Modelling direct sediment producers to climate change effects

Additional thesis - Floortje Burgers

TU Delft

Modelling direct sediment producers to climate change effects

Floortje Burgers

Supervision:

Dr. N.K. Browne	*Curtin University*
Dr. M.J. O'Leary	*University of Western Australia*
Dr.Ir. A.A. Verhagen	*Delft University of Technology*
Dr. M.F.S. Tissier	*Delft University of Technology*

Additional Thesis
Master of Applied Earth Science

Geoscience and Remote Sensing
Delft University of Technology
The Netherlands
March 2020

Contents

Abstract

The resiliency of coral reef islands to changing environments associated with climate change is controlled by the delicate balance between the import and export of sediment. The majority of the sediment is derived from coral reefs for which the stability of these islands is directly related to reef health. Understanding the sediment signature and its drivers is essential to assess island resiliency. We performed a study on sediments from the islands Eva and Fly in the Exmouth Gulf, Australia. We analysed the grainsize distribution and the abundance of sediment producers in order to desribe and discriminate the spatial distribution of these sediment characteristics and performed statistical analysis to identify corresponding key environmental drivers. We found that the sediments were typically course sand-sized ($500 - 1000$ [µm]) and the dominant constituent is reef-derived sediment. The median grainsize of Eva island (549 [µm]) is nearly equal to the median grainsize of Fly island (540 [µm]). The standard deviation of the grain size distribution of the sediments from Eva island was much larger than at Fly island. However, analysis of variance showed there were no significant differences between islands (Eva/Fly), hydrodynamic regimes (high/low), distance to shore (inshore/offshore) and local habitat (reef/no reef). Furthermore, a distance-based redundancy analysis showed no key environmental driver responsible for the distribution in grainsize and composition of the sediment. The environmental factors which were analyses were depth, temperature, pH, dissolved oxygen content and the oxidation-reduction potential. The spatiotemporal scales that were studied are potentially smaller than the scales on which climate change effects act, which explains the absence of significant spatial differences or key environmental drivers. Based on these findings it is not possible to assess the resiliency of Eva and Fly islands, however a study from Perry et al. (2011) found that islands with their particular characteristics (sand-sized and coral-dominated) are expected to undergo major morphological change under a range of predicted climate change scenarios. This research provides a baseline for future studies to assess the stability of Eva and Fly islands or sedimentological research other reef-derived islands.

Introduction

Coral reef islands are dynamic landforms that predominantly consist of unconsolidated carbonate sediments derived from adjacent reefs (Woodroffe, 1997). They are of global significance, providing habitable land for hundreds of thousands of people (Yamano et al., 2005) and native species of flora and fauna (Turner and Batianoff, 2007). These low-lying islands are often considered highly susceptible to climate change (McLean et al., 2001, Nicholls et al., 2007), especially to sea level rise (Woodroffe, 2008). The balance between import and export of sediment is also crucial in determining the morphological change of these landforms (Kench and Cowell, 2002). Changes in the physical and ecological environments of the reefs control the characteristics of the sediments (Perry et al., 2008), which in turn determine the geomorphological features and the geomorphic stability of reef islands (Kench, 2014). Sediment is supplied by carbonate-producing reef organisms and mobilised and transported by waves and currents (Stoddart and Steers, 1977). Environmental shifts such as rising temperatures and ocean acidification, affect reef health and subsequently alter the composition of the sediment supply (Hoegh-Guldberg, 1999). The influence of changes in ecological processes that alter sediment production may dominate the influence on island resiliency by changes in sea level (Kench and Cowell, 2002) and thus is linking reef ecology to sediment and island dynamics essential to assess the resiliency of coral reef islands (Morgan and Kench, 2014).

Sediments are strongly connected to coral reefs because they are composed almost completely of skeletal remains of reef biota (Harney et al., 2000, Perry et al., 2011, Dawson et al., 2014). Direct contributions are from the remains of infaunal and epifaunal calcareous organisms that live in the reef ecosystem, while the indirect contributions derive from destruction of the reef framework (Perry et al., 2011). Deterioration of the framework is caused by biological erosion (e.g. by borers, urchins, parrotfish) and by physical destruction (e.g. storm events) (Stearn et al., 1977, Hubbard et al., 1990). The dominant constituents of coral reef island sediments therefore include coral, mollucs, coralline red algae (CCA), green algae (e.g. Halimeda), foraminifera and echinoderms (Harney and Fletcher III, 2003). The link between ecology and geomorphology can be obtained from a sediment budget analysis, which quantifies the sinks, sources, and fluxes of sediment (Harney and Fletcher III, 2003). The transport of sediment controls the development of geomorphological features and for reef-derived sediments five depositionial sinks exist. Sediments can be reworked into the reef structure (Hubbard et al., 1990), can construct reef islands (Woodroffe, 1997, Perry et al., 2011), can be stored on the surface of the reef (Harney and Fletcher III, 2003), can fill lagoons (Kench, 1998) and can be transported away from the reef (Hughes and Connell, 1999). Carbonate sediment budgets have shown that reef islands act as temporary sediment sinks rather than a place of permanent deposition (Morgan and Kench, 2014). The composition of the sediments on reef islands is crucial input to sediment budgets and thus plays mapping the direct sediment producers an important role in the understanding of the response of coral reef islands to future ecological and environmental shifts.

Changing environments influence reef health and subsequently the sediment budget of the reef islands (Kleypas et al., 2001). Studies have identified complex stress factors, which include shifts associated with climate change and changes in water quality, such as sediments and nutrients (Fabricius et al., 2005). Increasing sea temperatures in combination with high irradiance have been indicated as the driver of the increasing intensity, spatial extent and temporal frequency of coral bleaching events and increasing coral mortality (Hoegh-Guldberg, 1999). Ocean acidification due to increasing CO_2 levels in the ocean as a result of increasing CO_2 levels in the atmosphere, has been demonstrated as the driver of reduced calcification (Kleypas et al., 2001). Reduced calcification limits reef growth and reduces skeletal density but enhances both biological and physical erosion of the reef (Hoegh-Guldberg et al., 2007). The imbalance between increased erosion and decreased calcification rates results in global loss of coral reefs (Hoegh-Guldberg et al., 2007). Sediments are also shown to negatively impact corals by increasing turbidity which limits light availability for photosynthesis and the production of energy, or smothering the corals when depositioned (Rogers, 1990). The total suspended sediment (TSS) in the water can be used to determine the turbidity of the water, which provides insight on the light availability for benthic habitats (Dorji et al., 2016).

Sediment characteristics vary spatially and temporally due to the variety of controlling processes and dynamics acting on different spatiotemporal scales. The physical and biological parameters of coral reefs are complex and vary in space and time (Storlazzi et al., 2010, Browne et al., 2012) and due to the strong connection to coral reefs are sediment characteristics directly affected by these variations. Furthermore, are environmental shifts also caused by external forces which act on temporal scales varying from the weather-scale (days) to the scale of climate change (decades). These shifting environments not only affect reef health and reef growth but also drive variations in the basic sedimentary properties of the different sediment producers (Perry et al., 2011). The relative abundance of the sediment producers varies across different reef zones which subsequently results in spatial variations of the sediment supply. This link between patterns across ecological reef zones and spatially varying sediment supply is a key feature of most coral reef islands (Perry et al., 2011). To be able to assess the spatial and temporal variations, a local reference scenario must be defined. A baseline study is key to identify reef islands most susceptible to the effects of climate change. By recognising the islands most at risk, governmental and industrial strategies and regulations can be created or adjusted to obtain sustainable solutions.

