

Applying a landscape mosaics technique to detect tropical cyclone impacts on coral reef community

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This study demonstrated that with an off-the-shelf underwater camera and the Adobe Photoshop software, end-users in developing countries with limited resources could use the video mosaics technique for reef monitoring and documenting storm impacts. This video-mosaic method provided a spatially accurate landscape view of the reef benthos. Images from the video-mosaic method revealed that up to 26% of the reef coral at Racha Island disappeared after the storm with 15% increase in sand, pavement and rubble. Most of the coral destroyed by the storm were foliaceous coral - i.e. *Montipora* sp.

[**Keywords:** Video survey, Landscape mosaics, *Montipora*, Coral reefs, Phuket, Thailand]

Introduction

An association between global warming and increasing storm frequency and its intensity has been suggested¹⁻⁴. Storm winds are strengthened by warm waters resulting in increases in rainfall, severe flooding and high levels of terrestrial runoff. Strong storms such as hurricane and typhoon have catastrophic impacts on coral reef worldwide, commonly influenced by the magnitude and duration of storm events, proximity to the reefs, depth on the reef, physical characters of reefs, community composition, coral morphology, and colony size⁵⁻²⁰. Strong storms can have physical and biological impacts on coral reefs. Physical impacts generated by strong storms include damages due to changes in sedimentation processes, damages due to increased turbidity, damages due to decreased salinity, and damages due to change in sea level^{14,21}. Biological impacts include a disruption of reef zonation^{6,22,23}, the reduction of coral cover^{24,25} and algae cover²⁶, the mitigation of coral bleaching^{27,28}, the creation of opening space for coral growth and recruitment^{29,30} and the enhancement of coral dispersal^{25,31}. Many studies reported changes in ecology and morphology of reefs brought about by tropical storms^{6,11,12,25,32-37}.

Due to the worldwide decline of coral reef communities occurring at an alarming rate, many

countries have initiated monitoring programs to document changes in reef communities^{38,39}. Various methods have been used to assess benthic communities on coral reefs such as photoquadrats⁴⁰⁻⁴² and line-intercept transects⁴³. These traditional methods result in long dive times, high expenses on reef monitoring and a lack of permanent visual record of the reef. With the recent technological advances, many monitoring programs^{17,44-46} now incorporate underwater photography or video into their survey design so that images can be analysed out of the water to measure metrics such as percent coral cover and coral colony sizes.

Landscape mosaics technique, with its large, spatially accurate and high resolution mosaic of reef communities, has been used to assess reef communities and storm impacts^{17,46-49}. The technique overcomes many limitations of the traditional methods while retaining most of their strengths. Moreover, video mosaics would be one of the ideal solutions for developing countries to use for reef monitoring and documenting storm impacts because of the economical, inexpensive, and commercially available imaging sensor. We propose a simple analytic tool to document the effects of storm impact on *Montipora* sp., and coral reef population using the landscape mosaics technique at Racha Island.

Materials and Methods

Racha Island is located in Phuket province, Thailand (Latitude 7.60488 °N, Longitude 98.37660 °E) (Fig. 1, Google Earth). Coral reefs in this area are typically shallow (1-15 m depth) fringing reefs. The tides are semi-diurnal with a range of 0.6 (neap tide) to 3.1 m (spring tides)⁵⁰. Mean sea level varies annually by 20 cm between the dry season from December to April and the wet season from May to November⁵¹.

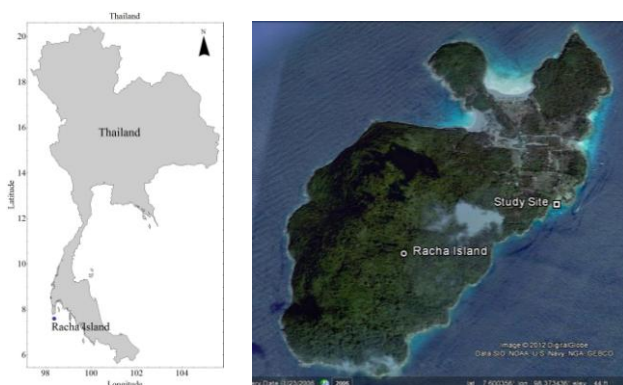


Fig. 1— Racha Island, Thailand

A Sea Bird SBE37 conductivity, temperature and depth sensor package (CTD) was deployed on the fringing reef in approximately 10 m water depth with 5-min sampling frequency. During 2011, hydrological measurements at the site had the mean $\pm$ SD water temperature of 29.12 ± 0.63 °C, salinity of 32.15 ± 0.55 ppt and water depth of 10.23 ± 0.56 m. The passage of November 2011 storm caused a decrease in water temperature (29.05 ± 0.66 °C) and salinity (31.41 ± 0.21 ppt) but an increase in water depth (10.31 ± 0.19 m). Large-scale bleaching was observed at this site in 1991, 1995 and 2009-2010 when sea temperatures exceeded the putative temperature threshold for bleaching of 30.1 °C⁵², 4.1-44.2% of coral mortality were reported⁵³. During 2009-2012 HOBO loggers recorded sea water temperatures of up to 33.0 °C during bleaching period in May 2010⁵⁴.

The Racha Island site is a logistically challenging environment for both researchers and instruments, characterised by large but shallow bays, storms, and occasional power and internet outages. An automatic weather station was deployed on shore with a 1-min sampling frequency. The climate is tropical with mean monthly temperatures of 28.19 ± 0.57 °C, relative humidity of 81.16 ± 2.35 (%), and monthly rainfall of 102.53 ± 80.42 mm.

