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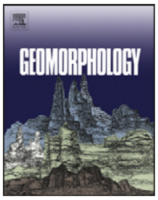

Formation and adjustment of typhoon-impacted reef islands interpreted from remote imagery: Nadikdik Atoll, Marshall Islands

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ABSTRACT

In 1905, a devastating typhoon hit Nadikdik Atoll (5°54′ N and 172°09′ E) in the southern Marshall Islands. Evidence suggests that large sections of reef islands on Nadikdik were overwashed and destroyed. Comparison of aerial photographs taken in 1945 and modern satellite imagery provides a unique record of the geomorphic adjustment of islands after the typhoon. Between 1945 and 2010 the vegetated area of islands on Nadikdik grew from 0.74 to 0.90 km^2. Observed changes to Nadikdik reef islands manifested through a range of styles and were largely accretionary. Of note, the formation of a new island was tracked from an embryonic deposit to a fully vegetated and stable island over a 61 year period. Similarly, a number of previously discrete islands have agglomerated and formed a single larger island. These changes were rapid and indicate that reef island formation can occur quickly. Evidence suggests that despite the typhoon occurring over a century ago the geomorphic adjustment of islands is still on-going.

1. Introduction

Reef islands are coherent accumulations of locally generated carbonate sediment deposited on coral reef platforms throughout the tropical and subtropical oceans, which provide the only sites for human habitation in coral reef archipelagos. There is considerable global interest concerning the future stability of these landforms with projected increases in sea level and climatic change (Barnett and Adger, 2003; Dickinson, 2009). In order to better resolve future island landform trajectories, there has been a recent increase in studies aimed at understanding the boundary controls on, and timeframes of, island formation and subsequent morphological dynamics (e.g. Woodroffe et al., 1999; Kench and Brander, 2006; Webb and Kench, 2010). Such studies have focussed at different timescales and considered differing mechanisms of island change.

At the geological timescale there have been a growing collection of studies defining the chronology of island formation (Woodroffe et al., 1999; Woodroffe and Morrison, 2001; Kench et al., 2005; Kayanne et al., 2011; Kench et al., 2012). Although relatively few in number, these studies have indicated that there was a major phase of island formation in the mid to late-Holocene (5000–2000 years ago). These studies have also identified differing styles of accumulation, with the core of some islands having formed in a narrow 500–1000 year window, while others formed incrementally and continuously from the mid-Holocene. Collectively, the studies suggest that islands have a geological persistence on reef surfaces spanning several thousand years. However, noteworthy adjustments of reef island shorelines have been observed across a range of timescales, suggesting that stability is not necessarily an intrinsic characteristic of reef islands.

At the medium timescale, several studies have begun to elucidate the multi-decadal shoreline dynamics of reef islands (Flood, 1986; Webb and Kench, 2010; Ford, 2011; Rankey, 2011; Ford, 2013; Yates et al., 2013). Such studies have documented subtle shifts in the position of existing shorelines, different styles of movement of islands on reef surfaces, and both erosional and accretionary adjustments over the past half century. At still shorter timescales island shoreline dynamics have been examined in response to seasonal variations in wind and wave climates (e.g. Kench and Brander, 2006) and extreme events such as tsunami (Kench et al., 2006); long period swell episodes (Hoeke et al., 2013) and cyclones (Stoddart 1963, 1971; Maragos et al., 1973). Of note, tropical storms and cyclones have caused a range of effects from catastrophic erosion and devegetation on sand islands (Stoddart, 1963, 1971; Bayliss-Smith, 1988; Harmelin-Vivien, 1994) to the delivery of vast quantities of reef rubble that can promote accretion of coral gravel islands (Maragos et al., 1973; Bayliss-Smith, 1988; Scoffin, 1993). Such observations are incorporated into Bayliss-Smith's (1988) conceptual morphodynamic model of island response to extreme events, which was dependent upon storm frequency and the grade of sediment comprising islands. Collectively, these observations of island response to extreme events have focussed on the immediate impacts of an event, with comparatively few studies documenting post-impact island morphological dynamics. Such studies are critical

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for resolving the timescales and styles of island formation and geomorphic adjustment, and for determining whether island construction can occur under recent/contemporary environmental conditions.

Here we report remotely-sensed observations of pronounced changes to reef islands including the formation, migration and stabilisation of islands on Nadikdik Atoll, located in the southern Marshall Islands, following a catastrophic typhoon in 1905. Descriptions of the impacts of this catastrophic event provide a framework to evaluate both island adjustment and morphological dynamics.

