between 1950 and 2010, demonstrating that relative sea level increased by 0.30 ± 0.04 m; a rate of 5.1 ± 0.7 mm/yr (Fig. 6.1). An inter-decadal fluctuation in regional sea level around Funafuti is associated with El Nino Southern Oscillation (ENSO) wind patterns (Fig. 6.1). Sea level at Funafuti during strong La Nina events can be up to 0.35 m higher than sea level during strong El Nino conditions (Becker, et al., 2012). There is strong agreement that global sea level is rising and will continue to rise for the next century (Nurse, et al., 2014). The fifth IPCC report discusses the variability in predicting future SLR and suggests a likely rise in global mean sea level between 0.35 m and 0.7 m by 2100 (Church, et al., 2013). For the purposes of this study, wave transformation was analysed in the context of present sea level and sea levels between 0.05 m and 1.5 m higher than contemporary spring high tide.
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6.3 Model experiments

6.3.1 Experiment 1: Wave processes with SLR and no reef growth

The first set of simulations examined changes in wave transformation processes using 71 sea levels (0.05 m increments) between -1 m and +2.5 m, relative to MSL = 0 (Fig. 6.2). This range starts at present day spring low tide (SL = -1 m) and extends to spring high tide with 1.5 m of SLR (Fig. 6.2). Wave processes within the present sea level range (SL = -1 m to SL = 1 m) were included in the numerical analysis to further understand contemporary processes and to allow direct comparison against the SLR scenarios (SL = 1.05 m to SL = 2.5 m). Experiment 1 is a highly simplified scenario of SLR with no change in reef or island morphology.
6.3.2 Experiment 2: Wave processes with SLR and vertical reef growth

The second set of simulations examined wave transformation at high tide (HT), mid-tide (MT) and low tide (LT) using four sea level scenarios (MSL +0 m, +0.5 m, +1 m, +1.5 m) and two hypothetical reef growth morphologies. The first growth response represents the outer reef accreting with low tide, creating a moat between the reef flat and shoreline. Encrusting corals and coralline algae are likely to colonise the outer reef flat first (Hopley, 2011) where reef elevation is closer to the contemporary low tide level due to the slightly sloping reef flat. The second growth morphology represents uniform accretion of the entire reef flat as the low tide level submerges the reef surface. This hypothetical growth morphology accounts for either sedimentary infill of the inner moat or uniform reef growth from corals re-populating the inner and outer reef flat (Hopley, 2011). Reef growth in equilibrium with approximate low tide is the maximum possible response a reef can have with SLR (Kench, et al., 2009c). Therefore, experiment 2 was designed to assess if keep-up reef growth can mitigate the increase in wave inundation expected with SLR. Island elevation and morphology remained static in experiment 2, which is a significant simplification of coastal morphodynamics.
6.3.3 Model wave field

Wave processes under each sea level scenario were simulated using mean wave conditions ($H_s = 1.3$ m, $T_p = 11$ s), a long period swell event ($H_s = 2.1$ m, $T_p = 16$ s) and shorter period storm wave event ($H_s = 2.6$ m, $T_p = 10$ s), as shown in Figure 6.3. Hindcast wave data for Funafuti (Durrant, et al., 2014), from 1979 to 2012 was used to identify wave statistics associated with mean, swell and storm conditions (Table 1). Mean conditions were calculated as the 33 year average wave height ($H_s$) and period ($T_p$). Swell waves and storm waves represent the largest events that are expected to impact Funafuti Atoll each year. Swell and storm wave statistics were calculated by averaging the annual maximum wave height associated with distant swell periods ($T_p > 12$ s) and localised storm periods ($T_p < 12$ s) for the 33 year hindcast data-set.

The swell and storm waves used for the purposes of this research are not ‘extreme events’ but are conditions that historically occur at least once each year. In order to achieve realistic predictions for setup and IG waves, it was important to use a realistic irregular wave field for each representative wave condition. Field measurements incident to Funafuti in June / July 2013 were used to select bursts that closely represented mean, swell and storm conditions (Fig. 6.3). The representative mean wave condition was characterised by a bi-modal peak in spectral density at 0.079 and 0.1 Hz (10 and 12.5 s) as shown in Figure 6.3a,d. One swell event was measured in the 2013 deployment that was representative of the largest mean annual swell condition identified using hindcast data. The 2013 swell event was characterised by a strong concentration of wave energy between 0.055 and 0.066 Hz (15 – 18 s), that peaked at 0.06 Hz (16.6 s) to provide the highest concentration of energy used in this study (Fig. 6.3b,e). No storm waves exceeding 2 m were recorded in 2013, therefore the storm wave field in Figure 6.3 was synthesised by amplifying wave heights from a burst with the same period but a slightly lower wave height ($H_s = 1.9$ m) to...
match hindcast wave height of 2.6 m. The storm wave field in Figure 6.3 is characterised by a broad peak in spectral density between 0.085 and 0.104 Hz (9.5 – 12 s), with a peak in energy at 0.0946 Hz (10.5s). Figure 6.3 shows that swell waves had the highest peak in spectral density but storm waves had a larger net spectral density because high spectral density was present across a wide frequency band.

Figure 6.3: a–c) Time series water level data and incident wave spectra d–f) for the three boundary wave conditions used in the controlled sea level wave transformation analysis. Mean waves represent the 34 year average wave height and period incident Funafuti. Swell waves represent the average maximum long period (Ts > 12 s) wave event that can be expected to impact Funafuti every year. Storm waves represent the average maximum short period (Ts < 12 s) wave event that can be expected to impact Funafuti every year. Note the change in scale on each y-axis.
6.3.4 **Analysis of outputs**

Output wave data were analysed by extracting time series free-surface data at strategic locations across the reef profile: the outer reef flat, the shoreline and the toe of beach (Fig. 6.2). Field data were collected at reef and shoreline instrument positions and the toe of beach sensor was located at the base of the beach face. Time-series data were collected at 10 Hz for the 2048 second simulation. Only data collected between 512 s and 1536 s (1024 seconds) were used for calculating wave parameters once the wave field had fully developed across the reef. A 0.04 Hz band pass filter was used to separate high and low frequency waves before calculating significant SS wave height ($H_{ss}$) and significant IG wave height ($H_{ig}$) using zero down-cross analysis. Power spectral density (PSD) was calculated from the raw time-series using a fast Fourier transform with 4096 point averaging and an overlapping hamming window resulting in 5 degrees of freedom. PSD outputs were used to calculate total spectral density within the wave field (0.0037 - 2 Hz), total spectral density within the SS wave band (0.04 - 2 Hz) and total spectral density within the IG wave band (0.0037 - 0.04 Hz). Profile data (1 m spacing) for maximum, mean and instantaneous water level were also extracted at the end of each simulation ($t = 2040$ s) and used to identify the point of maximum wave runup above tide level ($R_{max}$). The relative contribution that SS, IG, and setup have on runup was identified using model data for $H_{ss}$, $H_{ig}$, and $\eta$ from the shoreline instrument position. The setup contribution was equal to $\eta$ at the shoreline. The remaining $R_{max}$ value was split into SS and IG components proportional to the $H_{ss}$ and $H_{ig}$ at the shoreline.

6.4 **Results: Wave processes with SLR and no reef growth**

First, model results are presented to demonstrate how SS waves, IG waves, setup and spectra at the outer reef flat, shoreline and toe of beach respond to systematic SLR with static reef morphology. Results are discussed in the context of sea level (SL) between –1
m and 2.5 m, relative to modern MSL = 0 m. Therefore SL = -1 m represents contemporary spring low tide, SL = 1 m represents contemporary spring high tide, and sea levels above 1 m represent higher than present sea levels. For example, SL = 2 m is the same spring high tide with 1 m of SLR.

### 6.4.1 Sea level controls on wave transformation

#### 6.4.1.1 SS Waves

Model results show SS wave heights at the reef flat, shoreline and beach face present a near linear increase with SLR (Fig. 6.4). Between SL = -1 m and SL = 1 m, $H_{ss}$ associated with mean, swell and storm waves at the outer reef flat increased by 0.50, 0.58, and 0.45 m, per meter of SLR, respectively. For SL above 1 m, $H_{ss}$ at the reef flat increased by 0.27, 0.2, and 0.46 m, per meter of SLR, respectively. $H_{ss}$ at the shoreline also exhibited a linear increase with SLR (Fig. 6.4f). Shoreline $H_{ss}$ at SL = 1 m (present spring high tide) was 0.62 m, 0.8 m and 0.82 m for mean, swell and storm waves respectively. For SLR above present high tide, model results show an increase in mean, swell and storm $H_{ss}$ at a rate of 0.41, 0.35 and 0.54 m per metre of SLR, respectively.

Mean wave conditions at Funafuti required a minimum sea level of -0.15 m to reach the beach face (elevated 0.39 m above MSL). Therefore, waves impact the island beach for 58% of the contemporary spring tide cycle under regular incident conditions. Swell and storm waves were able to impact the beach face from any sea level above -0.7 m, resulting in an 85% open window for geomorphic interaction under the present sea level range. Therefore, SLR of 0.3 m will result in swell and storm waves impacting the beach face throughout the spring tide cycle. These results emphasise that SLR will increase the frequency of wave interaction at the shoreline and increase the magnitude of wave energy (based on wave height) received at each stage of the tide.
6.4.1.2 IG waves

IG wave behaviour appears to be less controlled by sea level. Model results for each wave condition show that $H_{ig}$ at each location initially increased with SLR and peaked at some point between SL = -0.5 m and SL = 1 m. A decreasing trend in $H_{ig}$ was observed for sea levels above 1 m, regardless of wave condition and reef location. The largest IG waves
were generated under storm wave conditions, followed by swell conditions (Fig. 6.4). IG waves were modeled to increase in height between the reef edge and shoreline, where maximum $H_{ig}$ was located. Under mean wave conditions, $H_{ig}$ at the shoreline increased steadily from SL = -0.9 m to peak at SL = 0 m ($H_{ig} = 0.38$ m) before slowly decreasing under all higher sea levels (Fig. 6.4h). Under swell wave conditions, IG waves at the shoreline increased in height between SL = -1 m and SL = 0.35 m where peak IG wave height was achieved ($H_{ig} = 0.68$ m). Sea levels above 0.35 m recorded a steady decrease in $H_{ig}$ at the shoreline under swell conditions. Storm conditions generated the largest IG waves with maximum heights ($H_{ig} = 0.91$) modeled at the shoreline when sea level was between -0.1 m and 0.6 m (Fig. 6.4h). A similar trend between $H_{ig}$ and sea level was modeled at the beach toe (Fig. 6.4m). However, $H_{ig}$ at the beach toe peaked between SL = 0.7 m and SL = 1 m for each wave condition.

6.4.1.3 Setup
Wave setup decreased with SLR under each wave condition (Fig. 6.4). Under mean waves, setup at the shoreline peaked at 0.6 m when sea level was -0.85 m and decreased to 0.09 m for SL = 1 m. Setup at the shoreline under swell and storm conditions peaked at 0.95 m for SL = -1 m and decreased to ~0.3 m for SL = 1 m. Sea levels above 1 m were associated with continued decrease, with shoreline setup = 0.02 m, 0.11 m and 0.18 m when sea level was 2 m above MSL, under mean, swell and storm waves, respectively (Fig. 6.4).

6.4.2 Sea level controls on wave spectra
Model results show that as sea level increased from SL = -1 m to SL = 2.5 m there was a reasonably consistent increase in total spectral density at the outer reef flat, shoreline and beach face (Fig. 6.5). At lower sea levels, total spectral density was primarily a function of IG wave activity. Higher sea levels were associated with a decrease in IG motions and an increase in energy within the SS wave band. The relative importance of SS wave energy
and IG wave energy was slightly different at each reef location and depended on incident wave conditions (Fig. 6.5).

![Diagram of wave processes and sea level rise on Funafuti Atoll](image)

**Figure 6.5:** Left axis shows how sea level controls the percentage contribution that SS frequency (blue line) wave spectra (0.0037 Hz to 0.04 Hz) and IG frequency (red line) wave spectra (0.04 Hz to 2 Hz) have on net wave spectra at the outer reef flat (left), shoreline (centre) and toe of beach (right). Sea level controls on net wave spectra (grey) between 0.0037 Hz and 2 Hz relate to the right axis.

