This file is part of the following reference:


Access to this file is available from:

An investigation of wave-dominated coral reef hydrodynamics

Thesis submitted by

Ron Karl Hoeke

Master of Physical Oceanography (Melbourne, Florida, USA)

In October 2010

for the degree of Doctor of Philosophy
School of Engineering and Physical Sciences
James Cook University
Statement of the contributions of others

Research funding:
NOAA/University of Hawaii Joint Institute for Marine and Atmospheric Research (stipend for 3.5 years) $72,000
US Geological Survey Coral Reef Project (project funding) $40,000
AIMS@JCU (project funding) $15,000
Graduate Research School, James Cook University $2,800
NOAA Coral Reef Conservation Program (in kind support) (NA)
US Geological Survey Coastal and Marine Geology (in kind support) (NA)
NOAA Coral Reef Conservation Program (in kind support) (NA)

Thesis committee:
Professor Peter Ridd, School of Engineering and Physical Sciences, James Cook University
Dr Richard Brinkman, Australian Institute of Marine Science
Professor Mark Merrifield, School of Ocean and Earth Science and Technology, University of Hawaii

Statistical and analytical support:
Dr. Curt Storlazzi (US Geological Survey)
Professor Peter Ridd
Dr. Jerome Aucan (Bermuda Institute of Ocean Science)
Dr. Edwin Elias (US Geological Survey)
Sean Vitousek (Stanford University)
Professor Mark Merrifield

Editorial support:
Professor Peter Ridd
Dr. Curt Storlazzi
Dr. Jerome Aucan
Professor Mark Merrifield
Dr. Gayle Kim Philip (University of Hawaii)
Amanda Toperoff (NOAA)
Dr. Rusty Brainard (NOAA)
Acknowledgements

First, I must thank my advisor Peter Ridd. He always provided insight and guidance, while maintaining good wit and cheer and, along with Thomas Stieglitz, showed me a bit of the Australian bush that I would have otherwise surely missed. Séverine Choukroun was a great fellow student who helped navigate the PhD candidature at James Cook University and to exchange research ideas with. I am also very appreciative of the academic and administrative assistance provided by the staff of the School of Engineering and the Graduate Research School, especially Barbara Pannach and Helene Marsh.

I owe big thanks to the support of the folks at the US Geological Survey’s Marine and Coastal Geology Program, specifically to Edwin Elias, Mike Field, Josh Logan, Kathy Presto, and Curt Storlazzi. Without this support, the Hanalei Bay portion of this work would not have happened. In addition to material support, Curt in particular offered great encouragement and mentoring along the way.

I also owe big thanks to many people at the NOAA Pacific Islands Fisheries Science Center Coral Reef Ecosystem Division and the closely connected University of Hawaii’s Joint Institute for Marine and Atmospheric Research. Rusty Brainard supported and encouraged my decision to return to graduate school; Kevin Wong kindly fostered my work towards the goals of the PhD research and also provided clear, lucid thinking on how to reach them. He, Lee Higa, Mike Seki, and especially Seema Balwani all helped steer the project through NOAA’s requisite bureaucracy. John Rooney, Frances Lichowski, and Jonathon Weiss provided geospatial expertise, and Jake Asher, Marie Ferguson, and Frank Mancini picked project instruments off the sea floor when I couldn’t get there. I cannot possibly sufficiently express my gratitude to my dearest friends and long-time co-workers Jamie Gove, Danny Merritt, Molly Timmers, Oliver Vetter, Jubilee-Felsing Watkins, and Chip Young, suffice to say they were all formative to me.

The inspiration for this course of study came largely from discussions with my dear friend Jerome Aucan, which occurred on Jen Homey’s front lanai in little Haleiwa town. Many of the ideas presented in this thesis have their root in these (sometimes late-night) discussions and any acknowledgments would be remiss without mentioning them. Sean Vitousek, Mark Merrifield, and others at the
University of Hawaii’s School of Ocean and Earth Science and Technology also provided insight, support and assistance along the way.

