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Coral reefs reduce tsunami impact in model simulations

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[1] Significant buffering of the impact of tsunamis by coral reefs is suggested by limited observations and some anecdotal reports, particularly following the 2004 Indian Ocean tsunami. Here we simulate tsunami run-up on idealized topographies in one and two dimensions using a nonlinear shallow water model and show that a sufficiently wide barrier reef within a meter or two of the surface reduces run-up on land on the order of 50%. We studied topographies representative of volcanic islands (islands with no continental shelf) but our conclusions may pertain to other topographies. Effectiveness depends on the amplitude and wavelength of the incident tsunami, as well as the geometry and health of the reef and the offshore distance of the reef. Reducing the threat to reefs from anthropogenic nutrients, sedimentation, fishing practices, channel-building, and global warming would help to protect some islands against tsunamis. **Citation:** Kunkel, C. M., R. W. Hallberg, and M. Oppenheimer (2006), Coral reefs reduce tsunami impact in model simulations, *Geophys. Res. Lett.*, *33*, L23612, doi:10.1029/2006GL027892.

[2] We analyze the effectiveness of coral reefs as natural barriers against tsunamis. Previous studies indicate a decrease in energy of wind-driven waves of at least 80% across reefs [*Lugo-Fernandez et al.*, 1998a; *Gourlay*, 1994]. Empirical evidence indicates that coral reefs provide an effective buffer against tsunamis while it has been suggested that man-made or natural gaps in a reef can funnel the energy of a tsunami, resulting in greater run-up [*Marris*, 2005; *Fernando et al.*, 2005]. On the other hand, in Banda Aceh, Indonesia which experienced very large wave amplitudes in the 2004 Indian Ocean tsunami because of its proximity to the source, the presence or absence of coral reefs reportedly did not make a significant difference [*Adger et al.*, 2005]. Observations are not sufficient to quantitatively determine the importance of different reef parameters, such as width, offshore distance, and health, in blocking tsunami energy. To our knowledge, this numerical study represents the first attempt to address these questions.

[3] An estimated 30% of reefs are severely degraded and nearly 60% may die by 2030 due to anthropogenic pressures that cause bleaching or direct destruction and increase vulnerability to natural factors like disease and severe storms [*Hughes et al.*, 2003]. The drag a reef exerts on a wave is expected to decrease as live coral cover decreases because dead coral skeletons are fragile [*Bellwood et al.*, 2004], tend to break up and erode over time, and are less able to withstand the force of severe storms or tsunamis. Replacement of live coral by macro-algae, which sometimes occurs on highly stressed reefs, might also reduce drag [*Bellwood et al.*, 2004; *Hughes and Connell*, 1999]. Field studies indicate that the bottom drag coefficient (0.03–0.1) for a reef is at least an order of magnitude larger than the bottom drag coefficient for sand [*Baird et al.*, 2004; *Lugo-Fernandez et al.*, 1998b; *Thomas and Atkinson*, 1997; *Kraines et al.*, 1998; *Nelson*, 1996; *Falter et al.*, 2004; *Feddersen et al.*, 1998].

[4] We use a numerical model with idealized topography to estimate the effect of coral reefs on tsunami run-up. The run-up is defined as the elevation of the maximum distance inland reached by the tsunami. The Hallberg Isopycnal Model, a nonlinear shallow water model, was selected in part for its demonstrated skill in reproducing the observed global tides [*Arbic et al.*, 2004] and for its accurate reproduction of the 2004 Indian Ocean tsunami [*Smith et al.*, 2005]. The model is adapted to model nearshore propagation by using a minimally diffusive, positive definite, second-order spatial differencing scheme for the continuity equation. Bottom drag is parameterized using a quadratic drag law. The bottom drag coefficient on the reef is set to 0.05 and the bottom drag off of the reef to 0.0025, consistent with the published literature [*Baird et al.*, 2004; *Lugo-Fernandez et al.*, 1998b; *Thomas and Atkinson*, 1997; *Kraines et al.*, 1998; *Nelson*, 1996; *Falter et al.*, 2004; *Feddersen et al.*, 1998].

[5] Important parameters include reef health (modeled as variable bottom drag), incident tsunami wavelength and amplitude, and reef geometry. The incident tsunami is modeled as a Gaussian pulse. The wavelength was defined as the distance between the two points where the amplitude is 1% of its maximum value. For most of these simulations, the tsunami was initialized with 1 m amplitude and wavelength approximately 100 km over an initial depth of 1000 m; this corresponds to a tsunami with 0.7 m amplitude over the open ocean (4000 m depth).