### 6.4.2.1 Mean wave conditions

IG waves contributed the dominant mode of wave energy at the outer reef flat between SL = -1 m and SL = -0.8 m. The concentration of energy in the SS band increased proportional to SLR as reef depth accommodated larger wave heights. SS frequencies accounted for at least 42% of total wave spectra received at the outer reef flat which increased to over 90% when SL reached 0.7 m (Fig. 6.5a). IG wave motions generated by mean waves became
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much more important at the shoreline. Spectra within the IG wave band was the dominant mode of shoreline energy until sea level reached 0.65 m when SS wave spectra became superior at the shoreline (Fig. 6.5d). Sea levels above 1 m were associated with spectral density 70 – 95 % concentrated in the SS wave band. Mean waves were able to reach the toe of beach from SL = -0.3 m with IG waves remaining the dominant mode of shoreline interaction until SL = 0.4 m (Fig. 6.5g). Despite the clear transition from IG to SS wave energy occurring at different sea levels, all locations across the reef observed a near linear increase in total spectral density between SL = -1 m and SL = 2.5 m (Fig. 6.5).

6.4.2.2 Swell wave conditions
Swell waves produced considerably more energy than mean waves, resulting in much higher net spectral density on the outer reef flat for each sea level (Fig. 6.5b). Absolute wave energy in the IG band (not shown) increased from SL = -1 m to peak at SL = 0 m before decreasing at higher sea levels. However, the increase in SS wave activity at the reef edge associated with SLR resulted in a predominantly incident wave driven process regime at all sea levels (Fig. 6.5b). Much of the SS wave energy observed at the outer reef flat was dissipated across the reef flat, with energy at the shoreline mainly concentrated in the IG band between SL = -1 and SL = 1.2 m (Fig. 6.5e). Absolute IG wave energy at the shoreline under swell wave conditions peaked at SL = 0.15 m (not shown) before decreasing towards high tide. SS wave spectra increased steadily with SLR but did not exceed IG wave energy until SL = 1.2 m. As IG energy decreased and SS energy slowly increased between SL = 0.15 m and SL=1.2 m there was a plateau in net wave energy at the shoreline (Fig. 6.5e). However, once SS wave energy became dominant from SL = 1.2 m there was a rapid increase in total spectral density impacting the island. Swell wave conditions result in a combination of SS and IG energy at the beach face at all tested sea levels, especially above SL = 0.5 m (Fig. 6.5h). Net wave energy at shoreline increased rapidly from SL = -0.5 m
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until SL = 1.15 m due to a combination of SS and IG wave energy. Net spectra continued
to increase at higher sea levels, but at a slower rate due to the reduced influence of IG
waves. The beach face was initially activated by an IG dominant signal at low tide and then
by an equal contribution from SS and IG waves between SL= -0.5 m and SL = 0.2 m (Fig.
6.5e). Absolute IG wave energy (not shown) increased until SL = 0.85 m before decreasing
at higher sea levels. SS wave energy became dominant at the beach face from SL = 0.25 m,
accounting for 70% of total spectral density at SL = 1 m and 87% at SL = 2 m (Fig. 6.5h).

6.4.2.3 Storm wave conditions
IG motions generated by storm waves contributed the main form of energy on the reef flat
between SL = -1 m and SL = -0.6 (Fig. 6.5c). However, absolute IG wave energy (not
shown) continued to increase until SL = 0.65 m. Under storm conditions, total spectral
density at the shoreline was dominated by IG energy until SL = 1.4 m even though absolute
IG energy peaked at SL = 0.65 m. SS wave energy increased slowly between SL = 0 m and
SL = 1 m before dramatically increasing for sea levels above 1 m (Fig. 6.5f). The clear shift
from IG energy to SS energy had minimal impact on the progressive increase in total
spectral density with SLR. Wave energy at the beach face was also controlled by IG
frequencies for all sea levels below 1.55 m. IG wave energy on the beach face began to
decrease from SL = 1.4 m, however the linear increase in SS energy resulted in a
progressive rise in net spectral density on the beach face as sea level increased (Fig. 6.5i).

6.4.3 Sea level controls on wave runup
Maximum runup relative to MSL ($R_{max}$) is a combination of sea level, tide level, setup and
the swash limit form SS and IG waves. Model results show a linear increase in $R_{max}$ with
incremental SLR, eventually resulting in wave inundation over the island berm (Fig. 6.4a-
c). Despite the linear relationship between sea level and runup, the combination of
processes that contribute to $R_{max}$ dramatically changed with SLR (Fig. 6.4d-f).
6.4.3.1 Mean wave conditions

Under mean wave conditions, $R_{\text{max}}$ reached the conglomerate platform at $\text{SL} = -1$ m and did not make it to the beach face until $\text{SL} = -0.45$ m (Fig. 6.6a). Note, this is lower than the minimum sea level of -0.15 m that was required for wave heights to be calculated in section 4.1. Mean wave conditions at $\text{SL} = 1$ m (contemporary spring high tide) produced maximum runup on the upper beach face with $R_{\text{max}} = 2.35$ m (Fig. 6.6a). $R_{\text{max}}$ gradually increased with higher sea levels until wave over-topping first occurred at $\text{SL} = 1.9$ m (Fig. 6.6a).

Processes contributing to wave runup show significant variability as sea level increased from -1 m to 2.5 m (Fig. 6.6d). $R_{\text{max}}$ between $\text{SL} = -1$ and -0.5 m was predominantly a function of wave setup, with a significant contribution from IG waves and minimal influence from SS waves. As setup decreased with SLR, IG wave became the dominant mechanism driving wave runup between $\text{SL} = -0.5$ to 0.45 m (Fig. 6.6d). As incident wave attenuation decreased, sea levels above 0.5 m were primarily associated with SS wave generated runup.
6.4.3.2 Swell wave conditions

Runup from swell waves was able to impact the beach face at SL = -1 m, through a combination of large setup and strong IG waves resulting in runup 1.3 m above MSL.

Runup at SL = 1 m (current spring high tide) reached an elevation near the top of the ocean berm (3.17 m above MSL) without causing over-wash. Swell waves were first able to overtop the ocean berm when sea level reached 1.35 m (Fig. 6.6b) which could happen with 0.35 m of SLR. For SL < -0.5 m wave setup and IG waves accounted for a near equal
portion of $R_{max}$ with limited influence from SS waves (Fig. 6.6e). As setup decreased and SS waves slowly increased with higher sea levels, IG waves became the dominant mode of runup between SL = -0.5 m and SL = 0.6 m. SS waves became the dominant model of runup from SL = 0.6 m, however, the contribution from IG waves did remain around 35% for sea levels above 1 m (Fig. 6.6e).

6.4.3.3 Storm wave conditions

Maximum runup from storm waves at SL = -1 m reached an elevation 1.05 m above MSL, exceeding the beach toe but not reaching as far up the beach face as swell waves (Fig. 6.6c). Runup from storm waves had the lowest sea level threshold (SL = 1.3 m) for breaching the ocean berm and flooding the island. This is only 0.3 m above the present spring tidal range. Storm waves produced the largest IG wave heights of all the incident conditions, which were the primary runup contribution between SL = -0.55 m and SL = 0.95 m (Fig. 6.6f). Therefore, runup from storm waves at spring high tide is characterised by a near equal contribution of SS and IG waves (Fig. 6.6f). SS waves were the dominant mode of runup for sea levels above 1.0 m, with IG waves accounting for 25 – 43% of runup. Overall, storm waves produced the largest runup levels due to the energetic IG waves modeled across all tested sea levels. IG waves remained significant after the overtopping sea level was reached however the primary mode of inundation was from SS waves (Fig. 6.6f).

6.5 Results: Wave processes with SLR and vertical reef growth

6.5.1 Wave transformation with reef growth and sea level rise

This section presents model results for wave transformation at low tide, mid tide and high tide with SLR of 0 m, 0.5 m, 1 m and 1.5 m, in the context of no reef growth, vertical growth of the outer reef flat and uniform growth of the entire reef flat (Fig. 6.7). Morphology and elevation of Fatato Island remained constant through these simulations.
Chapter 6: Wave processes and sea level rise on Funafuti Atoll

6.5.1.1 SS waves

Results from experiment 1 indicate that wave energy at the shoreline increases proportional to the rise in sea level between SL = -1 m and SL = 2.5 m. However, if the outer reef flat accretes vertically to retain equilibrium with low tide level, much of the increase in $H_{ss}$ is mitigated and lower wave heights are recorded at the shoreline (Fig. 6.8a,d,h; Table 6.1). SLR with outer reef growth resulted in the same high tide wave heights that are currently observed on Funafuti under mean and swell conditions, mitigating a potential rise in shoreline wave height by up to 34% and 24%, respectively. Under storm wave conditions, outer reef growth mitigated the increase in SS wave energy compared to no reef growth, but a net increase was observed in model results when compared to present conditions (Fig. 6.8h). Under all wave conditions at mid-tide and low tide, the outer reef growth morphology increased shoreline $H_{ss}$ compared to present day, but decreased shoreline $H_{ss}$ compared to
SLR and no reef growth (Fig. 6.8). Full reef growth with SLR resulted in near preservation of contemporary $H_{ss}$ at the shoreline under all SLR scenarios, significantly mitigating the increase in shoreline wave energy modeled in the previous section (Fig. 6.8).

Figure 6.8: The response of SS wave height (top) IG wave height (middle) and setup (bottom) at the shoreline to different reef growth morphologies, under mean, swell and storm wave conditions for SLR = 0 m, 0.5 m, 1 m and 1.5 m. Results are presented for low tide (LT), mid tide (MT) and high tide (HT) for each sea level and reef morphology. Data used to make this figure are presented in Table 6.1.

6.5.1.2 IG waves

With no change in reef morphology, $H_{ig}$ at high tide decreased with SLR under mean (Fig. 6.8b), swell (Fig. 6.8e) and storm (Fig. 6.8i) wave conditions. Compared to no reef growth, IG wave heights at the shoreline were higher when the outer reef flat retained equilibrium with sea level. However, the IG wave heights observed with outer reef growth were lower
than what is currently observed at high tide (Fig. 6.8). The three reef morphologies produced higher IG waves at mid-tide compared to high and low tide with the two reef growth morphologies producing higher IG waves compared to the no reef growth scenario. Minimal variation in IG wave behaviour was observed between the moat and full reef growth morphology (Fig. 6.8b,e,i). Overall, reef growth increased the height of IG waves at low and mid tide but reduced the influence from IG waves at high tide (Fig. 6.8).

6.5.1.3 Setup
Wave setup is inversely related to reef depth and therefore increases as the outer reef flat accretes vertically with SLR (Fig. 6.8c,f,j). The increase in setup with reef growth was most notable for storm (Fig. 6.8f) and swell (Fig. 6.8j) waves, especially at higher magnitudes of SLR. At these higher levels of SLR, the increase in setup observed with reef growth (compared to SLR and no reef growth) was observed at low tides (Fig. 6.8f,j). Trends in the response of setup were similar using both morphologies, however the magnitude of setup was slightly larger with full reef growth compared to outer reef growth.
### Chapter 6: Wave processes and sea level rise on Funafuti Atoll

#### Table 6.1: Shoreline wave statistics under different reef morphologies, SLR magnitudes and tide levels,

<table>
<thead>
<tr>
<th>Tide</th>
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<th>SLR=1m</th>
<th>SLR=1.5m</th>
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<td></td>
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Shoreline Setup (m): Moat reef growth

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Shoreline Setup (m): No reef growth

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Shoreline Hss (m): No reef growth

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Shoreline Hss (m): Moat reef growth

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Shoreline Hig (m): No reef growth

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Shoreline Setup (m): Full reef growth

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Shoreline Setup (m): Moat reef growth

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Shoreline Setup (m): Full reef growth

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Shoreline Setup (m): No reef growth

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Shoreline Setup (m): Moat reef growth

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Shoreline Setup (m): Full reef growth

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<td>High</td>
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6.5.2 Wave overtopping

The decrease in shoreline wave height achieved with reef growth did not significantly offset the potential for wave inundation because island elevation and morphology remained static and less energy was required for swash to overtop the berm. Model results show maximum water level and inundation are similar for no reef growth, outer reef growth and full reef growth scenarios, at high and low tide (Fig. 6.9). Over-topping occurs at high tide on all reef morphologies under swell and storm waves with 0.5 m of SLR. Mean waves cause a weak inundation event with 1 m of SLR at high tide and no reef growth (Fig. 6.9c). No overtopping was recorded with either reef growth morphology, but maximum water level was extremely close to breaching the berm limit (Fig. 6.9c).

