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# REPLY

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## INTRODUCTION

Payo and Muñoz-Perez (2013) (here, termed *PMP2013*) raise a number of issues surrounding the hydrodynamic interpretations and management implications presented in Ford, Becker, and Merrifield (2012) (here, termed *FBM2012*), concerning observations of a wave-driven inundation event at a Majuro Atoll, Marshall Islands, fringing reef and the impact of an excavation pit on shoreline wave energy levels. Based largely on scaling arguments obtained from laboratory experiments and models (Massel and Gourlay, 2000), PMP2013 contend that (1) wave breaking may be a more important dissipation mechanism than bottom friction on the reef flat; (2) across-shore changes in sea and swell (SS) and infragravity (IG) wave energy levels may be due to nonlinear energy transfer (Henderson *et al.,* 2006; Thomson *et al.,* 2006), as opposed to the claim of FPM2012 that these changes are due to spatially variable dissipation and disruption of the cross-shore IG energy structure caused by the presence of the excavation pit; (3) that the IG energy on the reef flat is due to bound waves; and (4) that lateral variation of incident wave conditions and shoreline reflectivity might explain lower wave heights landward of the excavation pit relative to the unmodified reef.

The alternative explanations of PMP2013 for the observations presented in FBM2012 have merit, and we welcome the opportunity to comment on our findings in more detail than in FBM2012. We emphasize that the data set collected at Majuro Atoll is insufficient to evaluate the claims of PMP2013 rigorously, and we strongly agree with PMP2013 that further studies are required to resolve these issues (also stated in FBM2012). However, based on recent studies of wave activity on fringing reefs similar to the Majuro Atoll study site, the observations presented in FBM2012, and our own visual observations during the field experiment, we contend that the explanations presented in FBM2012 are more plausible than are those proposed by PMP2013. We first consider the four points raised above and then comment on the implications for coastal management raised by PMP2013.

## REEF FLAT WAVE PROCESSES AND EXCAVATION PITS

### (1) Wave Dissipation on the Reef Flat

PMP2013 suggest from a scaling argument that breaking is potentially more important than bottom friction for energy dissipation on the reef flat. FBM2012 note that decreased bed roughness and increased water depth resulting from the excavation pit are possible mechanisms for the observed slight increase in SS wave height at sensor 1 (shoreward of the pit) *vs.* sensor 5 (shoreward of the unmodified reef flat). The observations of FBM2012 show that, during the incident wave conditions of deployment 1, waves had broken seaward of sensor 4 (FBM2012 Figure 5). Visual observations indicate that wave breaking occurs at the fore reef and reef edge and that most of the SS energy is dissipated in a narrow surf zone. The SS wave heights reported by FBM2012 at the mid and inner reef flat (FBM2012 Figure 2) scale with local water depth consistent with depth-limited breaking occurring seaward of the location of sensor 4 during both deployments (and during the overwash event).

On the mid to inner reef flat there was no indication of turbulent rollers or prevalent bubbles and white water on the reef flat (see FBM2012 Figure 3), although direct visual observations during the inundation event were not available. We believe that turbulent dissipation in the surf zone had already served to depth-limit the wave heights by the time they reached instrument 4 and, contrary to the speculation of PMP2013, the breaker zone did not extend to instrument 4 or shoreward of that location. Because the reef flat does not slope

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toward shore as on a sand beach, there is no cause for further steepening and breaking of waves as they propagate toward shore.

Previous observational and modeling studies of SS waves at study sites similar to Majuro Atoll (Péquignet *et al.,* 2011; Pomeroy *et al.,* 2012; Van Dongeren *et al.,* 2013) strongly suggest that wave breaking is important in a narrow surf zone near the reef edge and that frictional dissipation over the shallow, rough substrate of the reef flat is the primary dissipation mechanism for SS waves as they propagate toward shore. Hence, the water depth and bed roughness are two key considerations for assessing frictional dissipation.