In this study, we used the landscape mosaic technique to document the tropical storm impact on a population of the laminar coral (*Montipora* sp.) at Racha Island within 3-5 m of water depth. Three video mosaics of the same reef area were created using different survey focal lengths (Table 1). Survey focal length was chosen to minimise lens distortion, maximise field of view and increase overlapping regions of the stitching images. The first (July 2011) and second (February 2012) video surveys were collected with Canon Power Shot G11 still camera with housing. Third (June 2012) video survey was collected using the same camera model with dome lens. Without dome lens, the camera restored the original 28 mm focal length instead of the 37 mm focal length produced by the flat port of the housing. In the field, the camera was deployed in a down-looking position. Diver swam approximately 1-2 m above the reef area in a lawnmower pattern of side-by-side strips. The method was composed of three steps: (1) capturing the series of parallel underwater videos to still images, a set of key frames was used based on an image superposition criterion (typically 65-80%) using the FrameShotsTM software, (2) rotating half of the underwater videos 180° - i.e. when divers swam back, (3) stitching overlapping images and blending the overlapping areas together with the Adobe PhotoshopTM CS5.

To quantify the benthic cover from video mosaics, a sample grid was established so that 20 sub-sections of 1.00 m^2 - i.e. the same dimensions as the quadrats used by the standard protocol - were used. Each sub-section was assigned a unique number and drawn a sample by choosing 20 sub-sections from the complete set at random. The images were analysed using CPCe software developed by the National Coral Reef Institute (<http://www.nova.edu/ocean/cpce/index.html>)⁵⁵. This application superimposed a user-determined number of points over digital image. Once the points were placed, the user identified the benthic categories under each point just as done in the field. The program created, as an output, a file that summarised the information for each image and calculated the percentage cover of each image and the percentage cover of each category by quadrats and by sites^{47,55}. Percent benthic cover in each quadrat was estimated from 20 randomly distributed points using CPCe software with quadrat data pooled for each transect and averaged across transects at each measurement period. In this study, 12 main benthic

categories were identified: (1) coral, (2) gorgonians, (3) sponges, (4) zooanthids, (5) macro-algae, (6) other live, (7) dead coral with algae, (8) coralline algae, (9) diseased corals, (10) sand, pavement and rubble, (11) unknowns, and (12) tape, wand, and shadow. Coral was identified up to species level as follows: *Millepora platyphylla*, *Montipora* sp. and *Porites lutea*. Dead coral with algae was classified into three subcategories: dead coral with algae, old dead coral,

and recently dead coral. CPCe performed image calibration, planar area and planar length calculation of benthic feature. CPCe automatically generated analysis spread sheets in the Microsoft Excel based on the supplied species/substrate codes. Statistical parameters of each species/substrate type and the calculation of diversity indices for each species were done automatically⁵⁵.

Table 1- Description of the three mosaics constructed based on digital video collected at Racha Island, Thailand at the depth of 3-5 m

Survey	Date	Re-sample Image size (pixels)	Focal length (mm)	Altitude (m)	Area covered (m ²)
1	09/07/2011	(640 × 480) ~0.3 MP	37	1.0	~100
2	05/02/2012	(640 × 480) ~0.3 MP	37	1.5	~100
3	24/06/2012	(640 × 480) ~0.3 MP	28	2.0	~100