This study aims to asses reef island resiliency in connection with shifts associated with climate change, for the islands Eva (21°55'19.6"S, 114°25'56.2"E) and Fly (21°48'24.0"S, 114°33'06.1"E) in the mouth of the Exmouth Gulf, Australia. We obtained sediment samples, water samples and suspended sediment samples to investigate the link between sediment producers and climate change effects. The objective is to describe and discriminate the spatial distribution of the characteristic grain size distribution and the abundance of sediment producers and identify key environmental drivers. The results of this study will support the development of carbonate budget models and by creating a reference scenario, we provide opportunities for future research.

Methods

2.1 Site description

The Exmouth Gulf is a northward facing embayment located in north-west Australia. The gulf is approximately 100 km long and 20 to 50 km wide and water depths range from 12 to 22 m (Orpin et al., 1999). West of the gulf the Cape Range Tertiary limestones form a ridge extending 300 m above sealevel. The eastern shores consist of extensive supratidal salt flats with mangroves. North of the gulf stretch several small islands, reefs and shoals that consist of consolidated to unconsolidated bioclastic and reef-derived sediments, which also extend into the bay (Brown, 1988). This study presents the results of a sedimentological study on two of these islands, Eva and Fly.

The hydrodynamic regime in the Exmouth Gulf is dominated by semi-diurnal micro tides (< 2m) (Holloway, 1983). These tides of the Indian Ocean force a counter-clockwise circulation in the gulf (Brunskill et al., 2001). The offshore wave climate is controlled by a persistent, low to moderate-energy wave regime, and is characterised by south to southwesterly swell (Sanderson et al., 2000). The gulf is sheltered from ocean waves and thus it is subject to local wind waves only which results in a tide-dominated system (Short and Woodroffe, 2009). Freshwater input from run-off from the mainland is very small, estimated it to be four times less the tidal input from the Indian Ocean (Brunskill et al., 2001). Input of terrestrial sediments is minor and groundwater inflow is considered negligible (Brunskill et al., 2001). Summers are hot with an average maximum temperature of 38°C and winters are mild with average maximum of 24°C (Paling et al., 2008). The average annual rainfall is 270 mm/year of which most is associated with tropical storms (Paling et al., 2008). The formation of tropical cyclones is enhanced by high sea surface temperatures (Emanuel, 2005) which makes the north west coast of Australia one of the most cyclone prone parts of the world (Lough, 1998). Cyclone season runs from mid December to April with a mean occurrence of four cyclones per year (Paling et al., 2008). Throughout the year the winds are predominantly south to southeasterly (Lough, 1998, *Climatic atlas of Australia*, n.d.). During spring and summer strong southerly winds prevail, while during autumn and winter lighter but variable winds dominate, with directions fluctuating from the dominant southeast to north and northeast winds (Brunskill et al., 2001). The wind regime is dominated by the interaction between the southeasterly trade wind system, the sea breeze generated by the west coast and a sea breeze developed within the Gulf (Brunskill et al., 2001). During winter wind conditions are mild, however during summer strong easterly to southwesterly winds prevail and wind speeds of >30 km/h occur on more than 70% of the days (Sanderson et al., 2000). The extreme rainfall, tides, winds and waves that are associated with cyclones affect sediment dynamics. The amount of sediment transported during and the total energy associated with a single storm event may equal months or years of regular conditions (Porter-Smith et al., 2004). Analysis of the sediments of the gulf reflect strong hydrodynamic influences from tides and storm events (Brown, 1988). The ecological habitats surrounding the islands are coral reef flats and patched column reefs ("bommies"), sea grass meadows and stretches of bare sand. Among the corals are massive Porites and Acropora colonies. Coral communities in the gulf have not been extensively documented however, Cooper et al. (2012) analysed core samples of some Porites corals in the Exmouth Gulf and their results showed a declination in calcification rates which can be indicative of changing environments.

2.2 Field data collection

Four light loggers (Odyssey™) and two temperature loggers (HOBO™) were installed to asses the influence of the amount of light on the characteristics of the sediment, and its relation to temperature (Figure 2.1). The light loggers were installed on the north and south side of both islands and the temperature loggers were installed at the same location as the two southern light loggers. The light loggers record the photosynthetically active radiation (PAR), defined as the light energy absorbed by photosensitive pigments [μmol photons $m^{-2}s^{-1}$] (Brooks, 1964, Long et al., 2012). The light loggers at Eva were deployed earlier that year, the light loggers at Fly were newly installed. Recording were obtained for a period of two week during the field trip from 02/09/2018 to 16/09/2018.

Surface water samples (1000 ml) were collected at different epochs in the vicinity of the light and temperature loggers (n = 16) to calibrate total suspended sediment to light loggers. Suspended sediment was collected by filtering the samples through pre-weighed 63 μm pore size filter paper using a suction filter. The samples were oven dried for 48 hours at 60 °C and reweighed.

Twenty-three sediment samples were collected in September 2018 for analysis on the islands (Eva (n = 12) and Fly (n = 11)). Sample locations were recorded using a hand-held GPS (Garmin eTrex 20x). Samples were taken at the start of shore-parallel underwater transects covering four delineated zones which were based on the expected hydrodynamic energy regime (high/low) and location with respect to shore (near/far). Bulk samples of 100 g were carefully collected by hand with use of a zip-lock bag to prevent any loss of fines (method after (Browne et al., 2013)). Water samples were taken from the sediment sample location to record environmental parameters. A calibrated hand-held multimeter kit (OxyGuard) was used to obtain temperature, pH, DO and ORP. Additional samples (250 mL) were collected and laboratory tested for alkalinity. Furthermore water depth and local habitat were recorded. Habitat classification was based on the presence of coral reef at the sample site (reef/no reef).

