![frontiers]

Supplementary Materials

for the manuscript:

Hydrodynamic drivers and morphological responses on small coral islands – The Thoondu spit in Fuvahmulah, the Maldives

C. Gabriel David[1,*] and Torsten Schlurmann[1].

[1] *Ludwig-Franzius-Institute for Hydraulics, Estuarine and Coastal Engineering, Faculty of Civil Engineering and Geodesy, Leibniz Universität Hannover, Hanover, Germany*

Correspondence*:
C. Gabriel David, Leibniz Universität Hannover, Ludwig-Franzius-Institute for Hydraulics, Estuarine and Coastal Engineering, Nienburger Straße 5, 30167 Hannover, Germany
david@lufi.uni-hannover.de

TIDE

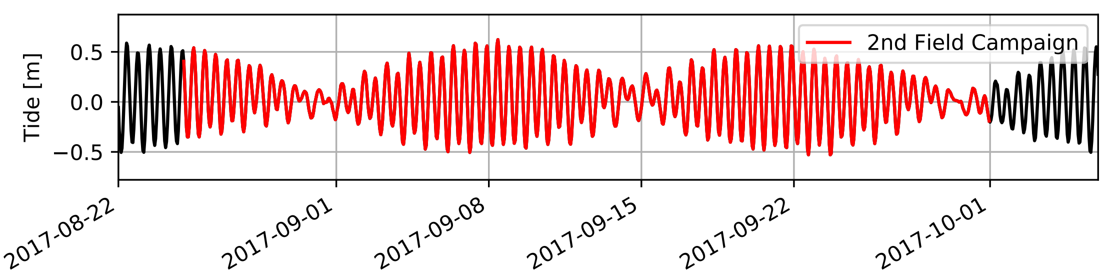

Figure S1: Tide from August 22nd, 2017 to October 5th, 2017 (tide levels for the field is red). The tide data is research data for the Gan, the Maldives, tide gauge from UHSLCCaldwell et al. (2015) which is about 53 km away from Fuvahmulah.

Figure S1 shows the tide data for the second field campaign (Caldwell et al., 2015). The data comes from University of Hawai'i Sea-Level Center (UHSLC), accessed 2019-12-29, and shows a mixed semidiurnal tide with a tidal range of $1\,\mathrm{m}$ for the neighbouring tide gauge on Gan. Gan is approximately $50\,\mathrm{km}$ away from Fuvahmulah. Experiences made with three day hydrodynamic measurements in the field campaign show, that the accuracy between tide predictions and actual water levels on Fuvahmulah is sufficient for survey planning.