2. Setting

The Republic of the Marshall Islands (RMI) consists of two largely parallel island chains made up of 29 atolls and 5 mid-ocean reef islands stretching from 4°34′ to 14°43′ N and 160°48′ to 172°10′ E. (Fig. 1). Nadikdik Atoll, also known as Knox Atoll, is located in the southern part of the Republic of the Marshall Islands (RMI) at 5°54′ N and 172°09′ E (Fig. 1). Nadikdik is ~3.5 km south of Mili Atoll and is separated by the Klee passage. Nadikdik measures approximately 8 km long and 1.5 km wide and has no passes connecting the open ocean to the lagoon (Fig. 2A). Unlike other atolls in the RMI, the lagoon is relatively shallow with the sea floor clearly visible in all areas of the lagoon in both aerial photographs and satellite imagery. We were unable to verify the lagoon depth as no published surveys have been identified and are unlikely to have been attempted due to the restricted access to the lagoon.

Despite the proximity to the equator, historic records show the southern Marshall Islands have been struck by a number of devastating typhoons (Blumenstock, 1958; Spennemann and Marschner, 1995). Additionally, a number of weaker typhoons and tropical storms occurred within the southern Marshall Islands over the last century. Reconstruction of the 1905 typhoon suggests that it passed directly between Nadikdik and Mili (Spennemann, 2009), with reports indicating that the entire population was killed with the exception of two survivors who drifted on coconut logs for 24 h before rescue (Spennemann, 2009). Spennemann (1996) provides a brief description of the geomorphic impacts of the 1905 typhoon through the comparison of a survey by the US Exploring Expedition in 1841 and a 1946 US Army Map Service map. Spennemann (1996) notes the likely break-up of a continuous island along the western rim of the atoll as a result of the 1905 typhoon. At present, the majority of islands are located on the western rim of the atoll, with a smaller number of islands located on the eastern rim in the northeast quadrant of the atoll.

3. Materials and methods

Relative to continental coastal systems, there is a paucity of aerial photo collections within atoll settings and few continuous records of shoreline position. However, due to the strategic role of the Marshall Islands during WWII there are detailed collections from this period. Beyond a handful of surveys in the mid-1970s, which appear to have excluded Nadikdik, there are few vertical aerial photographs in the Marshall Islands between WWII and the launch of high resolution satellite sensors in the early 21st century. Aerial photos of Nadikdik taken on 21/01/1945 as well as Quickbird satellite imagery captured on 26/05/2006 and WorldView2 satellite imagery from 2010 were used in this study to map island change. The 2010 WorldView2 scene is a mosaic of three separate scenes captured between 1/10/2010 and 20/12/2010. Aerial photos and the 2010 image were georeferenced using the 2006 satellite image as the source of ground control points. With the absence of anthropogenic features on Nadikdik, a range of stable geological features were used as ground control points. Images were transformed using a second order polynomial with an RMS error of <2.0 m. The edge of vegetation was chosen as an analogue for the shoreline as it is easily identifiable in all images, regardless of tidal level, based on a combination of image colour, texture and tone. The edge of vegetation was digitised within ArcMap by a single operator at a constant scale (Ford, 2011, 2013). The island shorelines were converted to polygon features in ArcMap in order to calculate island areas. Photos taken from the International Space Station in 2001 provide an additional view of Nadikdik but are considered unsuitable for mapping and are interpreted in a descriptive capacity.