We note that SS waves on the reef flat at times did resemble solitary bores (FBM2012 Figure 3b), and in that regard, turbulent dissipation may be important at the bore front. To our knowledge, this dissipation mechanism has not been investigated for reef flat waves. As suggested by PMP2013, it is possible that the excavation pit disrupted the bore propagation in such a way as to diminish the bore front turbulence, which would be an explanation in addition to bottom friction for why SS waves at the shore were slightly higher shoreward of the pit than they were at the unmodified reef site.

### (2) Nonlinear Energy Transfer between SS and IG Waves

We do not believe that nonlinear energy transfer between SS and IG waves on the reef flat is a dominant mechanism for explaining the observed wave height variations. Péquignet (2012) and Pomeroy *et al*., (2012) directly estimated the nonlinear energy transfer between SS and IG waves at fringing reefs similar to our study site and found that the rates were negligible compared with dissipation rates caused by bottom friction. Van Dongeren *et al*. (2013) used models to show that bottom friction over the reef flat strongly dissipated both SS and IG waves and concluded that nonlinear energy losses were not important. As pointed out by Pomeroy *et al*. (2012), laboratory and model studies of fringing reefs that have suggested the importance of nonlinear energy transfer on the reef flat (Demirbilek, Nwogu, and Ward, 2007; Nwogu and Demirbilek, 2010; Sheremet *et al.,* 2011) were based on idealized smooth substrates with considerably less bed roughness than found at field sites such as Majuro Atoll.

### (3) Character of IG Energy on the Reef Flat

PMP2013 further speculate as to whether the IG energy on the reef flat is due to bound waves or free long waves. We emphasize that the observations in FBM2012 on the reef flat and at the offshore wave buoy are insufficient to determine whether the IG energy observed during the pit experiment are due to bound waves nonlinearly driven by groups of swell. We speculate that variable SS wave breaking at the fore reef and reef edge is the dominant source of IG energy on the reef, as has been reported for similar sites by Péquignet (2012) and Pomeroy *et al*. (2012). Bound incident waves approach the study site are another potential source of IG energy. In either case, the IG waves accompany the incident SS waves, and their generation occurs when SS waves are energetic, *i.e*. seaward of the break zone (bound) or as waves shoal and break on the outer reef (locally generated), not when the SS waves are weak and actively dissipating (*i.e.* on the reef flat). Whether the waves are bound or locally generated does not alter our argument regarding the potential augmentation of the IG waves once on the reef flat.

As pointed out by Péquignet (2012), Pomeroy *et al*. (2012), and Van Dongeren *et al*. (2013), frictional dissipation on the reef flat is an important dissipation mechanism for IG waves, like it is for SS waves. The mechanism is strong enough that, on shallow, wide reefs, the IG wave energy may dissipate significantly before reaching the shoreline (Pomeroy *et al.,* 2012). In the case of the Majuro Atoll study site during the inundation event, we do see evidence for shoreline reflection and subsequent excitation of a one-quarter wavelength, quasistanding mode, similar to that reported during an inundation event at a fringing reef at Ipan, Guam (Péquignet, 2009). That analysis is supported by the findings that the peak frequency of the IG energy ($f_p \sim 0.007$ Hz) on the reef flat is consistent with that of a one-quarter wavelength mode (FBM2012 Figure 10) and that the amplitude of the IG energy on the reef flat increases shoreward, consistent with the spatial structure of a one-quarter wavelength mode and inconsistent with frictional dissipation of a shoreward propagating IG wave. Modal excitation has been observed conclusively at similar locations around the Republic of the Marshall Islands with more extensive measurements (Becker, Merrifield, and Ford, unpublished data). We speculated that the abrupt depth changes of the excavation pit alter the cross-shore structure of the IG mode in such a manner as to lower the wave amplitude at the shoreline. Further study is required to assess this mechanism relative to frictional dissipation.