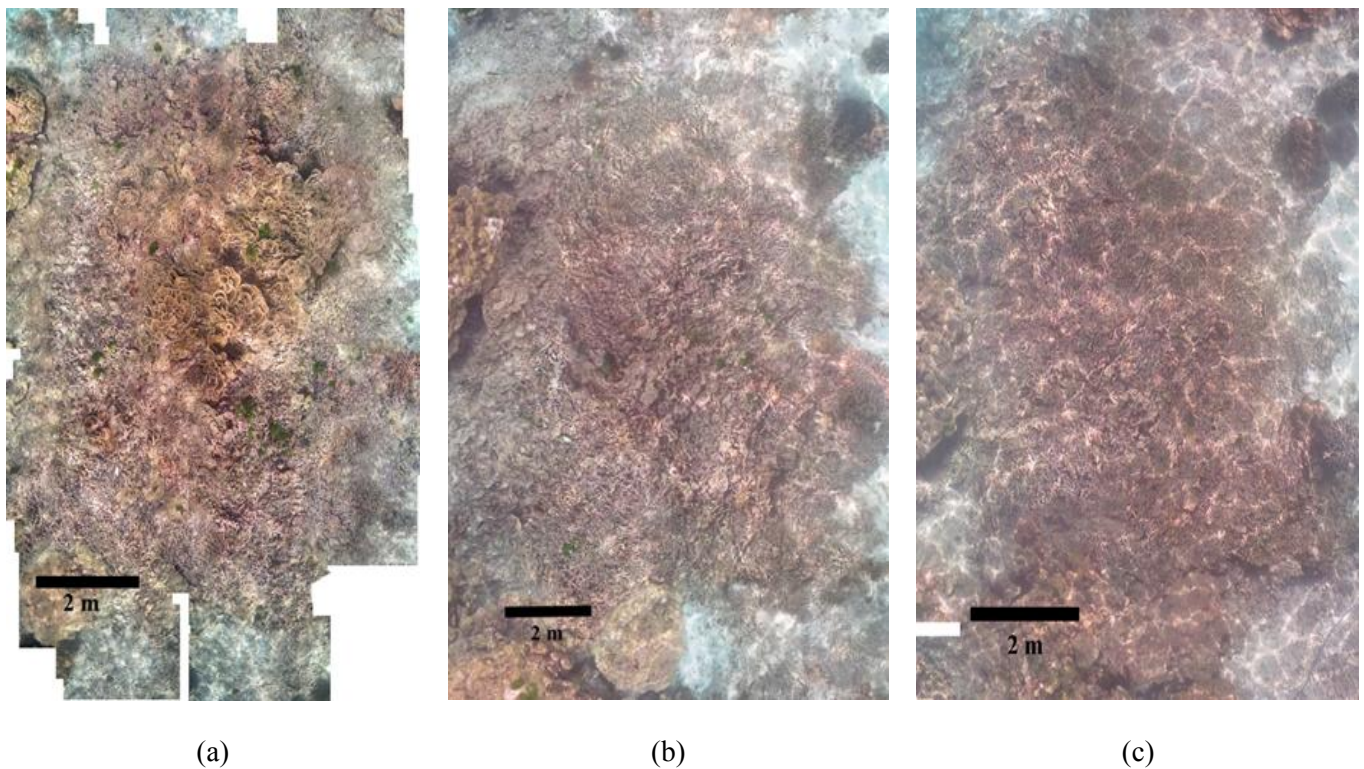


Fig. 2—Landscape mosaic constructed with video collected from hand-held digital camera during 2011-2012 at Khonkae Bay (depth 3-5 m). (a) landscape mosaic in 09 July 2011, (b) landscape mosaic in 25 February 2012 and (c) landscape mosaic in 24 June 2012

Data analysis

For differences among main categories, two-way ANOVA and post-hoc Dunnett T3 tests were used to test for significant differences between type of substrate covers - i.e. coral, macro-algae, dead coral, sand, pavement, and rubble, times and its interaction between type of substrate cover and times. For the differences within subcategories, two-way ANOVA and post-hoc Dunnett T3 tests were used to test for significant differences between times, its interaction and (1) within coral types - i.e. *Millepora platyphylla*, *Porites lutea* and *Montipora* sp., (2) within dead coral types - i.e. dead coral with algae, old dead coral, and recently dead coral, and (3) within sand, pavement and rubble. One-way ANOVA and post-hoc Dunnett T3 tests were used to test for the passage of November 2011 storm affecting *Montipora* sp. All statistical tests were two-tailed.

Results

The video mosaics taken in July 2011, February 2012 and June 2012 were generated (Fig. 2a-c). After the passage of November 2011 storm, most *Montipora* sp. colonies were removed and absent from the plot (Fig. 2a-c). There were four main substrates found: macro-algae (1.64%), sand, pavement and rubble (12.50%), live coral (18.69%) and dead coral cover (66.28%) (Fig. 3a). There were some differences between main substrate categories but no difference between times and its interactions (Two-way ANOVA test: substrate: $F_{3,340} = 18.007$, $P < 0.001$, time: $F_{2,340} = 0.032$, *ns*; interaction between substrate and time: $F_{6,340} = 1.177$, *ns*, Fig. 3a). Post-hoc Dunnett T3 tests showed that the percentage of dead coral cover was the highest and the percentage of coral cover was higher than the percentage of macro-algae cover (Fig. 3a).

There was only turf macro-algae (1.64%) found at Racha Island during the study period. The percentage of turf algae in the first measurement (July 2011) was higher than in the third measurement (June 2012) (One-way ANOVA test with post-hoc Dunnett T3 test: $F_{2,33} = 4.472$, $P < 0.05$, Fig. 3a).

Averaged percentage of pavement, rubble and sand cover were 0.17%, 4.00% and 8.33% respectively. There were some differences between sand, pavement, and rubble cover, times and its interactions (Two-way ANOVA test: sand, pavement and rubble cover: $F_{2,101} = 15.512$, $P < 0.001$, time: $F_{2,101} = 9.122$, $P < 0.001$; interaction between types and time: $F_{4,101} =$

4.759, $P < 0.005$, Fig. 3a,b). Post-hoc Dunnett T3 tests showed that the percentage of pavement cover was the lowest and there was no difference between the percentage of sand and rubble cover (Fig. 3b). The percentage of sand, pavement and rubble cover in the first measurement was the lowest and there was no difference between the second and the third measurements (One-way ANOVA test with post-hoc Dunnett T3 test: $F_{2,101} = 6.679$, $P < 0.05$, Fig. 3a).