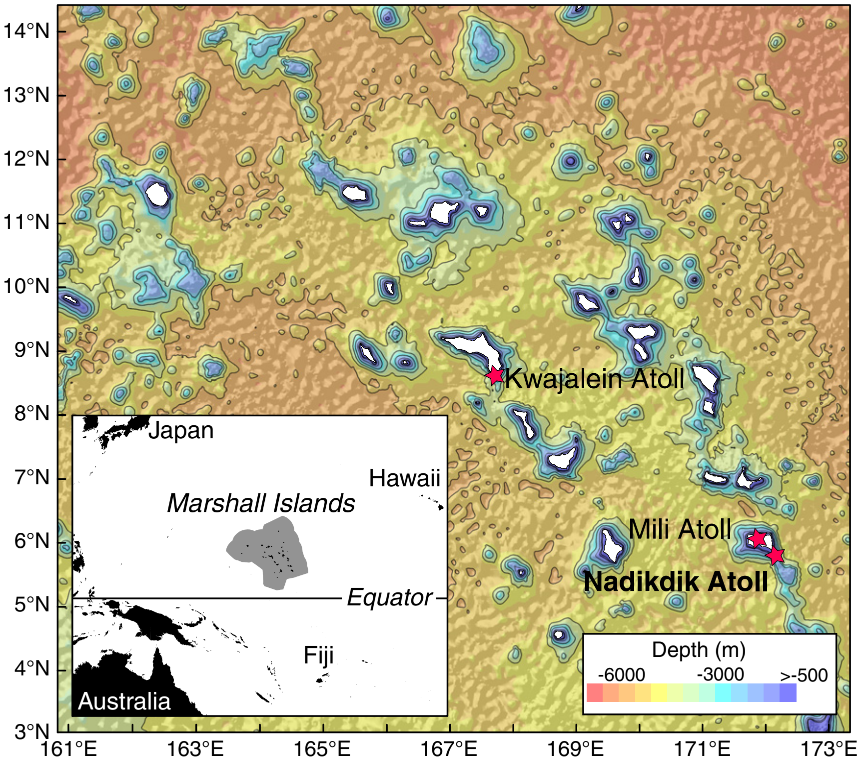

Fig. 1. The Republic of the Marshall Islands in the central Pacific Ocean, showing Nadikdik Atoll at 5°54′ N and 172°09′ E.

