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Multi-decadal shoreline changes in response to sea level rise in the Marshall Islands

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ABSTRACT

Low-lying reef islands are considered highly vulnerable to the impacts of climate change. Accelerating rates of sea level rise as a result of anthropogenic climate change are expected to destabilise islands and threaten to render entire nations uninhabitable. Using historic aerial photographs and recent high-resolution satellite imagery, shoreline changes on six atolls and two mid-ocean reef islands in the Republic of the Marshall Islands were analysed. Results reveal that since the middle of the 20th century more shoreline has accreted than eroded, with 17.23% showing erosion, compared to 39.74% accretion and 43.03% showing no change. The net result of these changes was the growth of the islands examined from 9.09 km^2 to 9.46 km^2 between World War Two (WWII) and 2010. Analyses of shoreline changes since the 1970s show that shorelines are accreting albeit at a slower rate, with rates of change between the 1970s and 2010 of 0.29 m/dec compared with 0.77 m/dec between WWII and 1970s. The observed shoreline changes occur in the context of locally rising sea level. As sea level continues to rise there is a critical need for regular monitoring of reef islands in order to better understand the spatio-temporal variability of reef island change and guide future adaptation efforts within atoll nations.

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1. Introduction

Atoll islands are coral reef associated sedimentary deposits found in subtropical and tropical oceans. The islands are comprised of unconsolidated or weakly lithified carbonate sediment derived from the skeletal remains of the reef framework and benthic organisms. Most chronologies of island development indicate islands are geologically young, having only formed in the mid-late Holocene, and were fully formed 5000–2000 years BP (Woodroffe et al., 1999, 2007; Woodroffe and Morrison, 2001; Kench et al., 2005; Kayanne et al., 2011; Kench et al., 2012, 2014a). However, recent chronologies and observations indicate some islands formed within the past 1000 years (Kench et al., 2014b; Ford and Kench, 2014). Once the islands have formed, reef island shorelines have been shown to be highly dynamic, with shoreline change driven by both local and distal storms (Stoddart 1963, 1971; Maragos et al., 1973; Ford and Kench, 2014; Smithers and Hoeke, 2014), tsunami (Kench et al., 2006), as well as seasonal and decadal variations in wave climate (Flood, 1986; Kench et al., 2006; Kench and Brander, 2006). Despite their relatively recent formation, atoll islands have been sites of human habitation since the first few centuries AD (Weisler, 2001; Kayanne et al., 2011). Today, atoll islands provide the bulk of habitable land in the atoll nations of the Maldives, Tuvalu, Kiribati and the Marshall Islands. In addition, several other countries in the Pacific and Indian Oceans have substantial populations residing on atoll islands.

Due to their limited land area, low elevation and limited economic and technical capacity atoll islands are considered vulnerable to the impacts of climate change, particularly sea level rise (SLR) (Barnett and Adger, 2003; Woodroffe, 2008). A suite of sea level rise impacts are considered likely to manifest on atoll islands including: increased marine inundation, increased groundwater salinity and chronic coastal erosion (Mimura, 1999; Barnett and Adger, 2003; Woodroffe, 2008). Sea level rise is commonly expected to destabilise island shorelines and lead to widespread loss of land as a result of erosion (Dickinson, 2009). Accounts and projections of islands being 'washed away' are a mainstay of political discussions and popular media reports of climate change impacts on atolls (Johnson, 2014; Lewis, 2015). Despite the widespread attention of the plight of atoll islands, there has been a paucity of evidence presented to underpin such assertions. Recently, the popular narrative of reef islands 'disappearing' has been considered overly simplistic and unhelpful for strengthening the resilience and adaptive capacity of island communities

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(Kelman, 2014; McCubbin et al., 2015). Likewise, evidence of the physical resilience of islands has emerged showing a notable absence of widespread chronic erosion (Webb and Kench, 2013; Yates et al., 2013).

Relative to shorelines on continental landmasses, few studies have systematically examined changes to reef island shorelines over multi-decadal time scales, coincident with records of rising sea level (McLean and Kench, 2015). Pacific atolls are typically remote, and with the exception of a small number of densely populated urban islands, sparsely populated. As a result, field-based monitoring efforts of island erosion are limited (Kench and Harvey, 2003). Recently, remote sensing approaches, used for several decades along continental shorelines, have been applied in the study of reef island shoreline change (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013). Within this recently emerging body of shoreline change studies on atoll islands there is little evidence of widespread reef island erosion. To the contrary, several studies have documented noteworthy shoreline progradation and positional changes of islands since the mid-20th century, resulting in a net increase in island area (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013; Kench et al., 2015). Within densely populated urban atoll settings, such as Majuro in the Marshall Islands and Tarawa in Kiribati, human activities such as land reclamation and causeway construction have been recognised as a significant factor responsible for increasing island size (Ford, 2011; Biribo and Woodroffe, 2013; Duvat, 2013). A wide range of shoreline armouring strategies have been employed to effectively maintain a shoreline position within urban atoll settings. Likewise, land reclamation has led to the expansion of islands on both ocean and lagoon facing shorelines, while causeways have linked previously disconnected islands. In contrast, the sparsely populated "outer islands" have been subjected to few engineering interventions at the shoreline, with shoreline changes reflecting morphodynamic responses to changing boundary conditions.

The use of remotely sensed imagery to study reef island change is still in its infancy, with an active phase of research only emerging since 2010 (Webb and Kench, 2010; Ford, 2011; Rankey, 2011; Yates et al., 2013). McLean and Kench (2015) provide a review of recent reef island change studies. To date, studies of shorelines along sparsely populated and uninhabited islands have revealed a prevalence of shoreline accretion compared to erosion, leading to an increase in island size (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013). However, this limited set of observations has been derived from relatively small datasets and it is still unclear if accretion of reef-islands has been the prevalent mode of shoreline change over recent decades. Here we present analysis of shoreline change on 127 islands on six atolls and two mid-ocean platform islands within the Republic of the Marshall Islands.

2. Setting

The Republic of the Marshall Islands (RMI) is comprised of 29 atolls and five mid-ocean platform islands (Fig. 1). Two parallel chains of atolls extend from 4°34′N (Ebon Atoll) to 14°43′N (Bokak/Taongi) and from 160°48′E (Ujelang Atoll) to 172°10′E (Nadikdik Atoll) forming an exclusive economic zone of ~2.1 million square kilometres. The 2011 census shows the population of the Marshall Islands was 53,158, with 74% residing on Majuro and Kwajalein atolls, both characterised by densely populated and highly modified islands (EPPSO, 2012). The remaining atolls have relatively low populations, with larger villages typically found on one island per atoll. The eight atolls in this study span a latitudinal range from Ebon Atoll in the south (4°34′N, 168°43′E) to Rongerik Atoll in the north (11°22′N, 167°27′E). The collection of islands in this study comprises both atolls and mid-ocean platform islands (Fig. 2, Table 1).