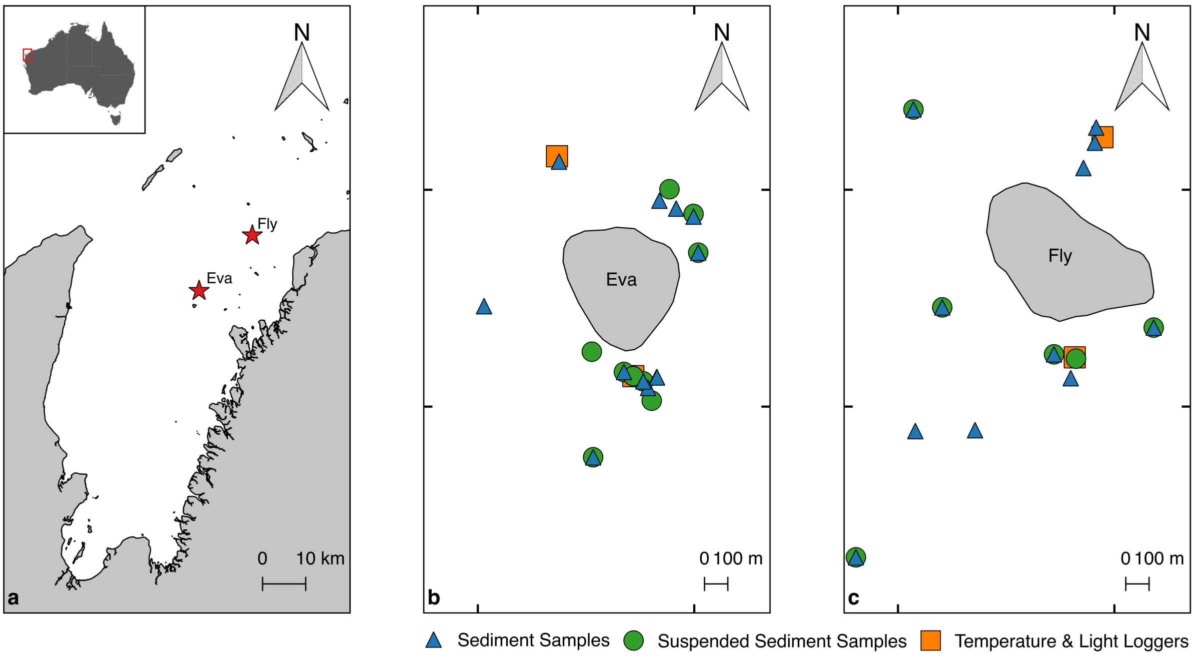


Figure 2.1: Sample locations across Eva and Fly Island

2.3 Laboratory analysis

The grain size distribution was obtained by analysing the samples through a sieve stack. Samples were oven dried for 48 hours at a temperature of 60 °C to prepare for dry sieving. Approximately 100 g was taken for sieving into the following six size fractions: $\geq$4000 μm, 2000-4000 μm, 500-2000 μm, 250-500 μm, 63-250 μm and <63 μm. A mechanical sieve shaker was used for five minutes to separate the individual grains. The sediment was collected and weighed per sieve. Results were analysed for grain size statistics after (Folk and Ward, 1957) and samples were descriptively classified according to (Wentworth, 1922) with the use of GRADISTAT V4 (Blott and Pye, 2001). Results of the grain size distribution were also statistically analysed for zonal patterns and principle components with the use of PRIMER.

The abundance of sediment producing organisms was assessed by identifying grains from the four largest size fractions. The two largest size classes were assessed by identifying all grains. The following two classes were assessed by systematically identifying approximately 100 grains per sample from two photos taken with a Tucsen ISH500 camera mounted on a Nikon SMZ745T microscope. Samples were washed in a sonic bath and oven dried for 24 hours prior to assist identification. Twelve classes were identified: hard coral, molluscs (bivalves and gastropods), foraminifera, serpulidae, crustose coralline algae (CCA), echinoderms, bryozoans, crustacaen debris, terrigineous sediments, clusters and indeterminate sediments. Results of the abundances were statistically analysed with the use of PRIMER for zonal patterns and principle components.

2.4 Data analysis

To form a first impression on local temperature and light climates, data from loggers and suspended sediment samples were analysed. Temperature and light data were assessed to obtain insight on the local water temperature and light attenuation. Timeseries of corresponding dates from the different locations were visually compared to assess potential differences between sites. To support the observations from the light loggers, total suspended sediment concentrations were evaluated. Basic statistical analyses were performed to gain insight on the average local conditions and to assess if there is a large spread in the suspended sediment concentration across the different sample sites.

The sediment characterics data (grain size and abundance) were checked for normality with the Shapiro-Wilk test and for homogeneity of the variance with Levene's test. To assess if there is a pattern in grain size distribution and abundancy of the sediment producers, group average hierarchical cluster analyses were performed on a distance-based Bray-Curtis (BC) similarity matrix of the square-root transformed biological data sets. Clusters were defined based on a 80% similarity cut off from the dendrograms. Non-metric multidimensional scaling (nMDS) was used to visualise the patterns.

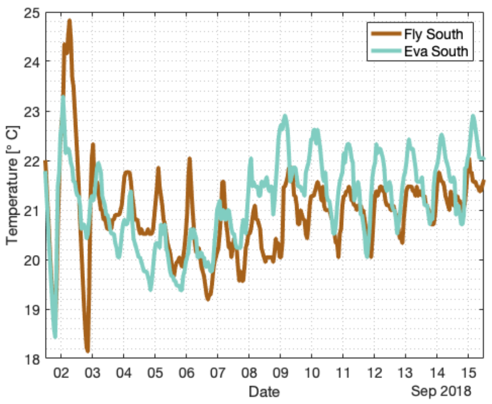
Analysis of variance is a statistical method to test the hypotheses of individual terms in a complex linear model. Variance analyses were performed to assess the hypothesis that there is a significant difference between sites, driven by the distribution of grainsize and the composition of the sediment. To assess the hypothesis that there is a significant difference in sediment characteristics between islands (Eva/Fly), hydrodynamic regimes (high/low), distance to shore (inshore/offshore) and local habitat (reef/no reef), the distributions of grainsize and compostion were tested. Four one-way multivariate variance analysis were performed (MANOVA) for which significance was set to a probability smaller than 5% ($p < 0.05$) (maximum number of permutation = 9999). One three-way MANOVA was performed to assess the interaction of the factors island, energy and shore, again significance was set to a probability smaller than 5% ($p < 0.05$).

To explore the hypothesis that the distribution of grainsize and composition of the sediment are explained by external forcings, redundancy analysis (RDA) was performed. A Distance-Based RDA (dbRDA) was conducted, using a Distance Linear Model (DistLM). The dbRDA method is based on a matrix of dissimilarities or distances and can be used to test interaction terms (Legendre and Anderson, 1999). The normalised environmental parameters were stepwisely added to the BC similarity matrix of the biological data to analyse if and which combinations of parameters explain the most variation in sediment characteristics. The external factors that were analysed are depth, temperature, pH, dissolved oxygen content (DO) and the oxidation-reduction potential (ORP). The DistLM ran a best fit selection procedure and Akaike Information Criterion (AIC) selection criterion with 9999 permutations.

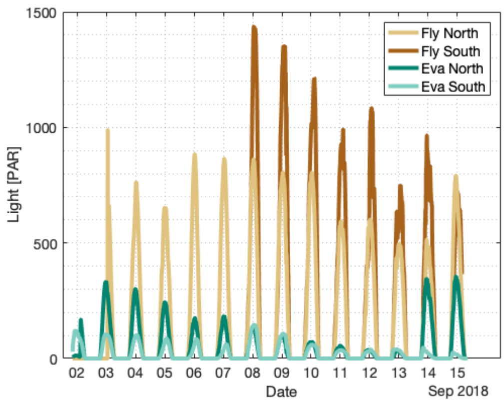
Results

3.1 Temperature and light

Continuous water temperature measurements were obtained from two locations, one south of Eva and one south of Fly island (Fig. 3.2a). The daily temperature cycle is clearly visible in the signal. Recorded temperatures for the first week are lower for Eva island, while temperatures in the second week are higher for Eva island. Timeseries from light intensity measurements were obtained for two additional locations (Fig. 3.2b). Observed intensities at Eva island are significantly lower compared to observation at Fly island. For all four timeseries a (slight) decrease in temperature over time is observed. Recordings from the logger at the north side of Eva island spike remarkably at September 14 and 15.



(a) Temperature



(b) Light

Figure 3.2: Temperature and light timeseries from continuous measurments at Eva and Fly islands

3.2 Total suspended sediment

The mean concentration of suspended sediment across all sites is 35.5 $[mg]$ with a standard deviation of 1.79 $[mg]$ (Fig. 3.3). The average across the sites from Eva island (n = 10) is slightly lower 35.2 $[mg]$ but the spread is slightly larger with a standard deviation of 2.06 $[mg]$. Fewer samples were obtained around Fly island (n = 6). The average of the total suspended sediment is higher at 36.1 $[mg]$ while the standard deviation is lower at 1.19 $[mg]$.