### (4) Lateral Variation of Incident Wave Conditions and Shoreline Reflectivity

PMP2013 argue that incident wave energy may be higher at the unmodified reef flat than it is at the excavated profile, providing as evidence the differences in wave conditions between sensors 3 and 6. We assume incident wave energy at the reef crest is laterally homogenous, an assumption we consider valid given the limited, alongshore, morphological variations seen at this site and others around Majuro Atoll and the close proximity of the sensor lines to each other (~72 m). We see no evidence of any physical process or geomorphic feature that we could reasonably attribute to any along-reef differences in wave energy on the outer reef flat, although we acknowledge our limited instrumentation in this study does hinder our ability to confirm that. Follow-up studies at a nearby reef (~1 km east, in preparation) show no statistically significant difference in wave heights between two sensors, which are ~190 m apart and equidistant from the reef crest in ~5 m water depth on the forereef. The width, surface texture, and cover of the reef flat at both transects are comparable. From an experimental perspective, both sensors 1 and 5 were deployed the same distance from the reef crest and from the seaward boundary of the conglomerate platform, on sections of reef flat with negligible difference in elevation (FBM2012 Figure 2). The underlying assumptions of the experimental design appear valid, and we attribute any difference in wave conditions between sensors 1 and 5 to the presence of the excavation pit.

Differences between wave heights measured at sensors 3 and 6 are attributed to bias because of the linear wave theory and because of unresolved processes occurring as the waves enter and propagate the pits. PMP2013 contend that this bias should have been quantified in FSM2012. Given the abrupt changes in water depth (*i.e.* vertical side walls), the similar horizontal length scales of the pit and the SS waves, and the strong attenuation of high-frequency wave amplitudes at the depths of the pit floor, we are not aware of a simple way to quantify that bias.

PMP2013 speculate that variances in wave reflection from the different slopes of the shoreline at the two instrument profiles might explain the lower wave heights observed at sensor 1 relative to sensor 5. Ford (2011) discusses the widespread modification of the urban sections of the Majuro Atoll shoreline, including the vicinity of the study site, noting the land in the area is largely an anthropogenic artifact. PMP2013 comment on the difference in the beach profile between the profiles, suggesting the possibility that the differences in beach slope is evidence of a potential morphodynamic feedback in response to lower wave energy at the unmodified section of reef. The shoreline at the study site is characterized by a revetment and a small, unconsolidated, mixed sand-and-gravel beach (FBM2012). The small beach at the study site is likely composed of material used for fill in the construction of the causeway, rather than being derived from the reef. The island shoreline at this location is an artifact of anthropogenic development (FBM2012 Figure 3A), and the differences in shoreline slope and composition are a function of engineering actions, rather than a morphodynamic response.

Between the island shoreline and sensors 1 and 5 is a laterally continuous conglomerate platform, composed of naturally cemented coral rubble (Figure 3A, FBM2012). The elevation and morphology is generally consistent alongshore, with small variations because of the rough surface. For waves to reach the island shoreline and be reflected, water levels must exceed ~0.5 m above mean sea level. Given a spring tide range of ~1.60 m, there is only a relatively brief window of time in which water levels would enable waves to reach the shoreline. Figure 9 in FBM2012 shows a strong linear relationship between S (complete wave field), SS, and IG at both high and low tide. If variation in shoreline slope between the profile lines drove the differences in wave height between sensors 1 and 5, it would likely be detected as a departure from the linear relationship at high tide when water level exceeds the elevation of the conglomerate platform and enables shoreline reflection. Further, FBM2012 present regression coefficients at both higher and lower water levels in table 1. Results indicate a statistically significant reduction in wave height at lower water levels, when waves would not have reached the island shoreline. As a result, we attribute negligible influence of the differing slope of the island shoreline on wave conditions measured on the inner reef flat at sensors 1 and 5.

## COASTAL MANAGEMENT IMPLICATIONS

We strongly agree with PMP2013 regarding the potential for negative outcomes from reef flat excavation and find their example from Cadiz, Spain, to be a powerful reminder of the risks of poorly planned engineering interventions within the coastal zone. The Marshall Islands are faced with the challenge of finding sustainable sources of aggregate and armorstone to maintain and develop coastal protections along Majuro Atoll's heavily urbanized and highly engineered shorelines. FBM2012 note that there are a number potential environmental impacts of reef flat excavation and focused on one of those impacts, providing the first account of the effects of excavation pits on reef flat wave transformation. The nature and magnitude of the suite of potential impacts arising from reef flat excavation are largely unresolved and in need of further scientific study to better inform decision makers within the Marshall Islands.