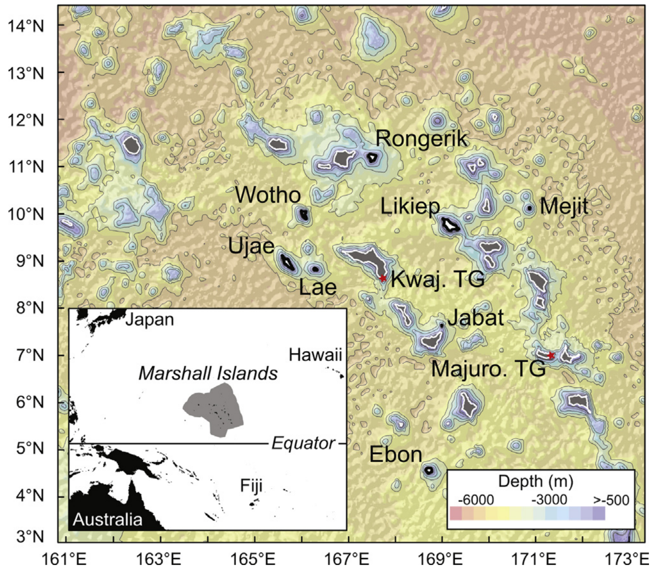

Fig. 1. The Republic of the Marshall Islands, including atolls examined in this study and the location of tide gauges on Kwajalein and Majuro Atolls (red stars).

2.1. Oceanographic setting

The Republic of the Marshall Islands (RMI) have among the lengthiest sea level records in the central Pacific (Becker et al., 2012). Currently tide gauges are operational at Uliga dock on Majuro Atoll and at the United States Army base on Kwajalein Atoll. The Majuro tide gauge record is comprised of two separate records collected by the University of Hawaii Sea Level Centre (UHSLC) from 1968 to 1999 and by the Australian National Tidal Facility from 1993 to present (Fig. 3). The Kwajalein tide gauge has been operating near-continuously since 1946 (Fig. 3). Sea level has risen at 2.2 mm/yr and 3.7 mm/yr at Kwajalein and Majuro respectively (Becker et al., 2012). Few long-term records of wave conditions exist for the RMI. However, Durrant et al. (2013) provide a hindcast of wave conditions at 4 arcmin resolution between 1978 and 2010. In general, there is a latitudinal and longitudinal gradient in average wave heights with atolls in the north and east of the archipelago characterised by higher average wave heights than in the southern RMI (Fig. 4).

3. Materials and methods

3.1. Image properties and processing

Remotely sensed assessments of shoreline change along shorelines within developed nations typically involve the use of temporally-rich collections of aerial photographs spanning several decades (e.g. Romine et al., 2009). However, atoll nations in the Pacific are remote and have limited collections of aerial photographs. Within the Marshall Islands the most active period of aerial photography was during the later stages of World War Two (WWII). WWII-era imagery was collected between 1943 and 1945. Following WWII, three aerial photograph surveys occurred in the Marshall Islands during the 1970s. The advent of high-resolution satellite sensors in the early 2000s has greatly increased the spatial and temporal coverage of imagery of the Marshall Islands. To study shoreline change we compare shoreline positions interpreted from historic aerial photographs captured between 1943 and 1978 with those interpreted from modern, high-resolution Worldview-2 satellite imagery collected since 2010, providing a window of analysis up to 68 years in length.

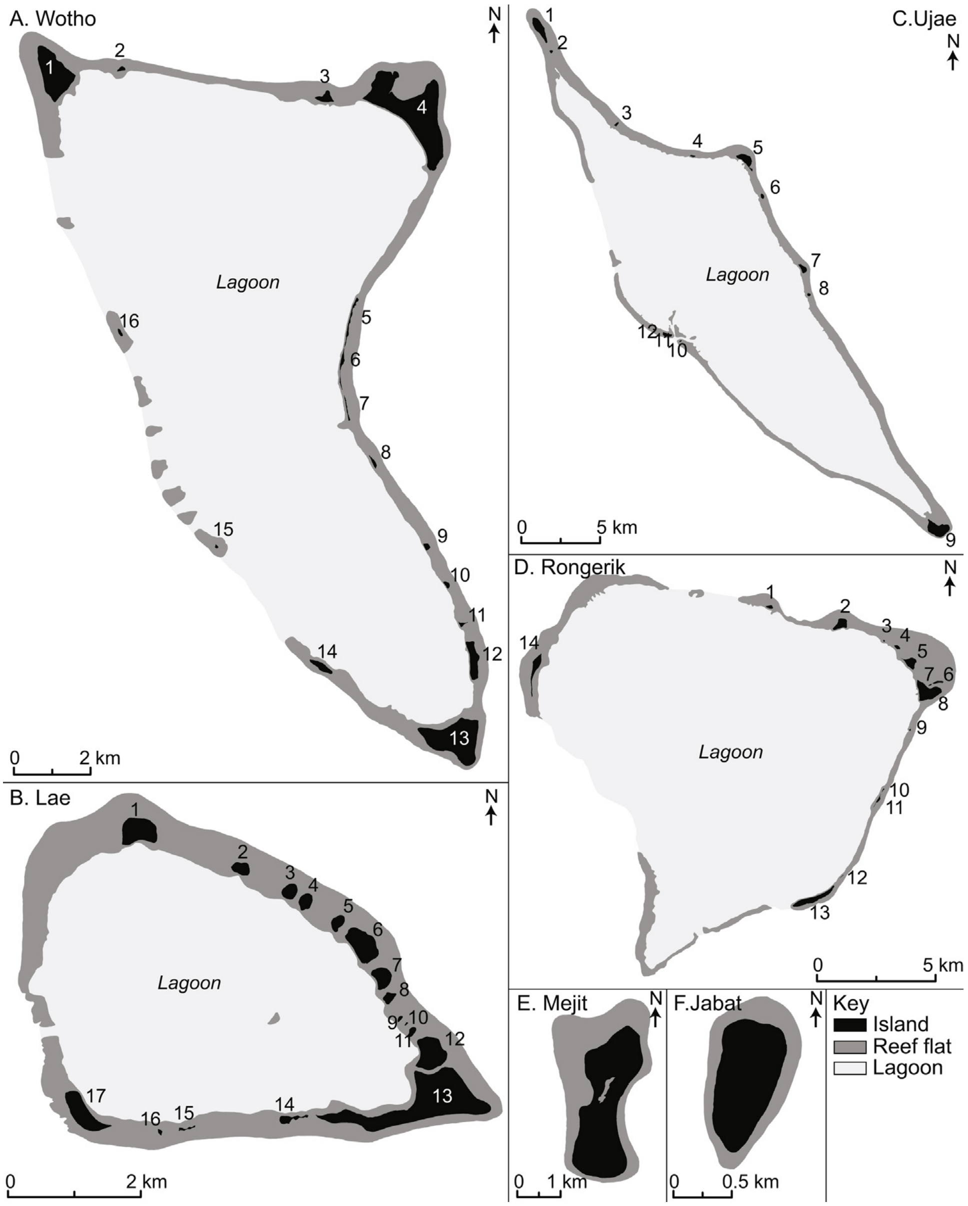

Fig. 2. Location of the islands studied on Wotho, Ujae, Rongerik and Lae Atolls, and the two platform islands examined, Mejit and Jabat. Location of islands studied on Likiep and Ebon Atolls.