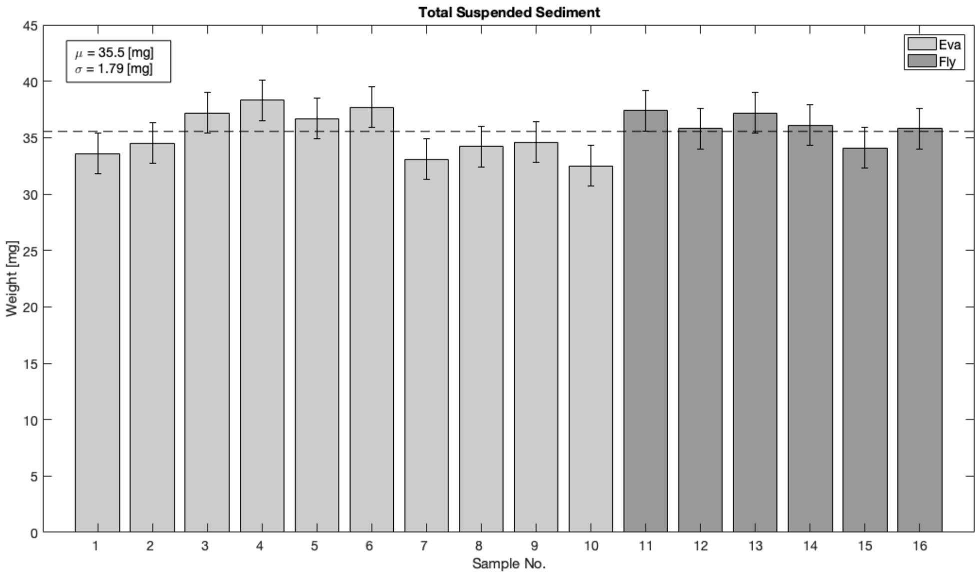


Figure 3.3: Total suspended sediment of n = 16 sites across Eva and Fly Island

3.3 Sediment characteristics

Sediments were classified based on the grain size distribution according to Folk and Ward (1957) (Figure 3.4). Six unique classes were assigned, respectively fine gravel ($> 2000[\mu m]$), very coarse sand ($1000 - 2000[\mu m]$), coarse sand ($500 - 1000[\mu m]$), fine sand ($125 - 250[\mu m]$), very fine sand ($63 - 125[\mu m]$)and mud ($< 63[\mu m]$). Fractions are representative of percentages by weight. The dominant size class of all samples is coarse sand (n = 10 samples). Sediments of Eva Island consist of five size classes, very fine gravel, very coarse sand, coarse sand, medium sand and fine sand. The dominant size is coarse sand (n = 5). Sediments of Fly Island cover are distributed across four size classes, coarse sand, medium sand, fine sand and very fine sand. The dominant class is coarse sand (n = 5).

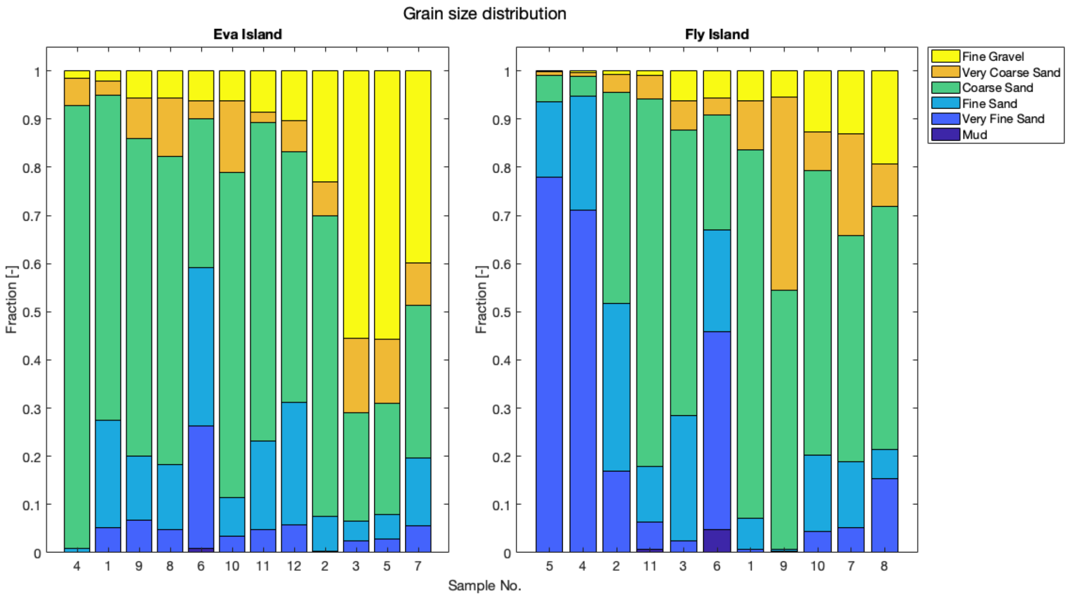


Figure 3.4: Grain size distribution of sediments of individual samples displayed from smallest median grain size to largest median grain size at Eva and Fly Island

Sediments were classified based on their sorting into three groups, poorly sorted, moderately sorted and well sorted (Table 3.1). The majority of the samples is poorly sorted (n = 15). Sediments at Eva Island are predominantly poorly sorted (n = 9 out of 12) while at Fly just over half of the sites is poorly sorted (n = 6 out of 11).

Sediments were classified based on their textural group according to Wentworth (1922) (Table 3.1). Three textural groups were classified, respectively sandy gravel (30-80% gravel), gravelly sand (5-30% gravel) and slightly gravelly sand (0.1-5% gravel). The most abundant textural group across all samples is gravelly sand, dominating in 14 out of 23 samples. Sediments of Eva Island consist of two textural groups, sandy gravel (n = 4) and gravelly sand (n = 8). Sediments of Fly Island consist of three textural groups, sandy gravel (n = 2), gravelly sand (n = 6) and slightly gravelly sand (n = 3). The dominant textural group is equal for both island however the distribution of the textural groups demonstrates that Fly Island consists of more fine-grained material.

Table 3.1: Sorting and textural group classes based on grain size analysis of sediments from Eva and Fly Island

Island	Parameter	Sample No. 1	2	3	4	5	6	7	8	9	10	11	12
Eva	Sorting	PS	PS	MS	PS	PS	MS	PS	PS	PS	PS	WS	PS
	Textural Group	SG	GS	GS	SG	GS	GS	GS	GS	SG	GS	GS	SG
Fly	Sorting	PS	MS	MS	PS	PS	MS	PS	MS	MS	PS	PS	
	Textural Group	GS	SGS	SGS	SGS	GS	GS	GS	SG	GS	SG	GS	

Abbreviations: PS = poorly sorted, MS = moderately sorted, WS = well sorted,
SGS = slighly gravelly sand, GS = gravelly sand, SG = sandy gravel

The average grain size distributions per island were assessed to assess difference between Eva and Fly island (Figure 3.5). The average contribution of each size class was computed to obtain the average grain size distribution per island. The cumulative grain size distribution was also obtained to support the comparison of the grain size distribution between the two islands.

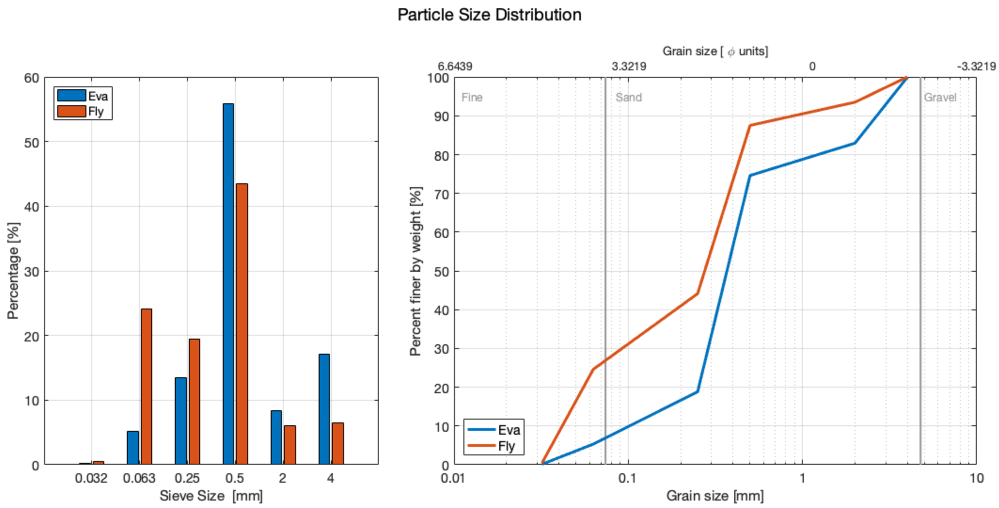


Figure 3.5: Average particle size distribution of sediments of Eva and Fly Island

The median grain size for Eva island (549[µm]) is nearly equal to the median grain size at Fly (540[µm]) (Table 3.2). The variation across the samples from Eva island (σ = 1382µm]) is much larger than across the samples from Fly island (σ = 204µm]). The sediments from Fly island are thus more uniformly sorted than those across Eva.