Figure 6.9: Maximum water level at high tide and low tide (see annotations on plot a) for different levels of SLR (top to bottom) with no reef growth (red line), moat reef growth (green line) and full reef growth (blue line) under mean (left), swell (centre) and storm (right) wave conditions. Maximum water level lines that exceed the island berm identify that at least one inundation event occurred during the simulation.
Model results show that the increase in IG wave activity and wave setup associated with reef growth compensate for the decrease in SS wave height, resulting in similar runup levels for all three reef morphologies (Fig. 6.9). These results suggest that the only way to prevent frequent over-topping with SLR is for island elevation to increase proportional to SLR. Contemporary inundation thresholds will prevail if island elevation and reef elevation can maintain equilibrium with SLR.

6.6 Discussion

6.6.1 Contemporary process regime

The contemporary process regime on the ocean side reef of Funafuti near Fatato Island is associated with wave dissipation between 52% and 100%, depending on tide level and incident wave height (Fig. 6.4g). Field data show that $H_{ss}$ at the shoreline is strongly controlled by reef depth, highlighting similar tidal modulation trends that have been observed across a range of reef settings (Kench and Brander, 2006b, Kench, et al., 2009a, Péquignet, et al., 2011). SS wave attenuation at low tide results in minimal incident frequency energy at the shoreline with large wave setup and energetic IG waves across the reef flat. Similar magnitudes and tidal trends in wave setup have been measured on atoll reefs in the Marshall Islands (Becker, et al., 2012). IG wave heights increase between the reef edge and shoreline at Fatato and exert a strong influence on runup throughout the contemporary tide cycle (Fig. 6.4). A shoreward increase in $H_{ig}$ was also measured on a morphologically similar (~100 m wide) reef on Majuro Atoll (Ford, et al., 2013) and on a smooth 250 m wide reef on Kwajalein Atoll, Marshall Islands (Quataert, et al., 2015). However, measurements on wider reefs typically show a decrease in IG wave height on the central reef flat and a tidally modulated signal on the inner reef flat (Péquignet, et al., 2014, Pomeroy, et al., 2012, Van Dongeren, et al., 2013). Model results in Figure 6.4 highlight a subtle tidal influence on infragravity waves at the shoreline, characterised by a peak in $H_{ig}$.
near MSL for each wave condition. Model wave spectra results under contemporary sea level at Fatato Island indicate that incident frequency wave energy only becomes important at the shoreline near high tide, with IG wave motions prevailing at low and mid tides (Fig. 6.6).

6.6.2 Wave processes at higher than present sea level
Recent research has started to resolve how SLR will change wave processes on coral reefs, using numerical models (Quataert, et al., 2015, Storlazzi, et al., 2011) or field based empirical formula (Becker, et al., 2014, Merrifield, et al., 2014). All previous assessments of how wave processes will respond to SLR indicate that larger waves will reach the shoreline as rising sea levels increase water depth on the reef flat, including the model results presented here. Few investigations have considered how increased water level on the reef flat will influence the importance of secondary wave processes at the shoreline. A negative feedback response from SLR is that the decrease in wave setup may actually offset a rise in mean water level near island shorelines. However, field derived empirical results from Becker et al (2014) show that the decrease in setup associated with SLR will not be enough to mitigate a rise in mean water level. Field data and numerical results from Fatato support estimates from Becker et al (2014) showing that setup will decreases at approximately half the rate of SLR. Therefore, net water level on the reef flat will increase with SLR but the decrease in setup will slow down the rate of SLR in surf-zone environments. Quataert, et al. (2015) also highlight the decrease in setup as being smaller than the rise in sea level.

Model results from Fatato also show that the decrease in SS attenuation forced by SLR will be associated with less energy transferred to the IG wave band. Consequently, each wave condition used in this analysis was associated with a sea level threshold where processes at the shoreline shift from being IG dominant to being SS dominant. The sea level thresholds
for $H_{ss}$ to exceed $H_{ig}$ at the shoreline were 0.4 m, 0.6 m and 1.1 m for mean, swell and storm waves, respectively (Fig. 6.4). However, the threshold for spectral density at the shoreline to transition from being IG dominant to SS dominant occurred later, when sea level reached 0.65 m, 1.2 m and 1.4 m for mean, swell and storm waves, respectively. The higher sea level threshold for spectral transition to SS dominance is because spectra is a function of wave height and period, meaning lower amplitude IG waves can have a higher spectral density than larger SS waves. Results for IG wave behaviour on Fatato are different from the controlled sea level results presented in Quataert et al. (2015), where IG wave heights at the shoreline were assumed to increase with SLR. However, the larger incident waves ($H_{rms} = 2-6$ m) and lower maximum sea level ($< h_r = 2$ m) used in Quataert, et al. (2015) resulted in the surf-zone always being saturated, which possibly explains why a sea level associated with peak $H_{ig}$ was not observed in their results.

Wave breaking on coral reefs typically occurs at the reef edge, with a surf-zone developing across the reef flat (Roeber and Cheung, 2012b). SLR on reef coastlines may be associated with a sea level threshold that results in no wave breaking due to a relatively small wave height. Gourlay (1994) explains that waves do not break when $H_o/h_r$ is below 0.4, resulting in no setup on the reef flat. The release of IG waves through dynamic setup and group bound mechanisms also require incident SS waves to break and dissipate on the reef flat (Péquignet, et al., 2014). Therefore, SLR on coral reefs may result in no setup and limited IG wave motions on the reef flat, under regular incident wave conditions. Deviation from the multiple surf-zone processes that currently operate on Funafuti in favour of direct transmission of SS waves will fundamentally alter the physical processes that control geomorphic development on the reef surface. Kench and Brander (2006b) show that the potential for geomorphic change on island shorelines is a function of the time that SS frequency waves can propagate across the reef flat. Model results presented here show that
the ‘energy window’ on Fatato Island will be open for a significantly longer period of time with SLR because larger waves will impact the shoreline for longer periods of the tide cycle. Further, a breakdown in wave setup and IG wave motions will alter reef flat velocity dynamics and consequently influence sediment transport processes between the reef edge and beach face. Setup on coral reefs has been identified as the primary influence on mean circulation patterns that dictate sediment transport pathways on the reef surface (Hearn, 1999, Symonds, et al, 1995). Without the influence of wave setup, sediment transport and larvae dispersal will be controlled by the asymmetric orbital velocity structures that develop as waves propagate across the reef flat (Huntley, 2013). The influence of IG waves on reef flat circulation is not well understood but a decrease in IG frequency waves surging across the reef flat will potentially result in less lagoon directed sediment transport on atoll reefs.

6.6.3 Wave inundation on atoll islands

Atoll island morphology is typically characterised by an elevated storm berm that is comprised of coarse material deposited during high energy events (Woodroffe, 2008). Ridge formation is associated with wave runup during extreme events when sediment is deposited to build a berm high enough that inundation is not observed under non-extreme conditions (Woodroffe, 2008). Reconstruction of inundation events for the last 30 years on Marshall Island atolls shows that wave driven flooding occurs approximately once every 3-4 years at present sea level (Merrifield, et al., 2014). Merrifield, et al. (2014) show that overtopping events are limited to episodes when swell or storm waves coincide with a spring high tide or normal high tides during strong La Nina conditions. Extending their analysis to future sea levels, Merrifield et al (2014) suggest that any rise in MSL above 0.4 m will result in multiple inundation events each year, with SLR of 1 m resulting in over 50 inundation events per year.
Chapter 6: Wave processes and sea level rise on Funafuti Atoll

Model results presented here provide detail on the physical processes that combine to generate wave inundation on reef shorelines. The swell and storm waves used in this analysis are not extreme events, but are conditions that can be expected at least once each year on Funafuti. Therefore, it is not surprising that modeled $R_{\text{max}}$ did not supersede berm elevation within the present sea level range.

Model results for $R_{\text{max}}$ location show a uniform lagoon-ward migration of the swash limit with SLR (Fig. 6.6a-c). However, the combination of processes that influence $R_{\text{max}}$ are highly variable as depth increases on the reef flat (Fig. 6.6d-f). Model results from Fatato show that the runup mode shifts from being controlled by IG waves at contemporary sea levels, to being controlled by SS waves at higher sea levels that cause inundation (Fig. 6.6).

Analysis of wave spectra and water level outputs from the berm crest further highlight the nature of how overwash flow changes between wave conditions and sea level (Fig. 6.10).

Model results show that when sea level reaches the threshold where waves can initially breach the berm the overwash flow is limited to one or two wave groups surging over the berm crest (Fig 6.10a-c). This results in a low energy spectral density (Fig 6.10j-l) that is a combination of both SS and IG waves (Fig 6.10g-i). Overwash flow at higher sea levels is associated with consistent inundation (Fig 6.10d-f) that is primarily driven by SS frequency waves, with a minor contribution from IG waves (Fig 6.10g-i). Spectral density results show that overwash flow energy becomes much more significant when SS waves are the primary mode of inundation. This occurs under mean waves when SL is 2.25 m and from SL = 1.7 m for swell and storm waves (Fig 6.10g-l). Model results show that minor overwash flow will occur at SL = 1.9 m under mean waves, with significant overwash flow SL = 2.2 m. This is approximately equal to spring high tides (SHT) with 1 m of SLR. Minor inundation from swell and storm waves occurs from SL = 1.3 m (SHT with 0.3 m of SLR).
with serious inundation occurring from SL = 1.7 m and nonstop inundation from SL = 2.2 m.

SS waves carry less momentum compared to IG waves, due to their significantly lower wave length (Holman and Sallenger, 1985). Therefore, runup and swash from IG waves penetrates higher up the beach face (Guza, et al., 1984) and inundation from IG waves can cause significantly more devastation compared to overwash from SS waves (Roeber and...
Chapter 6: Wave processes and sea level rise on Funafuti Atoll

Bricker, 2015). Inundation on coral reefs at present sea level requires extreme wave conditions that generate energetic IG waves which can lead to destructive inundation (Hoeke, et al., 2013, Roeber and Bricker, 2015, Shimozono, et al., 2015). Model results for overwash on Fatato Island associated with SLR under moderate wave conditions show that inundation will primarily be driven by SS waves that carry less potential to penetrate landward and damage island infrastructure. Therefore, the shift from IG associated overwash in favour of SS driven overwash will lead to more frequent inundation but the nature of SS overwash may cause less destruction to islands.

6.6.4 Reef growth and sea level rise

Reef growth analogues from the Holocene suggest that coral reefs in the tropical Pacific can keep-up and catch-up with mean SLR at rates of 5-8 mm/yr (Kench, et al., 2009c). The reef flat at Funafuti grew vertically at an average rate of 5 mm/yr in the Holocene, accreting vertically to extend 25 m above the Pleistocene reef (Ohde, et al., 2002). However, past conditions for reef growth may have been very different to that of today, with contemporary reefs subjected to ocean acidification, bleaching, pollution, overfishing and diseases that negatively impact coral health and limit reef growth (Hoegh-Guldberg, et al., 2007, Hughes, et al., 2003, Salvat, 2015). Despite such concerns, a number of studies have observed recent colonisation of reef flat surfaces in response to a rise in absolute or relative sea level (Brown, et al., 2011, Saunders, et al., 2015, Scopéritis, et al., 2011). Therefore, the response of coral reef morphology to future SLR remains uncertain and is likely to be highly variable in space and time (Jones, et al., 2015).

This study presents a preliminary assessment of how vertical reef growth with SLR can mitigate a linear rise in shoreline wave energy. Model results from Fatato suggest that vertical growth concentrated at the outer reef flat or growth of the entire reef flat at the same pace as sea level will essentially preserve the contemporary range of surf-zone
processes that are observed between the reef edge and shoreline. Reef growth is therefore effective in mitigating the linear increase in SS wave energy observed with static SLR, however it also means the influence from IG waves and setup does not decrease with SLR. Consequently, maximum runup on the two reef growth morphologies was only slightly lower than runup with no reef growth and the presence of IG waves and setup resulted in similar overtopping thresholds at high tide. Model results from Fatato emphasise that vertical reef growth actually has limited potential to mitigate wave inundation with SLR, under the assumption that island morphology remains static. To mitigate inundation, the elevation difference between the berm crest and mean sea level needs to be maintained, requiring geomorphic adjustment of the existing island shoreline.

6.6.5 Island response to sea level rise

No sediment transport or morphodynamic response was simulated in the model. In reality, island morphology will continuously adjust to any future changes in sea level, sediment supply or wave conditions. Potential physical changes in island morphology in response to SLR include vertical island growth, lagoon island migration and erosion (Kench and Cowell, 2001). Atoll island elevation is controlled by the wave energy required to overwash sediment on top of or over the ocean berm (Woodroffe, 2008). For example, observation of tsunami wave inundation in the Maldives have been linked with deposition of overwash sediment that resulted in the formation of an elevated island ridge on a number of reef islands (Kench, et al., 2006) and storm wave inundation (Scoffin, 1993). Model results from Fatato and empirical calculations from Merrifield, et al. (2014) highlight that SLR will reduce the wave energy threshold required for overtopping, resulting in more frequent wave inundation events.