WAVE TRANSFORMATION

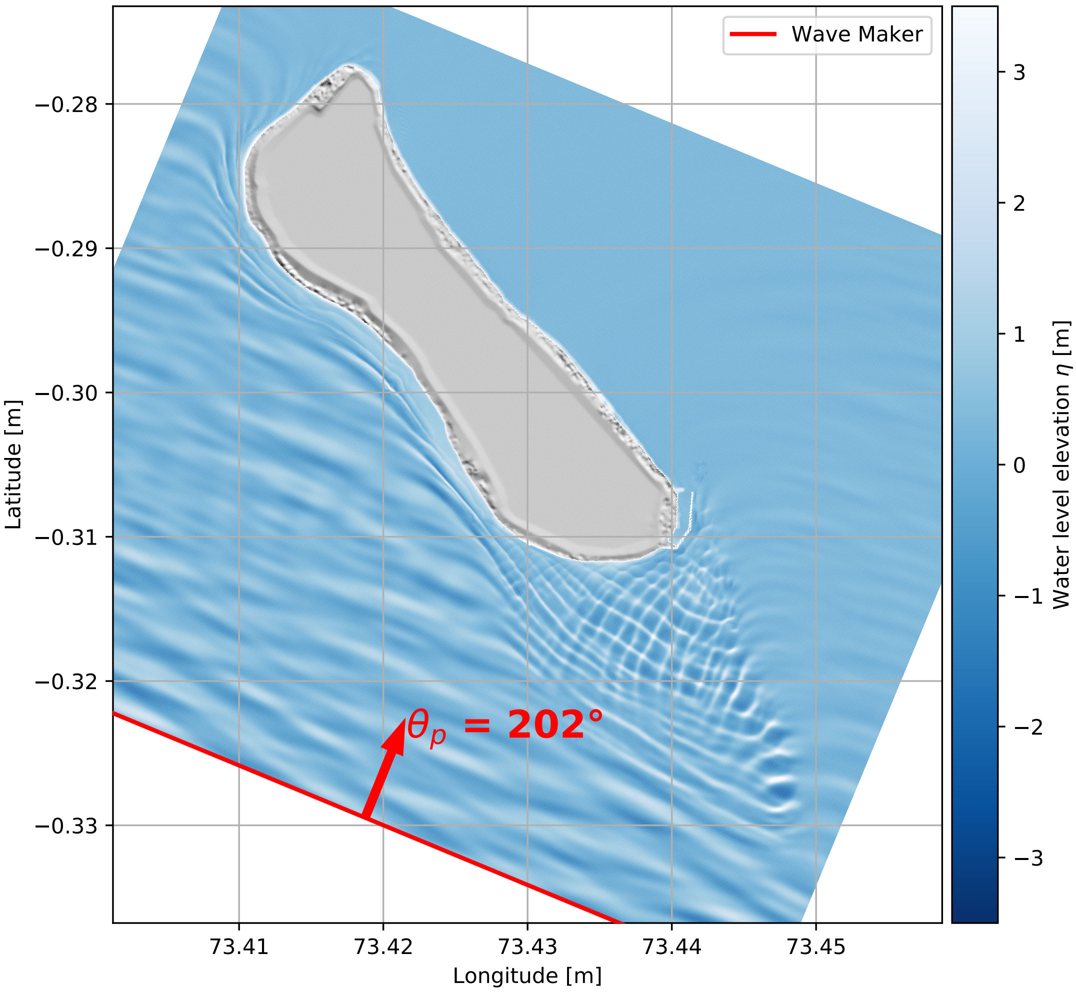

Figure S2: Water level elevation η computed by BOSZ, showing how waves transform over the reef.

The study in the main manuscript uses wave climate data from the global climate reanalysis models for the region of Fuvahmulah – the numerical, phase-resolving Boussinesq Ocean and Surf Zone model (BOSZ) is able to use the off-shore fifth generation atmospheric reanalysis of the global climate (ERA5) data of European Centre for Medium-Range Weather Forecasts (ECMWF) to compute waves propagating from deeper waters onto the fringing reef and over irregular bathymetries (Roeber and Cheung, 2012). Figure S2 shows a snapshot of water level elevation for a computation time of $4800\,\mathrm{s}$ (1.33 hours).

THOONDU SPIT EVENT, WET SEASON 2019

Figure S3 shows the formation of the Thoondu spit in September and October 2019. Usually the sand spit is located on the tip of the headland (see main paper), however in the wet season 2019, the spit formed on the adjacent Geiymiskih beach and covered almost the whole reef width. This event received special attention regionally. An inhabitant form the island reports, that *on these days [...] even, Engine Dhoani [note from the author: a motorized fisher boat] can reach to [the] beach[...]. Old Citizens told that they have never seen this happened in [their] whole life.* (personal conversation over a social network between Ali A., inhabitant of Fuvahmulah and C. Gabriel David, author). This special occasion was well acknowledged by locals and national tourists and trended on social media channels, as well as on local news. Figure S3 also shows the associated results from the CERC-formulation (CERC, 1984), which is able to capture the northward directed sediment transport rate.

The Australian Bureau of Meteorology (BOM) calculates the Indian Ocean Dipole (IOD) in form of the Dipole Mode Index (DMI). The IOD is an oscillation of sea surface temperatures between the western Indian Ocean and the tropical south-eastern Indian Ocean comparable with El Niño (Saji et al., 1999). A positive DMI over a threshold of $\pm 0.4° - 0.7°$ (Saji et al., 1999; **?**) leads to an inverse atmospheric convection, and thus winds, from east to west over the Indian ocean, approaching Fuvahmulah as swell waves. For the recording time of the images in Figure S3, the DMI was especially high (Figure S4) and a likely cause for this special beach protusion.