Table 3.2: Median grain size distribution of sediments on Eva and Fly islands

Island	Median Grain Size [μm]	Standard Deviation [μm]	Dominant Textural Group	D90 Percentile Average [μm]	Number of Samples
Eva	549	1382	Gravelly sand	2245	12
Fly	540	204	Gravelly sand	2127	11

Analysis of the abundance of sediment producers across all samples shows coral is the dominant component with a mean contribution of 47.2% (Fig. 3.6). After coral the dominating constituents are molluscs (gastropods and bivalves; 24.6%) and foraminifera (8.3%). The box and whisker plot displays the median abundance of each component and the first and third quartile as the boxes. The minimum and maximum values are depicted by the barred ends of the dashed lines. Outliers are displayed with the + symbol.

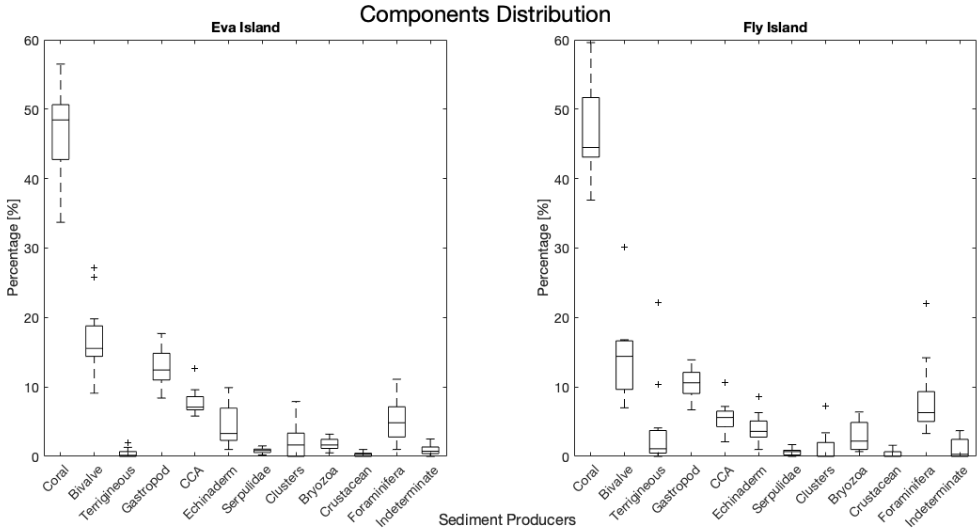


Figure 3.6: Box and whisker plots showing mean composition distribution of sediments from Eva and Fly island

3.4 Statistical analysis

Cluster analysis of the sediment characteristics (grain size and abundance) with an 80% similarity cut off shows four hierarchical clusters (Figure 3.7). Analysis of the components shows the dominant characteristics and the deviations (Figure 3.8). The sediments of Eva and Fly can be described by a majority cluster (cluster A; n = 16). The prevalent size class (56.1%) is coarse to very coarse sand (500-2000 μm), followed medium sand (250-500 μm). The dominant constituent is coral (45.1%), followed by molluscs (bivalves and gastropods; 25.6%) and foraminifera (6.3%). Three deviating clusters are distinguished. Cluster B (n = 2) is characterised by smaller sediments with very fine to fine sand (63-125 μm) the prevalent size class (51.2%). The contributions of molluscs are lower (18.8%) while the abundance of foraminifera is much larger (15.2%). Cluster C (n = 2) also predominantly consists of coarse to very coarse sand (73 %) but the remainder of its sediment is coarser, its secondary class is fine gravel (23%). The abundance of coral is larger than that of the majority (55.7%). Cluster D is defined by much larger sediments with the dominant size class coarse gravel (>4000 μm; 50.4%). The abundance of molluscs is much larger (37.9%) while that of foraminifera is smaller (2.5%).

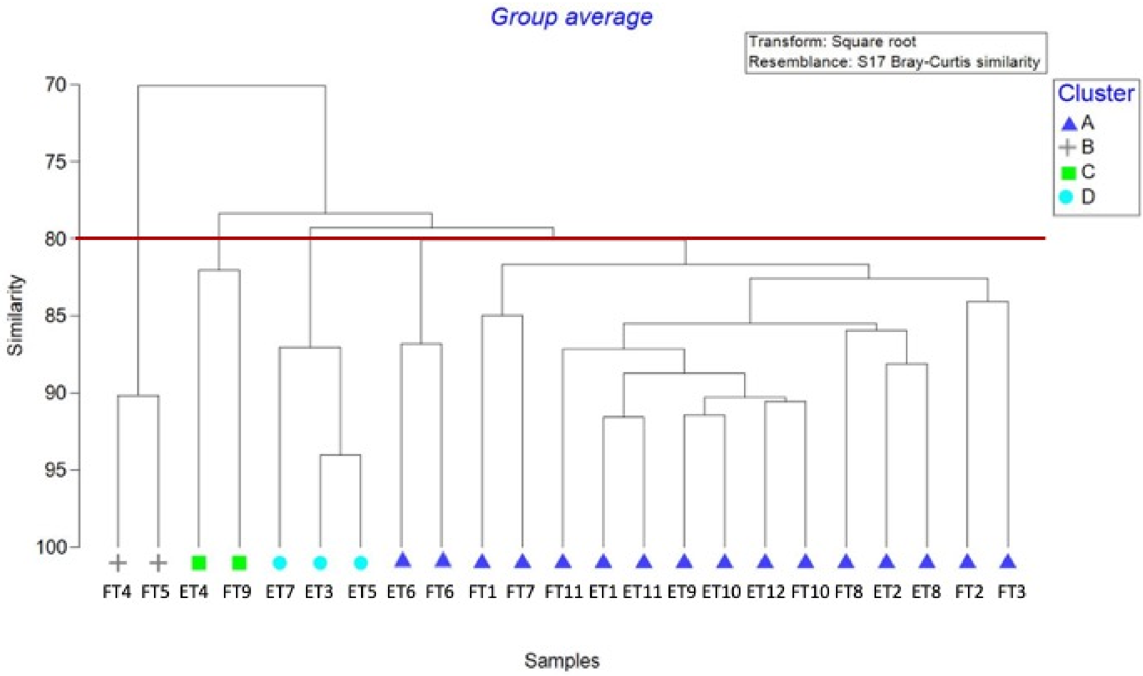


Figure 3.7: Dendrogram of the cluster analysis for grain size and component abundancy for Eva and Fly Island