Coral reefs islands have the ability to adapt in morphology as a response to SLR (Kench and Cowell, 2001, McLean and Kench, 2015). If sediment is being generated on the reef
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Flat and can be transported by overwash flow, islands have the potential to grow vertically with SLR. Therefore, the potential for island growth will depend on sediment production on the reef producing material of a size that is suitable for entrainment on the reef and deposition on the berm (Perry, et al., 2011). If island building does not occur naturally, maintaining the contemporary elevation difference between the island ridge and reef flat is a suitable nourishment target for engineering the response of islands to SLR.

Wave transformation simulations on Fatato Island indicate that SLR will increase the period of time that the beach face is exposed to wave activity. This will significantly open the ‘energy window’ when morphodynamic change can occur on the beach face under normal and episodic wave conditions (Kench and Brander, 2006b). Recent analysis of shoreline change reveal that Fatato Island has retained a stable ocean side shoreline position during a period when sea level increased by 0.3 m (Kench, et al., 2015). Results from Kench, et al. (2015) show decadal shoreline change on Fatato is characterised by lateral island extension to the south.

6.7 Summary
This chapter presented one of the first investigations of how SLR will alter the physical process that impact sedimentary landforms on coral reefs, with model results revealing new insights regarding how different frequency wave processes will respond to rising sea levels. Under the assumption of no morphodynamic adjustment from the reef or island, model results show that SLR is associated with a significant increase in SS wave activity at the shoreline due to less attenuation through breaking and friction across the reef surface. This decrease in SS wave attenuation results in less energy being transferred into the IG wave band and dramatically decreases the magnitude of wave setup across the reef flat. A decrease in the presence of IG wave motions and wave setup will fundamentally alter the nature of wave processes interacting with island shorelines. The transition to SS wave
dominant processes on the reef flat is associated with a linear increase in spectral density at the shoreline. Model results also show a linear lagoon-ward migration of runup level with SLR. This is observed despite a considerable transition in the mechanisms influencing runup, as setup and IG wave activity begin to decrease with SLR and SS waves become the primary mode of shoreline interaction.

Inundation results show that annual maximum swell and storm events will overtop the ocean berm at spring high tide with approximately 0.3 m of SLR, driven by a combination of SS and IG waves. However, inundation at lower levels of SLR was limited to one or two wave groups, with limited penetration across the island. Inundation at higher levels of SLR was associated with consistent overwash from SS waves and limited inundation from IG wave motions. Overwash flow without the influence of IG waves may reduce the landward impact of inundation because SS waves carry less momentum to surge across the island.

Vertical reef growth is a potential natural response to SLR, but the impact of reef growth on hydrodynamic processes has been neglected in previous assessments of SLR and wave inundation. Model results show that vertical reef growth at the same rate as SLR will mitigate the linear increase in shoreline wave energy that is observed with SLR on a static reef. However, reef growth also maintains the influence of wave setup and IG motions and consequently has a limited ability to mitigate wave inundation with SLR when island morphology remains unchanged. To mitigate the impact of overwash with SLR, the island ridge needs to grow vertically to maintain the contemporary elevation above the reef flat. This is possible on natural reef environments where sediment is being generated on the reef flat and can be deposited on top of the berm during overtopping events. This natural mechanism for island growth is encouraging for environments with a healthy reef and a natural shoreline but is of little assistance to islands that have a developed shoreline.
Chapter 7: Morphology and sea level controls on wave processes and inundation on atoll islands

7.1 Introduction
This chapter examines how wave processes and inundation on coral reefs are influenced by reef and island morphology. Basilisk GN was used to simulate wave processes on a series of idealised reefs with variable morphology. Model outputs were used to understand how reef morphology influences the magnitude of wave processes at the shoreline and to assess whether residual wave energy at the shoreline can cause inundation. The chapter develops a conceptual understanding of how reef and island morphology influences wave inundation on atoll island environments. Chapters 5 and 6 developed new insights of how reef depth influences different wave processes on the reef flat and identified how these processes contributed to runup elevation and wave inundation on Fatato Island, Funafuti Atoll. However, application of these results beyond Funafuti may be limited due to the large global variation in reef and island morphology (Quataert, et al., 2015). Fatato is an end member of the morphological spectrum in terms of having a relatively narrow reef width (100 m), a steep reef slope (23.5°), and a high island berm elevation (4 - 4.5 m above the central reef flat). As discussed in Chapter 6, wave processes on Funafuti are not necessarily representative of what is observed on wider reefs, especially in terms of IG wave behaviour. Therefore, further analysis of how reef and island morphology influence wave processes and inundation is critical for assessing the vulnerability of atoll landforms to SLR.
Climate change will have an unprecedented impact on coastal environments, with populated coastlines around the world threatened by increased erosion, tidal flooding and wave inundation (Cazenave and Cozannet, 2014, Nicholls and Cazenave, 2010, Nicholls, et al., 2011, Woodroffe and Murray-Wallace, 2012). A recent assessment of the vulnerability of tropical coastlines to SLR suggested that over 100 million people currently receive risk reduction benefits from the natural dissipation of wave energy across coral reef structures (Ferrario, et al., 2014). For coral fringed coastlines, the impact and significance of SLR may vary depending on reef structure (Quataert, et al., 2015) and island morphology (Woodroffe, 2008). Islands that occupy atoll reef platforms are consistently highlighted as being one of the most sensitive landforms to SLR (Bindoff, et al., 2007, Church, et al., 2013). However, the majority of climate change literature regarding atoll environments focuses on the social and political elements of vulnerability (Barnett, 2005, Barnett and Adger, 2003, Dickinson, 2009, Farbotko and Lazrus, 2012, Lazrus, 2012, McAdam, 2010, Mimura, 1999, Patel, 2006). Comparatively few studies have examined the physical processes that result in tidal flooding (Lin, et al., 2014), wave runup (Merrifield, et al., 2014), wave inundation (Quataert, et al., 2015) and shoreline change on atoll islands (Kench, et al., 2015).

A preliminary understanding of how wave transformation processes are influenced by reef morphology was established by Quataert, et al. (2015) using the XBeach model to simulate wave processes on a series of idealised coral reefs. The range of reef morphology parameters tested in Quataert, et al. (2015) include fore-reef slope (1:1 - 1:100), reef width (50 - 1000 m), and roughness, with simulations extending for the duration of a 1 m amplitude tidal cycle, reaching maximum reef depth of ~2 m.

Results from Quataert, et al. (2015) provide a preliminary analysis on how reef flat processes respond to changes in tidal water level and reef morphology and highlight that
the most vulnerable reef landforms are characterised by a steep fore-reef slope, a narrow reef flat and low roughness. However, the analysis in Quataert, et al. (2015) is limited to contemporary sea levels and results only extended to higher sea levels under the assumptions that the relationship between wave processes and reef depth remains constant. As shown in Chapter 6, this is not a valid assumption for IG wave behaviour because the relationship between IG wave height and sea level does not remain consistent when higher than present sea levels are considered. Another limitation in Quataert, et al. (2015) is that island morphology remained constant, preventing an assessment of how beach slope and berm height above the reef flat influence the potential for shoreline wave processes to cause an inundation event.

The research presented in this chapter was designed to test and extend the results presented in Quataert, et al. (2015) using Basilisk GN to simulate wave transformation and inundation on a series of idealised coral reefs with variable reef and island morphology. The primary aim of this work was to identify how different morphological parameters (fore-reef slope, reef width, reef depth, friction, beach slope, berm elevation) influence wave processes and inundation on atoll islands. The 1D nature of these simulations does not account for the two-dimensional complexity of wave transformation processes that occur on reefs with significant variations in alongshore morphology (Lowe, et al., 2010). Therefore, the results are most applicable to atoll rim reefs where across reef wave and circulation processes are not heavily influenced by channels, ridges or curvature.

A secondary aim of this chapter is to resolve how incident wave conditions, reef depth and reef width influence the behaviour and significance of IG waves on coral reefs. A key finding from the field and modeling results presented in Chapters 5 and 6 was that IG waves increased in height between the reef edge and shoreline on Fatato Island and exhibited no significant relationship with reef depth throughout the tidal cycle. As discussed in Chapter
6, the shoreward increase in $H_{ig}$ is not unique to Fatato, but has also been observed on atoll reefs in the Marshall Islands, where reef width is below 300 m (Ford, et al., 2013, Quataert, et al., 2015). Field measurements on wider reefs (>400 m) typically show that IG wave height is dissipated through friction on the inner reef flat, leading to minimal long wave energy at the shoreline (Péquignet, et al., 2014, Pomeroy, et al., 2012, Van Dongeren, et al., 2013). However, under extreme incident wave conditions generated by a local typhoon, a shoreward increase in IG wave height has been modeled on wider reefs, resulting in serious inundation (Roeber and Bricker, 2015, Shimozono, et al., 2015). Roeber and Bricker (2015) explain that IG wave amplification occurs when the peak infragravity frequency ($f_{ig}$) is close to the reefs resonant frequency ($f_{reef}$) and a standing wave is formed with a node at the reef edge and an antinode at the shoreline. Since $f_{reef}$ is a function of reef depth and reef width and $f_{ig}$ is a function of incident wave grouping, the potential for resonant amplification is heavily influenced by reef morphology and will likely change with SLR. Therefore, the discussion of wave processes presented in this chapter is primarily focused on the response of IG waves to changes in sea level and reef morphology.

7.2 Model experiments

Basilisk GN was used to simulate wave processes across a range of reef morphologies, island morphologies, sea levels and wave conditions. In total, three wave conditions were simulated with two reef slopes ($\beta_r = 1:2, 1:6$), four reef widths ($W_r = 100, 300, 600, 1000$ m), two friction values ($C_f = 0.02, 0.06$), two beach slopes ($\beta_{beach} = 1:7, 1:14$), four berm elevations ($Z_{berm} = 2, 3, 4, 5$ m) and six reef depths ($h_r = 0.5, 1, 1.5, 2, 2.5, 3$ m), as described in Figure 7.1. The three wave conditions are the same as those used to investigate how sea level controls wave processes and runup on Funafuti Atoll (Chapter 6; Fig. 6.1), and represent mean conditions ($H_s = 1.3$ m, $T_s = 10$ s), an annual swell event ($H_s = 2.1$ m, $T_s = 16$ s) and an annual storm event ($H_s = 2.6$ m, $T_s = 10$ s). These wave conditions are based
on wave climate data from Funafuti Atoll but are analogous of annual wave conditions in many areas of the tropical Pacific Ocean.

7.2.1 Model inputs

Water level data representing each wave condition were imported at the left boundary to generate the model wave field. Simulations were performed using 768 morphology combinations for each wave condition, resulting in 2,304 model runs. Each bathymetry was imported into the model with 1 m horizontal resolution with the reef edge (x = 0 m) located 800 m from the left boundary (x = -800 m). Each combination of reef width, fore-reef slope, beach slope and berm height was simulated using six reef depths and two \( C_f \) values. \( C_f = 0.02 \) was used to represent a smoother reef flat surface and \( C_f = 0.06 \) was used to represent a rougher reef flat surface. The slope threshold for removing the dispersive source term in Basilisk GN remained at \( B = 1 \) for all simulations.
7.2.2 Model outputs

Each simulation ran for 2048 seconds with mean water level on the 1000 m wide reef stabilising at \( t \approx 800 \) s. Therefore, a 1024 s sample between 1000 s and 2024 s was used to calculate wave statistics and assess inundation. Water level data were extracted at time-sensor locations positioned every 50 m across the model reef (Fig. 7.1). Time-series outputs were specifically located offshore, at the reef slope, the reef edge, the central reef flat and at the shoreline. Output water level data were separated using a 0.04 Hz band pass filter before wave heights associated with SS waves (\( H_{ss} \)) and IG waves (\( H_{ig} \)) were calculated.