Worldview-2 (WV2) satellite imagery was pan-sharpened and mosaicked by the Natural Resource Conservation Service of the United States Department of Agriculture. The WV2 sensor has a swathe width ~16 km. As a result, satellite images of larger atolls are mosaics of a number of scenes captured at different times. Similarly, cloud cover or other image quality issues often necessitate mosaicking several scenes in order to generate largely unobscured atoll-wide coverage. The majority of WV2 imagery comprising the mosaics was captured in 2010. As a result, the WV2 dataset is referred to as the 2010 mosaic, despite some earlier

Table 1
Number of islands examined in this study, values in parenthesis refer to the number of islands for which an area was able to be calculated.

		Number of islands analysed			
Atoll	Location	WWII–2010	WWII–1970s	1970s–2010	WWII–1970s–2010
Ebon	4°34′N, 168°43′E	7 (4)	7 (4)	19 (19)	7 (4)
Jabat	7°45′N, 168°59′E	1 (1)	0 (0)	0 (0)	0 (0)
Lae	8°56′N, 166°14′E	2 (2)	2 (2)	15 (15)	2 (2)
Likiep	9°55′N, 169°07′E	38 (35)	38 (35)	58 (56)	38 (35)
Mejit	10°17′N, 170°52′E	1 (1)	0 (0)	0 (0)	0 (0)
Rongerik	11°22′N, 167°27′E	0 (0)	0 (0)	11 (11)	0 (0)
Ujae	9°04′N, 168°43′E	5 (4)	4 (4)	9 (8)	4 (3)
Wotho	10°06′N, 165°59′E	1 (1)	1 (1)	15 (15)	1 (1)
Total		55 (48)	52 (46)	127 (124)	52 (45)

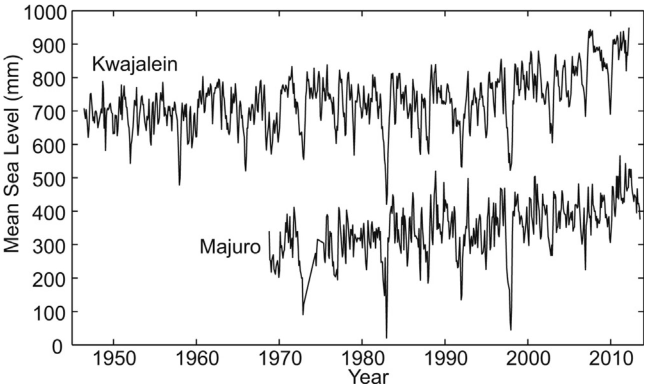

Fig. 3. Monthly average sea level recorded at Kwajalein Atoll between June 1946 and March 2012 and Majuro Atoll between October 1968 and July 2013. Monthly averages are calculated from fast delivery daily average sea level obtained from the University of Hawaii Sea Level Centre. Note: records are offset to avoid overlap.

and more recent imagery used to generate the mosaics. Likewise, the imagery from the 1970s includes aerial photographs from 1971 (Ebon) and photos taken over several months in 1978, shorelines from this period are referred to as the 1970s dataset. A similar approach is taken with military aerial photographs from the mid-1940s which are referred to as the WWII dataset. All rate of change calculations are derived from the actual date of imagery capture. Details of aerial photos and satellite imagery utilised in this study are summarised in Supplementary Table 1. Satellite imagery provided the sources of ground control points for georeferencing imagery. Given the paucity of stable anthropogenic features on outer islands, a range of natural features such as cemented conglomerate and beachrock were used as ground control points. Images were georeferenced in ArcMap and transformed using a second order polynomial transformation.

3.2. Shoreline Interpretation and Analysis

The edge of vegetation is widely used as a proxy for the shoreline within island change studies in atoll settings (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013). The edge of vegetation is readily identifiable in nearly all imagery, regardless of image color and contrast and irrespective of environmental conditions, particularly glare and waves, both of which can impede interpretation of sub- and intertidal features such the toe of beach or high water mark. It represents the vegetated core of the island and filters short-term noise associated with beach shorelines. As a result, we use the edge of vegetation as a shoreline proxy which was digitized at a fixed scale by a single operator within ArcMap.

Following Ford (2013) three sources of uncertainty were considered when calculating the positional uncertainty in edge of vegetation. These were: rectification, pixel and digitizing errors. Digitizing error was calculated as the standard deviation of shoreline position from repeated digitization of the same section of coast by a single operator. Total shoreline error (Te) was calculated as the root sum of all shoreline positional errors and ranged between 1.51 and 4.07 m (Supplementary Table 1).

The Digital Shoreline Analysis System (DSAS) is a widely used analytical tool for measuring changes in planform positions of vectorized shorelines (Thieler et al., 2009). DSAS runs as an extension within the GIS software package ArcMap. DSAS analyses change by recording the intersection of shorelines and transects cast perpendicular to a user-generated baseline. In this study transects were cast every 10 m along the baseline. A range of change statistics are then calculated automatically using the position of the intersection of shorelines and transects. In environments with high temporal resolution records of shoreline positions regression-derived measures of shoreline change rates are widely used (Genz et al., 2007; Romine et al., 2009). However, due to the low temporal resolution of shorelines used in this study regression-derived shoreline change rates are unreliable. As a result, we utilised two measures of island change. First, net Shoreline Movement (NSM), the distance between two selected shorelines was calculated. Second, the annualised rate of change between two shorelines, known as the End Point Rate (EPR) was calculated. Given the multi-decadal timeframe of the dataset the EPR is expressed as decadal rate of change (i.e. m/dec). A confidence interval of 2σ (95.5%) was applied when calculating shoreline change rates. Transects where the confidence intervals do not cross zero are considered erosional (−/ve EPR) or accretionary (+/ve EPR), the remaining transects are classified as exhibiting no detectable change. Where a continuous shoreline

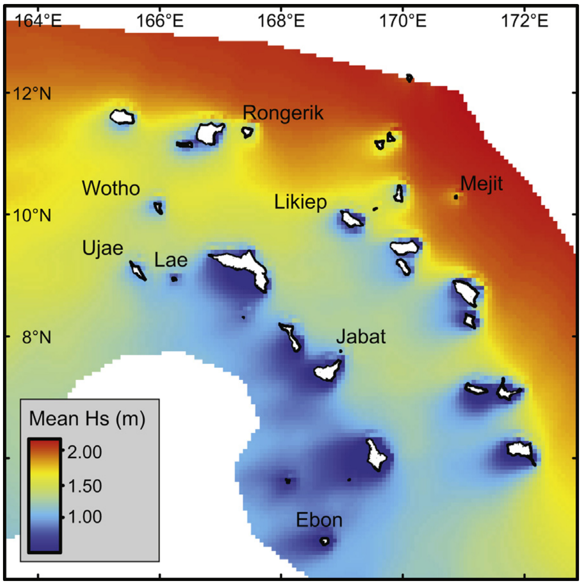

Fig. 4. Average significant wave height in the RMI. Calculated from a 4 arcmin resolution WaveWatch3 hindcast between 1978 and 2010 (Durrant et al., 2013). Source: Bureau of Meteorology and CSIRO© 2013

forms an unbroken island perimeter the island area was calculated by converting shorelines to polygon features in ArcMap.