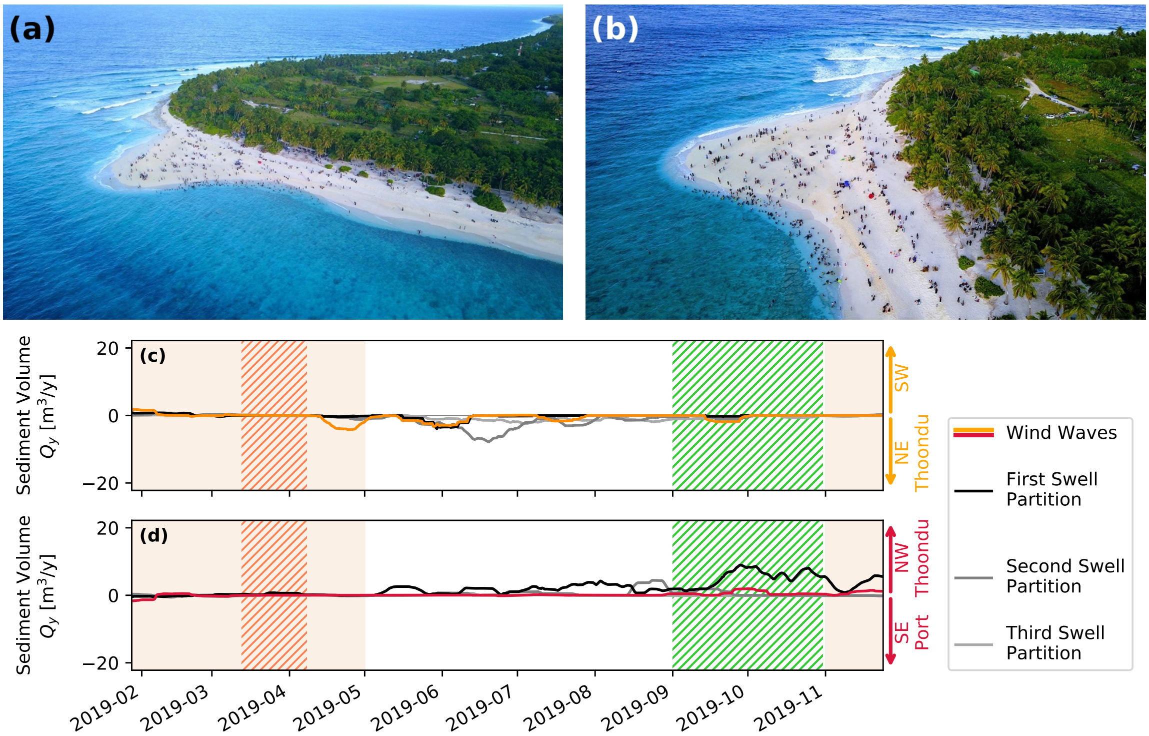

Figure S3: **(a,b)** Aerial images, showing the beach formation in northern Fuvahmulah in the second half of the 2019 wet season. These images where distributed over Facebook by the profile @Fuvahmulah.FVM. **(c)** and **(d)** are the sediment transport rates $q_{y,p}$ associated with 2019. The hatched green area is the time of the displayed events.

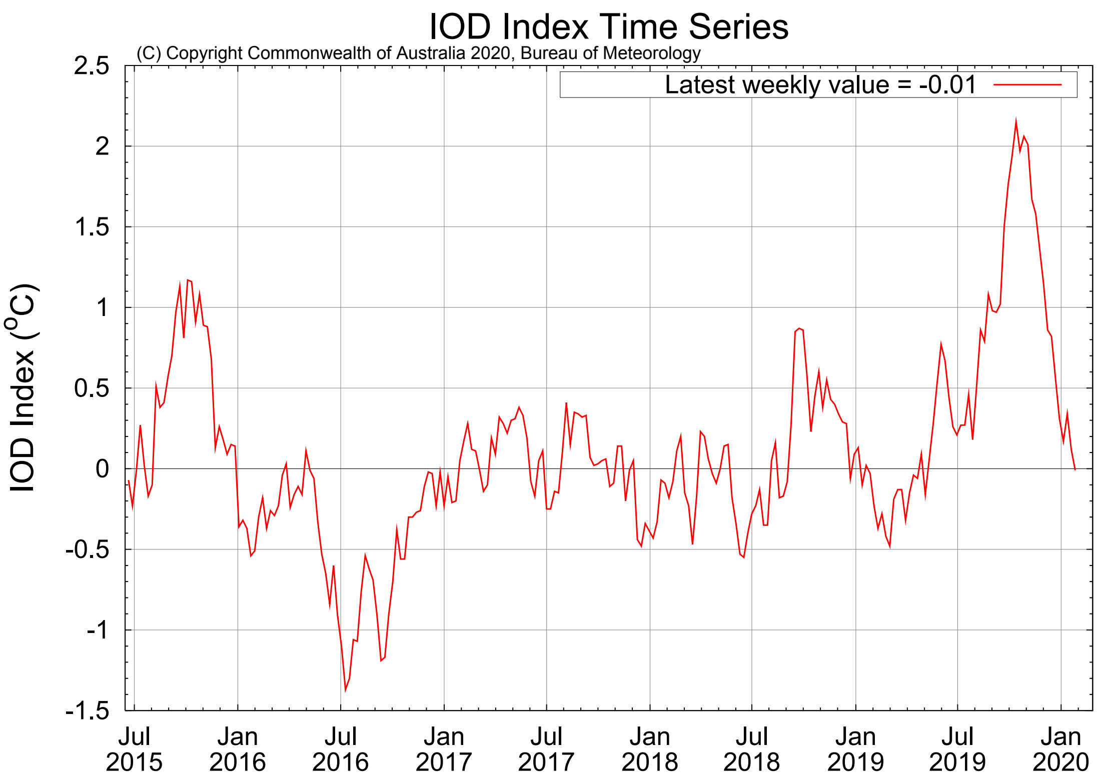

Figure S4: Dipole Mode Index (DMI) of the Indian Ocean Dipole (IOD), measured by the BOM and provided through their homepage. The graph shows the high sea-surface temperature (SST) oscillation in the Indian Ocean in October 2019. This event led to the beach formation in late wet season 2019 on Fuvahmulah.