Wave setup (\( \bar{\eta} \)) was calculated as the mean free-surface displacement. To understand conditions that promote resonant forcing of IG waves, the frequency associated with peak IG energy (\( f_{ig} \)) was calculated at the reef edge and matched with the reefs natural frequency (\( f_{ref} \)) which can be calculated using equation (7.1). \( f_{ref} \) is a function of reef width (\( w_r \)), reef depth (\( h_r \)), gravity (\( g = 9.8 \)) and the number of nodes. Assuming there is a node at the reef slope and an antinode at the shoreline, \( n = 1 \):

\[
f_{ref} = \left( \frac{4w_r}{(2n-1)\sqrt{gh_r}} \right)^{-1}
\]  

(6.1)

7.2.3 Inundation criteria

A key output parameter was whether wave inundation occurred at any point during the model simulation. A location at the leeward side of the ocean berm was used as the threshold for identifying inundation (Fig. 7.1). An inundation event was flagged if water reached the threshold location at any time during the simulation. Results are presented to show how each morphological parameter influenced the potential for inundation under each wave condition.
7.3 Results: Morphological controls on wave transformation

Model results identified reef depth and reef width as the primary controls on wave transformation. Friction and fore-reef slope provided secondary controls on across-reef wave transformations. The impact that each reef characteristic had on wave transformation is outlined below.

7.3.1 Reef depth

Reef depth has a fundamental control on wave processes at the shoreline on coral reefs (Fig. 7.2). For a given incident wave condition, reef depth is the main parameter that influences SS wave dissipation and the magnitude of wave setup across the reef flat (Fig. 7.2). Incrementally increasing reef depth is associated with a near-linear increase in $H_{ss}$ and a decrease in setup at the shoreline, regardless of reef morphology (Fig. 7.2) suggesting that previous results regarding SS waves and setup on Fatato are transferable to other settings. Figure 7.3 shows how increasing reef depth slows down the rate of SS wave attenuation across the reef flat which is reciprocated by a proportional decrease in setup magnitude.

Model results show that IG wave height at the shoreline has the same relationship with reef depth that was identified in Chapter 6, but also reveal that the threshold sea level for peak $H_{ig}$ increases as reef width increases (Fig. 7.2b,e,h). Reef depth had the greatest influence on IG wave height at the shoreline when reef width was 100 m, but the influence of reef depth on IG wave height decreased as reef width increased (Fig 7.2). Reef depth also influenced the across reef behaviour of IG waves, with larger proportional changes in $H_{ig}$ between the reef edge and shoreline observed on shallower reefs (Fig. 7.3). Peak shoreline $H_{ig}$ on the 100 m wide reef was observed between $h_r = 0.5 - 1$ m, depending on the incident wave condition, with IG wave height steadily decreasing as reef depth increased (Fig.7.2). Peak $H_{ig}$ at the shoreline shifted to $h_r = 1 - 1.5$ m on the 300 m wide reef, with less difference
between high and low sea levels (Fig. 7.2). IG waves at the shoreline on wider reefs (600 and 1000 m) were less sensitive to increasing reef depth, and observed a slight increase in $H_{ig}$ until reef depth reached 2.5 – 3 m under swell and storm conditions, with peak $H_{ig}$ observed at $h_r = 1$ m for mean waves (Fig. 7.2).

Figure 7.2: Wave processes at the toe of beach under different reef depths (x-axis), and reef widths (line colour) and wave conditions using $C_f = 0.02$, $Z_{borm} = 5$ m, $\beta_r = 1:2$ and $\beta_{beach} = 1:14$. 

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7.3.2 Reef width

Reef width has a strong influence on the magnitude of SS and IG waves that reach the shoreline (Fig. 7.2; Fig. 7.3). In contrast, reef width has comparatively minimal influence
on the magnitude of wave setup across the reef flat (Fig. 7.2). For each reef depth and wave condition, shoreline $H_{ss}$ decreased as reef width increased. This was most notable under the higher friction scenario ($C_f = 0.06$) when more wave energy was attenuated across the reef flat (Fig. 7.4). Model results show that reef width had a greater influence on shoreline $H_{ig}$ when compared to the influence of reef depth, with maximum IG waves always observed on the 100 m wide reef (Fig. 7.2). IG wave heights were modeled to increase between the reef edge and shoreline on narrow ($W_r = 100$ m) and shallow ($h_r \leq 1.5$ m) reefs under each wave condition (Fig. 7.3). IG waves decreased in height between the reef edge and shoreline on wider and deeper reefs. Maximum $H_{ig}$ on reefs wider than 100 m was typically observed near the reef edge or on the outer reef flat (Fig. 7.3). However, each reef width observed a slight increase in $H_{ig}$ between the inner reef flat and the beach toe. This is potentially due to interference from IG wave reflection developing a standing wave. Wave setup was not strongly influenced by reef width, with a marginal decrease in setup magnitude on the wider reefs (Fig. 7.3).

7.3.3 Friction

Friction has a deterministic influence on wave processes and was the subject of detailed investigation in Chapters 4 and 5. Therefore, only two friction values were tested in this analysis to highlight how wave processes change on a relatively smooth reef ($C_f = 0.02$) compared to a relatively rough reef ($C_f = 0.06$). IG waves were the most responsive variable to friction, with a substantial decrease in shoreline $H_{ig}$ observed when friction increased from $C_f = 0.02$ to $C_f = 0.06$ (Fig. 7.4). For example, IG waves generated under storm conditions on the 100 m reef decreased from 0.82 m to 0.6 m ($h_r = 1$ m) when $C_f$ changed from 0.02 to 0.06 (Fig. 7.4). The influence of friction on IG waves was most pronounced on shallow reefs because the numerical implementation of friction reflects how waves are more influenced by topographic roughness as depth decreases. SS wave height at the
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Shoreline also decreased when friction increased from $C_f = 0.02$ to $C_f = 0.06$, although the magnitude was not as severe compared to the influence of friction on IG waves (Fig. 7.4). Model results show that setup at the shoreline was approximately 0.2 m lower using $C_f = 0.06$ compared to $C_f = 0.02$, for $h_r < 1$ m (Fig. 7.4c,f). The difference in setup using the higher and lower friction values decreased as reef depth increased, with similar setup observed for $C_f = 0.02$ and $C_f = 0.06$ when $h_r$ was 3 m (Fig. 7.4c,f).

Figure 7.4: Model outputs for SS wave height (top), IG wave height (middle) and setup (bottom) at the shoreline under storm wave conditions as a function of reef depth (x-axis) and reef width (marker colour) using different friction values ($C_f = 0.02$, left; $C_f = 0.06$, right) for $\beta_r = 1:2$ (x marker) and $\beta_r = 1:6$ (+ marker).
7.3.4 Reef slope
Offshore reef slope provides a deterministic control on wave processes at the shoreline. The steeper reef slope (1:2) resulted in larger SS waves, larger IG waves and higher setup for each wave condition and each reef width (Fig. 7.4). The influence of reef slope on each wave process was most pronounced on narrow and shallow reefs (Fig. 7.4). Under storm conditions on narrow (100, 300 m) and shallow reefs ($h_r < 2$ m), the steeper reef slope amplified $H_{ss}$ by 0.15 m, increased $H_{ig}$ by 0.23 m and elevated setup by 0.18 m, on average. A steeper reef slope compresses the shoaling zone for incoming SS waves, resulting in rapid wave height amplification prior to breaking. Model results show that this amplification leads to larger IG waves and higher setup across the reef flat. The influence of reef slope is most pronounced when reef depth is shallow and incident waves are large. Many fringing reefs are characterised by a flatter reef slope than what was considered in this study. The same wave conditions on reefs with a flatter offshore slope would result in lower amplitudes for SS wave height, IG wave height and setup at the shoreline.

7.4 Morphological controls on wave inundation
An inundation event was recorded on 25%, 39% and 43% of the 678 reef morphology combinations under mean, swell and storm wave conditions respectively. Of the six geomorphic parameters, primary controls on inundation were identified as berm height, reef depth and reef width (Fig. 7.5a-c). Model outputs show that friction, fore-reef slope and beach slope provide an important but secondary control on inundation (Fig. 7.5d-f).
7.4.1 Primary controls on inundation

7.4.1.1 Berm height

Berm elevation above the reef flat has no impact on reef flat hydrodynamics but does dictate the threshold elevation required for wave runup to result in inundation for a given water level. Of the 192 simulations that had a berm height 2 m above the reef flat, 57% resulted in inundation under mean wave conditions, inclusive of all other morphologic variations (Fig. 7.5a). The occurrence of inundation increased to 77% and 78% under swell and storm wave conditions respectively. Logically, there was a proportional decrease in inundation for each wave condition as berm elevation increased (Fig. 7.5a). Maximum berm elevation was 5 m above the reef flat and was associated with 0%, 2% and 4% inundation under mean, swell and storm waves respectively. Inundation with a 5 m berm was limited to \( h_r = 3 \text{ m}, W_r = 100 \text{ m}, \beta_r = 1:6, \beta_{beach} = 1:7 \) and \( C_f = 0.02 \).

7.4.1.2 Reef depth

Reef depth has an important control on inundation for two reasons. Firstly, reef depth determines the magnitude of SS wave attenuation and the development of secondary wave
processes across the reef flat. Secondly, the relationship between reef depth and berm elevation determines the amount of shoreline wave energy required for inundation. Inundation on the shallowest reef \((h_r = 0.5 \, \text{m})\) occurred on 0%, 5% and 7% of the morphology combinations tested under mean, swell and storm waves, respectively (Fig 7.5b). These shallow water inundation events were limited to berm height \(= 2 \, \text{m}\) and \(W_r = 100 \, \text{m}\) and were primarily associated with setup elevated water level and a concentration of wave energy within the IG band (Fig. 7.3). As reef depth increased towards \(h_r = 3 \, \text{m}\), inundation events became progressively more common as islands with higher berms and wider reefs became more accessible (Fig 7.5b). For \(h_r = 1.5 \, \text{m}\), inundation occurred on 9%, 27% and 30% of simulations under mean, swell and storm waves, respectively (Fig 7.5b). Inundation under moderate water depths was primarily associated with IG wave motions, with a significant contribution from both SS waves and setup (Fig. 7.3). At the maximum depth \((h_r = 3 \, \text{m})\), inundation occurred on 56%, 69% and 79% of simulations under mean, swell and storm waves, respectively. Inundation for deeper reefs was primarily associated with direct propagation of SS waves with a significant contribution from IG waves on wider reefs (Fig. 7.3).

7.4.1.3 Reef width
Reef width had a clear influence on wave inundation events (Fig. 7.5c). Inundation under mean wave conditions occurred on 29%, 22%, 19% and 17% of 192 simulations with each respective reef width \((100 \, \text{m}, 300 \, \text{m}, 600 \, \text{m} \text{ and} 1000 \, \text{m})\). Inundation under swell waves occurred on 47%, 36%, 29% and 24% of simulations, respectively. Storm waves caused the most inundation for each reef respective width \((53\%, 40\%, 31\% \text{ and} 28\%)\). The decrease in inundation with increasing reef width is a result of smaller SS and IG wave heights at the shoreline. Therefore, reef width is most effective when the reef is shallow and friction is high.
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7.4.2 Secondary controls on inundation

7.4.2.1 Friction
More inundation events were observed during simulations using the lower friction coefficient \( C_f = 0.02 \) representative of a relatively smooth reef surface. Overtopping events were observed on 25%, 39% and 44% of simulations under mean, swell and storm waves, respectively using \( C_f = 0.02 \) (Fig. 7.6d). Less overtopping events were observed using \( C_f = 0.06 \), with 20%, 29% and 31% of simulations identifying inundation under each respective wave condition (Fig. 7.6d). The decrease in overtopping with higher friction is attributed to a greater rate of SS and IG wave attenuation across the reef flat (Fig. 7.2).

7.4.2.2 Reef slope
Two representative reef slopes were simulated, highlighting slightly more inundation events with the steeper 1:2 (27°) reef compared to the flatter 1:6 (9.5°) reef. Inundation occurred on 23%, 37% and 41% of simulations under mean, swell and storm waves, respectively for the 1:2 slope (Fig. 7.5e). Inundation events decreased to 22%, 32% and 34% under mean, swell and storm waves, respectively for the 1:6 slope. The increase in inundation associated with the steeper reef slope was attributed to the larger amplitude SS and IG waves that are generated when incident wave shoaling is concentrated at the reef edge (Fig. 7.4).

7.4.2.3 Beach slope
The steeper 1:7 (8°) sloping beach face resulted in more inundation events compared to the flatter 1:14 (4°) beach slope. Mean waves resulted in inundation under 24% of the 384 simulations using a 1:7 slope, which decreased to 21% when the 1:14 slope was used (Fig. 7.5f). Inundation from swell waves decreased from 36% (1:7) to 32% (1:14) when beach slope decreased. Beach slope had less influence under storm wave conditions, with inundation occurring on 38% (1:7) and 36% (1:14) of the simulations (Fig. 7.6f). The lower
beach slope was effective in reducing over-topping in the model because berm height above the reef flat remained the same, meaning waves had to travel a greater horizontal distance to cause inundation on islands with a flatter beach face.