Considerable variability in the spelling of island names was found in previously published maps and reports from throughout the Marshall Islands. Some uninhabited islands or small cays appear unnamed. For consistency, a numbering system of islands is adopted whereby the northernmost island on an atoll was labelled Island 1, with islands then numbered sequentially in a clockwise direction around the atoll rim (Fig. 2).

Rates of shoreline change are considered over two time periods. First, 55 islands which have both a WWII and 2010 shoreline are examined to provide the longest possible record of shoreline change. Second, more recent shoreline changes are examined using the 1970s and 2010 shorelines from 127 islands. Aerial photos from the 1970s have greater spatial coverage than WWII-era photographs, including the addition of Rongerik Atoll and numerous additional islands on Ebon, Wotho, Likiep and Ujae atolls. Finally, a subset of 52 islands which have WWII, 1970s and 2010 shorelines are considered to provide a uniform sample of shorelines across both time periods.

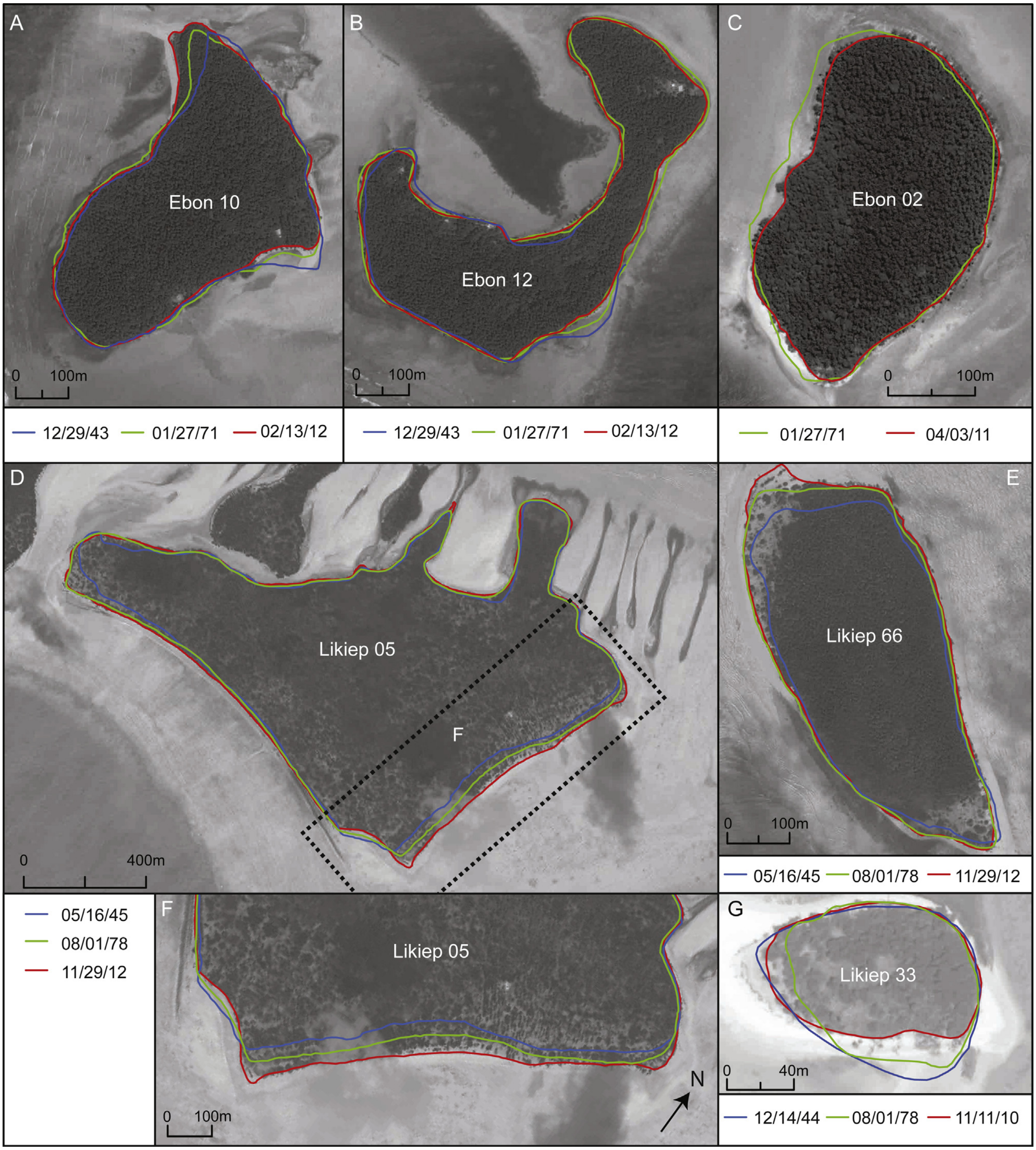

Fig. 5. Edge of vegetation lines from selected islands on Likiep and Ebon Atolls. This figure includes copyrighted material of DigitalGlobe, Inc., All Rights Reserved.