GNSS AND DEM ERROR

The rover consisted of a Septentrio AsteRx-U receiver and another NAVX-3G antenna, recording between 12 and 18 ground control point (GCP) per tile. The GCP measurements were corrected in RTKLIB 2.4.3 b31 with the signal of the reference point, leading to a median standard deviation of $\tilde{\sigma}_{GNSS} = 3.4\,\mathrm{cm}$. The software estimates σ_{GNSS} for each dimension, which will result in the total standard deviation for the method by using

$$\sigma_{GNSS} = \sqrt{\sigma_N^2 + \sigma_E^2 + \sigma_U^2} \tag{S1}$$

where the indices N, E and U represent northing, easting and up-ward respectively. The aerial images and the GCPs of the third campaign were then post-processed in Agisoft Photoscan 1.4.5 build 7354 to digital elevation models (DEMs) of each tile. Photoscan implemented the GCPs with a median standard deviation of $\tilde{\sigma}_{GCP} = 2.8\,\mathrm{cm}$ (estimated by the software). When considering

$$\tilde{\sigma}_{DEM,3} = \tilde{\sigma}_{GNSS} + \tilde{\sigma}_{GCP} \tag{S2}$$

the total median positioning error $\tilde{\sigma}_{DEM,3}$ within EPSG:4326 (WGS84) will be $6.2\,\mathrm{cm}$ for the DEMs recorded in the dry season of 2019. This campaign will then serve as reference for the DEMs recorded in the other campaigns. The median standard deviation of the implemented virtual Ground Control Points (vGCPs) and thus the median relative error between the GCPs of the dry seasons is $\tilde{\sigma}_{vGCP} = 12.7\,\mathrm{cm}$. Between the DEMs of the dry season 2019 and wet season 2017, the median standard deviation is $\tilde{\sigma}_{vGCP} = 13.6\,\mathrm{cm}$. The median absolute error in a geographic coordinate system for the DEMs are then

$$\tilde{\sigma}_{DEM,i} = \tilde{\sigma}_{DEM,3} + \tilde{\sigma}_{vGCP,i} \tag{S3}$$

with i for the DEMs from the respective field campaigns. Here, $\tilde{\sigma}_{\text{DEM,dry season 2017}} = 18.9\,\mathrm{cm}$ and $\tilde{\sigma}_{\text{DEM,wet season 2017}} = 19.8\,\mathrm{cm}$ within EPSG:4326 (WGS84) (Figure S5).

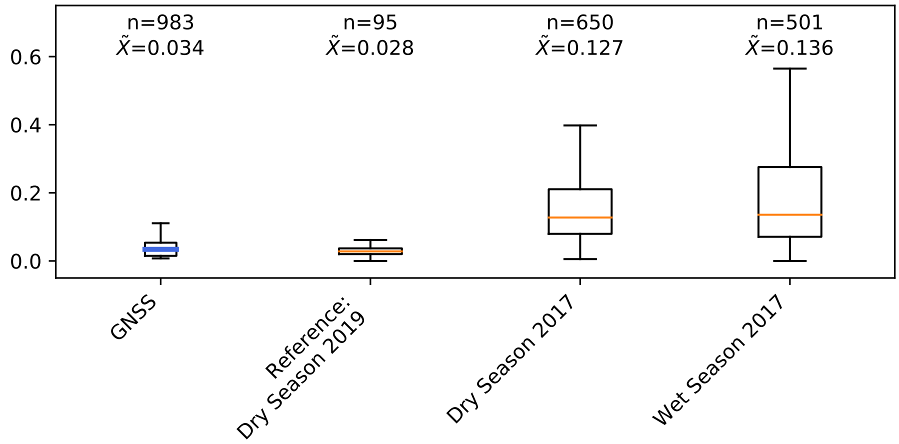

Figure S5: Standard deviations for the GNSS measurements σ_{GNSS} (blue median) as well as for the GCPs of the 2019 reference DEMs $\sigma_{DEM,3}$ and the 2017 dry season and wet season DEMs $\sigma_{DEM,1}$ and $\sigma_{DEM,2}$ (orange medians) in the DEMs

REFERENCES

Albert, S., Leon, J. X., Grinham, A. R., Church, J. A., Gibbes, B. R., and Woodroffe, C. D. (2016). Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environmental Research Letters* 11, 054011. doi:10.1088/1748-9326/11/5/054011

Andersson, A. (2015). A fundamental paradigm for coral reef carbonate sediment dissolution. *Frontiers in Marine Science* 2, 52. doi:10.3389/fmars.2015.00052

Atkinson, A. L., Baldock, T. E., Birrien, F., Callaghan, D. P., Nielsen, P., Beuzen, T., et al. (2018). Laboratory investigation of the bruun rule and beach response to sea level rise. *Coastal Engineering* 136, 183 – 202. doi:doi.org/10.1016/j.coastaleng.2018.03.003

Austin, M. J. and Masselink, G. (2006). Swash–groundwater interaction on a steep gravel beach. *Continental Shelf Research* 26, 2503 – 2519. doi:doi.org/10.1016/j.csr.2006.07.031

Bidlot, J.-R. (2016). *Ocean wave model output parameters*. European Centre for Medium-Range Weather Forecasts (ECMWF)

Bosboom, J. and Stive, M. J. F. (2015). *Coastal Dynamics I*, vol. 0.5 (Delft, the Netherlands: Delft Academic Press)