### 7.4.3 Berm Emergence and Inundation

Model results show that reef depth and berm height have the most significant influence on wave inundation. When integrated, berm height above the still water level (berm emergence, $BE$) has a fundamental influence on inundation (Fig. 7.6). In total, the 4 berm elevations and 6 reef depths resulted in 12 $BE$ values between -1 m and 4.5 m, (at 0.5 m increments). Model results show inundation will always occur when sea level is equal or above berm height ($BE \leq 0$ m), regardless of reef morphology or wave condition (Fig. 7.6). Alternatively, $BE = 3$ m resulted in no inundation and $BE = 2.5$ m only resulted in inundation during storm wave conditions when reef width 100 m (Fig. 7.6c). Berm emergence increasing from 0.5 m to 2 m resulted in a steady decrease in wave inundation, with narrow reefs and larger incident waves resulting in more wave inundation events (Fig. 7.6). Of note, some low $BE$ values represent a shallow reef flat and a low island ($hr = 1$ m, $Z_{berm} = 2$ m) with the same $BE$ possible on a deep reef with a high island ($hr = 3$ m, $Z_{berm} = 4$ m). Figure 7.4 shows how $BE = 1$ on shallow and deep reefs can both result in inundation, with setup and IG waves influencing runup on shallow reefs ($hr < 1.5$ m) and a combination of SS and IG waves controlling runup on deeper reefs ($hr < 3$ m).
Chapter 7: Morphology controls on wave processes and inundation

7.5 Discussion

7.5.1 Reef morphology controls on wave transformation

Reef morphology determines how incident waves are transformed across the reef flat and consequently dictates the range and magnitude of wave processes that reach the shoreline of coral reef islands (Kench and Brander, 2006b, Quataert, et al., 2015). It is well recognised that reef depth and reef width control the height of SS waves at the shoreline, with higher energy shorelines characterised by a narrow and deep reef flat (Kench and Brander, 2006b). Model outputs presented here, and simulations from Quataert, et al. (2015) also highlight that SS wave height at the shoreline increases proportional to fore-reef slope and decreases with higher friction. The influence of reef morphology on wave setup is also reasonably well understood, with larger setup observed when reef depth
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decreases, due to a greater rate of SS wave attenuation (Becker, et al., 2014, Gourlay, 1994, Gourlay, 1996b). Wave setup is also understood to increase when fore-reef slope increases, due to the greater amplification of wave height prior to breaking (Gourlay, 1996b, Gourlay, 2011a, Quataert, et al., 2015). Model results presented here agree with these previous studies and further highlight that setup observes a subtle decrease when reef width or friction increase.

The numerical simulations in this chapter reveal significant new insights into the morphological controls on the behaviour of IG on coral reefs. Chapter 6 noted that across reef changes in IG wave height is different on wider reefs compared to narrow reefs. To summarise, shoreward amplification has been observed on narrow \( W_r < 300 \text{ m} \) reefs (Beetham, et al., 2016, Ford, et al., 2013, Quataert, et al., 2015) but shoreward dissipation is typically observed on wider \( W_r < 300 \text{ m} \) reefs under moderate incident wave conditions (Pomeroy, et al., 2012, Van Dongeren, et al., 2013). Under the wave conditions used in this analysis, model results show that shoreward amplification of IG wave height is most pronounced on the 100 m wide reef, with a greater proportional amplification when reef depth decreases (Fig. 7.3). IG wave heights at the shoreline on the 300 m wide reef were marginally larger than at the reef edge, with the increase in height mainly observed on the inner reef flat. IG wave height on the 600 m and 1000 m wide reefs typically decreased towards the shoreline on shallow reefs \( h_r < 2 \text{ m} \). However, a shoreward increase was observed on wider reefs with \( h_r < 2 \text{ m} \) (Fig. 7.3). Morphological characteristics that promote shoreward amplification can be explained by comparing the frequency of incident IG waves with the natural frequency of the reef (Fig. 7.7). Resonant amplification occurs when the frequency of incident IG waves is similar to the natural frequency of the reef, a function of reef depth and width (Péquignet, et al., 2009, Roeber and Bricker, 2015).
The natural frequency of the 100 m wide reef was consistently closest to the frequency of incident IG waves, especially under swell and storm wave conditions at lower reef depths (Fig. 7.7), which are the conditions that promoted maximum shoreward amplification (Fig. 7.3). However, IG wave periods were not long enough to create single node resonant amplification on reefs wider than 100 m, under any of the tested wave conditions. Shoreline amplification is possible on the wider reefs under extreme conditions or under moderate wave conditions if multiple standing wave nodes are established across the reef with an antinode at the shoreline (Roeber and Bricker, 2015). The presence of a multi-node standing wave would explain the oscillations observed in Figure 7.3 and the increase in $H_{ig}$ that was typically observed between the inner reef flat and shoreline. The natural frequency of a reef decreases as reef depth increases, meaning IG wave amplification will become more accessible at higher sea levels (Péquignet, et al., 2009). This decrease in natural frequency associated with increasing reef depth may explain why shoreward amplification started to occur on the wider reefs when $h_r$ exceeded 2 m (Fig. 7.3).

![Figure 7.7: Correlation between peak IG frequency at the reef edge and the reefs’ resonance frequency for each reef width and depth combination using $C_f = 0.02$, $\beta_r = 1:2$, $\beta_{beach} = 1:14$ and $Z_{berm} = 5$ m under a) mean, b) swell and c) storm wave conditions.](image)

IG wave resonance is typically only considered during extreme wave conditions, when the shoreward amplification of IG waves can cause devastating runup and inundation (Péquignet, et al., 2009, Roeber and Bricker, 2015, Shimozono, et al., 2015). However, the
analysis presented throughout this thesis shows that resonant amplification of IG waves can occur on narrow reefs under moderate swell and storm wave conditions. Shoreward amplification of IG waves on reefs such as Fatato is a fundamental characteristic of the contemporary process regime and results in IG wave activity at the shoreline throughout the tidal cycle (Beetham, et al., 2016).

Results in Chapter 6 showed how SLR will decrease the influence of IG waves at the shoreline on Fatato Island, with runup and inundation being largely associated with SS frequency waves. However, the analysis presented here demonstrates that IG waves will remain a significant component of the reef flat process regime with SLR on wider reefs. Peak $H_{lg}$ at the shoreline under storm wave conditions was observed at $h_r = 1$ m on the 300 m reef but was not reached until $h_r = 2 - 2.5$ m on the 600 m and 1000 m reefs (Fig. 7.2). Therefore, SLR on wider reefs may be associated with a slight decrease in $H_{lg}$ at high tide but will result in larger IG waves at the shoreline at low and mid tides, which will potentially increase the net magnitude of shoreline IG wave activity over a full tidal cycle.

At contemporary sea levels, wider reefs require a greater water depth and longer period IG waves to force resonant modes, limiting shoreward amplification to extreme incident conditions (Péquignet, et al., 2009, Shimozono, et al., 2015). However, SLR will decrease the frequency required for IG amplification on wider reefs, which will lower the incident wave energy required for shoreward amplification.

Overall, wave transformation results identify how reef morphology and sea level determine the magnitude and significance of wave processes at the shoreline. This residual wave energy at the shoreline dictates elevation of wave runup on island shorelines and determines whether inundation will occur on a given island morphology.
7.5.2 The island inundation index ($I^3$)

The simulations presented in this chapter provide a unique analysis of how reef morphology, island morphology and sea level (reef depth) influence wave processes on the reef flat and inundation on atoll islands. Wave inundation on atoll islands is a combined influence of sea level, tide level, setup and swash from IG and SS waves (Merrifield, et al., 2014). Therefore, the potential for inundation is primarily determined by how incident wave energy is transformed across the reef flat and the magnitude of secondary wave motions that reach the island shoreline (Merrifield, et al., 2014). Model results show that the magnitude of wave processes at the shoreline is primarily controlled by reef depth and reef width. A ratio between reef depth and reef width, termed the ‘reef energy window’ (Eq. 2.4) was identified by Kench and Brander (2006b) to evaluate the relative wave energy available for geomorphic work at the shoreline. Whether residual wave processes at the shoreline cause inundation is fundamentally determined by island morphology, especially berm elevation above the still water level (Fig. 7.6).

The ratio between reef depth and reef width was combined with berm emergence to create the island inundation index (Fig. 7.8). The island inundation index ($I^3$) was developed by identifying the percentage occurrence of inundation under all possible combination of $h_r/W_r$ and $BE$ from the 2,304 simulations, encompassing all wave conditions and morphology variations (reef slope, beach slope and friction). The $I^3$ index is potentially a widely applicable classification scheme for identifying inundation vulnerability under moderate to high energy wave conditions ($H_s = 1.3 – 2.6$ m and $T_p = 10 – 16$ s). Six inundation levels are identified in Figure 7.8 with the lowest level being no inundation and the highest level being constant inundation. No inundation was identified when no overtopping events were observed using certain combinations of depth, width and berm height. Under moderate wave conditions the minimum $BE$ required to prevent inundation can be calculated as:
where \( \ln \left( \frac{h_r}{W_r} \right) \) is the natural logarithm of the reef energy window. Equation 7.2 was developed by fitting logarithmic trend line to the 0% inundation line in Figure 7.8, characterised by \( R^2 = 0.97 \). Constant inundation was identified in the \( I^3 \) scale when all simulations characterised by a specific set morphological parameters observed inundation (Fig. 7.8). Between ‘no inundation’ and ‘constant inundation’ four inundation levels were characterised at 25% intervals as mild (1 – 25 %), moderate (26 – 50 %), severe (51 – 75 %) or chronic (76 – 100 %) inundation (Fig. 7.8). The true location of a reef within the spectrum will also depend on friction, slope and wave climate, but the \( I^3 \) scale is designed to provide a generalised understanding of the morphologic controls on inundation that encompass the range of slopes and friction values used in this analysis. To test the application of the island inundation index, islands from a number of previous studies are located on the \( I^3 \) spectrum, with reef depth and \( BE \) relative to contemporary spring high tide (Table 7.1).
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Figure 7.8: The island inundation index. Different levels of inundation vulnerability are identified using reef depth, reef width and berm emergence. Inundation levels are based on model outputs for all 2,304 simulations, inclusive of the three incident wave conditions and all morphological variations. The location where Fatato Island sits on the inundation spectrum is highlighted, along with other reef islands that have data for wave transformation or inundation. The $BE$ value and $hr$ values used for each location relate to spring high tide. The geomorphic characteristics of each island are presented in Table 7.1.

Table 7.1. Morphologic characteristics for each island located in Figure 7.8. *STR is spring tide range, Berm elevation is relative to MSL, $hr$ is reef depth at spring high tide, $BE$ is berm elevation above spring high tide.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Island Name</th>
<th>$Wr$ (m)</th>
<th>*$hr$ (m)</th>
<th>STR* (m)</th>
<th>*Berm (m)</th>
<th>$h/Wr$</th>
<th>*BE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuvalu</td>
<td>Beetham et al. (2016)</td>
<td>Fatato</td>
<td>100</td>
<td>1.77</td>
<td>2.0</td>
<td>3.5</td>
<td>0.0177</td>
</tr>
<tr>
<td>Australia</td>
<td>Kench and Brander</td>
<td>Warraber</td>
<td>2700</td>
<td>1.95</td>
<td>3.6</td>
<td>3.7</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>(2006b)</td>
<td>*LEI, East</td>
<td>400</td>
<td>2.75</td>
<td>4.0</td>
<td>4.0</td>
<td>0.0069</td>
</tr>
<tr>
<td>Marshall Islands</td>
<td>Ford et al. (2013)</td>
<td>Majuro, South</td>
<td>110</td>
<td>0.8</td>
<td>1.6</td>
<td>2.0</td>
<td>0.0073</td>
</tr>
<tr>
<td></td>
<td>Quataeret al. 2015</td>
<td>Roi-Namur, NW</td>
<td>250</td>
<td>0.8</td>
<td>1.6</td>
<td>2.8</td>
<td>0.0032</td>
</tr>
<tr>
<td></td>
<td>Merrifield et al. (2014)</td>
<td>Majuro, East</td>
<td>250</td>
<td>0.8</td>
<td>1.6</td>
<td>2.0</td>
<td>0.0032</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roi-Namur, NE</td>
<td>350</td>
<td>0.8</td>
<td>1.6</td>
<td>2.0</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

Fatato Island is located within the upper bracket of the mild inundation level, with an approximate 10% chance of inundation under 2.6 m high incident waves (Fig. 7.8). Results from Chapter 6 show that runup under storm waves will be very close to overtopping the berm on Fatato at spring high tide, with a 0.3 m rise in MSL required before inundation.
occurs on Fatato. Therefore, the simplified morphology and generalised range of friction, reef slope and beach slope values that were used to cover a broad range of reef types mean the location of Fatato in Figure 7.8 is not perfect, but is close results presented in Chapter 6. The location on Fatato in Figure 7.8 also implies that inundation would occur on an island similar to Fatato that is characterised by a smoother reef flat or a steeper reef slope.