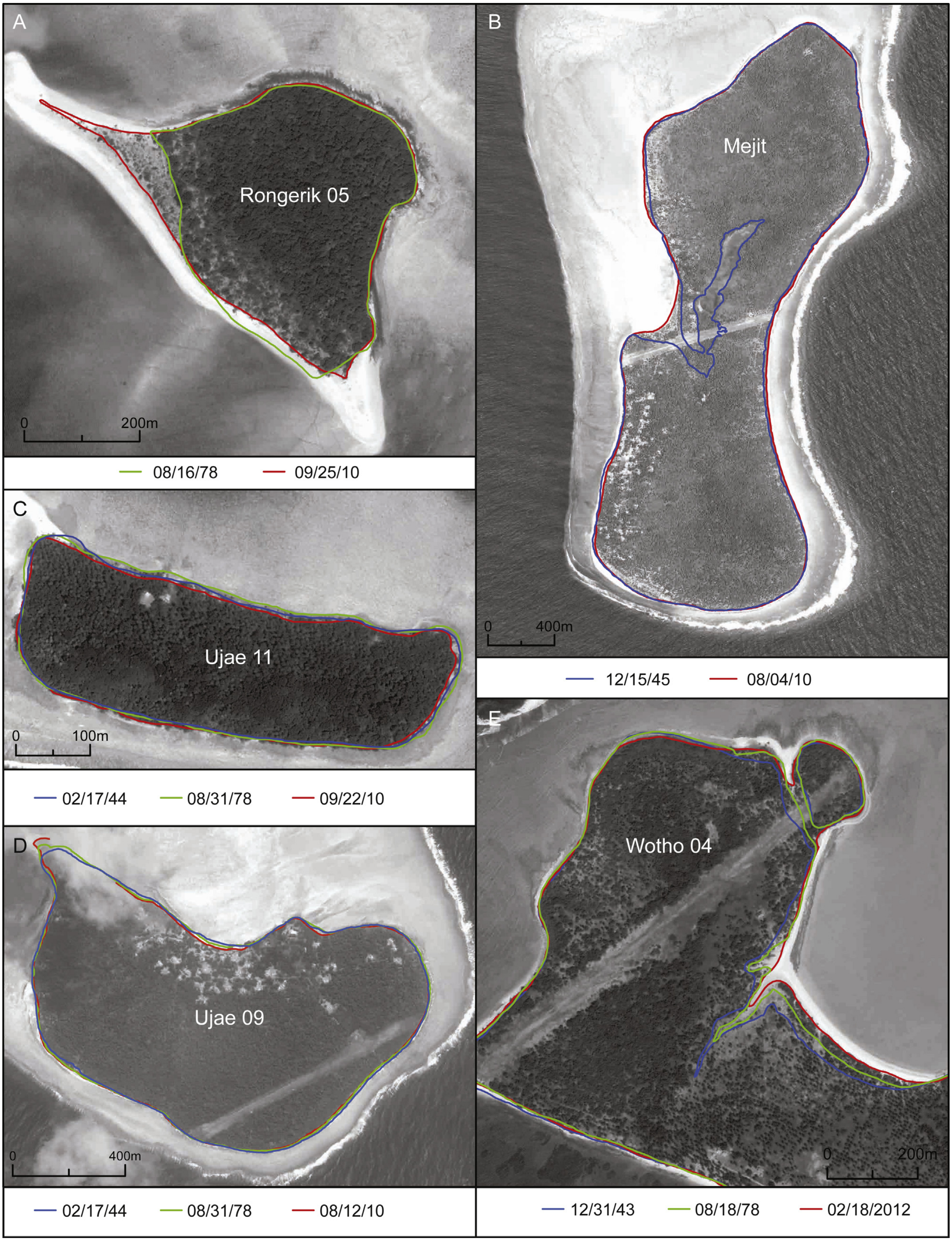

Fig. 6. Edge of vegetation lines from selected islands on Rongerik, Ujae, Mejit and Wotho Atolls. This figure includes copyrighted material of DigitalGlobe, Inc., All Rights Reserved.

4. Results

4.1. Shoreline changes WWII-2010

Noteworthy changes in the position of island shorelines and island areas were observed between WWII and 2010 (Figs. 5 and 6). With the exception of Rongerik, all atolls and platform islands have some WWII-era aerial photo coverage. In total 10,523 transects, from 55 islands intersected both a WWII and 2010 shoreline (Table 2). Of the total transects, 1914 (18.19%) were characterised by erosion, 4195 (39.87%) accretion and 4414 (41.95%) showed no statistically significant change. The proportion of transects indicating accretion varied between 27.27% at Jabat and 51.73% at Lae. The atoll-average NSM varied between −0.49 m (Jabat) and 4.59 m (Likiep). Of the 55 islands, 44 islands (80%) had positive average Net Shoreline Movement (NSM), indicating net island accretion. The remaining 11 islands (20%) had negative average NSM values (Supplementary Table 2).

The net outcome of changes in the entire shoreline of an island is adjustment in island planform area. Planform island area is examined only for the 48 islands where the complete island shoreline is able to be interpreted from imagery. Of the 48 islands examined, 40 (83%) increased in area over the study period. Islands from the WWII period had a total planform area of 12.77 km^2, compared with 13.25 km^2 in 2010, a 3.75% increase (Table 3). With the exception of Jabat, a reef platform island, the total landmass on all atolls increased over the study period. Likiep had the greatest absolute and percentage increase in land area, with islands examined increasing from 5.61 km^2 to 5.88 km^2 (4.72%), between WWII and 2010. Planform areas of all islands examined are provided in Supplementary Table 3.

4.2. Shoreline change 1970s–2010

With the exception of Jabat and Mejit, all atolls had aerial photo coverage from the 1970s. A total of 21,507 transects from 127 islands intersect both a 1970s and 2010 shoreline. In total 5302 (24.65%) and 6120 (28.46%) transects are characterised by erosion and accretion respectively. The remaining 10,085 (46.89%) transects showed no statistically significant change. The atoll-average NSM on each atoll varied between −2.53 m (Ebon) and 2.82 m (Rongerik), equating to decadal rates of change between −0.63 m/dec and 0.88 m/dec. Shoreline change statistics of all islands are presented in Supplementary Table 4. Of the 124 islands for which both a 1970s and 2010 area was calculated, 60 increased in size and 64 decreased in size. The total area of these 124 islands increased from 22.53 km^2 to 22.64 km^2.

4.3. Shoreline change WWII–1970s–2010

Focussing on the subset of transects which intersect WWII, 1970s and 2010 shorelines provides a record of shoreline change from 9303 transects from 52 islands on Ebon, Lae, Likiep, Ujae and Wotho. Between WWII and the 1970s 16.48% of transects showed erosion and 34.77% showed accretion. In total, 11 islands had negative average NSM values and 41 had positive average NSM values. Between the 1970s and 2010 the same 9303 transects revealed erosion on 22.83% of transects with 30.81% of transects revealing shoreline accretion. Planform area was calculated for 45 islands at all three time periods. Between WWII and the 1970s 38 islands increased in size and 7 decreased. The total area of the 45 islands increased from 9.09 km^2 to 9.35 km^2. Between 1970s and 2010 22 islands increased in size while 23 decreased. However,

Table 2
Summary of atoll-averaged shoreline change analysis.