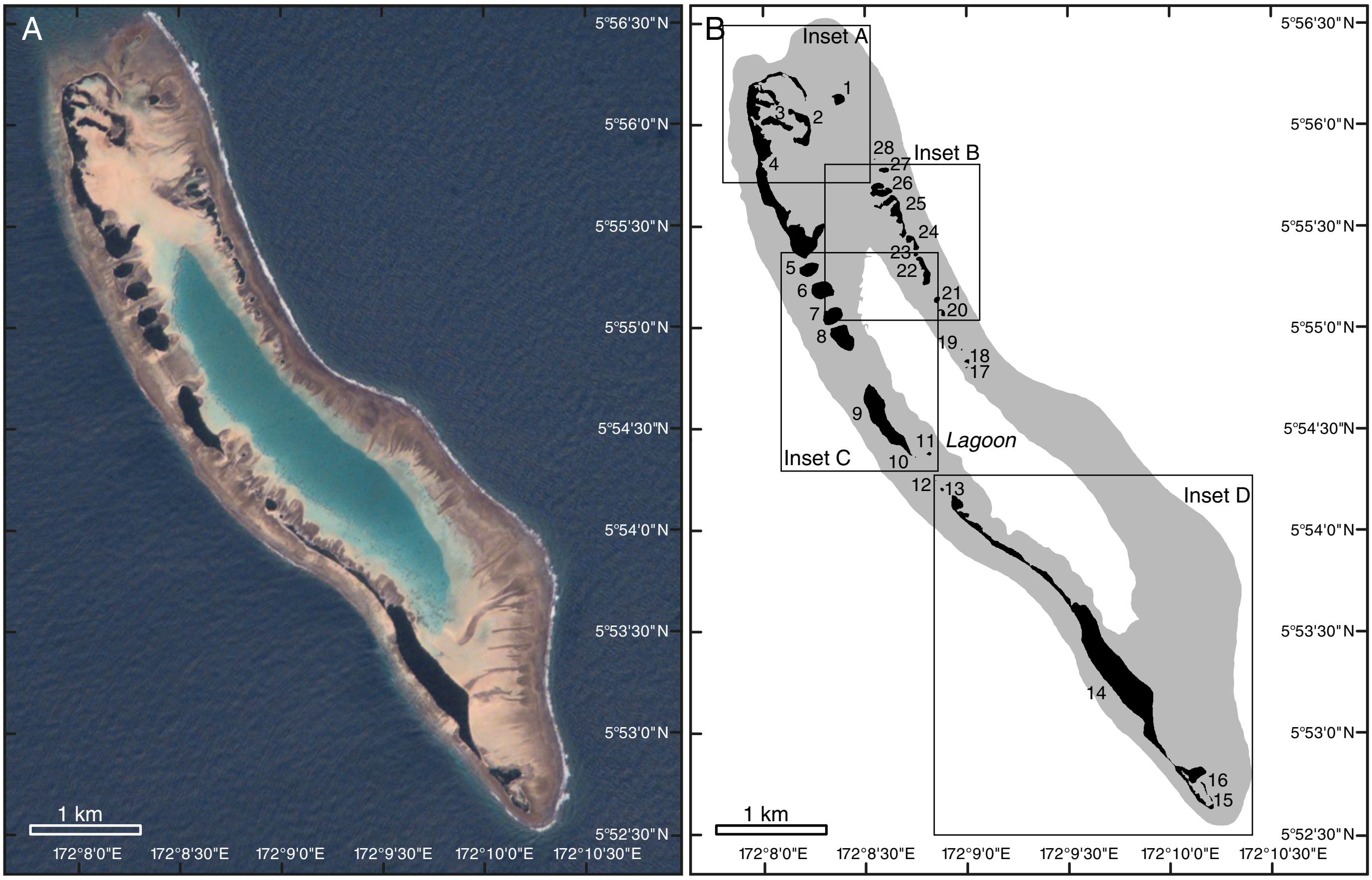

Fig. 2. A) Photo of Nadikdik Atoll taken from the International Space Station on 21/05/2001 (Image Science and Analysis Laboratory, NASA-Johnson Space Center, 2013). B) Location of islands analysed in this study based on island positions in 2010.

4. Results

4.1. Description of and quantification of island changes

Analysis of all islands on Nadikdik reef platform shows a net increase in vegetated land area from 0.74 km^2 in 1945 to 0.90 km^2 in 2010, which is an increase of approximately 23%. Fourteen island units present in 1945 and 2010 showed a distinct increase in vegetated land area ranging from 5.6 to 434%. Largest absolute increases of 48,839 m^2 (28%, Island 4) and 47,245 m^2 (14.6%, Island 14) occurred on the larger islands on the western margin of the reef platform. Greatest proportional increases in land area of 434% and 207% generally occurred on smaller islands on the northeast sector of the atoll (Fig. 3A, B, Table 1). Two islands reduced in vegetated land area across the 65 year timeframe of analysis. Island 18 lost 765 m^2 (~37%) and island unit 27–29 reduced in area by 339 m^2 (~9.0%). Both islands were located on the northeastern sector of the atoll.

The documented changes in island area on Nadikdik Atoll manifest through a range of styles of island planform adjustment, which can also involve positional movement on the platform surface. A striking feature of the results is the formation of one island and rapid expansion of several other islands on the northeast sector of the atoll (Fig. 3A). Island 1 formed rapidly from a small crescent-shaped deposit of approximately 1546 m^2 in 1945 to a vegetated island 7901 m^2 in 2006 and 8247 m^2 in 2010. This rapid formation was accompanied by migration across the reef flat of ~40 m. Since 2006 the island appears to have remained relatively stable. Indeed, the presence of a tree on the lagoon shoreline with a canopy > 15 m in diameter suggests that the island has been close to its present position for a significant period of time.

Migration of islands across the reef toward the lagoon is a characteristic mode of island behaviour of a set of smaller, disconnected islands along the northeastern quadrant of the atoll rim (Fig. 3B, Islands 20–29). Between 1945 and 2006 the islands migrated lagoonward across the reef flat by as much as 100 m. The migrating elongate cays have increased in size markedly during this time with the total land area of Islands 20–29 increasing from 35,913 to 68,909 m^2. Between 2006 and 2010 Island 29 disappeared. However, Islands 20–28 increased in size to 73,442 m^2 and continued to migrate, with the centroid of individual islands shifting up to 4.0 m lagoonward. Contemporary expansion of vegetation along the lagoon shoreline is also noteworthy, with a number of lightly vegetated lagoon facing areas in the 2006 image appearing densely vegetated in the 2010 image.

Island migration and vegetation of the barrier/bank at the northern end of the atoll are two of the most striking morphological changes on Nadikdik over the past 65 years (Fig. 3A). The narrow barrier migrated ~200–250 m south and rotated to the west, now forming a hook-shaped deposit which is up to 40 m wide and densely vegetated. Islands in the lee of the bank, which were present in 1945, are now fully established and expanding. There is little evidence to indicate that this migration is continuing under contemporary conditions, with no lagoonward shoreline change detected between 2006 and 2010. Between 1945 and 2006 the shoreline along the western section of island 4 has migrated lagoonward with a relatively consistent displacement of ~20 m along 500 m of shoreline (Fig. 3A).