Wave transformation studies on Lady Elliot Island (LEI) and Warraber Island were used to develop the reef energy window presented in Kench and Brander (2006b). Warraber Island has a very wide reef flat (2.7 km) and even with a large spring tide range had the lowest energy window in Kench and Brander (2006b), with minimal wave activity observed at the shoreline (Brander, et al., 2004). The reasonably high berm and extremely low \( h_r/W_r \) ratio clearly classify Warraber as having little chance of inundation at spring high tide, with incident \( H_s \) up to 2.6 m (Fig. 7.8). The eastern (ocean side) shoreline of LEI was shown to have a small chance of inundation at spring high tide. LEI has a similar berm emergence to Warraber but the deeper and narrower reef flat result in much higher wave energy at the shoreline. Nevertheless, LEI is not frequently exposed to energetic ocean waves exceeding \( H_s = 2 \) m and is therefore reasonably well protected from inundation at present sea levels.

The majority of recent studies of wave transformation and inundation specific to atoll islands have come from field based experiments in the Marshall Islands (Becker, et al., 2014, Ford, et al., 2013, Merrifield, et al., 2014, Quataert, et al., 2015), where reefs are characteristically narrow and shallow (Table 7.1). Narrow reef widths combined with a berm emergence of 1.2 m classified Roi-Namur northeast and Majuro east in the mild inundation level (Fig. 7.8), with Majuro south located in the moderate inundation level. Majuro south had the narrowest reef width of studies in the Marshall Islands and is where an overtopping was observed by Ford, et al. (2013) under moderate swell conditions \( (H_s = 2 \) m, \( T_s = 16 \) s). These observations support the classification of Majuro south as being
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prone to inundation, the most vulnerable of all islands located in Figure 7.8. Analysis by Merrifield, et al. (2014) shows that wave inundation occurs on Majuro east and Roi-Namur northeast approximately every 3-4 years, when moderate to high energy wave events ($H_s = 2 – 3$ m) coincide with a spring high tide. This supports the location of Majuro east and Roi-Namur northeast at the more critical limit of mild inundation, with Majuro east slightly more vulnerable due to the narrow reef width (Fig. 7.8). Roi-Namur northwest has similar reef properties as Majuro east (Table 7.1, Quataert, et al. (2015)) but is characterised by a higher berm emergence that results in 0% chance of inundation under the tested wave conditions (Fig. 7.8).

The conceptual summary of atoll island susceptibility to inundation (Figure 7.8) is not designed to replace detailed site specific analysis, such as presented in Chapter 6 for Fatato Island. However, the inundation index is a suitable guide for assessing inundation vulnerability across a wide range of settings and spatial scales, using easily measured morphologic properties. The index does not consider the potential for inundation under extreme wave conditions (incident $H_s > 2.6$ m) but was designed to assess how average and annual event scale wave events can lead to berm overtopping and island flooding.

7.5.3 Sea level rise implications for atoll islands

The mechanisms associated with reef island formation typically result in an island morphology that reflects the environmental processes it was formed under (Kench, et al., 2009c). Island height, distance from the reef edge and sediment composition are influenced by the texture of reef derived sediment and the energy regime required to transport and deposit entrained material (Bayliss-Smith, 1988, Gourlay, 1988, Kench, 1998a, Woodroffe, 2008). For example, Fatato on Funafuti Atoll is a motu island comprised of coarse sediment that is located within 100 m of the reef edge and is frequently exposed to energetic wave action. However, the berm on Fatato is elevated 3-4 above mean sea level (~5 m above the
central reef flat) and prevents over-topping during annual storm and swell wave conditions (Chapter 6). Sea level rise will move island morphology out of equilibrium with contemporary boundary conditions, resulting in greater energy at the shoreline and a greater risk of over-topping and inundation (Fig. 7.9). Without reef growth, SLR will increase the $h_r/W_r$ ratio that dictates wave energy transformation across the reef flat, forcing islands to shift towards the right side of the island inundation index (Fig. 7.9). Without island growth, berm emergence will also decrease with SLR, meaning less energy is required for inundation and islands will move downward on the inundation index (Fig. 7.9).

![Figure 7.9: The island inundation index showing the shift in vulnerability to inundation on the labelled island, with SLR up to 1 m (0.1 m increments). Island locations at present spring high tide (SHT) are shown in green (same as Figure 7.8). The trajectory of island vulnerability is shown in black, with the inundation vulnerability with 1 m of SLR identified in red.](image)

The trajectory of changes in vulnerability with SLR between 0.1 and 1 m is shown for each island in Figure 7.9. Each island crosses at least one level in the inundation spectrum, while migrating down and to the right (Fig. 7.9). The SLR trajectory is characterised by a different gradient for each island in Figure 7.9, with a flatter gradient reflecting a more significant change to the energy window, resulting in greater wave energy at the shoreline. The SLR trajectory for Warraber Island is characterised by a steep gradient, highlighting that SLR will have minimal impact on wave energy reaching the shoreline because the wide reef flat
can accommodate a 1 m change in depth with minimal change to the $h/W$ value. Therefore, the increased potential for inundation is primarily associated with a decrease in berm emergence (Fig. 7.9). The SLR trajectory for Warraber Island shows that mild inundation will initially occur with SLR between 0.8 - 1 m. However, the location of Warraber in the Torres Strait shelters the island from exposure to energetic incident waves which further indicates a minimal threat of inundation with up to 1 m of SLR. The flatter gradient in the trajectory for LEI indicates a more significant increase in shoreline wave energy with SLR. Combined with a decrease in berm emergence, LEI shifts into the severe (<50%) level of inundation with 1 m of SLR (Fig. 7.9). Roi-Namur northwest will observe a significant change to the wave process regime with SLR and will observe severe inundation with 1 m of SLR (Fig. 7.9). The relatively high berm on Roi-Namur northwest protects the island from more serious inundation observed at the other Marshall Island locations. The low berm elevation and sensitivity to changes in wave transformation on Roi-Namur northeast, Majuro east and Majuro south result in a significant shift towards chronic or constant inundation with 1 m of SLR (Fig. 7.9). Majuro south has the narrowest reef flat of the Marshall Island locations and was therefore identified as the most vulnerable island to inundation. Fatato Island is characterised by a similar trajectory of change when compared to Majuro south, but the relatively high berm emergence means Fatato only moves to the severe inundation level with SLR of 1 m. The higher berm elevations on Fatato, LEI and Roi-Namur northwest mean these islands accommodate higher energy at the shoreline and delays the onset of serious inundation predicted for the two Majuro locations and Roi-Namur northeast (Fig. 7.8).
7.6 Summary

Sea level rise will fundamentally change the nature of wave transformation on coral reefs, resulting in more wave energy reaching the shoreline of atoll islands. However, increasing sea level will influence different wave frequencies in varying ways. The influence of SLR on wave processes at the shoreline will largely depend on reef morphology. Model results show that SS wave height, IG wave height and setup are maximum on narrow reefs with low friction and a steep offshore reef slope. The response of IG waves to SLR will depend on reef width. Narrow reefs that currently observe shoreward amplification of IG waves under moderate storm and swell conditions will show a decrease in IG wave height at the shoreline with SLR. However, the magnitude of IG waves on wider reefs will initially increase with SLR as the natural frequency for shoreward amplification decreases. Model results show that the sea level for peak $H_{ig}$ at the shoreline increases proportional to reef width, highlighting that the sea level threshold for a decrease in IG wave height at higher levels of SLR on wider reefs. For islands with a wide reef flat, this means IG waves will still influence wave runup and inundation at moderate levels of SLR, whereas SS frequency waves will control inundation on islands with a narrow reef flat.

Model results show that the key morphologic characteristics that determine the nature of wave transformation on coral reefs are reef depth and reef width. This observation supports the conceptual reef energy window developed by Kench and Brander (2006b) and was used to develop an inundation index for atoll island vulnerability to wave overtopping. Analysis from the 768 morphological combinations indicates that the potential for inundation under a given shoreline wave regime is a function of berm height above the still water level. The island inundation index combines the reef energy window from Kench and Brander (2006) with berm emergence to predict the potential for wave inundation under any combination of reef depth, reef width and berm height.
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Application of the island inundation index to a number of studied reef islands further highlights how reef and island morphology dictate island vulnerability to inundation with SLR. Islands with a narrow and shallow reef flat will observe significant changes to wave transformation processes with SLR, resulting in significantly higher energy reaching the shoreline (e.g. Fatato, Majuro South). Berm emergence decreases at the same rate as SLR. This means that as more wave energy reaches the shoreline, less energy is actually required for wave inundation. Since reef depth influences both axes on the inundation spectrum, reef island vulnerability to wave overtopping rapidly increases with SLR. Model results suggest that islands on wider reefs have a greater capacity to resist inundation with SLR because the magnitude of shoreline wave energy is less sensitive to reef depth (e.g. Warraber Island).

The island inundation index and the discussion in Chapter 6 emphasise that the primary way to mitigate wave inundation is for islands to maintain their contemporary elevation above spring high tide. There is potential for island growth to occur naturally, through sediment deposition during over-wash events (Kench and Cowell, 2001, Woodroffe, 2008). Alternatively, shoreline protection structures on developed islands can be designed to maintain a minimum height above projected future sea levels. Equation (7.2) can be used to calculate the minimum berm elevation (above spring high tide) required to prevent inundation under moderate wave conditions.
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8.1 Research context and rational

Sea level in the tropical Pacific has risen since 1950 and is projected to continue rising by up to 0.7 m before 2100 (Becker, et al., 2012, Church, et al., 2013, Church and White, 2011). The potential impacts of SLR on low lying atoll islands has raised global concern regarding their existence over the next 100 years (Cazenave and Cozannet, 2014, Connell, 2003, Lazrus, 2012, Leatherman, 1997). However, a recent review by McLean and Kench (2015) indicates that reef islands are dynamic landforms that continuously adapt their morphology in response to changing boundary conditions. Dissipation and transformation of wave energy provides a key control on reef island morphology and location (Gourlay, 1988, Kench, 2013). However, despite the highlighted importance of wave energy dissipation on reef systems (Ferrario, et al., 2014), the impact of SLR on wave transformation processes on coral reefs is not well understood. This thesis examined how wave driven physical processes that influence reef island morphology will respond to SLR.

A primary concern for populated reef islands is that SLR will increase the frequency and magnitude of wave inundation events that could devastate infrastructure, agriculture and fresh water supplies (Hoeke, et al., 2013, Merrifield, et al., 2014). Understanding the vulnerability of atoll islands to inundation relies on a detailed understanding of how reef depth controls wave processes at the shoreline. However, minimal work has been done to understand the contemporary wave transformation processes that lead to wave runup and inundation (Merrifield, et al., 2014) and few studies have considered how the wave transformation processes on coral reefs will change with SLR (Quataert, et al., 2015,
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Storlazzi, et al., 2011). The majority of research on wave transformation has focused on SS wave dissipation across the reef flat, leading to a comprehensive understanding of tidal controls on shoreline wave height (Brander, et al., 2004, Ferrario, et al., 2014, Kench and Brander, 2006b, Péquignet, et al., 2011). However, inundation at present sea level is not typically associated with SS waves, but is largely attributed to wave setup and over-wash from IG waves (Ford, et al., 2013, Hoeke, et al., 2013, Merrifield, et al., 2014, Roeber and Bricker, 2015). A lag in attempts to understand how sea level controls setup (Becker, et al., 2014) and IG waves (Beetham, et al., 2016) on coral reefs has significantly limited any detailed assessment of how SLR will change wave runup and inundation processes which is critical for improved vulnerability assessments.

8.2 Major research findings

The primary aim of this thesis was to resolve how sea level (reef depth) controls the wave transformation processes that contribute to wave runup and inundation on coral reef islands. This aim was achieved using a combination of field data and numerical model simulations leading to a new understanding of physical processes on coral reef systems. Specifically, this study presents the first assessment of how SLR will alter wave transformation processes, runup and inundation using Fatato Island, Funafuti Atoll as a test site. The analysis has also been extended across a series of idealised reefs with variable morphologies. Model simulations were used to develop a morphology based index to classify atoll island vulnerability to wave inundation at present and higher sea levels.