Burcharth, H. F., Hawkins, S. J., Zanuttigh, B., and Lamberti, A. (2007). Design tools related to engineering. In *Environmental Design Guidelines for Low Crested Coastal Structures*, eds. H. F. Burcharth, S. J. Hawkins, B. Zanuttigh, and A. Lamberti (Oxford: Elsevier Science Ltd), chap. 13. 203 – 333. doi:doi.org/10.1016/B978-008044951-7/50033-6

[Dataset] C3S (2017). ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate by the Copernicus Climate Change Service (C3S). `https://cds.climate.copernicus.eu/cdsapp#!/home`. doi:10.24381/cds.adbb2d47. Copernicus Climate Change Service Climate Data Store (CDS). Last date of access: 2019-12-06

Cai, W., Santoso, A., Wang, G., Weller, E., Wu, L., Ashok, K., et al. (2014). Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming. *Nature* 510, 254–258. doi:10.1038/nature13327

Caldwell, P. C., Merrifield, M. A., and Thompson, P. R. (2015). *Sea level measured by tide gauges from global oceans — the Joint Archive for Sea Level holdings (NCEI Accession 0019568)*. Dataset. Version 5.5, NOAA National Centers for Environmental Information,. doi:10.7289/V5V40S7W

Callaghan, D. P., Nielsen, P., Cartwright, N., Gourlay, M. R., and Baldock, T. E. (2006). Atoll lagoon flushing forced by waves. *Coastal Engineering* 53, 691 – 704. doi:10.1016/j.coastaleng.2006.02.006

Casella, E., Collin, A., Harris, D., Ferse, S., Bejarano, S., Parravicini, V., et al. (2016). Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. *Coral Reefs* 36, 269–275. doi:10.1007/s00338-016-1522-0

Casella, E., Drechsel, J., Winter, C., Benninghoff, M., and Rovere, A. (2020). Accuracy of sand beach topography surveying by drones and photogrammetry. *Geo-Marine Letters* doi:10.1007/s00367-020-00638-8

CERC (1984). *Shore Protection Manual*, vol. 1 (Coastal Engineering Research Center (CERC) Dept. of the U.S. Army, Waterways Experiment Station, Corps of Engineers, Coastal Engineering Research Center)

Chave, K. E., Smith, S. V., and Roy, K. J. (1972). Carbonate production by coral reefs. *Marine Geology* 12, 123 – 140. doi:10.1016/0025-3227(72)90024-2

Cheriton, O. M., Storlazzi, C. D., and Rosenberger, K. J. (2016). Observations of wave transformation over a fringing coral reef and the importance of low-frequency waves and offshore water levels to runup, overwash, and coastal flooding. *Journal of Geophysical Research: Oceans* 121, 3121–3140. doi:10.1002/2015JC011231

Collins, M., Sutherland, M., Bouwer, L., Cheong, S.-M., Frölicher, T., Combes, H. J. D., et al. (2019). Extremes, Abrupt Changes and Managing Risk. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, eds. H.-O. Pörtner, D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. Weyer (In Press). 589–655

Dangendorf, S., Hay, C., Calafat, F. M., Marcos, M., Piecuch, C. G., Berk, K., et al. (2019). Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change* 9, 705–710. doi:10.1038/s41558-019-0531-8

David, C. G., Roeber, V., Goseberg, N., and Schlurmann, T. (2017). Generation and propagation of ship-borne waves - Solutions from a Boussinesq-type model. *Coastal Engineering* 127, 170 – 187. doi:10.1016/j.coastaleng.2017.07.001

David, C. G., Schlurmann, T., and Roeber, V. (2019). Coastal Infrastructure on Reef Islands – the Port of Fuvahmulah, the Maldives as Example of Maladaptation to Sea-Level Rise? In *Coastal Structures 2019*, eds. N. Goseberg and T. Schlurmann (Hannover, Germany: Bundesanstalt für Wasserbau), 874–885. doi:doi.org/10.18451/978-3-939230-64-9_087

David, C. G., Schulz, N., and Schlurmann, T. (2016). Assessing the Application Potential of Selected Ecosystem-Based, Low-Regret Coastal Protection Measures. In *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice*, eds. F. G. Renaud, K. Sudmeier-Rieux, M. Estrella, and U. Nehren (Cham: Springer International Publishing). 457–482. doi:10.1007/978-3-319-43633-3_20

Duvat, V. K. E. and Magnan, A. K. (2019). Rapid human-driven undermining of atoll island capacity to adjust to ocean climate-related pressures. *Scientific Reports* 9. doi:10.1038/s41598-019-51468-3

East, H. K., Perry, C. T., Kench, P. S., Liang, Y., and Gulliver, P. (2018). Coral Reef Island Initiation and Development Under Higher Than Present Sea Levels. *Geophysical Research Letters* 45, 11,265–11,274. doi:10.1029/2018GL079589

Emanuel, K. (1988). The maximum intensity of hurricanes. *Journal of the Atmospheric Sciences* 45, 1143–1155