Island agglomeration is a further pattern of island change as a consequence of island expansion and linear extension of islands along the reef rim. The two largest islands within the northwest quadrant of the atoll joined together between 1945 and 2006, resulting from the deposition 18,727 m^2 of additional land forming the weld (Fig. 3A). The merging process for these islands appears to have occurred some time ago, with differences in the vegetation density between the newly accreted and the pre-existing island seemingly undetectable from the most

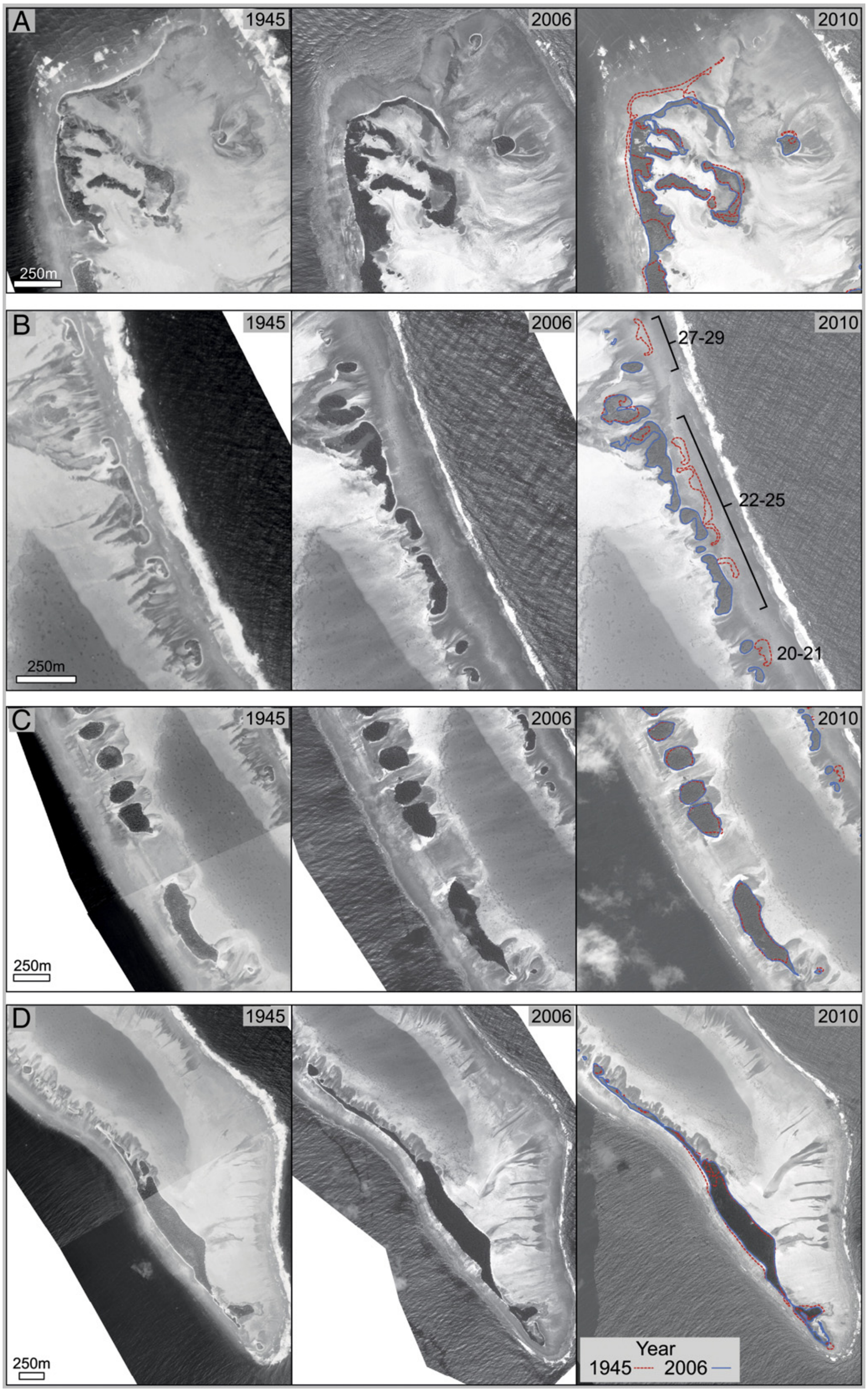

Fig. 3. Changes in the planform characteristics of islands between 1945 and 2010 at Nadikdik Atoll. A) The formation of Island 1, merging islands along the western rim and rotation of the northern spit. B) The lagoonward migration, breakup and expansion of islands in the northeast quadrant. C) Island expansion along the western atoll rim. D) Extension and merging of islands in the southwest quadrant of the atoll. 2006 and 2010 images are Copyright DigitalGlobe, 2013 all rights reserved.

stable parts of the islands (Fig. 3A). The merging of islands also appears to be the most prominent mechanism of change on the southwest sector of the atoll. At present a continuous island (14) extends 3.7 km from the southern tip of the atoll along the western rim measuring 0.37 km^2 in 2010. In 1945 the contemporary footprint of Island 14 encompassed 12 individual islands, with one large island in the south (0.27 km^2) and 11 smaller islands (<21,750 m^2). Between 1945 and 2006 the islands joined together through northward extension from the large

Table 1
Island areas and changes across study period.