[6] We use an idealized coral reef topography based on a typical barrier reef, as shown in Figure 1 [*Kaplan*, 1982]. Empirical evidence, including the effect of the 2004 tsunami on reef structure, suggests that it is acceptable to model a healthy barrier reef as rigid [*Baird et al.*, 2005; *Campbell et al.*, 2005; *Obdura and Abdulla*, 2005; *Pennisi*, 2005]. The reef is separated from the beach by a 4 m deep lagoon (defined here as the shoal seaward of the beach, whether or not bounded by a reef); the lagoon slopes up to sea level over a distance of 100 m at the shore. The back-reef is 20 m wide. For our simulations, the reef crest varies in width from 60–500 m and is 0–4 m deep. The reef crest lies behind a fore-reef, with average slope 40 degrees, to a depth

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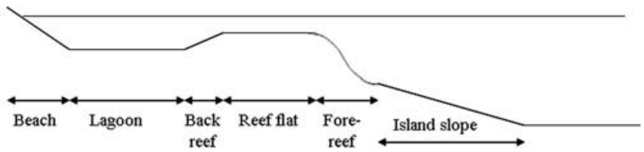

Figure 1. Zones of a reef. Not to scale.

of 85 m and a 10 degree slope down to the ocean floor. Key variables are the depth and width of the reef, as well as the width of the lagoon. The run-up results are not very sensitive to other topographic parameters. The beach slope is 2.3°, which is steep enough to prevent the wave from breaking before it reaches the maximum run-up. Horizontal resolution is 20 m, although higher resolutions give similar results.

[7] Figure 2a shows the variation of run-up with lagoon width and incident wavelength; the reef is less effective if the lagoon is narrower relative to the wavelength in the lagoon. (For a linear wave, the wavelength in the lagoon is reduced from the open ocean wavelength by a factor of the square root of the lagoon depth to the open ocean depth, or a factor of about 16 for the parameters here.) If no lagoon is present, there is only 120 m of back-reef and beach between the reef and the shoreline; the leading edge of the wave starts running up almost immediately after the reef. As the leading edge of the wave is running up and reflecting from the beach, part of the wave is still interacting with the reef which reduces the sea surface height gradient driving the wave into the lagoon. This results in a lower onshore velocity. The reduced velocity over the reef leads to significantly less frictional dissipation of wave energy, making the reef less effective, as shown in Figure 2a. For the 100 km wave, the total amount of energy lost to drag on the reef from the time when the wave is incident on the reef to when the maximum run-up occurs is 17 times less in the case of no lagoon compared to the case of a 1000 m lagoon. For a sufficiently broad lagoon, bottom drag there (although much weaker than over the reef) can significantly reduce the amplitude of the run-up, even in the absence of a reef. Halving the bottom drag coefficient over the lagoon for the case of a 4000 m lagoon and no reef increases the run-up by almost 20%. With a very narrow lagoon, the simulated run-up with or without a reef is roughly the value for a wave pulse reflecting off a vertical wall, namely twice its incident amplitude.

[8] The remainder of the simulations use a lagoon of 1000 m width. Figure 2b shows the variation of run-up with