I must also thank my mother and father, Rainer and Marcia Hoeke for their love and continued support, despite my now more than ten years of tertiary education. Gayle Kim Philip also has been patient throughout the more stressful periods of my PhD candidature. For that, and for her adventurous, funny and kind companionship, I will always thank her.

And lastly, but certainly not least, I must thank my grandfather, Ronald L. Cooksey, who helped open my eyes to the natural world and instilled a keen interest to try to discover how it all works. He would be proud.
Abstract

The coastal zone is of great societal and economic value. Understanding anthropogenic impacts and natural processes is a prerequisite to effective management of coastal resources, and a key part of this understanding is the prediction (both past and future) of the coastal zone’s hydrodynamics. Methods of predicting the hydrodynamics of coral reef systems, which tend to be morphologically complex and subject to a variety of oscillatory and non-oscillatory motions over a large range of space and time scales, remain poorly developed.

Recent advances in numerical modeling have allowed the practical solution of the two- and three-dimensional shallow water Navier-Stokes equations at spatial scales on the order of tens of meters. This has allowed unprecedented prediction of coastal hydrodynamics, and its use is expanding, particularly in mid- to high latitude continental margins regions. Few researches have yet applied these advances to coral reef systems, however.

The goal of this work is to improve the understanding and prediction of relevant hydrodynamic processes in coral reef systems. This is accomplished by the combined analysis of in situ oceanographic instrument data and climate information, as well as the application of a coupled wave-flow numerical model at two different study sites. The study sites, Hanalei Bay and Midway Atoll, both in the Hawaiian Islands (Figure 1.1), constitute two fundamentally different reef morphologies, a fringing reef embayment and an atoll, respectively. Both are subjected to a wide range of wind-wave energy, which is shown to force the most energetic hydraulic motions at both sites.

Results include an evaluation of the numerical models used, a statistical analysis of wind-wave climate that identifies major modes of coastal circulation, and the calculation of flushing times and other coastal hydrodynamic metrics under different conditions. Model evaluation shows that if the spatially varying hydraulic roughness and wave dissipation approximations presented here are used, coupled wave/flow numerical model skill for steep and morphologically complex coral reefs may approach that of milder sloped mid-latitude continental margin coasts. The results also highlight important hydrodynamic differences between prevailing (wind and wave) conditions and episodic storm wave events. These events incur water
levels, current velocities, flushing rates, and inferred sediment transport several orders of magnitude greater than those of prevalent conditions. For instance, flushing (residence) times at both study sites are on the order of 1-3 days during prevalent conditions, whilst during large storm wave events flushing time may reduce to several hours. The high near-bed flows and associated shear stresses episodically mobilize and transport seafloor sediment and heavily impact the benthic biological community.

The number and magnitude of these episodic events are shown to exhibit high interannual variability linked to climate indices for El Niño/Southern Oscillation (ENSO) and the North Pacific Index (NPI). The historically small (but variable) number of these events (between 0 and approximately 20) indicate that annual differences in net sedimentation and water quality are very large at both sites, and most likely sensitive to long-term changes in annual recurrence. Additionally, large changes in sea level anomaly during these large wave events, evident in model predictions and confirmed by tide gauge data at Midway Atoll, introduce an unaccounted for variable in contemporary sea-level trend analyses, possibly at many in situ sea level monitoring sites in the Pacific and Indian Oceans.
Publications produced during the PhD Candidature

Peer-Reviewed:


Reports:


Brainard R.E., Bainbridge S., Brinkman R., Eakin C.M., Field M., Gattuso J.P.,
Gledhill D., Gramer L., Hendee J., **Hoeke R.K.**, Holbrook S., Hoegh-
Guldberg O., Lammers M., Manzello D., McManus M., Moffitt R., Monaco
M., Morgan J., Obura D., Planes S., Schmitt R., Steinberg C., Sweatman H.,
Ecosystem Observing Systems (I-CREOS)” *OceanObs Community White

**Presentations:**

embayment from offshore directional spectral model input”, *Presented at the
10th International Workshop on Wave Hindcasting and Forecasting*. Turtle
Bay, Hawaii.

system of the U.S. flagged Pacific Islands.” *Presented at the Workshop for
Coral Reef Managers: Responding to Mass Coral Bleaching and Climate
Change*, Lady Elliot Island, Queensland, Australia.