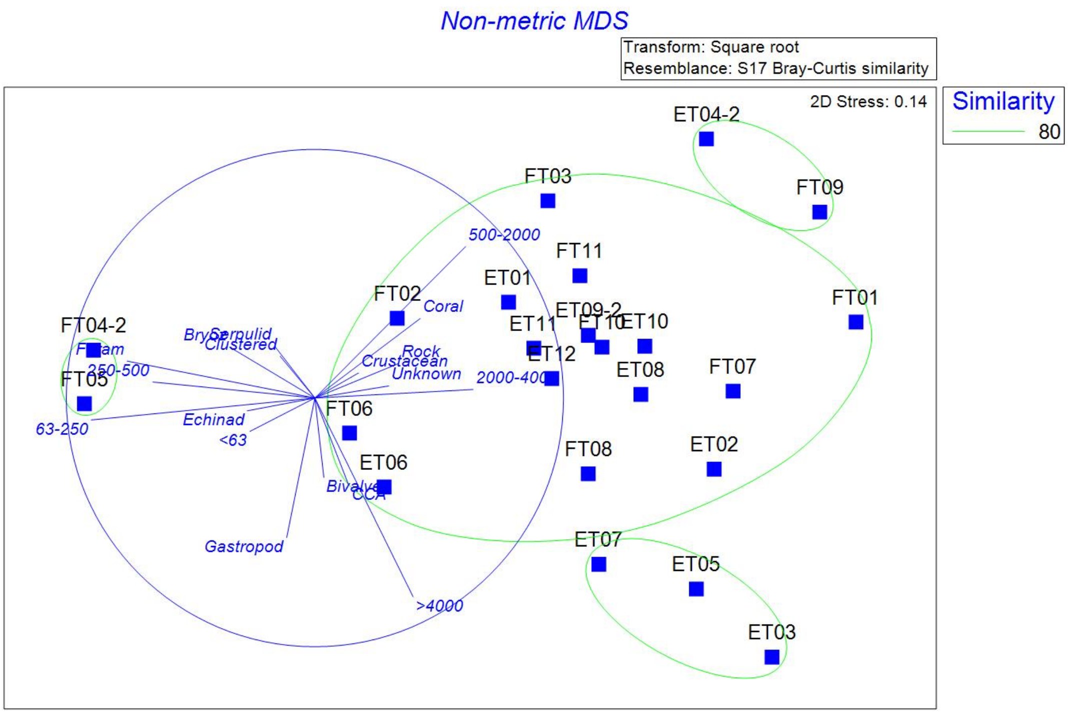


Figure 3.8: Non-metric MDS plot showing the common characteristics and the clusters from the cluster analysis of the sediments based on an 80% similarity cut-off

The one-way MANOVA analyses of the sediment characteristics showed no significant differences among sample sites experiencing different levels of the four factors island (Eva/Fly), energy (high/low), shore (inshore/offshore) and habitat (reef/no reef) (Table 3.3). The three-way MANOVA analysis of the three factors island, energy and shore also showed no significance difference of the interaction terms between sample locations (Table 3.4).

Table 3.3: MANOVA results for four factors; island, energy, shore and habitat

Factor	df	SS	MS	Pseudo-F	P-value
Island	1	394.12	394.12	1.8141	0.1107
Energy	1	109.2	109.2	0.4731	0.8394
Shore	1	78.746	78.746	0.33902	0.9244
Habitat	1	254.54	254.54	1.1368	0.3276

Abbreviations: df = degrees of freedom, SS = sum of squares, MS = mean sum of squares

Table 3.4: Three-way MANOVA results for three factors; island, energy and shore and the interaction terms

Factor	df	SS	MS	Pseudo-F	P-value
Island	1	382.47	382.47	1.6072	0.1674
Energy	1	133.69	133.69	0.56178	0.7384
Shore	1	110.32	110.32	0.46358	0.8248
Island×*Energy*	1	211.38	211.38	0.88824	0.4696
Island×*Shore*	1	242.55	242.55	1.0192	0.3699
Energy×*Shore*	1	127.05	127.05	0.53388	0.7667
Island×*Energy* × *Shore*	1	183.63	183.63	0.77161	0.5499
Residuals	15	3569.7	237.98		
Total	22	4956.5			

Abbreviations: df = degrees of freedom, SS = sum of squares, MS = mean sum of squares

The redundancy analysis (dbRDA) showed no statistically significant environmental driver responsible for the distribution of the sediment characteristics, respectively grain size and abundance of the components (Table 3.5).

Table 3.5: dbRDA results for the external factors depth, temperature, pH, DO and ORP

Environmental Variable	SS	Pseudo-F	P-value	Percentage of Variance
Depth	143.49	0.62606	0.7112	0.028949
Temperature	239.23	1.065	0.3448	0.048266
pH	42.407	0.18122	0.9888	0.008558
DO	149.27	0.65207	0.6767	0.030116
ORP	153.66	0.67186	0.6521	0.031002

Abbreviations: DO = dissolved oxygen, ORP = oxidation-reduction potential, SS = sum of squares

Discussion

This study presents three key findings: (1) the sediments are sand-sized and the dominant constituent is reef-derived; (2) no significant spatial differences occur between sample locations; and (3) no key environmental driver could be identified. Based on these findings it is not possible to thoroughly assess the resiliency of the island to climate change impacts. However the results can be compared to similar studies, in order to establish a referenced baseline study.

The most abundant constituents in the sediments are coral (46.7%), molluscs (24.6%) and foraminifera (8.3%) and the dominant textural group is gravelly sand. The median grain size of Eva (549 μm) and Fly (540 μm) is nearly equal, however the standard deviation of the observations is very different. The spread at Eva (1382 μm) is much larger compared to Fly (204 μm) which may be an indication of larger wave energy at Eva. Considering the D90 percentile average, the sediment at Fly consists of finer grained material than Eva. The findings on the dominant constituents and average grain size are in line with the results of Orpin et al. (1999), who found predominantly carbonate-rich sands in the open northern part of the Exmouth Gulf. Cuttler et al. (2019) found similar contributions (34%) of coral to the sediment, just outside of the Exmouth Gulf at Tantabiddi. Large contributions of forams were also found by Perry et al. (2011), who stated that sand-sized sediments in the Indo-Pacific are often foraminifera dominated. The mean abundance of foraminera on Fly is higher than on Eva, which is in agreement with the expectation that foraminifera, which are in general smaller than $1mm$, are likely to be found in smaller grain size fractions. Similar results were found in other studies on sedimentary environments such as Lidz (1965).

Analysis of variance of the grain size and abundance of sediment producers reveals homogeneity across the sample sites around the islands of Eva and Fly. No spatial differences between the two islands, the high and low energetic zones, the onshore and offshore locations and sites with or without reef were identified. Given the proximity of the islands (approximately 15 km), no large differences between the islands were expected. Similar results with no distinct trends from individual islands, were found by grain size analysis of sediments in Indonesia by Janßen et al. (2017).

Redundancy analysis of the sediment characteristics (grain size and abundance) in relation to environmental parameters show no key environmental driver. Cyclic variations of e.g. water temperature occur on tidal, daily, seasonal, inter-annual and centennial time scales. Daily variations are clearly visible in our observations however, the timeframe on which water quality was observed, is not sufficient to distinguish the rest of these cyclic variations. The timescales on which these variations affect reef health are larger than the duration of the fieldwork, therefore it is not expected that the observed fluctuations affect sediment producers. Similarly, the spatial scales on which these environmental drivers act, may be much larger than sampled in this study.

The strong link between reef ecology, sediment supply and island morphology dictates the resiliency of the islands to the effects of climate change. Changes in the sediment characteristics due to changes in reef health or changes in the abundance of sediment producers control the geomorphic stability of the islands. Different dominant constituents respond differently to environmental changes. Reef island sand-sized sediments dominated by coral are expected to experience major morphological change in most predicted scenarios (Perry et al., 2011). Cuttler et al. (2019) found that reef islands where coral coverage is low but detriments are highly abundant in the sediments, may be less affected by environmental shifts altering reef health. The analysed sediments of Eva and Fly are coral dominated sands hence the islands can be expected to be very sensible to climate change effects however more information on e.g. coral cover would improve predictions.