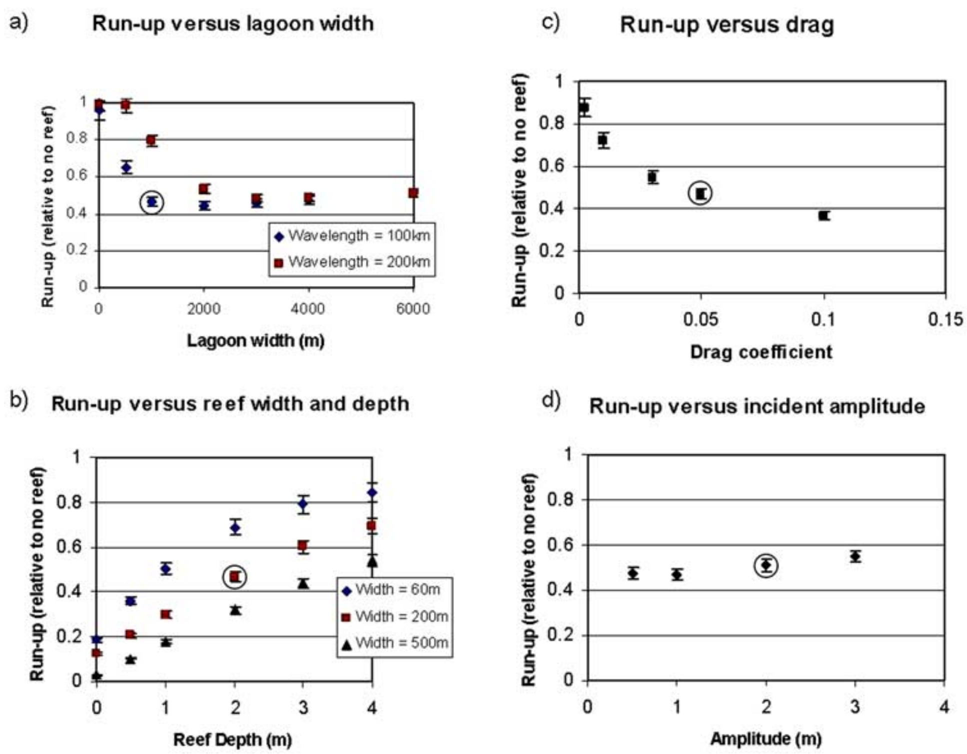

Figure 2. Numerical run-up results for one-dimensional simulations. Circled points are the 1 m amplitude, 100 km wavelength wave incident on a 200 m wide and 2 m deep reef 1000 m offshore. (a) Run-up as a function of lagoon width and incident wavelength, relative to "no reef" scenarios. The incident wave has 1 m amplitude, and the reef is 200 m wide, 2 m deep, with bottom drag coefficient 0.05. The reef is less effective when the lagoon is narrow relative to the incident wavelength. (b) Run-up as a function of depth and reef width (60 m, 200 m, 500 m), relative to corresponding "no reef" scenario. The incident wave has amplitude 1 m and wavelength 100 km, and the reef has bottom drag coefficient 0.05. Broader and shallower reefs are more effective barriers. (c) Run-up as a function of bottom drag, relative to "no reef" scenario. The incident wave has amplitude 1 m and wavelength 100 km, and the reef is 200 m wide and 2 m deep. (d) Run-up as a function of incident tsunami amplitude, relative to "no reef" scenarios. The incident wave has wavelength 100 km, and the reef is 200 m wide and 2 m deep with bottom drag coefficient 0.05.

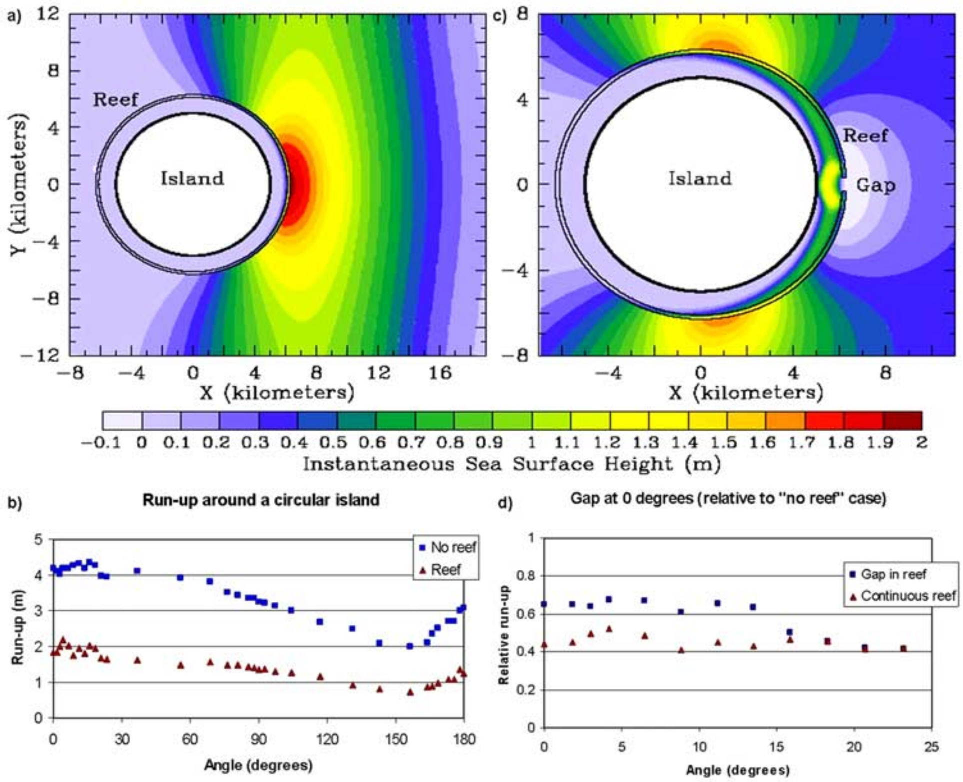

Figure 3. Numerical run-up results for two-dimensional simulations. The incident wave has 1 m amplitude and wavelength 30 km; the island has radius 5 km and is surrounded by a reef of 200 m width and 2 m depth which is separated from the shore by 1000 m. (a) Contour plot of sea-surface height for the tsunami incident on the island surrounded by a reef. (b) Run-up around the island with and without a reef. (c) Contour plot of sea-surface height after the tsunami has passed through a 600 m gap in the reef. (d) Run-up (relative to "no reef" case) for the 600 m gap versus a continuous reef.