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., and Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications* 5. doi:10.1038/ncomms4794

Gawehn, M., van Dongeren, A., van Rooijen, A., Storlazzi, C. D., Cheriton, O. M., and Reniers, A. (2016). Identification and classification of very low frequency waves on a coral reef flat. *Journal of Geophysical Research: Oceans* 121, 7560–7574. doi:10.1002/2016jc011834

Gourlay, M. R. and Colleter, G. (2005). Wave-generated flow on coral reefs—an analysis for two-dimensional horizontal reef-tops with steep faces. *Coastal Engineering* 52, 353 – 387. doi:10.1016/j.coastaleng.2004.11.007

Hamylton, S. M., Duce, S., Vila-Concejo, A., Roelfsema, C. M., Phinn, S. R., Carvalho, R. C., et al. (2017). Estimating regional coral reef calcium carbonate production from remotely sensed seafloor maps. *Remote Sensing of Environment* 201, 88 – 98. doi:10.1016/j.rse.2017.08.034

Hanson, J. L. and Phillips, O. M. (2001). Automated Analysis of Ocean Surface Directional Wave Spectra. *Journal of Atmospheric and Oceanic Technology* 18, 277–293. doi:10.1175/1520-0426(2001)018⟨0277:AAOOSD⟩2.0.CO;2

Harris, D. L., Rovere, A., Casella, E., Power, H., Canavesio, R., Collin, A., et al. (2018). Coral reef structural complexity provides important coastal protection from waves under rising sea levels. *Science Advances* 4. doi:10.1126/sciadv.aao4350

Hermes, J. C., Masumoto, Y., Beal, L. M., Roxy, M. K., Vialard, J., Andres, M., et al. (2019). A Sustained Ocean Observing System in the Indian Ocean for Climate Related Scientific Knowledge and Societal Needs. *Frontiers in Marine Science* 6, 355. doi:10.3389/fmars.2019.00355

Hildebrandt, A., Schmidt, B., and Marx, S. (2019). Wind-wave misalignment and a combination method for direction-dependent extreme incidents. *Ocean Engineering* 180, 10 – 22. doi:10.1016/j.oceaneng.2019.03.034

Horrillo, J., Grilli, S. T., Nicolsky, D., Roeber, V., and Zhang, J. (2014). Performance benchmarking tsunami models for NTHMP's inundation mapping activities. *Pure and Applied Geophysics* 172, 869–884. doi:10.1007/s00024-014-0891-y

IPCC (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. In *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*, eds. C. B. Field, V. Barros, T. F. Stocker, Q. Dahe, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, and P. M. Midgley (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press). 582 pp.

Kench, P. S. (2012). Compromising Reef Island Shoreline Dynamics: Legacies of the Engineering Paradigm in the Maldives. In *Pitfalls of Shoreline Stabilization: Selected Case Studies*, eds. J. A. G. Cooper and O. H. Pilkey (Dordrecht: Springer Netherlands). 165–186. doi:10.1007/978-94-007-4123-2_11

Kench, P. S. and Brander, R. W. (2006). Response of reef island shorelines to seasonal climate oscillations: South Maalhosmadulu atoll, Maldives. *Journal of Geophysical Research: Earth Surface* 111. doi:10.1029/2005JF000323

Kench, P. S. and Mann, T. (2017). Reef Island Evolution and Dynamics: Insights from the Indian and Pacific Oceans and Perspectives for the Spermonde Archipelago. *Frontiers in Marine Science* 4, 145. doi:10.3389/fmars.2017.00145

Kumar, P., Kaur, S., Weller, E., and Min, S.-K. (2019). Influence of Natural Climate Variability on the Extreme Ocean Surface Wave Heights Over the Indian Ocean. *Journal of Geophysical Research: Oceans* 124, 6176–6199. doi:10.1029/2019JC015391

Longuet-Higgins, M. S. (1970). Longshore currents generated by obliquely incident sea waves: 2. *Journal of Geophysical Research (1896-1977)* 75, 6790–6801. doi:10.1029/JC075i033p06790

Lynett, P. J., Gately, K., Wilson, R., Montoya, L., Arcas, D., Aytore, B., et al. (2017). Inter-model analysis of tsunami-induced coastal currents. *Ocean Modelling* 114, 14 – 32. doi:doi.org/10.1016/j.ocemod.2017.04.003

Magnan, A., M., G., Gattuso, J.-P., J., H., Hilmi, N., Holland, E., et al. (2019). Integrative cross-chapter box on low-lying islands and coasts. In *Special Report on Ocean and Cryosphere in a Changing Climate*, eds. H.-O. Pörtner, D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegriá, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. Weyer (In press). 657–674

Mandlier, P. G. and Kench, P. S. (2012). Analytical modelling of wave refraction and convergence on coral reef platforms: Implications for island formation and stability. *Geomorphology* 159-160, 84 – 92. doi:doi.org/10.1016/j.geomorph.2012.03.007