## LITERATURE CITED

Becker, J.M.; Merrifield, M.A., and Ford, M.R., 2012. Observations of infragravity motions for reef fringed islands and atolls. *American Geophysical Union's 45th Annual Fall Meeting* (San Francisco, California), Abstract GC22A-07.

Demirbilek, Z.; Nwogu, O.G., and Ward, D.L., 2007. *Laboratory Study of Wind Effect on Runup over Fringing Reefs*. Report 1: Data report. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center. *Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-07-4*, 83p.

Ford, M., 2011. Shoreline changes on an urban atoll in the central Pacific Ocean: Majuro Atoll, Marshall Islands. *Journal of Coastal Research,* 28(1), 11–22. doi:10.2112/JCOASTRES-D-11-00008.1.

Ford, M.R.; Becker, J.M., and Marrifield, M.A., 2013. Reef flat wave processes and excavation pits: observations and implications for Majuro Atoll, Marshall Islands. *Journal of Coastal Research,* 29(3), 545–554.

Henderson, S.M.; Guza, R.T.; Elgar, S.; Herbers, T.H.C., and Bowen, A.J., 2006. Nonlinear generation and loss of infragravity wave energy. *Journal of Geophysical Research: Oceans,* 111, C12007. doi:10.1029/2006JC003539.

Massel, S.R. and Gourlay, M.R., 2000. On the modelling of wave breaking and set-up on coral reefs. *Coastal Engineering,* 39(1), 1–27.

Nwogu, O. and Demirbilek, Z., 2010. Infragravity wave motions and runup over shallow fringing reefs. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 136(6), 295–305.

Payo, A. and Muñoz-Perez, J.J., 2013. Discussion of: Ford, M.R., Becker, J.M., and Merrifield, M.A., 2013: Reef flat wave processes and excavation pits: observations and implications for Majuro Atoll, Marshall Islands. *Journal of Coastal Research*, 29(5), 1241–1246.

Péquignet, A.-C., 2012. Transformation of Wave Energy across the Fringing Reef of Ipan, Guam. Manoa, Hawaii: University of Hawaii at Manoa, doctoral dissertation, 157p.

Péquignet, A.C.N.; Becker, J.M.; Merrifield, M.A., and Aucan, J., 2009. Forcing of resonant modes on a fringing reef during tropical storm Man-Yi. *Geophysical Research Letters,* 36(3), L03607. doi:10.1029/2008GL036259.

Péquignet, A.C.N.; Becker, J.M.; Merrifield, M.A., and Boc, S.J., 2011. The dissipation of wind wave energy across a fringing reef at Ipan, Guam. *Coral Reefs,* 30(1), S71–S82, doi:10.1007/s00338-011-0719-5.

Pomeroy, A.; Lowe, R.; Symonds, G.; Van Dongeren, A., and Moore, C., 2012. The dynamics of infragravity wave transformation over a fringing reef. *Journal of Geophysical Research*. 117, C11022. doi:10.1029/2012JC008310.

Sheremet, A.; Kaihatu, J.M.; Su, S.-F.; Smith, E.R., and Smith, J.M., 2011. Modeling of nonlinear wave propagation over fringing reefs. *Coastal Engineering,* 58(12), 1125–1137.

Thomson, J.; Elgar, S.; Raubenheimer, B.; Herbers, T.H.C., and Guza, R.T., 2006. Tidal modulation of infragravity waves via nonlinear energy losses in the surfzone. *Geophysical Research Letters,* 33(5), L05601. doi:10.1029/2005GL025514

Van Dongeren, A.; Lowe, R.; Pomeroy, A.; Trang, D.M.; Roelvink, D.; Symonds, G., and Ranasinghe, R. 2013. Numerical modeling of low-frequency wave dynamics over a fringing coral reef, *Coastal Engineering,* 73(1), 178–190.