reef width and depth. Figure 2c shows the variation of run-up with the bottom drag coefficient over the reef. Over the range of reef bottom drag coefficient values given in the literature (0.03–0.1) [*Baird et al.*, 2004; *Lugo-Fernandez et al.*, 1998b; *Thomas and Atkinson*, 1997; *Kraines et al.*, 1998; *Nelson*, 1996; *Falter et al.*, 2004], the relative run-up varies by about 50%, and is roughly half the relative run-up with no reef. This sensitivity to a proxy for reef health is consistent with field observations [*Fernando et al.*, 2005]. Figure 2d shows the variation of run-up with incident amplitude. Reefs are less effective against larger amplitude waves because the reef is effectively deeper, which more than offsets the increased quadratic bottom drag due to the larger velocities.

[9] Figure 3 shows run-up results for a circular island using a 2-D model. The island radius is 5 km; the reef is 200 m wide and separated from the island by a 1000 m lagoon of 4 m depth. We chose to consider a small radius island because effects from refraction should be most pronounced in this case; since we found that refraction did not significantly alter the effectiveness of the reef in reducing run-up, this conclusion should hold for islands of larger radius. The incident wavelength is 30 km; it was necessary to use a relatively small wavelength incident wave to reduce computational expense. (Tsunamis typically have a period in the range of 100–2000 seconds [*Ward*, 2002], which translates into wavelengths in the range 20–400 km in the open ocean.)

[10] The tsunami is split by the island, and these two waves refract and recombine in the back of the island to produce a peak in run-up there and significant run-up at all locations around the island, in qualitative agreement with experimental and numerical results in another study [*Cho and Liu*, 1999]. Figure 3b shows the run-up with and without a reef surrounding the island. The reef is essentially equally effective around the entire perimeter because the presence of the reef does not significantly affect the refraction pattern. Dependence of run-up on bottom drag and reef depth is similar to the results in the one-dimensional simulations.

[11] In order to assess the implications of natural and man-made gaps in the reef, we considered 4 cases: a 600 m gap located at 0°, 90°, and 180°, as well as a 3 km gap at 0°, where the angles are measured from the point of direct tsunami impact. We do not see any evidence of wave energy being focused through a gap in the reef, in contrast to an earlier study [*Fernando et al.*, 2005]. The wave pattern for the smaller gap at 0° is shown in Figures 3c–3d. The size of the gap is small relative to the incident wavelength, so to first order the gap acts as a point source and radiates circular wavefronts. The influence of the gap is felt over a range of about 15° to either side of gap, or 30° in total (the gap itself occupies only 6°). Outside this range, the run-up approaches the case of the continuous reef, as shown in Figure 3d. There are similar patterns for gaps at 90° and at 180°. The gap reduces the effectiveness of the reef by approximately

the same amount no matter where it is located. This result also applies for gaps smaller than 600 m, since in this case the gap width is again small relative to the incident wavelength. The circular diffraction pattern is largely destroyed for a 3 km gap because the gap is no longer small relative to the incident wavelength; in this case, the run-up opposite the gap approximates the case where there is no reef around the island.

[12] Both reflection and frictional dissipation are significant in reducing the energy transmitted over the reef. The broader and shallower the reef, the more protection it provides. The ratio of lagoon width to incident wavelength is also an important parameter. Reefs are less effective barriers against longer wavelength and larger amplitude tsunamis. A reef very close to the shore is ineffective, especially against longer tsunamis. But for many islands, the reef is sufficiently far offshore to allow significant dissipation of tsunami energy over the reef, as shown in Figure 2a. Numerical solutions are sensitive to the drag coefficient, which is not well-known for coral reefs.

[13] A barrier reef within a meter or two of the surface that is separated from the island by at least a few hundred meters can play an important role in reducing tsunami impact. Results may apply, for example, to some of the islands in French Polynesia [*Gabrie and Salvat*, 1985] or Kiribati [*Paulay*, 1997]. In such cases, the potential effectiveness of coral reefs as a buffer against tsunamis provides another motivation for protecting reefs. Our results are most directly applicable to an isolated volcanic island (where there is no continental shelf). We expect similar results for topographies with continental shelves, but in such cases the topography is generally less steep so that less wave energy is reflected; thus we expect a larger tsunami amplitude seaward of the reef, making the reef slightly less effective. Because of the idealized topography used, maximum run-up values are of order 5 meters; in reality, there could be focusing from non-idealized topography, reducing effectiveness of the barrier by increasing the wave amplitude. Healthier reefs are expected to have larger bottom drag which reduces tsunami impact. The sensitivity of the bottom drag to anthropogenic disturbances is an important area for future study.

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