Island	Island area (m^2)			1945–2010 change (m^2)	1945–2010 change (%)
	1945	2006	2010		
1	1546	7901	8247	6702	433.51
2	22,621	25,790	26,316	3695	16.33
3	11,881	15,363	15,609	3728	31.37
4	173,882	219,627	222,721	48,839	28.09
5	15,657	17,438	16,593	936	5.98
6	22,198	26,543	25,639	3441	15.50
7	20,469	22,187	21,708	1239	6.05
8	31,044	35,592	34,137	3093	9.96
9	73,220	83,340	82,930	9710	13.26
10			97	97	
11	903	1043	953	50	5.57
12		159	60	60	
13		826	772	772	
14	324,097	372,932	371,342	47,245	14.58
15			501	501	
16		1550	1680	1680	
17			194	194	
18	2087	1590	1322	−765	−36.65
19		125	183	183	
20–21	4181	4335	4616	435	10.41
22–25	15,956	45,563	48,928	32,972	206.64
26	12,007	15,663	16,468	4462	37.16
27–29	3769	3348	3430	−339	−9.01
Total	735,518	900,916	904,446	168,928	22.97

Island group 20–21 consisted of a single island in 1945 that split into two islands between 1945 and 2006 (Fig. 3B).
Island group 22–25 consisted of four islands in both 1945 and 2010. However, due to island splitting and agglomeration we cannot confidently track the changes of individual islands. As a result, islands 22–25 are treated as one unit (Fig. 3B).
Island group 27–29 consisted of a single island in 1945 that had split into 3 islands by 2006 with 2 islands remaining in 2010 (Fig. 3B).

stable southern island. The core of the largest 1945 island remains largely intact, with the joining of islands and extension resulting in the formation of a fully vegetated island ~1075 m long and up to 60 m wide. Of note, a 3390 m^2 island visible at the southern end of the atoll in 1945 is no longer present, having seemingly shifted northwest and amalgamated with island 14 (Fig. 3D).

Four circular islands (5–8) in the central section of the NW quadrant of the atoll have remained positionally stable but expanded their footprint on the reef surface over the 65-year window of analysis (Fig. 3C). However, there has been a degree of shoreline adjustment with the growth of the islands and the rotation and growth of the spit at the southern end of Island 8. Island 9 measured ~630 m long and between 100 and 140 m wide in 1945, with an area of 73,220 m^2. Between 1945 and 2010 both ocean and lagoon facing shorelines have predominately accreted resulting in an increase in island area to 82,930 m^2. Changes to the shoreline of Island 9 have predominantly been small (<10 m), with the exception of the northern and southern ends of the island, which have extended by 24 m and 107 m, respectively.

Despite the majority of islands in the atoll increasing in size and undergoing a range of planform changes, two islands decreased in size (18, 27–29). These islands have split into discrete entities. Island 28 was ~160 m long and visible in the 1945, with the remnants potentially splitting into three small cays present in the 2006 image (27–29) (Fig. 3B). Of note, one of the remnant cays was no longer present in the 2010 image, suggesting that the migration and destruction of the original island have been on-going.

5. Discussion

Analysis of aerial photographs and satellite imagery reveals noteworthy changes to islands on Nadikdik Atoll between 1945 and 2010. Nadikdik Atoll is situated considerably south of the north Pacific typhoon belt, with high intensity storms occurring infrequently (Scoffin, 1993). Reconstruction and accounts of the 1905 typhoon indicate that the event was highly energetic, causing devastating impacts to anthropogenic systems and driving noteworthy geomorphic change on a number of atolls in the southern Marshall Islands (Spennemann, 2009). Given the low frequency of typhoon events in the area, and following the interpretations of Spennemann (1996, 2009) we attribute the geomorphic changes observed on Nadikdik Atoll between 1945 and 2010 to the readjustment of islands following the 1905 typhoon.