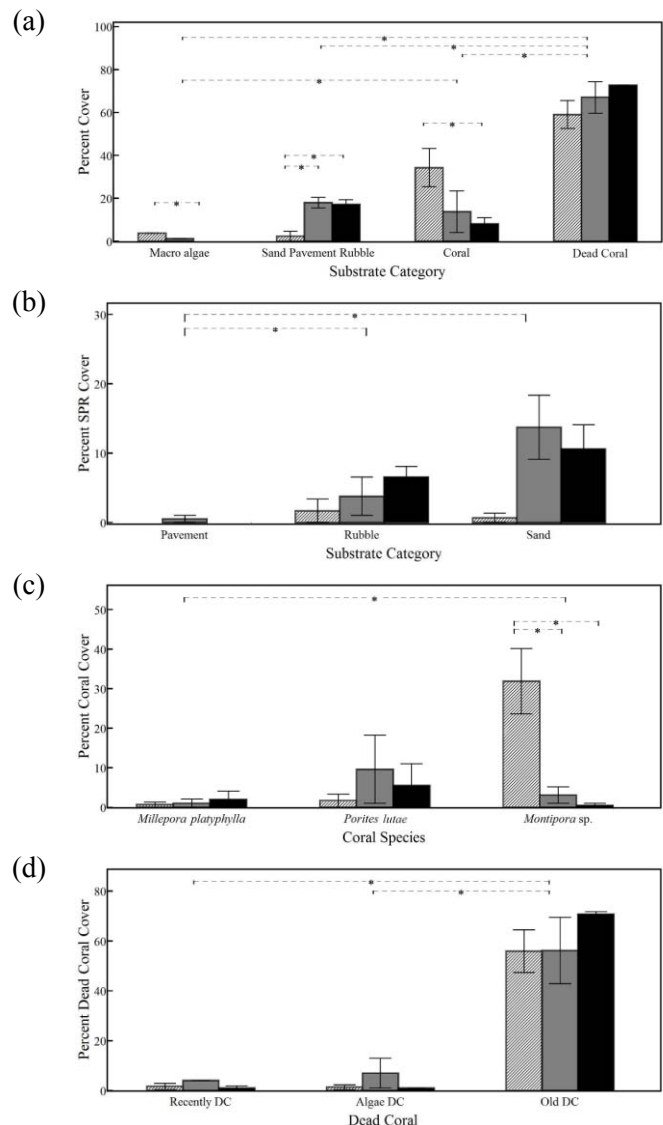


Fig. 3—Mean $\pm$ SE of benthic substrate categories (%) as estimated by re-sampled from the landscape mosaic over three times measurement. Dashed, gray and black boxes represent benthic cover during July 2011, February 2012, and June 2012, respectively. (a) percent of main benthic substrate categories, (b-d) the subcategories of (a), (b) percentage of sand, pavement, and rubble, (c) percentage of coral species cover, and (d) percentage of dead coral with algae

There were three coral species found: *Millepora platyphylla* (1.24%), *Porites lutea* (5.45%) and *Montipora* sp. (11.83%) (Fig. 3b). There were some differences between coral types, times and its interactions (Two-way ANOVA test: coral types: $F_{2,101} = 5.508$, $P < 0.001$, time: $F_{2,101} = 5.029$, $P < 0.01$; interaction between coral types and time: $F_{4,101} = 9.680$, $P < 0.001$, Fig. 3c). Post-hoc Dunnett T3 tests showed that the percentage of *Montipora* sp. cover was higher than the percentage of *Millepora platyphylla* cover. The percentage of *Porites lutea* cover did not differ from the percentage of *Millepora platyphylla* and *Montipora* sp. cover. There were some differences between *Montipora* sp. among three measurement times (One-way ANOVA test: $F_{2,33} = 9.919$, $P < 0.001$, Fig. 3c). Post-hoc Dunnett T3 tests showed that the percentage of *Montipora* sp. cover during July 2011 was the highest and there was no difference of *Montipora* sp. cover after storm event between February 2012 and June 2012 (Fig. 3c). *Millepora platyphylla* and *Porites lutea* did not differ in their percentage cover during three measurement times (One-way ANOVA test: $F_{2,33} = 0.496$, ns ; $F_{2,33} = 1.495$, ns , Fig. 3c).

The averaged percentage of recently dead coral cover, dead coral with algae cover and old dead coral cover were 2.24%, 3.13% and 60.00%, respectively. There were some differences between dead coral categories but there was no difference among three times and its interactions (Two-way ANOVA test: substrate: $F_{2,101} = 160.709$, $P < 0.001$, time: $F_{2,101} = 0.857$, ns ; interaction between dead coral and time: $F_{4,101} = 1.344$, ns , Fig. 3d). Post-hoc Dunnett T3 tests showed that the percentage of old dead coral cover was the highest and there was no difference between the percentage of recently dead coral and dead coral with algae cover (Fig. 3d).

Discussion

This study demonstrates that video mosaics produced images that showed continuity of large underwater features like coral boulders, similar to a single 2600x4800 pixels (300 dpi) photographic image which is impossible to be taken with a single-lens camera with this kind of distortion and coverage. The landscape mosaics generated in this study provide a unique view of the reef benthos that facilitates the documentation of colony-level as well as large-scale structural changes to the reef framework¹⁷. Mosaic scan enable long-lasting visual information on the

state of the reef, reef mapping, and monitoring changes over time without trained, expert scientific divers, and/or extensive dive time^{17,43-44, 47,56-57}.

Our study clearly demonstrated that with an off-the-shelf underwater camera and the Adobe Photoshop software, end-users in developing countries with limited resources could use the video mosaics technique for reef monitoring and documenting storm impacts. This technique enables rapid and more frequent surveys of reefs at affordable cost resulting in the best reef assessment for coastal communities. The precise documentation of such large-scale modifications to the structure of the reef was only possible because of the landscape view provided by the landscape mosaics.