Heights at a Coral Atoll." *Presented at the AGU/ASLO/TOS Ocean Sciences
2008 Meeting*, Orlando, FL.

reef embayment; Hanalei Bay, Hawaii." *Presented at 11th International Coral
Reef Symposium*, Ft. Lauderdale, FL.

Coral Growth and Mortality Over the Next 100 Years in the Hawaiian
Archipelago." *Presented at 17th Hawaii’i Conservation Conference*, Honolulu,
Hawaii, USA.

circulation to sedimentation patterns and distribution of benthic habitats in a
fringing coral reef embayment." *Presented at the AGU/ASLO/TOS Ocean
Sciences 2010 Meeting*, Portland, Oregon.
Contents

List of Figures ................................................................................................................................. xi
List of Tables ........................................................................................................................................ xii

1. Introduction ...................................................................................................................................... 1
   1.1 Thesis Layout ......................................................................................................................... 4
   1.2 References ............................................................................................................................... 5

2. Hydrodynamics of a bathymetrically complex fringing coral reef embayment:
   wave climate, in situ observations and wave prediction .............................................................. 8
   Abstract ....................................................................................................................................... 8
   2.1 Introduction ............................................................................................................................ 9
   2.2 Methods .................................................................................................................................. 10
      2.2.1 Study Area Description ................................................................................................. 10
      2.2.2 Determination of Wave Climate .................................................................................. 12
      2.2.3 Nearshore In-situ Data Collection .............................................................................. 14
      2.2.4 Wave Model Implementation ....................................................................................... 15
   2.3 Results ..................................................................................................................................... 19
      2.3.1 Wave climate .................................................................................................................. 19
      2.3.2 Nearshore In-situ Observations .................................................................................... 21
      2.3.3 Wave Model Simulations ............................................................................................... 27
   2.4 Conclusions ............................................................................................................................. 36
   2.5 Acknowledgments ................................................................................................................... 39
   2.6 References ............................................................................................................................... 40

3. Hydrodynamics of a fringing coral reef embayment: circulation, flushing times, and
   implications for water quality and sediment transport ............................................................... 44
   Abstract ....................................................................................................................................... 44
   3.1. Introduction ............................................................................................................................ 45
   3.2. Study Area ............................................................................................................................. 47
   3.3. In situ Observations .............................................................................................................. 49
   3.4. Numerical Modeling ............................................................................................................. 50
      3.4.1 Computational grid, boundary design, and model application ................................... 51
      3.4.2 Wind and Wave Input ..................................................................................................... 53
      3.4.3 Wave dissipation ............................................................................................................. 53
   3.5 Results ..................................................................................................................................... 58
      3.5.1 In situ observations ......................................................................................................... 58
      3.5.2 Modeling ......................................................................................................................... 61
List of Figures

Figure 1.1 - Overview of the Hawaiian Archipelago with study areas indicated. ...3

Figure 2.1: Study site location maps: (a) Hawaiian Archipelago with the position of NOAA NDBC Buoy 51001 indicated (b) Hanalei Bay. .................................................12

Figure 2.2: Climatological monthly mean, standard deviation, mean monthly min/max and total observed min/max significant wave height. ...19

Figure 2.3: a–d. Seasonal directional wave climatologies generated from model hindcast data from 1996 to 2009 (WW3) and in situ buoy data, 2005–2009 (Buoy 1). Error! Bookmark not defined.

Figure 2.4: In situ waves, winds, and currents during observation period June 5, 2006 to April 10, 2007. ..........................................................22

Figure 2.5: Variance ellipses and Eularian mean vectors of in situ ADCP data plotted at their respective locations in Hanalei Bay. ........................................24

Figure 2.6: Principal axis of current velocities at the Wall site ($\vec{u}_p$) compared to wave energy flux values. Error! Bookmark not defined.