Masselink, G., Tuck, M., McCall, R., van Dongeren, A., Ford, M., and Kench, P. (2019). Physical and Numerical Modeling of Infragravity Wave Generation and Transformation on Coral Reef Platforms. *Journal of Geophysical Research: Oceans* 124, 1410–1433. doi:10.1029/2018JC014411

McCall, R., Masselink, G., Poate, T., Roelvink, J., Almeida, L., Davidson, M., et al. (2014). Modelling storm hydrodynamics on gravel beaches with XBeach-G. *Coastal Engineering* 91, 231 – 250. doi:10.1016/j.coastaleng.2014.06.007

McLean, R. and Kench, P. (2015). Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdisciplinary Reviews: Climate Change* 6, 445–463. doi:10.1002/wcc.350

MEE (2014). *Environment & Social Assessment & Management Framework - Climate Change Adaptation Project*. Tech. rep., Ministry of Environment and Energy, Republic of Maldives. Last accessed Dec. 27 through `http://documents.worldbank.org/curated/en/939971468329099370/pdf/E47010SAR0EA0P1533010Box385392B00PUBLIC0.pdf`

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B. K., et al. (2014). Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience* 7, 727–731. doi:10.1038/ngeo2251

Naeem, H. (2006). *Foahmulaku Beach Erosion Survey & Coastal Protection Report*. Tech. rep., Ministry of Environment, Energy and water

Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., van Wesenbeeck, B., Pontee, N., et al. (2016). The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLOS ONE* 11, 1–17. doi:10.1371/journal.pone.0154735

Nielsen, P., Robert, S., Møller-Christiansen, B., and Oliva, P. (2001). Infiltration effects on sediment mobility under waves. *Coastal Engineering* 42, 105 – 114. doi:doi.org/10.1016/S0378-3839(00)00051-X

Nurse, L. A., McLean, R. F., Agard, J., Briguglio, L. P., Duvat-Magnan, V., Pelesikoti, N., et al. (2014). Small Islands. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*, eds. V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press). 1613–1654

Oppenheimer, M., Glavovic, B., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., et al. (2019). Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities. In *IPCC Special Report on the Ocean and Cryosphere in a Changing*

Climate, eds. H.-O. Portner, D. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegriá, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. Weyer (In press). 702

Paul, M. and Gillis, L. (2015). Let it flow: how does an underlying current affect wave propagation over a natural seagrass meadow? *Marine Ecology Progress Series* 523, 57–70. doi:10.3354/meps11162

Perry, C. T., Alvarez-Filip, L., Graham, N. A. J., Mumby, P. J., Wilson, S. K., Kench, P. S., et al. (2018). Loss of coral reef growth capacity to track future increases in sea level. *Nature* 558, 396–400. doi:10.1038/s41586-018-0194-z

Perry, C. T., Kench, P. S., Smithers, S. G., Riegl, B., Yamano, H., and Leary, M. J. O. (2011). Implications of reef ecosystem change for the stability and maintenance of coral reef islands. *Global Change Biology* 17, 3679–3696. doi:10.1111/j.1365-2486.2011.02523.x

Pisapia, C., Burn, D., and Pratchett, M. S. (2019). Changes in the population and community structure of corals during recent disturbances (February 2016-October 2017) on Maldivian coral reefs. *Scientific Reports* 9. doi:10.1038/s41598-019-44809-9

Pomeroy, A. W., Lowe, R. J., Dongeren, A. R. V., Ghisalberti, M., Bodde, W., and Roelvink, D. (2015). Spectral wave-driven sediment transport across a fringing reef. *Coastal Engineering* 98, 78 – 94. doi:10.1016/j.coastaleng.2015.01.005

Pomeroy, A. W. M., Lowe, R. J., Ghisalberti, M., Storlazzi, C., Symonds, G., and Roelvink, D. (2017). Sediment transport in the presence of large reef bottom roughness. *Journal of Geophysical Research: Oceans* 122, 1347–1368. doi:10.1002/2016JC011755

Pomeroy, A. W. M., Lowe, R. J., Ghisalberti, M., Winter, G., Storlazzi, C., and Cuttler, M. (2018). Spatial Variability of Sediment Transport Processes Over Intratidal and Subtidal Timescales Within a Fringing Coral Reef System. *Journal of Geophysical Research: Earth Surface* 123, 1013–1034. doi:10.1002/2017JF004468

Ratter, B., Hennig, A., and Zahid (2019). Challenges for shared responsibility – Political and social framing of coastal protection transformation in the Maldives. *DIE ERDE - Journal of the Geographical Society of Berlin* 150, 169–183

Roeber, V. and Bricker, J. D. (2015). Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan. *Nature Communications* 6. doi:10.1038/ncomms8854

Roeber, V. and Cheung, K. F. (2012). Boussinesq-type model for energetic breaking waves in fringing reef environments. *Coastal Engineering* 70, 1 – 20. doi:10.1016/j.coastaleng.2012.06.001