With regard to physical disturbance caused by typhoons, cyclones or tropical storms, most literature focused on direct destruction of the reef corals such as demolishment of branching corals⁵⁸⁻⁵⁹, reduced living coral coverage⁶⁰⁻⁶¹, and dislodgment of reef frame blocks (up to 2 m³) and massive corals^{14,18}. Changes in coral cover, abundance, and condition can be easily discerned from traditional before-and-after surveys but changes to the structure of reefs are harder to quantify. Previous studies^{24,58} reported that storm surge in May 1986 caused 100% coral loss in the upper zone of the reef on the south-east end of Phuket Island, Thailand. Branching *Acropora* spp. were washed ashore and the coral fragments piled nearly 2 m high along the shore during that storm. Our results show that the impact of the storm in November 2012 at Racha Island was less severe than that of the storm in May 1986. Only 26% of the coral covers disappeared after the November 2012 storm.

Many studies^{14,62-64} report that shallow reefs tend to suffer more severe damages from storm waves than deeper ones. In the Caribbean, the upper reef slope with a depth between 3-10 m suffers the highest damage from storm waves than deeper reefs^{6,62,65-67}. On the other hand, in the Pacific, shallow outer reefs (0-10 m) in Hawaii and Guam suffer less damage from storm waves than deeper reefs. This could be due to the fact that corals growing there are highly adapted to strong hydrodynamic conditions and high wave energy^{22,68-70}. In this study, landscape mosaic mappings of coral reefs at Racha Island taken within 3-5 m of water depth revealed that up to 26% of the reef coral at Racha Island disappeared after the storm. This indicates that corals in a shallow area at this site suffer some damages from storm waves. Coral forms

at this site might shift from a branching form to a massive form to survive increases in wave energy. Our results also show that macro-algae disappeared after the storm. Most of this macro-algae growing on the coral substratum might be broken loose by the action of waves and currents resulting in loss in abundance and species richness⁷¹⁻⁷².

Several studies^{68,73-75} report that in the Pacific, *Acropora*, *Pocillopora*, *Stylophora*, *Montipora*, and *Millepora* spp. are branched coral colonies that are most susceptible to storm waves breaking them into pieces. On the other hand, massive coral colonies of *Porites*, *Goniastrea* and *Platygyra* are less affected by storm and suffer lower mortality¹⁴. Our results support previous findings^{6-8,14,15,68,73-75} that most of the coral that disappeared after the storm passage at Racha Island were branching coral colonies - i.e. *Montipora* sp. On the other hand, massive colonies of *Porites lutea* were less affected by storms, better survived transportation by storms and colonised new habitats¹¹.

After the storm passage, a large proportion of broken corals faced immediate mortality due to mechanical abrasion, sand scouring and piling up. Most coral fragments that were still alive 1-2 weeks after the storm, died within five months^{6,79}. Our results show that there were 17% increases in sand, pavement and rubble during the six-month period after the storm passage. This delayed mortality of storm-generated coral fragments is well documented in many places such as in Belize⁶³, the U.S. Virgin Islands⁷, and Guadeloupe⁸⁰. Increases in the abundance of coral colonies through fragment formation and reattachment after storm has been documented^{7,65} but the increases were not observed in this study. This may be because fragmented reattachment and coral recovery requires longer time than six months after the storm passage.

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References

1. Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T. & Held, I.M., Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes, *Science*, 327(2010) 454-8.
2. Knutson, T.R., McBride, J., Chan, J., Emanuel, K.A., Holland, G., Landsea, C., Held, I.M., Kossin, J., Srivastava, A.K. & Sugi, M., Tropical cyclones and climate change, *Nat. Geosci.*, 3(2010) 157-63.
3. Holland, G.J., Hurricanes and rising global temperatures, *Proc. Natl. Acad. Sci. USA*, 109(2012) 19513-4.
4. Grinsted, A., Moore, J.C. & Jevrejeva, S., Projected Atlantic hurricane surge threat from rising temperatures, *Proc. Natl. Acad. Sci. USA*, 110(2013) 5369-73.
5. Stoddart, D.R., Effects of Hurricane Hattie on the British Honduras reefs and cays, Oct. 30-31, 1961, *Atoll Res. Bull.*, 95(1963) 1-142.
6. Woodley, J.D., Chornesky, E.A., Clifford, P.A., Jackson, J.B.C., Kaufman, L.S., Knowlton, N., Lang, J.C., Pearson, M.P., Porter, J.W., Rooney, M.C., Rylaarsdam, K.W., Tunnicliffe, V.J., Wahle, C.M., Wulff, J.L., Curtis, A.S.G., Dallmeyer, M.D., Jupp, B.P., Koehl, M.A.R., Neigel, J. & Sides, E.M., Hurricane Allen's impact on Jamaican coral reefs, *Science*, 214(1981) 749-55.
7. Rogers, C.S., Suchanek, T.H. & Pecora, F.A., Effects of hurricanes David and Frederic (1979) on shallow *Acropora palmata* reef communities: St. Croix, U.S. Virgin Island, *Bull. Mar. Sci.*, 32(1982) 532-48.
8. Jackson, J.B.C. & Hughes, T.P., Adaptive strategies of coral-reef invertebrates, *Am. Sci.*, 73(1985) 265-74.
9. Harriott, V.J. & Fisk, D.A., The effects of storms and cyclones on corals at Green Island Reef, in: *The Offshore Effects of Cyclone Winifred*, edited by I.M. Dutton, (GBRMPA Workshop Series 7) 1986, pp. 52-8.
10. Kjerfve, B., Magill, K.E., Porter, J.W. & Woodley, J.D., Hind casting of hurricane characteristics and observed storm damage on a fringing reef, Jamaica, West Indies, *J. Mar. Res.*, 44(1986) 119-48.
11. Done, T.J. & Potts, D.C., Influences of habitat and natural disturbances on contributions of massive *Porites* coral to reef communities, *Mar. Biol.*, 114(1992) 479-93.
12. Woodley, J.D., The incidence of hurricanes on the north coast of Jamaica since 1870: are the classic reef descriptions atypical?, *Hydrobiologia*, 247(1992) 133-38.
13. Blair, S.M., McIntosh, T.L. & Mostkoff, B.J., Impacts of Hurricane Andrew on the offshore reef systems of central and northern Dade County, Florida, *B. Mater. Sci.*, 54(1994) 961-73.
14. Harmelin-Vivien, M.L., The effects of storms and cyclones on coral reefs: a review, *J. Coast. Res.*, 12(1994) 211-31.
15. Lirman, D. & Fong, P., Susceptibility of coral communities to storm intensity, duration and frequency, *Proc. 8th Int. Coral Reef Symp.*, 1(1997) 561-6.
16. Lirman, D., Fragmentation in the branching coral *Acropora palmata* (Lamarck): growth, survivorship, and reproduction of colonies and fragments, *J. Exp. Mar. Biol. Ecol.*, 251(2000) 41-57.
17. Gleason, C.R.A., Lirman, D., Williams, D., Gracias, R.N., Gintert, E.B., Madjidi, H., Reid, R.P., Boynton, C.G.,