Atoll	Time period	Transect count	Erosion (transects)	Accretion (transects)	No Change (transects)	Erosion (%)	Accretion (%)	No Change (%)	Average NSM (m)	Average EPR (m/dec)	Number of islands eroding/accreting
Ebon	WWII–1971[b]	1410	194	395	821	13.76	28.01	58.23	1.21	0.45	2/5
	1971–2010[b]	1410	411	307	692	29.15	21.77	49.08	−0.69	-0.17	7/0
	WWII–2010[a,b]	1410	356	457	597	25.25	32.41	42.34	0.52	0.08	3/4
	1971–2010[a]	5156	2007	743	2406	38.93	14.41	46.66	−2.53	-0.63	19/0
Jabat	WWII–2010[a]	275	67	75	133	24.36	27.27	48.36	−0.49	-0.07	1/0
Lae	WWII–1978[b]	346	14	185	147	4.05	53.47	42.49	4.63	1.34	0/2
	1978–2010[b]	346	74	43	229	21.39	12.43	66.18	−0.84	-0.26	2/0
	WWII–2010[a,b]	346	36	179	131	10.40	51.73	37.86	3.79	0.57	0/2
	1978–2010[a]	1832	399	393	1040	21.78	21.45	56.77	0.21	0.07	9/6
Likiep	WWII–1978[b]	5874	1133	2075	2666	19.29	35.33	45.39	2.74	0.82	8/30
	1978–2010[b]	5874	1207	2223	2444	20.55	37.84	41.61	1.87	0.55	17/21
	WWII–2010[a,b]	5874	822	2458	2594	13.99	41.85	44.16	4.59	0.68	5/33
	1978–2010[a]	8581	1692	3029	3860	19.72	35.30	44.98	1.54	0.46	26/32
Mejit	WWII–2010[a]	874	229	391	254	26.20	44.74	29.06	4.35	0.67	0/1
Rongerik	1978–2010[a]	1518	275	695	548	18.12	45.78	36.10	2.82	0.88	3/8
Ujae	WWII–1978[b]	852	107	348	397	12.56	40.85	46.60	2.99	0.87	1/3
	1978–2010[b]	852	332	89	431	38.97	10.45	50.59	−2.13	-0.67	4/0
	WWII–2010[b]	852	290	284	278	34.04	33.33	32.63	0.85	0.13	2/2
	WWII–2010[a]	923	305	316	302	33.04	34.24	32.72	1.06	0.16	2/3
	1978–2010[a]	1530	522	269	739	34.12	17.58	48.30	−1.47	−0.46	8/1
Wotho	WWII–1978[b]	821	85	232	504	10.35	28.26	61.39	2.32	0.67	0/1
	1978–2010[b]	821	100	204	517	12.18	24.85	62.97	1.47	0.44	0/1
	WWII–2010[a,b]	821	99	319	403	12.06	38.86	49.09	3.79	0.56	0/1
	1978–2010[a]	2890	407	991	1492	14.08	34.29	51.63	2.03	0.61	4/11
Total/average	WWII–2010[a]	10523	1914	4195	4414	18.19	39.87	41.95	3.49	0.52	11/44
	1970s–2010[a]	21507	5302	6120	10085	24.65	28.46	46.89	0.40	0.15	69/58
	WWII–1970s[b]	9303	1533	3235	4535	16.48	34.77	48.75	2.56	0.77	11/41
	1970s–2010[b]	9303	2124	2866	4313	22.83	30.81	46.36	0.98	0.29	30/22
	WWII–2010[b]	9303	1603	3697	4003	17.23	39.74	43.03	3.53	0.52	10/42

[a] Refers to all transects intersecting shorelines from the two time periods.

[b] Refers only to transects which intersect shorelines from all three time periods.

Table 3
Summary of island areas.

	Island area (km^2)											
	Period			Period			Period			Period		
Atoll	WWII[a]	2010[a]	Change	WWII[a]	1970s[a]	Change	1970s[a]	2010[a]	Change	WWII[b]	1970s[b]	2010[b]
Ebon	0.61	0.62	0.01	0.61	0.62	0.01	4.99	4.86	−0.13	0.61	0.62	0.62
Jabat	0.50	0.50	0.00									
Lae	0.33	0.35	0.02	0.33	0.35	0.02	1.84	1.85	0.01	0.33	0.35	0.35
Likiep	5.61	5.88	0.26	5.61	5.78	0.16	8.45	8.58	0.14	5.61	5.78	5.88
Mejit	3.16	3.26	0.10									
Rongerik							1.46	1.51	0.05			
Ujae	0.58	0.61	0.03	1.48	1.52	0.04	1.42	1.42	−0.01	0.55	0.59	0.58
Wotho	1.98	2.04	0.05	1.98	2.02	0.03	4.36	4.42	0.06	1.98	2.02	2.04
Total	12.77	13.25	0.48	10.02	10.28	0.26	22.53	22.64	0.12	9.09	9.35	9.46

[a] Refers to all islands for which planform area was able to be calculated from the two time periods.
[b] Refers only to islands for which area was able to be calculated at all three time periods.

despite more islands decreasing in size the total area of the 45 islands increased from 9.35 km^2 to 9.46 km^2. Across the entire window of analysis island area increased by 4.1%.

5. Discussion

The dataset comprises observations from 127 islands in the Marshall Islands over a period coincident with local sea level rise of ~2.2 mm/yr (Becker et al., 2012). Of note, no islands were completely eroded from their reef platform over the time period of analysis. Rather the dominant mode of shoreline change was accretion. The analysis of all shoreline changes between WWII and the most recent satellite imagery utilised in this study reveals 39.87% of shorelines underwent statistically significant accretion while 18.19% eroded and 41.95% exhibited no detectable change. Analysis of all shoreline change between the 1970s and 2010 shows a slightly higher proportion shoreline accretion compared with erosion (28.46% vs 24.65%). Collectively the outcome of shoreline changes over both time periods considered in this study was the growth of islands, resulting in an increase in the areal extent of islands throughout the Marshall Islands of approximately 4% (Table 3). Our observations are at odds with widespread assertions that the islands are currently being destabilised and eroded. However, the findings of this study are broadly consistent with island stability and island growth documented on other atolls since the mid-late 20th century (Webb and Kench, 2010; Yates et al., 2013; Ford, 2013; Kench et al., 2015).

Despite the overall trend of island growth the data suggest a slowdown in the rates of shoreline accretion since the 1970s (Table 2). The average decadal rate of change from all transects in each study period reveals shoreline change reduced from 0.77 m/dec between WWII and 1970s to 0.15 m/dec between 1970s and the 2010 (Table 2). When considering only transects which intersect shorelines from the three time periods examined we note the rates reduced from 0.77 m/dec to 0.29 m/dec (Table 2, Fig. 7). Likewise, the proportion of eroding shorelines was greater during the 1970s–2010 period (22.83%) than between WWII and the 1970s (16.48%) (Table 2). As a result, the growth in planform area of islands slowed, with the total area of islands measured at all three time periods increasing from 9.09 km^2 to 9.35 km^2 between WWII and 1970s, ultimately reaching 9.46 km^2 in 2010 (Table 3).

5.1. Variability of island change

Overlaying the trend of island growth is considerable variability in shoreline change at the archipelagic, atoll and island scales.