Roeber, V., Cheung, K. F., and Kobayashi, M. H. (2010). Shock-capturing Boussinesq-type model for nearshore wave processes. *Coastal Engineering* 57, 407 – 423. doi:http://dx.doi.org/10.1016/j.coastaleng.2009.11.007

Rutten, J., Ruessink, B. G., and Price, T. D. (2017). Observations on sandbar behaviour along a man-made curved coast. *Earth Surface Processes and Landforms* 43, 134–149. doi:10.1002/esp.4158

Ryan, E. J., Hanmer, K., and Kench, P. S. (2019). Massive corals maintain a positive carbonate budget of a Maldivian upper reef platform despite major bleaching event. *Scientific Reports* 9. doi:10.1038/s41598-019-42985-2

Saji, N. and Yamagata, T. (2003). Possible impacts of Indian Ocean Dipole mode events on global climate. *Climate Research* 25, 151–169. doi:10.3354/cr025151

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., and Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature* 401, 360–363. doi:10.1038/43854

Schoonees, J. S. and Theron, A. K. (1995). *Accuracy and Applicability of the SPM Longshore Transport Formula* (American Society of Civil Engineers), chap. 188. 2595–2609. doi:10.1061/9780784400890.189

Schoonees, T., Mancheño, A. G., Scheres, B., Bouma, T. J., Silva, R., Schlurmann, T., et al. (2019). Hard Structures for Coastal Protection, Towards Greener Designs. *Estuaries and Coasts* 42, 1709–1729. doi:10.1007/s12237-019-00551-z

Shope, J. B. and Storlazzi, C. D. (2019). Assessing Morphologic Controls on Atoll Island Alongshore Sediment Transport Gradients Due to Future Sea-Level Rise. *Frontiers in Marine Science* 6, 245. doi:10.3389/fmars.2019.00245

Skirving, W. J., Heron, S. F., Marsh, B. L., Liu, G., De La Cour, J. L., Geiger, E. F., et al. (2019). The relentless march of mass coral bleaching: a global perspective of changing heat stress. *Coral Reefs* 38, 547–557. doi:10.1007/s00338-019-01799-4

Smith, E. R., Wang, P., Ebersole, B. A., and Zhang, J. (2009). Dependence of Total Longshore Sediment Transport Rates on Incident Wave Parameters and Breaker Type. *Journal of Coastal Research* , 675–683doi:10.2112/07-0919.1

Stive, M. J., de Schipper, M. A., Luijendijk, A. P., Aarninkhof, S. G., van Gelder-Maas, C., van Thiel de Vries, J. S., et al. (2013). A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. *Journal of Coastal Research* , 1001–1008doi:10.2112/JCOASTRES-D-13-00070.1

Storlazzi, C. D., Elias, E. P., and Berkowitz, P. (2015). Many Atolls May be Uninhabitable Within Decades Due to Climate Change. *Scientific Reports* 5. doi:10.1038/srep14546

Storlazzi, C. D., Gingerich, S. B., van Dongeren, A., Cheriton, O. M., Swarzenski, P. W., Quataert, E., et al. (2018). Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances* 4. doi:10.1126/sciadv.aap9741

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., and Vriend, H. J. D. (2013). Ecosystem-based coastal defence in the face of global change. *Nature* 504, 79–83. doi:10.1038/nature12859

Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M., et al. (2015). Profiling risk and sustainability in coastal deltas of the world. *Science* 349, 638–643. doi:10.1126/science.aab3574

Tory, K. J. and Frank, W. M. (2010). Tropical Cyclone Formation. In *World Scientific Series on Asia-Pacific Weather and Climate* (World Scientific Publishing). 55–91. doi:10.1142/9789814293488_0002

Turner, I. L. and Masselink, G. (1998). Swash infiltration-exfiltration and sediment transport. *Journal of Geophysical Research: Oceans* 103, 30813–30824. doi:10.1029/98JC02606

van Rijn, L. C. (2005). *Principles of Sedimentation and Erosion Engineering in Rivers, Estuaries and Coastal Seas* (Amsterdam, The Netherlands: Aqua Publications)

Wessel, P. and Luis, J. F. (2017). The GMT/MATLAB Toolbox. *Geochemistry, Geophysics, Geosystems* 18, 811–823. doi:10.1002/2016GC006723

Wiese, A., Staneva, J., Schulz-Stellenfleth, J., Behrens, A., Fenoglio-Marc, L., and Bidlot, J.-R. (2018). Synergy of wind wave model simulations and satellite observations during extreme events. *Ocean Science* 14, 1503–1521. doi:10.5194/os-14-1503-2018

Wing, M. G., Eklund, A., and Kellogg, L. D. (2005). Consumer-Grade Global Positioning System (GPS) Accuracy and Reliability. *Journal of Forestry* 103, 169–173. doi:10.1093/jof/103.4.169

Woodroffe, C., McLean, R., Smithers, S., and Lawson, E. (1999). Atoll reef-island formation and response to sea-level change: West Island, Cocos (Keeling) Islands. *Marine Geology* 160, 85 – 104. doi:10.1016/S0025-3227(99)00009-2