This study provides the first multi-decadal, remotely-sensed assessment of the geomorphic response of reef islands after a catastrophic and geomorphically significant typhoon over a century after the event. Previous accounts of storm-induced geomorphic impacts have typically documented the immediate effects of the event and the response of islands over relatively short timescales (months to decades) (Maragos et al., 1973; Bayliss-Smith, 1988). Over recent years, a growing number of studies have presented atoll island shoreline changes over the later part of the 20th century (Webb and Kench, 2010; Ford, 2011; Rankey, 2011; Ford, 2013; Yates et al., 2013). Within the body of atoll island shoreline change studies the changes documented on Nadikdik are unique for both the magnitude and styles of change observed. Existing reef island shoreline change studies have typically revealed relatively small, predominantly accretionary shifts in existing island shoreline position over the second half of the 20th century. Observations presented in this study indicate that islands on Nadikdik have undergone significant shifts in morphology, size and reef flat position which we attribute to changes in the sediment reservoir initiated by a typhoon over a century ago in 1905 as explained in the following sections.

5.1. Post-typhoon island adjustment

Relatively few details of reef island geomorphology on Nadikdik can be found prior to 1945 in order to accurately describe the instantaneous impact of the typhoon. However, Spennemann (1996) provides a map redrawn from the U.S. Exploring Expedition map, surveyed in 1841. The redrawn U.S. Exploring Expedition map indicates a near-continuous island along the western rim of the atoll. In places, modern satellite imagery reveals the presence of a relatively continuous, reef crest-parallel feature on the western reef, approximately the same distance from the reef crest as the shoreline of modern islands. We cautiously interpret this feature as consolidated beachrock which supports the Spennemann (1996) interpretation of the presence of a largely continuous island prior to the 1905 typhoon. These interpretations are consistent with the typhoon impacts reported by Jeschke (1905, reported in Spennemann 1996) which noted: the break-up of a continuous island on the western rim of the atoll; most islands experienced overwash which dispersed the sediment away from islands, and; only occasional sandbanks and minimal vegetation surviving.

Against this context of immediate island impacts our results have identified substantive island reformation/development over the past century. The prominent changes documented between 1945 and 2006–2010 suggest that the geomorphic adjustment of islands after the 1905 typhoon is on-going. The continuous island which was present along the western rim prior to the 1905 typhoon has not yet fully reformed. However, there is evidence (Fig. 3C) to suggest that the reformation of the laterally continuous island is in progress. A number of small islands present in 1945 either formed after the typhoon or were surviving remnants of the pre-1905 island. In many cases these islands have now been incorporated into the northward extension of Island 14 (Fig. 3C). A photo taken from the International Space Station (I.S.S.) in 2001 (Fig. 2A) reveals that islands at both the northern and southern ends of Island 14 have merged with Island 14 between 2001 and 2006, further indicative of the active readjustment of the island.

The reconnection of islands along the western rim of the atoll suggests that a return towards a pre-storm state has been driven by an equilibrium island configuration, which is likely driven by the process regime of wave-driven currents and sediment fluxes around the reef rim and reef platform surface. Significantly, our results show that post-typhoon island geomorphic development has occurred across a centennial timeframe, and may still be progressing, which provides a temporal dimension to the relaxation timescales implied for sand islands in Bayliss-Smith's (1988) conceptual model of island dynamics in response to typhoon events. In contrast, Bayliss-Smith (1988) found that geomorphic recovery of islands in Ontong Java, following hurricane disturbance, was largely complete.

There are two factors that may have also controlled the pace of island geomorphic development on Nadikdik. First, the occurrence of additional storm events may compromise the recovery of islands to a pre-storm condition, though this is not believed to have been significant on Nadikdik where there have been few significant events since 1905. Second, the availability of sediment is critical in island development (Perry et al., 2011). The destruction of islands clearly indicates that the typhoon redistributed the sediment contained within the islands on the surrounding reef flat, into the central shallow lagoon and potentially offreef. Deposition in the lagoon and export off the reef edge would act as long-term losses of sediment to the island system, though the precise volumes are unknown. Consequently, to return to a pre-storm condition would rely on the reworking of sediments from the reef and the generation of fresh sediment supplies from the surrounding reef system. There are two sources of new sediment to the reef platform: a discrete volume of sediment generated as a consequence of the 1905 typhoon, and; continuous sediment production shed from the productive reefs surrounding the atoll post-typhoon. There are no ecological surveys of the reef system at Nadikdik. However, the fact that the atoll historically had only a small population and since the 1905 typhoon has been uninhabited would suggest that the reefs are likely to be relatively free of anthropogenic impacts, and therefore, in a healthy condition. Consequently, the on-going geomorphic adjustment of islands may reflect continuous generation of sediment from the surrounding reef system.