- Negahdaripour, S., Miller, M. & Kramer, P., Documenting hurricane impacts on coral reefs using two dimensional video-mosaic technology, *Mar. Ecol.*, 28(2007) 254-8.
18. Yu, K., Zhao, J., Roff, G., Lybolt, M., Feng, Y., Clark, T. & Li, S., High-precision U-series ages of transported coral blocks on Heron Reefs (southern Great Barrier Reef) and storm activity during the past century, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 337-338(2012) 23-36.
 19. Park, Y.H. & Suh, K.-D., Variations of storm surge caused by shallow water depths and extreme tidal ranges, *Ocean Eng.*, 55(2012) 44-51.
 20. Brown, J.M., Bolaños, R. & Wolf, J., The depth-varying response of coastal circulation and water levels to 2D radiation stress when applied in a coupled wave-tide-surge modelling system during an extreme storm, *Coast. Eng.*, 82(2013) 102-13.
 21. Lugo-Fernández, A. & Gravois, M., Understanding impacts of tropical storms and hurricanes on submerged bank reefs and coral communities in the northwestern Gulf of Mexico, *Cont. Shelf Res.*, 30(2010) 1226-40.
 22. Dollar, S.J., Wave stress and coral community structure in Hawaii, *Coral Reefs*, 1(1982) 71-81.
 23. Grauss, R.R., Macintyre, I.G. & Herchenroder, B.E., Computer simulation of the reef zonation at Discovery bay, Jamaica: hurricane disruption and long-term physical oceanographic controls, *Coral Reefs*, 3(1984) 59-68.
 24. Phongsuwan, N. & Chansang, H., Coral reef resources of the Tarutao National Park, Thailand, *BIOTROP*, 29(1986) 141-56.
 25. Gardner, T.A., Côté, I.M., Gill, J.A., Grant, A. & Watkinson, A.R., Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in long-term decline, *Ecology*, 86(2005) 174-84.
 26. McClanahan, T., Polunin, N. & Done, T., Ecological states and the resilience of coral reefs, *Conserv. Ecol.*, 6(2002) 18.
 27. Van Veghel, M.L.J. & Hoetjes, P., Effects of tropical storm Bret on Curacao reefs, *Bull. Mar. Sci.*, 56(1995) 692-4.
 28. Manzanello, D.P., Brandt, M., Smith, T.B., Lirman, D., Hendee, J.C. & Nemeth, R.S., Hurricanes benefit bleached corals, *Proc. Natl. Acad. Sci. USA*, (2007), doi:10.1073/pnas.0701194104.
 29. Rogers, C.S., Hurricanes and coral reefs: the intermediate disturbance hypothesis revisited, *Coral Reefs*, 12(1993) 127-37.
 30. Treml, E., Colgan, M. & Keevivan, M., Hurricane disturbance and coral reef development: a geographical information system (GIS) analysis of 501 years of hurricane data from the Lesser Antilles, *Proc. 8th Int. Coral Reef Symp.*, 1(1997) 541-6.
 31. Lugo-Fernández, A., Deslarzes, K.J.P., Price, J.M., Boland, G.S. & Morin, M.V., Inferring probable dispersal of Flower Garden Banks coral larvae (Gulf of Mexico) using observed and simulated drifter trajectories, *Cont. Shelf Res.*, 21(2001) 47-67.
 32. Bourrouilh-Le Jan, F.G. & Talandier, J., Sédimentation et fracturation de haute énergie en milieu récifal: tsunamis, ouragans et cyclones et leurs effets sur la sédimentologie et la géomorphologie d'un atoll: motu et hoa, a Rangiroa, Tuamotu, Pacifique SE, *Mar. Geol.*, 67(1985) 263-333.