8.2.1 Numerical model evaluation

The first stage of this thesis focused on evaluating model skill and sensitivity for applying Basilisk GN to simulate wave processes on coral reef environments. At flume scale, Basilisk GN was capable of simulating the dissipation of irregular incident waves while representing the behaviour and magnitude of IG waves, setup and runup. Sensitivity
analysis was undertaken to understand the influence of breaking and friction parameters, with the highest collective model skill (0.93) achieved using $C_f = 0.005$ and $B = 0.7$. Model capability was further evaluated at field scale using measurements from Fatato to assess model skill, error and sensitivity (Chapter 5). Wave processes on Fatato were most accurately represented using $C_f = 0.04$ and $B = 1$, achieving skill > 0.96; MAE < 0.37; and $R^2 > 0.86$ for predicting $H_{ss}$, $H_{ig}$ and $\bar{\eta}$ at the shoreline, across 500 incident conditions. Model evaluation results show that Basilisk GN can be used to provide a confident representation of the wave processes that operate on coral reefs to influence wave runup and inundation.

8.2.2 Sea level controls on wave transformation across coral reefs

Results in this thesis provide the first assessment of wave transformation processes on Funafuti Atoll, a site that is frequently cited as being highly vulnerable to SLR (Connell, 1999, Connell, 2003, Dickinson, 1999, Farbotko and Lazrus, 2012, Patel, 2006). Field data from Funafuti reveal several new insights regarding wave transformation on atoll reefs, especially in the context of a narrow reef flat that is exposed to energetic incident waves. On average, SS wave height at the shoreline of Fatato Island was 78% of incident wave height, with less attenuation at high tide (65%) compared to low tide (90%). Wave setup on Fatato clearly reflects the tidal control on SS wave attenuation, with minimum setup at high tide ($0.08 - 0.27$ m) and maximum setup at low tide ($0.3 - 0.89$ m). Wave setup is significant on Fatato because the elevated water level at low tide typically submerges the reef flat, allowing IG waves to reach the shoreline at all tidal stages (Beetham, et al., 2016).

A number of key observations were made regarding IG wave behaviour on Funafuti. First, IG wave heights at the reef flat and shoreline were not influenced by tidal water level. Second, IG waves were amplified towards the shoreline, increasing in height by $0.1 - 0.2$ m between the reef edge and island, resulting in a maximum IG wave height of $0.77$ m at
the shoreline. This is in direct contrast to measurements taken on wider reefs that consistently show a shoreward dissipation of IG waves under similar wave conditions, with larger IG waves on the reef flat at high tide (Péquignet, et al., 2014, Pomeroy, et al., 2012, Van Dongeren, et al., 2013). Other field studies have previously commented on the shoreward amplification of IG wave height on narrow reefs (Ford, et al., 2013, Quataert, et al., 2015), but the conditions that promote this phenomenon remain poorly understood.

Further analysis in Chapter 7 revealed shoreward amplification of IG waves occurs under moderate wave conditions when the reef flat is narrow ($W_r < 300$) and shallow ($h_r \leq 2$ m). This resonant amplification is associated with the reef flat developing a natural frequency that is similar to the period of incident wave groups.

Systematic simulations of wave transformation with SLR indicate a linear increase in SS wave height, which significantly increases spectral density within the SS wave band at the shoreline. The increase in SS wave height is reciprocated by a significant decrease in setup magnitude across the reef flat, with setup decreasing at approximately half the rate of SLR. Model results indicate that the contemporary relationship between tide level, SS wave height and setup remains consistent with SLR scenarios up to 1.5 m. The response of IG waves to rising sea level is more complex. Field data and simulations on Fatato identified a threshold sea level for peak $H_{ig}$ at the shoreline somewhere between MSL and high tide, with the exact sea level a function of incident wave conditions. Model simulations on Funafuti show that SLR will be associated with a decrease in IG wave height at the shoreline because more energy is conserved within the SS wave band. These results are the first indication that the significance of IG waves on coral reefs will decrease with SLR. Similar IG wave behaviour was observed when simulating wave transformation processes on idealised reefs with a 100 m wide reef flat. However, when reef width was increased the sea level threshold for peak $H_{ig}$ also increased. These results imply that SLR will increase
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IG wave height at the shoreline of wider reefs at lower tide stages, with a decrease in IG wave height at higher tides.

8.2.3 Wave runup and inundation

The extent of incident wave dissipation across the reef flat determines the magnitude of wave setup, IG waves and SS waves at the shoreline. Combined, these three wave processes determine runup elevation above the still water (sea level + tide) elevation (Merrifield, et al., 2014). Berm elevation and beach face morphology determine whether wave processes at the shoreline cause an inundation event. Since IG waves on Fatato are amplified towards the shoreline and undergo no tidal modulation, IG motions were identified as the key process contribution to runup elevation at the shoreline. Model simulations on Fatato provide the first analysis of tidal controls on runup processes and elevation, highlighting that islands on the eastern rim of Funafuti are exposed to wave action for the majority (71%) of the tide cycle (Beetham, et al., 2016). Mean wave conditions at Funafuti were simulated to cause inundation on Fatato Island at spring high tide with 0.9 m of SLR. Swell and storm waves were predicted to cause inundation at spring high tide with 0.3 m of SLR. SLR on Fatato will be characterised by much more SS wave energy at the shoreline, with SS frequency waves providing the main source of inundation under all simulated levels of SLR, with all tested wave conditions. Analysis of SLR with reef growth on Fatato shows that vertical reef accretion can preserve the contemporary process regime. However, the continued importance of IG waves and setup associated with reef growth mean a keep-up reef response has limited potential to mitigate the increase in wave inundation with SLR, assuming non response in island morphology. Simulations with an idealised morphology show that islands characterised with a narrow reef flat, a steep reef slope, low roughness and a low island berm are most susceptible to inundation.
Chapter 8: Concluding discussion

8.2.4 Vulnerability of coral reef islands to sea level rise
Reef island morphology has developed in equilibrium with local wave processes, sediment characteristics and reef morphology over the last three to five thousand years of relatively stable sea level (Kench, 2013, Woodroffe, et al., 1999). A rise in mean sea level will shift island morphology out of equilibrium with local wave processes, resulting in more wave energy at the shoreline and frequent inundation events. However, not all islands are equally vulnerable to inundation with SLR. The reef energy window developed by Kench and Brander (2006b) was combined with berm height (above sea level) to develop the island inundation index, based on 768 reef and island morphology combinations and 3 incident wave conditions. The inundation index is a simple tool for assessing island vulnerability to wave inundation and was used to classify levels of inundation with SLR on a number of studied reef islands in the Pacific Ocean. Results highlight that SLR on coral islands with a narrow or shallow reef flat will substantially increase shoreline wave energy (e.g. Majuro, Fatato). Wave processes on islands with a wide (Warraber) or deep (LEI) reef flat are less sensitive to SLR and will only receive a moderate increase in wave energy. The increase in wave energy with SLR is combined with a decrease in the energy required for inundation, which means the frequency and magnitude of inundation on atoll islands will almost certainly increase with future SLR. Islands that are most vulnerable to inundation are characterised by a low berm height and a narrow reef flat. Inundation on atoll islands can be prevented if berm height maintains a threshold elevation above spring high tide level. This can occur naturally if sediment is deposited as over-wash material, or through engineering based berm nourishment.

8.2.5 Implications for coastal management
The new insights regarding wave transformation and inundation outlined in this thesis can be used to inform coastal management strategies. In particular, the results when applied to
other locations will be able to identify locations most at risk to wave inundation with SLR. Results of this study highlight considerable differences in process regimes and island inundation as a consequence of subtle variations in reef configuration and island elevation. Consequently, findings of this work provide the basis to develop a finer resolution analysis of variations in island vulnerability. The island inundation index provides a simplified tool for easily classifying the general vulnerability of an island to wave inundation. The simple morphologic parameters in the index allow for application at atoll scale or national scale to identify key areas of vulnerability. The simplified nature of the inundation index also means application will not always be sufficient. In these cases, Basilisk GN is free software that can be used for a more site specific identification of coastal vulnerability to wave inundation. The model evaluation work in Chapters 4 and 5, and the application of Basilisk GN to simulate SLR scenarios on Fatato provide a technical baseline for scientists and engineers to investigate wave transformation processes on reef environments using the GN equations.

This research highlights the significance of maintaining a threshold berm height to prevent inundation under annual wave conditions. Model results show that increasing berm height with SLR is more effective at limiting inundation when compared to decreasing shoreline wave energy. To mitigate wave inundation on developed islands, coastal managers can implement a nourishment scheme or upgrade shoreline defence structures to make sure berm elevation maintains a threshold elevation above spring high water level. The berm elevation required for preventing inundation under moderate wave conditions ($H_s = 2.6 \text{ m;} \ T_p = 10 \text{ s}$) can be calculated from reef width and reef depth using Equation (7.2).
8.3 Future research ideas

This thesis has identified a number of new insights regarding wave transformation and inundation on reef environments. The findings also highlight avenues for further research that include:

1. **Field measurements across a wider variety of reef morphologies**

   Field data collected for this thesis were limited to the ocean shoreline of one island on the eastern rim of Funafuti Atoll. Future work can be done to measure wave transformation processes across a wider range of natural and developed atoll and platform islands in Tuvalu and on other atolls in the Pacific and Indian Ocean (Kiribati, Tokelau, Marshall Islands, Maldives). It is also essential that wave data are collected for lagoon shorelines, where development is concentrated and berm elevation is lower.

2. **Two dimensional investigations of wave processes on coral reefs**

   Field data and numerical simulations in this thesis only considered wave transformation processes in one horizontal dimension. In reality, variations in incident wave direction and alongshore bathymetry result in refraction, diffraction and convergence processes that complicate wave processes on the reef flat. This is especially true on oval and circular platform reefs where wave refraction has a substantial influence on circulation patterns and island morphology (Flood, 1986, Gourlay, 1988, Mandlier and Kench, 2012). Field measurements of wave processes on platform reefs are limited to low energy settings where the influence of wave setup and IG waves is marginal or non-existent (Beetham and Kench, 2014, Kench, et al., 2009a, Kench, et al., 2009b). Mandlier and Kench (2012) highlight the importance of wave refraction on island formation, however little work has been undertaken to understand how SLR will change the nodal points of wave convergence that control island stability. Future research could examine and document wave refraction
processes on real and idealised platform reefs that are exposed to moderate or high energy wave conditions.

Boussinesq-type models are generally only used in 1D when applied to coral reef environments, with 2D simulations limited to Demirbilek and Nwogu (2007) and (Roeber and Cheung, 2012b). This is primarily due to the exponential increase in computational cost associated with solving processes in 2D. The quad-tree adaptive mesh implemented in Basilisk GN has proven to dramatically decrease computational costs in 2D (Popinet, 2015) but has not yet been applied to surf-zone processes on coral reefs. This research focused on using Basilisk GN in 1D to accommodate a large number of repeat model runs but future work will consider 2D simulations of wave refraction and convergence zone hydrodynamics on oval and circular reef platforms.

3. Analysis of island inundation across a wide range of incident wave conditions

It should be noted that this research only examined wave conditions that represent annual mean, swell and storm waves off the east coast of Funafuti Atoll. Future analysis using a greater range of incident wave conditions, including very low energy waves and very high energy waves would provide more detail on island vulnerability and could be used to add a wave height variable to the island inundation index.

4. Development of an eco-morphodynamic simulation model for reef environments

A major area of research that remains understudied is how island morphology will respond to SLR (McLean and Kench, 2015). This requires a greater understanding of the linkages between reef ecology and island sediment, and an improved understanding or wave processes and sediment transport dynamics. At present, there have been few attempts to numerically model wave generated sediment transport and morphodynamic feedbacks on coral reefs (Cowell and Kench, 2001, Kench and Cowell, 2001, Storlazzi, et al., 2011). One
reason for this is the numerical complexity required to represent sediment transport and the
different time-scales associated with wave transformation (seconds to minutes) and coastal
change (hours to decades). The eco-morphodynamic nature of coral reefs (Kench, 2013)
adds another complication when attempting to simulate reef island morphodynamics, and
there is a need to better understand links between reef ecology, sediment production and
island maintenance (Perry, et al., 2011). Developing an eco-morphodynamic computer
model for simulating interactions between reef ecology, sediment production, physical
processes, sediment transport, island formation and island change would dramatically
improve the potential for process based management on reef islands.


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