5.2. Implications for reef island development

The observations of island (re)formation and alteration on Nadikdik Atoll provide unique insights into the timescales and island formation and their dynamic behaviour. The results show that island formation/redevelopment has occurred relatively rapidly on the Nadikdik Atoll rim. Few previous studies have documented the pace of island change and to date none have noted the development of new islands. The significance of our results is profound as the islands of Nadikdik are modern analogues that demonstrate that island building is possible under present-day conditions. Furthermore, our observations of post-typhoon island recovery on Nadikdik have occurred in the context of rising sea level over the past century. Sea level in the Marshall Islands has been measured continuously since 1946 at Kwajalein Atoll (580 km WNW of Nadikdik) and has been rising at ~2.2 mm/yr (Becker et al., 2012). Clearly, the formation and growth of islands indicate that provided an adequate supply of sediment, such as that generated by the 1905 typhoon, island formation and expansion during periods of rising sea level are possible. These findings reveal a level of geomorphic complexity not widely recognised in projections of future reef island response to sea level rise (Dickinson, 2009). However, our findings are consistent with other studies that indicate that islands are geologically robust landforms that have an ability to adjust morphologically to changing process regimes driven by sea level change (Kench et al., 2005, 2009; Webb and Kench, 2010; Kench et al., 2012).

The results also reveal that the islands on Nadikdik have been morphologically dynamic over the past century. Such dynamism is expressed through a number of styles of island morphological behaviour. First, data from Island 1 shows the rapid accumulation of an island through the transition of detrital storm-generated material into an organised deposit and eventually a stable, vegetated island. The material currently comprising Island 1 was likely generated and organised by the 1905 typhoon, from this embryonic state the deposit developed into the lagoonward migrating crescentic deposit seen in the 1945 image. Between 1945 and 2006 the deposit migrated lagoonward ~40 m where rapid colonisation of the island vegetation occurred. The exact timing and style of island formation between 1945 and 2006 are uncertain. However, island formation occurred very rapidly; at the very latest the island has been in the present position and shape since the 2001 I.S.S. photo was taken, most likely earlier due to the presence of the large tree with a canopy >15 m in diameter on the lagoon shoreline. Second, lagoonward migration of islands was observed in a number of islands with some islands migrating up to 100 m. Third, alongshore extension of islands has promoted the merging of adjacent islands to yield larger extensive deposits that parallel the reef crest. Fourth, a number of islands expanded around their stationary core. The various modes of island behaviour observed on Nadikdik were also reported by Webb and Kench (2010) and show that these are common modes of island change on reef platform surfaces.

5.3. Implications for reef island geomorphic investigations

The bulk of reef island chronologies show that the age of material comprising islands spans several hundred to thousands of years, with island formation largely interpreted through various styles of incremental accretion (Woodroffe et al., 1999; Woodroffe and Morrison, 2001; Kench et al., 2005). In contrast, our results from Nadikdik show that island formation can be very rapid. A number of previous studies have also shown that extreme events such as typhoons can be important in generating large volumes of sediment from reef surfaces and forming islands, although across shorter time-periods than observed at Nadikdik (Maragos et al., 1973; Bayliss-Smith, 1988).

The results also have implications for interpreting the depositional history of reef islands. Islands on Nadikdik have been shown to have formed rapidly following a significant typhoon, observations which are only possible due to the period of island change coinciding with the collection of remote imagery. In contrast, similar interpretations of short-term reef island formation and dynamics within the geological record are problematic. The precision of radiocarbon dating techniques and the uncertainty of the sediment generation-deposition lag easily exceed the period of time in which islands were observed to have formed on Nadikdik. Within the geological record evidence of the rapid formation of reef-islands is scant. Given the lack of high-resolution island chronologies, it is difficult to verify whether storm-derived islands are present within the records of mid-late Holocene island formation and have to date been missed during relatively sparse sampling. Results from our study suggest that in reef regions affected by extreme events such as typhoons, obtaining a high fidelity chronostratographic depositional signature of island deposition may well be corrupted through continual reworking of the sediment reservoir.

5.4. Conclusions

Nadikdik Atoll was devastated by a typhoon in 1905 and the geomorphic impacts of this event are on-going. A range of styles of island development and adjustment are observed, including the agglomeration of existing islands, lagoonward island migration, and the expansion of existing islands about a stable core. Of note, we observe the development of a new, now fully vegetated island. There is evidence to suggest that some islands are reforming in the same positions as the pre-1905 islands, suggesting an equilibrium driven by hydrodynamic processes and sediment fluxes. This study has significant implications for the geomorphic understanding of reef islands, revealing timescales, magnitudes and styles of island change not previously recognised.

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