Analyses of the in-situ collected data from the temperature and light loggers and the TSS samples show results deviating from expectations. First, recorded TSS concentrations are higher than expected. Second, light recordings for Fly island are significantly higher than observations from Eva island. Considering these deviations, these results can only be used to illustrate local conditions. However, analysis of the variance of the TSS samples reveals homogeneity across the sample sites which is in line with our expectations that also the processes responsible for spatial variations in TSS act on spatial scales larger than these islands and temporal scales longer than the duration of the field campaign.

Pomeroy et al. (2018) found that the arrival of large swell waves drives most of the spatial variability in the TSS across the Ningaloo Reef. This forcing occurs on a slow-varying timescale that was not captured within this fieldtrip. The results of the analysis of the mean concentration of the TSS (35.5 mg/L) do not match expectations nor results from other studies. TSS concentrations of ~ 30 mg/L are typically found in low visibility conditions (2-3 m). No exact measure of the visibility at the time was taken but conditions were remarkably good. Dorji et al. (2016) performed analyses of the TSS based on MODIS observations, of a coastal site just north of the Exmouth Gulf. They found significantly lower average values of the TSS, respectively < 4 mg/L on a daily average and < 14 mg/L monthly average. Upon reflection we realised the TSS samples and filters were not flushed with deinoized water, therefore it is expected the unexpectedly high results include residual concentrations of salt. Light loggers at Eva island were installed early in the year 2018 during a preceding field campaign. Upon installation of the loggers at Fly island, the loggers at Eva island were not cleaned which disallows comparison of the data of the islands. The temperature and light recordings therefore only support the understanding of the local environments.

Conclusion

In conclusion, sediments of Eva and Fly islands are characterised by sand-sized grains with coral as dominant constituent. Perry et al. (2011) found that reef islands with these characteristics are likely to be subject to major morphological change under a range of predicted scenarios. Therefore, the signature of the sediment may be indicative of limited resiliency to changing environments. No spatial differences between sediment characterics across the two islands were found, suggesting no difference in adaptability between these two islands and their high and low energetic sides. No differences were also found across sites between inshore and offshore locations and sites with or without coral reef, suggesting these factors do not significantly influence the sediment characterics. Five environmental parameters were recorded and tested as potential drivers for the differences in sediment characteristics but no key driver was identified. However, the spatiotemporal scales on which these factors affect reef health and subsequently sediment characteristics are expected to be much larger than sampled in this study for which their influence may not be excluded. Currently, no baseline data exists for these two islands which is essential in assessing their resiliency to environmental shifts associated with climate change. This study poses this reference framework for future research and provides crucial input for models which analysis local sediment budgets.

Recommendations

The preparation and execution of the measurements are crucial and form a base for the analyses of the data. Unexpected circumstances always affect field trips which requires adaptability and innovation of the executors. This marine fieldwork was no different and despite external factors such as extreme weather conditions, the flexibility and creativity of our group of graduate research students resulted in a successful trip. Post-fieldwork and midst data processing I came across several aspects that were not executed perfectly and complicated the handling of the data afterwards. Below I provide an overview of the complications this thesis and how I suggest to improve them in the future.

The sample locations were proposed based on the hypotheses of this thesis in order to investigate the influence of the different factors (island, energy, shore, habitat) on the characteristics of the sediment. In the field these locations were not closely enough followed for multiple reasons. First, the practical aspects of driving a boat across coral reef platforms in shallow waters played a dominant role. Variations in water level due to tides and the presence of reef platforms and coral bommies made some of the selected sites inaccessible. Restrictions by time and fuel efficiency also meant none or little repeat visits to access selected sample sites. Secondly, the fieldwork included several research campaigns, each with a different purpose and different sample locations. The combination of the different experiments to be done proved a logistical challenge. Proposed locations from the different campaigns had to be adjusted into mutually acceptable sites. Thirdly, the recording of the GPS coordinates of the exact locations was not always executed accurately. This resulted unintentionally in sample locations right next to each other and required a lot of extra time prepossessing, to organise the data. For the few sample sites that were to visited repeatedly on the trip, this caused delays on the water, since the deployed temperature and light loggers were difficult to locate. The extra time consumed in the field and preprocessing is costly but not effect the results of the research. However the adjusted sample locations and their corresponding factors are crucial, the results of the MANOVA are completely dependent on this. Samples were not collected in distinctive high or low energy regimes which introduces extra uncertainty in the labelling of the sites. To avoid complications and extra uncertainties due to adjusted sample sites in the future, detailed preparation is key. This should include a study into local water depths and coral reefs, alternatives for inaccessible areas and overview of the tides. A map showing the proposed locations will ease the execution and accurate GPS recordings will eventually save time.

Collection of the sediment samples (for this thesis) and recording coral reef properties along transects (for another thesis) were the prioritised goals. The observation of the water quality parameters, collection of suspended sediment and handling of the temperature and light loggers were lower in priority which resulted in lesser and incautious measurements. Especially the total suspended sediment data is sparse and unevenly distributed which made its analysis more complex. New temperature and light loggers were deployed, but also data from older loggers which had been placed earlier was collected. These old loggers were not cleaned at the time new loggers were deployed, which complicated (hindered) the comparison of the already limited timeseries.

Bibliography

Blott, S. J. and Pye, K. (2001), 'GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments', *Earth Surface Processes and Landforms* **26**(11), 1237–1248.

Brooks, F. A. (1964), 'Agricultural needs for special and extensive observations of solar radiation', *The Botanical Review* **30**(2), 263–291.

Brown, R. (1988), 'Holocene sediments and environments, Exmouth Gulf, Western Australia', *P. G. & Purcell R. R. eds. The North West Shelf, Australia. Proceedings of Petroleum Exploration Society Australia Symposium, Perth* p. 85–93.

Browne, N., Smithers, S. and Perry, C. (2012), 'Coral reefs of the turbid inner-shelf of the Great Barrier Reef, Australia: An environmental and geomorphic perspective on their occurrence, composition and growth', *Earth-Science Reviews* **115**(1), 1 – 20.

Browne, N., Smithers, S. and Perry, C. (2013), 'Carbonate and terrigenous sediment budgets for two inshore turbid reefs on the central Great Barrier Reef', *Marine Geology* **346**, 101 – 123.

Brunskill, G., Orpin, A., Zagorskis, I., Woolfe, K. and Ellison, J. (2001), 'Geochemistry and particle size of surface sediments of Exmouth Gulf, Northwest Shelf, Australia', *Continental Shelf Research* **21**(2), 157 – 201.

Climatic atlas of Australia (n.d.).

Cooper, T. F., O'Leary, R. A. and Lough, J. M. (2012), 'Growth of western australian corals in the anthropocene', *Science* **335**(6068), 593–596.

Cuttler, M. V., Hansen, J. E., Lowe, R. J., Trotter, J. A. and McCulloch, M. T. (2019), 'Source and supply of sediment to a shoreline salient in a fringing reef environment', *Earth Surface Processes and Landforms* **44**(2), 552–564.

Dawson, J. L., Smithers, S. G. and Hua, Q. (2014), 'The importance of large benthic foraminifera to reef island sediment budget and dynamics at Raine Island, northern Great Barrier Reef', *Geomorphology* **222**, 68 – 81. Coral Reef Geomorphology.

Dorji, P., Fearns, P. and Broomhall, M. (2016), 'A semi-analytic model for estimating total suspended sediment concentration in turbid coastal waters of northern Western Australia using MODIS-Aqua 250 m data', *Remote Sensing* **8**(7), 556.