Figure 2.7: In situ wave observations and input model data for the trade wind conditions (August 2-9, 2006) ..........................................................28

Figure 2.8: In situ wave observations and input model data for the NW swell event (January 20-27, 2006). ..........................................................29

Figure 2.9: Comparison of overall composite root mean square skill scores (RMSSS) for selected local model runs. ...........................................................31

Figure 2.10: Comparison of varying model simulation resolution and propagation with in situ data during trade wind conditions, Aug 2-9, 2006. ................32

Figure 2.11: Comparison of varying model simulation resolution and propagation with in situ data during NW swell event, January 20-27, 2006. ........33

Figure 2.12: Modeled significant wave height ($H_s$) with peak direction ($\theta_p$) indicated by arrows. ..........................................................35

Figure 2.13: Calculated bed shear due to waves ($\tau_w$). ........................................36

Figure 3.1: Study site: North Coast of Kauai, with Hanalei Bay at the center. ....47

Figure 3.2: Principle axis current magnitude at the Wall Site ($|U_{p,0}|$), predicted from incident unit energy flux ($EC_g$), and mean normalized residuals for binned values of the Iribarren ($I_r$) parameter. ..................................................56

Figure: Comparison of bulk wave parameters and winds measured by Buoy 51001 during two one-week periods. ..................................................58

Figure 3.4: Comparison of conditions at the Wall site during the trade wind and NW swell periods. ..........................................................59

Figure 3.5: Comparison of CRAMP site and NW Reef site current vectors, water levels, and wave heights. ..........................................................60

Figure 3.6: Comparison of modeled values and observed values of $U_{max}$, $\eta$, $H_s$, and $\theta_p$ during the trade wind period: ........................................63
Figure 3.7: Comparison of modeled values and observed values of $U_{max}$, $\eta$, $H_s$, and $\theta_p$ during the NW swell period.................................................................64
Figure 3.8: Upper water column mean current vectors and magnitudes. ..................65
Figure 3.9: Unit volume flux over a cross section at the mouth of Hanalei Bay for 10 different idealized conditions..............................................................69
Figure 3.10: Mean current vectors and maximum bed shear stress ($\tau_{max}$).............70
Figure 3.11: Current/depth profiles near the center of the mouth of the bay...............73
Figure 3.12: Comparison of the annual number of episodic floods and episodic NWS events with the multivariate ENSO Index (MEI). ........................................766
Figure 4.1: Study site. (a) Midway Atoll's location in the Hawaiian archipelago. (b) Midway Atoll with in situ observation sites indicated.................................87
Figure 4.2: SLA at the Midway sea level station versus offshore wave energy flux ($EC_g$). .....................................................................................................................92
Figure 4.3: (a) Monthly correlation coefficients of SLA and inverse barometer effect (IBE), wind stress, wave energy flux (ECg) and satellite sea surface height deviation (SSHD). .................................................................93
Figure 4.4: Wave Climatology, Midway Atoll .......................................................95
Figure 4.5: Numerical model output during a large NW swell............................97
Figure 4.6: Model and observed significant wave height ($H_s$), sea-level anomaly (SLA), and depth-averaged cross-reef current magnitude ($|U|$) for the three selected modeling periods.................................................................99
Figure 4.7: The correlation of the annual number of wave events with MEI and NPI climate indices as predictors.................................................................101

List of Tables

Table 2.1: Instruments deployed in or near Hanalei Bay for this study. ....................14
Table 2.2: Mean and standard deviation (SD) of observed significant wave height ($H_s$) and current magnitude ($|U|$) .................................................................23
Table 3.1: Instruments deployed in or near Hanalei Bay for this study. ....................49
Table 3.2: Tidal constituent amplitudes and phases ..................................................52
Table 3.3: RMSE and model skill (IAS) ..................................................................62
Table 3.4: Mean, minimum and maximum modeled net volume flux (Qnet) across the mouth of the bay. .................................................................67
Table 4.1: Instruments deployed for model calibration ..............................................89
Table 4.2: Summary of conditions and model calculations during the three periods selected for numerical modeling.........................................................100