 33. Mah, A.J. & Stearn, C.W., The effect of Hurricane Allen on the Bellairs fringing reef, Barbados, *Coral Reefs*, 4(1986) 169-76.
 34. Massel, S.R. & Done, T.J., Effects of cyclone on massive coral assemblages on the Great Barrier Reef: meteorology, hydrodynamics and demography, *Coral Reefs*, 12(1993) 153-66.
 35. Blanchon, P., Jones, B. & Kalbfleisch, W., Anatomy of a fringing reef and shoreline around Grand Cayman: storm coral debris, not coral framework, *J. Sediment. Res.*, 67(1997) 1-16.
 36. Connell, J.H., Disturbance and recovery of coral assemblages, *Coral Reefs*, 16(1997), 101-13.
 37. Adjerdoud, M., Chancerelle, Y., Schrimm, M., Perez, T., Lecchini, D., Galzin, R. & Salvat, B., Detecting the effects of natural disturbances on coral assemblages in French Polynesia: a decade survey at multiple scales, *Aquat. Living Resour.*, 18(2005), 111-23.
 38. Dahl, A.L., Monitoring man's impact on Pacific Island reefs, *Proc. 3rd Int. Coral Reef Symp.*, 2(1977) 571-5.
 39. Oliver, J., Déath, G., Done, T., Williams, D., Furnas, M. & Moran, P., Long-term monitoring of the Great Barrier Reef. Status Report No. 1. (Australian Institute of Marine Science, Townsville) 1995, pp. 121.
 40. Connell, J.H., Diversity in tropical rain forests and coral reefs, *Science*, 199(1978) 1302-10.
 41. Done, T.J., Photogrammetry in coral ecology: a technique for the study of change in coral communities, *Proc. 4th Int. Coral Reef Symp.*, 2(1982) 315-20.
 42. Hughes, T.P., Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef, *Science*, 265(1994) 1547-51.
 43. English, S., Wilkinson, C. & Baker, V., Survey manual for tropical marine resources (Australian Institute of Marine Science, Townsville), 1997, pp. 390.
 44. Gleason, A., Lirman, D., Gracias, N., Moore, T., Griffin, S., Gonzalez, M., Gintert, B. & Reid, R., Damage assessment of vessel grounding injuries on coral reef habitats using underwater landscape mosaics, *Proc. 63rd Gulf and Caribbean Fisheries Institute*, (2011), 125-9.
 45. Gintert, B., Gracias, N., Gleason, A.C.R., Lirman, D., Dick, M., Kramer, P. & Reid, R.P., Second-generation landscape mosaics of coral reefs, *Proc. 11th Int. Coral Reef Symp.*, 1(2008) 584-8.
 46. Judilla, R.J., Jauod, J., Capili, E. & Soriano, M., Teardrop—a rapid reef mosaicking tool for coastal communities, *Proc. 12th Int. Coral Reef Symp.*, (2012).
 47. Lirman, D., Gracias, N., Gintert, B., Gleason, A., Reid, R., Negahdaripour, S. & Kramer, P., Development and application of a video-mosaic survey technology to document the status of coral reef communities, *Environ. Monit. Assess.*, 125(2007) 59-73.
 48. Park, J.Y., Choi, J.Y. & Jeong, E.Y., Applying an underwater photography technique to near shore benthic mapping: a case study in a rocky shore environment, *J. Coast. Res.*, 64(2011) 1764-8.
 49. Corpuz, F.J., Naval, P., Capili, E., Jauod, J., Judilla, R.J. & Soriano, M., Coral reef mosaicking using teardrop and fast image labeling, *OCEANS'12 MTS/IEEE*, (2012).
 50. Ditlev, H., Zonation of corals (scleractinia: coelenterate) on intertidal reef flats at Ko Phuket, Eastern Indian Ocean, *Mar. Biol.*, 47(1978) 29-39.