5.1.1. Inter- atoll variability

The proportion of eroding shoreline, as well as the magnitude of erosion varies considerably between atolls (Table 2). The proportion of all transects intersecting WWII and 2010 shorelines and eroding ranged between 10.40% (Lae) and 33.04% (Ujae). Conversely, the proportion of accreting transects ranged between 27.27% (Jabat) and 51.73% (Lae). Similar variability in the decadal rate of shoreline change is present over the WWII–2010 period, ranging between −0.07 m/dec (Jabat) and 0.68 m/dec (Likiep). The proportion of all transects from the 1970s–2010 period characterised by erosion varied between 14.08% (Wotho) and 38.93% (Ebon), with the proportion accreting ranging between 14.41% (Ebon) and 45.78% (Rongerik). Similarly, the atoll-averaged EPR varied between −0.63 m/dec (Ebon) and 0.88 m/dec (Rongerik). Strikingly, all 19 islands at Ebon eroded between 1971 and 2011/2012. In contrast, at Wotho only four of the 15 islands examined eroded between 1978 and 2012.

The results show no clear spatial patterns in shoreline behaviour across the archipelago. Ascertaining the mechanisms responsible for the inter-atoll variability in shoreline change rates is particularly problematic. Distinct latitudinal gradients exist within the RMI with respect to a range of environment variables including rainfall (Stoddart, 1992) and wave climate (Fig. 4). However, the degree of variability in shoreline change is consistent regardless of whether atolls are adjacent or at either end of the archipelago. The variability of atoll-scale shoreline change is well-illustrated at Lae, Ujae and Wotho, which are separated by <125 km, yet had 1978–2010 atoll-averaged shoreline change rates of 0.07 m/dec, −0.46 m/dec and 0.61 m/dec respectively. These differences in shoreline behaviour occur in a region where there is little variation in climatic or oceanographic boundary conditions, further complicating the attribution of drivers of change. Larger datasets comprised of islands from atolls spanning a range of oceanographic settings across basin scales provide the best opportunity to potentially elucidate any oceanographic and climatic drivers of shoreline change on the atoll-scale.

5.1.2. Within atoll variability

Within atolls, noteworthy variation in island-averaged shoreline change was observed. This variability of shoreline behaviour is observed even between islands in close proximity on the atoll rim (Supplementary Tables 3 and 4). Strikingly, on Likiep, the percentage of transects revealing erosion on each island varied between 0% and 61% and island-averaged accretion varied between 0 and 76% over the WWII–2010 period (Supplementary Table 2). Similarly, between 1978 and 2010 the island-average rate of

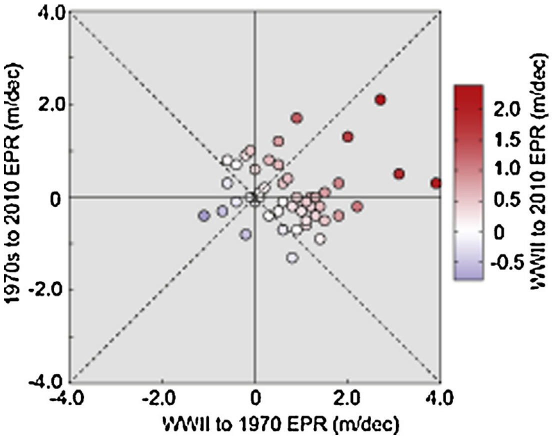

Fig. 7. Island-averaged shoreline change rate (EPR) between WWII–1970s and 1970s–2010, with resultant WWII–2010 shoreline change rates.

shoreline change on the NE facing rim of Likiep (between island #1 and #48) varied between −0.86 m/dec and 2.08 m/dec. This variability in shoreline change is observed along the same rim of the atoll, with the same wave exposure and seemingly similar environments. Considerable differences in the rates of shoreline change between nearby islands is characteristic of islands on all atolls throughout this study over both time periods examined (Supplementary Tables 2 and 4).

5.1.3. Island-scale variability

The average NSM and the resultant change in planform area of an island is a product of the collective adjustment of the entire island shoreline. Shoreline behaviour is rarely uniform around reef islands. For example, Webb and Kench (2010) and Ford (2013) both observed different rates of change on ocean-facing and lagoon-facing shorelines, as well as on elongate spits, which are often highly dynamic. The island-averaged NSM potentially masks considerable gross island changes, driven by differing rates and styles of changes between shorelines in different geomorphic zones. Islands may undergo extensive changes in the position of the shoreline with minimal change to island area or island-averaged shoreline change rates when erosion and accretion cancel.

On the island-scale a range of spatially varying shoreline responses are evident, including: shoreline progradation and erosion (Fig. 5F and G), embayment infilling (Fig. 6E) and spit extension, contraction and migration (Figs. 5 A and 6 A). One of the most striking examples of shoreline progradation is evident at the northern islands of Likiep. For example, a southeast-facing stretch of shoreline at Likiep 05 advanced seaward by 50 m between 1945 and 2012 (Fig. 5F). Similarly, the western shoreline of Likiep 01 has accreted ~23 m, while the eastern shore is largely stable, with an average NSM of 1.3 m. At Wotho 04 a natural embayment is infilling, with the shoreline advancing 39 m between 1943 and 2010 (Fig. 6E). Elongate spits are frequently characterised by large shifts in shoreline position either through extension (Fig. 6A) or migration (Fig. 5A).

5.2. Drivers of shoreline change

5.2.1. Sea level

It has been postulated that sea level is the primary control of reef island formation and stabilisation (Dickinson, 2004). However, recent research has documented reef island formation as sea level increased prior to the mid-Holocene highstand (Kench et al., 2014a), since sea level stabilised after falling from the highstand (Woodroffe et al., 2007; Kench et al., 2012) and under contemporary conditions (Ford and Kench, 2014, Kench et al., 2014b). The range of sea level states under which reef island formation has been observed suggests the treatment of sea level as the sole or primary driver of reef island change is an oversimplification of complex morphodynamic systems. The period across which shoreline changes were examined in this study is coincident with local sea level rise of ~2.2 mm/yr (Fig. 3). However, our observations suggest rising sea level has not caused uniform or widespread erosion of reef islands in the Marshall Islands. The accretionary trends evident across both time scales examined in this study occur in the context of considerable inter-island variability in shoreline behaviour. As a result, if signals of global or basin scale climatic or oceanographic processes are driving shoreline change they appear to be masked by local scale variability in morphodynamic processes at multi-decadal timescales.