Emanuel, K. (2005), 'Increasing destructiveness of tropical cyclones over the past 30 years', *Nature* **436**(7051), 686.

Fabricius, K., De'ath, G., McCook, L., Turak, E. and Williams, D. M. (2005), 'Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef', *Marine pollution bulletin* **51**(1-4), 384–398.

Folk, R. L. and Ward, W. C. (1957), 'Brazos River bar [Texas]; a study in the significance of grain size parameters', *Journal of Sedimentary Research* **27**(1), 3–26.

Harney, J. and Fletcher III, C. (2003), 'A budget of carbonate framework and sediment production, kailua bay, oahu, hawaii', *Journal of Sedimentary Research* **73**(6), 856–868.

Harney, J. N., Grossman, E. E., Richmond, B. M. and Fletcher III, C. H. (2000), 'Age and composition of carbonate shoreface sediments, kailua bay, oahu, hawaii', *Coral Reefs* **19**(2), 141–154.

Hoegh-Guldberg, O. (1999), 'Climate change, coral bleaching and the future of the world's coral reefs', *Marine and freshwater research* **50**(8), 839–866.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K. et al. (2007), 'Coral reefs under rapid climate change and ocean acidification', *science* **318**(5857), 1737–1742.

Holloway, P. E. (1983), 'Tides on the Australian North-west shelf', *Marine and Freshwater Research* **34**(1), 213–230.

Hubbard, D. K., Miller, A. I. and Scaturo, D. (1990), 'Production and cycling of calcium carbonate in a shelf-edge reef system (st. croix, us virgin islands); applications to the nature of reef systems in the fossil record', *Journal of Sedimentary Research* **60**(3), 335–360.

Hughes, T. and Connell, J. (1999), 'Multiple stressors on coral reefs: A long-term perspective', *Limnology and oceanography* **44**(3part2), 932–940.

Janßen, A., Wizemann, A., Klicpera, A., Satari, D. Y., Westphal, H. and Mann, T. (2017), 'Sediment composition and facies of coral reef islands in the spermonde archipelago, indonesia', *Frontiers in Marine Science* **4**, 144.

Kench, P. (2014), Coral Reefs, *in* 'Coastal Environments and Global Change', John Wiley Sons, Ltd, chapter 16, pp. 380–409.

Kench, P. and Cowell, P. (2002), Variations in sediment production and implications for atoll island stability under rising sea level, *in* 'Proceedings of the Ninth International Coral Reef Symposium, Bali, 23-27 October 2000,', Vol. 2, pp. 1181–1186.

Kench, P. S. (1998), 'Physical controls on development of lagoon sand deposits and lagoon infilling in an indian ocean atoll', *Journal of Coastal Research* pp. 1014–1024.

Kleypas, J. A., Buddemeier, R. W. and Gattuso, J.-P. (2001), 'The future of coral reefs in an age of global change', *International Journal of Earth Sciences* **90**(2), 426–437.

Legendre, P. and Anderson, M. J. (1999), 'Distance-based redundancy analysis: testing multispecies responses in multifactorial ecological experiments', *Ecological monographs* **69**(1), 1–24.

Lidz, L. (1965), 'Sedimentary environment and foraminiferal parameters: Nantucket bay, massachusetts', *Limnology and Oceanography* **10**(3), 392–402.

Long, M., Rheuban, J., Berg, P. and C. Zieman, J. (2012), 'A comparison and correction of light intensity loggers to photosynthetically active radiation sensors', *Limnology and Oceanography: Methods* **10**, 416–424.

Lough, J. (1998), 'Coastal climate of northwest Australia and comparisons with the Great Barrier Reef: 1960 to 1992', *Coral Reefs* **17**(4), 351–367.

McLean, R., Tsyban, A., Burkett, V., Codignotto, J., Forbes, D., Mimura, N., Beamish, R. and Ittekkot, V. (2001), 'Coastal zones and marine ecosystems', *Climate change* pp. 343–379.

Morgan, K. and Kench, P. (2014), 'A detrital sediment budget of a maldivian reef platform', *Geomorphology* **222**, 122–131.

Nicholls, R. J., Wong, P. P., Burkett, V., Codignotto, J., Hay, J., McLean, R., Ragoonaden, S., Woodroffe, C. D., Abuodha, P., Arblaster, J. et al. (2007), 'Coastal systems and low-lying areas'.

Orpin, A. R., Haig, D. W. and Woolfe, K. J. (1999), 'Sedimentary and foraminiferal facies in Exmouth Gulf, in arid tropical northwestern Australia*', *Australian Journal of Earth Sciences* **46**(4), 607–621.

Paling, E., Kobryn, H. and Humphreys, G. (2008), 'Assessing the extent of mangrove change caused by cyclone vance in the eastern exmouth gulf, northwestern australia', *Estuarine, Coastal and Shelf Science* **77**(4), 603 – 613.
URL: *http://www.sciencedirect.com/science/article/pii/S0272771407004866*

Perry, C. T., Kench, P. S., Smithers, S. G., Riegl, B., Yamano, H. and O'Leary, M. J. (2011), 'Implications of reef ecosystem change for the stability and maintenance of coral reef islands', *Global Change Biology* **17**(12), 3679–3696.

Perry, C. T., Spencer, T. and Kench, P. S. (2008), *Carbonate budgets and reef production states: a geomorphic perspective on the ecological phase-shift concept*, Vol. 27.

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**(5), 1013–1034.

Porter-Smith, R., Harris, P., Andersen, O., Coleman, R., Greenslade, D. and Jenkins, C. (2004), 'Classification of the Australian continental shelf based on predicted sediment threshold exceedance from tidal currents and swell waves', *Marine Geology* **211**(1), 1 – 20.

Rogers, C. S. (1990), 'Responses of coral reefs and reef organisms to sedimentation.', *Marine ecology progress series. Oldendorf* **62**(1), 185–202.

Sanderson, P., Eliot, I., Hegge, B. and Maxwell, S. (2000), 'Regional variation of coastal morphology in southwestern Australia: a synthesis', *Geomorphology* **34**(1), 73 – 88.

Short, A. D. and Woodroffe, C. D. (2009), *The coast of Australia*, Cambridge University Press.

Stearn, C., Scoffin, T. and Martindale, W. (1977), 'Calcium carbonate budget of a fringing reef on the west coast of barbadospart i—zonation and productivity', *Bulletin of Marine Science* **27**(3), 479–510.

Stoddart, D. and Steers, J. (1977), 3 - the nature and origin of coral reef islands, *in* O. JONES and R. ENDEAN, eds, 'Biology and Geology of Coral Reefs', Academic Press, pp. 59 – 105.

Storlazzi, C. D., Presto, M. K., Logan, J. B. and Field, M. E. (2010), 'Coastal circulation and sediment dynamics in maunalua bay, oahu, hawaii', *Measurements of waves, currents, temperature, salinity, and turbidity: November* pp. 2010–1217.

Turner, M. and Batianoff, G. N. (2007), 'Vulnerability of island flora and fauna in the great barrier reef to climate change'.

Wentworth, C. K. (1922), 'A Scale of Grade and Class Terms for Clastic Sediments', *The Journal of Geology* **30**(5), 377–392.

Woodroffe, C. (1997), Coral atolls, *in* 'Coastal Evolution - Late Quaternary Shoreline Morphodynamics', Cambridge University Press, chapter 7.

Woodroffe, C. (2008), 'Reef-island topography and the vulnerability of atolls to sea-level rise', *Global and Planetary Change* **62**, 77–96.

Yamano, H., Kayanne, H. and Chikamori, M. (2005), 'An overview of the nature and dynamics of reef islands', *GLOBAL ENVIRONMENTAL RESEARCH-ENGLISH EDITION-* **9**(1), 9.