51. Brown, B.E., Dunne, R.P., Phongsuwan, N. & Somerfield, P.J., Increased sea level promotes coral cover on shallow reef flats in the Andaman Sea, eastern Indian Ocean, *Coral Reefs*, 30(2011) 867-78.
52. Brown, B.E., Dunne, R.P. & Chansang, H., Coral bleaching relative to elevated sea water temperature in the Andaman Sea (Indian Ocean) over the last 50 years, *Coral Reefs*, 15(1996) 151-2.
53. Phongsuwan, N. & Chansang, H., Repeated coral bleaching in the Andaman Sea, Thailand, during the last two decades, *Phuket Mar. Biol. Cent. Res. Bull.*, 71(2012) 19-41.
54. Jaroensutasinee, M., Jaroensutasinee, K., Bainbridge, S., Fountain, T., Chumkiew, S., Noonsang, P., Kuhapong, U., Vannarat, S., Poyai, A. & Nekrasov, M., Sensor Networks Applications for Reefs at Racha Island, Thailand, *Proc. 12th Int. Coral Reef Symp.*, (2012).
55. Kohler, E.K. & Gill, M.S., Coral point count with Excel extensions (CPCe): a visual basic program for the determination of coral and substrate coverage using random point count methodology, *Comput. Geosci.*, 32(2006) 1259-69.
56. Lirman, D., Gracias, N., Gintert, B., Gleason, A., Deangelo, G., Dick, M., Martinez, E. & Reid, P., Damage and recovery assessment of vessel grounding injuries on coral reef habitats by use of geo-referenced landscape video mosaics, *Limnol. Oceanogr.-Meth.*, 8(2010), 88-97.
57. Gintert, B., Gleason, A.C.R., Cantwell, K., Gracias, N., Gonzalez, M. & Reid, R.P., Third-generation underwater landscape mosaics for coral reef mapping and monitoring, *Proc. 12th Int. Coral Reef Symp.*, (2012).
58. Phongsuwan, N., Recolonization of a coral reef damaged by storm on Phuket Island, Thailand, *Phuket Mar. Biol. Cent. Res. Bull.*, 56(1991) 75-83.
59. Nadaoka, K., Nihei, Y., Kumano, R., Yokobori, T., Omija, T. & Wakaki, K., A field observation on hydrodynamic and thermal environments of a fringing reef at Ishigaki Island under typhoon and normal atmospheric conditions, *Coral Reefs*, 20(2001) 387-98.
60. Perry, C.T., Storm-induced coral rubble deposition: Pleistocene records of natural reef disturbance and community response, *Coral Reefs*, 20(2001) 171-83.
61. Cheal, A., Coleman, G., Delean, S., Miller, I., Osborne, K. & Sweatman, H., Responses of coral and fish assemblages to a severe but short-lived tropical cyclone on the Great Barrier Reef, Australia, *Coral Reefs*, 21(2002) 131-42.
62. Stoddart, D.R., Coral reefs and islands and catastrophic storms, in: *Applied Coastal Geomorphology*, edited by J.A. Steers, (MacMillan Company, London) 1971, pp. 155-197.
63. Endean, R., Destruction and recovery of coral reef communities, in: *Biology and Geology of Coral Reefs*, edited by O.A. Jones & R. Endean, (Academic Press, New York), 2(1976), pp. 215-254.
64. Alvarez-Filip, L., Millet-Encalad, M. & Reyes-Bonilla, H., Impact of Hurricanes Emily and Wilma on the coral community of Cazumel Island, Mexico, *Bull. Mar. Sci.*, 84(2009) 295-306.
65. Highsmith, R.C., Riggs, A.C. & D'Antonio, C.M., Survival of hurricane-generated coral fragments and a disturbance model of reef calcification/growth rates, *Oecologia*, 46(1980) 322-9.
66. Hubbard, D.K., Parsons, K.M., Bythell, J.C. & Walker, N.D., The effects of hurricane Hugo on the reefs and associated environments of St.-Croix, U.S. Virgin Islands, a preliminary assessment, *J. Coastal Res.*, 8(1991) 33-48.
67. Fenner, D.P., Effects of hurricane Gilbert on coral reefs, fishes and sponges at Cozumel, Mexico, *Bull. Mar. Sci.*, 48(1991) 719-30.
68. Randall, R.H. & Eldredge, L.G., Effects of typhoon Pamela on the coral reefs of Guam, *Proc. 3rd Int. Coral Reef Symp.*, 2(1977) 526-31.
69. Ogg, J.G. & Koslow, J.A., The impact of Typhoon Pamela (1976) on Guam's coral reefs and beaches, *Pacific Sci.*, 32(1978) 105-18.
70. Pfeffer, R.A. & Tribble, G.W., Hurricane effect on an aquarium fish fishery in the Hawaiian Islands, *Proc. 5th Int. Coral Reef Symp.*, 3(1985) 331-6.
71. Matta, J.L., The effects of hurricane David on the benthic macroalgae of a coral reef in La Parguera. M.S. Thesis, (1981) 130 p.
72. Ballantine, D.L., Hurricane-induced mass mortalities to a tropical subtidal algal community and subsequent recoveries, *Mar. Ecol. Prog. Ser.*, 20(1984) 75-83.
73. Stephenson, W., Endean, R. & Bennett, I., An ecological survey of the marine fauna of Low Isles, Queensland, *Australian J. Mar. Freshwater Res.*, 9(1958) 261-318.
74. Connell, J.H., Population ecology of reef-building corals, in: *Biology and Geology of Coral Reefs*, edited by O.A. Jones & R. Endean, (Academic Press, London), 2(1973), pp. 205-45.
75. Connell, J.H., Competitive interactions and the species diversity of corals, in: *Coelenterate Ecology and Behavior*, edited by G.O. Mackie, (Plenum Press, New York) 1976, pp. 51-8.
76. Harmelin-Vivien, M.L., Tikehau Atoll, Tuamotu Archipelago, *Proc. 5th Int. Coral Reef Symp.*, 1(1985) 211-68.
77. Laboute, P., Evaluation des degats causes par les passages des cyclones de 1982-1983 en Polynesiefrancaisesur les pentesexternes des atolls de Tikehau et de Takapoto (Archipel des Tuamotu), *Proc. 5th Int. Coral Reef Symp.*, 3(1985) 323-9.
78. Van Woesik, R., Ayling, A.M. & Mapstone, B., Impact of tropical cyclone Ivor on the Great Barrier Reef, Australia, *J. Coastal Res.*, 7(1991) 551-8.
79. Knowlton, N., Lang, J.C., Rooney, M.C. & Clifford, P., Evidence for delayed mortality in hurricane-damaged Jamaican staghorn corals, *Nature*, 294(1981) 251-2.
80. Bouchon, C., Bouchon-Navaro, Y., Imbert, D. & Louis, M., Effets de l'ouragan Hugo sur les communautescotieres de Guadeloupe (Antilles Francaises), *Annales de l'Institut Oceanographique*, Paris, 67(1991) 5-33.