5.2.2. Storms

Relative to western Micronesia, typhoons are a relatively infrequent occurrence in the RMI (Camargo et al., 2007). However, despite the seemingly low frequency of storms, atolls in the RMI have been severely impacted by occasional typhoons throughout the 20th century (Spennemann, 2009). Powerful storms provide near-instantaneous impacts on reef islands, with high energy events destroying large sections of islands, while also generating sediment for the formation and recovery of islands (Blumenstock, 1961; Baines and McLean, 1976; Bayliss-Smith, 1988; Ford and Kench, 2014). Blumenstock (1961) reported widespread destruction of islands on Jaluit Atoll in the RMI as a result of tropical storm Ophelia in 1958. Likewise, Ford and Kench (2014) track the recovery of islands on Nadikdik Atoll in the southern RMI following a typhoon in 1905 and found an entirely new island had formed, while other islands recovering over a century after the typhoon. Similarly, swell generated by distant storms in the north Pacific has been shown to both inundate and drive erosion on atolls in the equatorial Pacific, including the RMI (Hoeke et al., 2013; Smithers and Hoeke, 2014). Despite our large set of observations we see no evidence of massive geomorphic impacts similar in nature to those reported by Bayliss-Smith (1988) in the Solomon Islands or Blumenstock (1961) and Ford and Kench (2014) in the RMI. However, storm-generated sediments may continue to contribute to the growth of reef island sediment reservoirs decades and possibly centuries after events (e.g. Bayliss-Smith, 1988; Ford and Kench, 2014). As such, it is possible that some observed island changes could be lag effects from storms pre-dating our observations.

5.2.3. Local controls on island stability

Atoll islands are carbonate landforms, with all sediments derived from the surrounding reef. This study assessed planform changes to reef islands, precluding volumetric estimations of island change. However, by assuming islands have maintained a constant, or increasing, elevation it is apparent that planform growth of reef islands are driven by an increase in the volume of reef island sediment reservoirs, rather than simply a readjustment of a fixed volume of sediment. Reef islands are part of morphodynamic systems in which the feedback between reef ecology/sediment generation and physical processes leads to morphological readjustment of the island as boundary conditions change (Kench and Cowell, 2001; Perry et al., 2011). In cases where net sediment input exceeds sediment loses it has been theorised that islands can respond through shoreline progradation, resulting in island growth (Perry et al., 2011). However, the responses of the ecological and physical components of the morphodynamic systems to changing climate is the critical control of future island stability, yet remains poorly understood. Most islands examined in this study are uninhabited and likely free of the anthropogenic impacts of pollution impacting urban atoll sedimentary systems (Osawa et al., 2010). As a result, it is likely that the surrounding reefs are actively generating sediment in sufficient volumes to drive island growth.

5.2.4. Anthropogenic impacts

The atolls studied are either unpopulated (Rongerik) or sparsely populated, with total populations ranging from 84 (Jabat) to 706 (Ebon) (EPPSO, 2012). Most islands examined in this study are uninhabited, with few structures visible in imagery across all time periods. For the most part, changes occur within systems free of local anthropogenic disturbances. However, there appear to be two significant anthropogenic interventions along the shorelines at Mejit and Wotho 04. Mejit appears to be significantly modified by human activity, with a large increase the land area attributed to the infilling of an inlet in order to build an airport (Fig. 6B). It is unclear whether the changes seen elsewhere on the island are directly attributable to the airport development or are naturally occurring independent of the airport construction. Similarly, airport construction at Wotho is the likely cause of the merging of a small island with Wotho 04 (Fig. 6E). Prior to 2010 the island was separated from Wotho 04, with the island now connected, forming the northeast end of the runway.

5.3. Implications for reef island adaption strategies and resilience

Despite our observations coinciding with locally increasing sea level we find no evidence islands are being “washed away”, a notion that is a mainstay of political discussions surrounding the impacts of climate change on atoll nations. As sedimentary landforms, islands have demonstrated an inherent physical resilience in the context of rising sea level and other environmental changes (Webb and Kench, 2010, Kench et al., 2015). A defining characteristic of the islands examined in this study, as well a previous studies, is that island shorelines appear to be in a state of continual adjustment to environmental boundary conditions. A number of striking features of island change are apparent. First, no islands have disappeared from their reef platform. Second, nearly all islands have experienced varying levels of erosion and accretion. Third, most islands have changed in planform area. Fourth, the types of change are highly variable with regard the magnitude of change and whether adjustments are accretional or erosional. Based on these observations of island change it is apparent future changes will not be uniform through time and across space.

Results have significant implications for atoll nations and their future adaptation strategies. Governments of small island nations need to acknowledge that island shorelines are highly dynamic and islands have persisted and in many cases grown in tandem with sea level rise (SLR). Accepting this reality will allow more focussed development of practical adaptive pathways for island communities. Our results, and those of previous studies, highlight the real and significant challenge for island nations. However, this challenge may not necessarily be one of imminent loss of habitable land. Rather, the challenge is how will atoll communities accommodate future change and coexist with islands that will continue to move about them. To address these challenges countries will need to improve their evidence base to support improved adaptive pathways. Future planning decisions must recognize the dynamism of islands and therefore, knowledge of which islands and sections of islands are eroding, accreting or stable is fundamental to support such decisions.

The spatio-temporal variability in the behaviour of shorelines at an island-scale is a particularly challenging issue to confront with respect to management/adaptation interventions. The implementation of shoreline protection strategies in atoll nations has historically been approached in an *ad hoc* and poorly planned fashion (Kench, 2012; Duvat, 2013). There is considerable risk in implementing shoreline protection or other adaptation options based on site-specific erosion assessments, rather than a whole-of-island approach (Webb and Kench, 2010). Erosion can occur as part of shoreline oscillations or island migration and readjustment, while the island as a whole might be unchanged. Without a robust understanding of the broader island-scale context of shoreline changes management and adaptation interventions risk interrupting morphodynamic systems, causing impacts to other sections of island shorelines resulting in maladaptation (Barnett et al., 2013). Adaptation plans, particularly those involving engineering responses focussed on sections of islands which are seemingly eroding potentially ignore what, on an island-scale might be a stable or growing landform. As such, understanding the spatio-temporal behaviour of reef islands is an essential prerequisite to any hazard mitigation or adaption plans focused on erosion.

To improve the evidence base for adaption there is an urgent need to undertake national scale assessments of land resources and island change, in a similar manner to that presented in this study. Such assessments could provide the baseline for ongoing island monitoring to resolve future island change and help decipher the potential drivers of shoreline change, whether drivers are episodic (i.e. storms), slow onset (i.e. SLR) or anthropogenic. Currently, there are few, if any, robust monitoring programs which can provide context for the changes in reef islands across a range of time-scales. As such, assessing historic and recent reef island change has been reliant on sparse, remotely-sensed records of shoreline position. The availability of high-resolution imagery provides the opportunity to assess the persistence of, and potential changes to, island growth trajectories observed in remote-sensing studies to date. The archives of high-resolution imagery, which span the early 2000s to present day for most atolls, provide the opportunities to elucidate relationships between shoreline change to climatic and oceanographic drivers. However, despite the rich archives of imagery and growing constellation of high resolution satellites we find little evidence of regular, remote monitoring of reef islands. Establishing such land resource monitoring programmes is in itself a challenge in atoll countries. However, the results would allow governments to identify islands more susceptible to change than others and provide a robust platform to design adaptation strategies that adopt a whole-of-island approach.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ancene.2015.11.002.

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