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Inundation of a low-lying urban atoll island: Majuro, Marshall Islands

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Abstract Majuro is a low-lying island perched on a coral atoll in the central Pacific Ocean and is home to nearly 28,000 people. Considered highly vulnerable to the impacts of marine inundation, Majuro is expected to experience increasingly severe inundation as a result of continued sea-level rise. Popular media, academic papers, government reports, disaster declarations and other online resources are used to document 18 inundation events at Majuro over the past 36 years, which caused considerable impact to local physical and anthropogenic systems. The physical drivers and impacts of the documented inundation events are examined using tide gauge and weather observations and wave model hindcasts. The ocean-facing shorelines of Majuro experience frequent inundation caused by swell waves generated by distant storms from both the north and the south Pacific Ocean. In some instances, complete overwashing of the island by swell waves has been reported. Less frequent, although potentially far more damaging, are inundation events associated with typhoons and tropical storms, with the most recent in 1997. Inundation along the sheltered lagoon-facing shoreline of Majuro has occurred in the absence of waves due to the coincidence of high sea levels during La Niña conditions and seasonally high tides, as in 2011. Lagoon inundation also appears to have been caused by offshore swell penetrating into the lagoon, most effectively at high tide, and by locally generated wind waves within the lagoon. The classes of inundation identified in this study have unique drivers and the impacts have varying spatial and temporal characteristics in terms of impact and predictability. The inundation events are discussed with respect to the drivers of inundation and the future outlook under rising sea-level conditions.

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1 Introduction

Atoll Islands are coral reef-associated landforms found throughout the tropical and subtropical oceans. Atoll Islands are low-lying, largely unconsolidated deposits typically found perched on the narrow reef flats which often enclose a marine lagoon. On a geological timescale the islands formed recently, with most islands deposited 5000–2000 years ago (Woodroffe and Morrison 2001; Kench et al. 2014). Despite the relatively recent formation of atoll islands, many islands have been inhabited for over a 1000 years (Weisler 2001; Kayanne et al. 2011) and today are occupied by an estimated 700,000 people (Yamano et al. 2007). Atoll Islands are considered highly vulnerable to a range of climate-driven hazards, many of which are projected to be magnified by continued climate change (Barnett and Adger 2003; Leatherman 1997; Mimura 1999; Roy and Connell 1991). Of the suite of climate change threats, continued sea-level rise (SLR) is widely expected to pose the greatest impact on atoll islands (Barnett and Adger 2003). Sea-level rise is predicted to destabilise atoll islands, leaving them at risk of chronic coastal erosion (Dickinson 2009). Likewise, SLR is expected to increase the frequency and severity of inundation, impacting groundwater availability and a range of ecological and anthropogenic systems (Yamano et al. 2007; Terry and Chui 2012; Merrifield et al. 2014). Within a number of Pacific (Marshall Islands, Kiribati and Tuvalu) and Indian Ocean nations (Maldives), atoll islands provide the majority of inhabited land. Urban atolls are characterised by limited land area and high population densities, which combine with exposure to existing climate-driven hazards to create high levels of vulnerability.

Atoll Islands are low-lying, with much of the land area < 3 m above mean sea level (MSL) (Woodroffe 2008). The highest elevation sections of atoll islands are typically found on the ocean side of the island and are associated with shore-parallel ridges comprised of coarse material derived from the adjacent reef. Landward of the berm the elevation lowers, often into a depression in the centre of the island (Owen et al. 2016). The lagoon shoreline is often characterised by a low elevation berm, although this feature is not as ubiquitous nor as pronounced as the oceanside ridge (Woodroffe 2008; Owen et al. 2016).

Atoll Islands are vulnerable to a range of inundation hazards generated by atmospheric and oceanographic processes, including typhoons and tropical storms (Blumenstock 1958), and far-field generated swell (Hoeke et al. 2013). Tsunamis pose a separate inundation threat for atoll islands (Kench et al. 2006a) that we do not consider in this study. A number of empirical and modelling studies have examined the inundation of ocean-facing island sections as a result of wave-driven processes (Merrifield et al. 2014; Quataert et al. 2015) and still-water inundation using 'bathtub' modelling approaches (Yamano et al. 2007; Owen et al. 2016). We could find no previous studies where the different modes, drivers and impacts of inundation along both ocean- and lagoon-facing sections of atoll islands have been examined. Using observations from tide gauges and meteorological stations along with outputs of numerical wave model and archival material from newspapers, government reports and scientific studies, we explore the drivers and impacts of recent inundation of Majuro Atoll, in the Republic of the Marshall Islands. The study highlights at least five different drivers for reported inundation events at Majuro, which may impact both ocean-facing and lagoon shorelines. We present case studies that highlight each of these risks.

2 Setting

The Republic of the Marshall Islands consists of two largely parallel island chains containing 29 atolls and five mid-ocean reef islands. The islands extend from 4°34′N latitude in the south and 14°43′N latitude in the north (Fig. 1). Majuro Atoll is situated at 7°06′N and 171°12′E and is elongated in shape with maximum dimensions of approximately 40 km by 10 km (Fig. 1). Majuro is the economic and political centre of the Marshall Islands with 27,797 residents, comprising approximately 52% of the national population (Economic Policy, Planning and Statistics Office 2012). Within Majuro, the population is largely concentrated within the Delap-Uliga-Djarrit (D.U.D.) urban area with 15,846 residents, equating to a population density of 8506 people per km^2. Within Majuro, traditional approaches to both the planning and construction of housing have been largely replaced by modern western building techniques as the D.U.D. area developed (Spennemann 1996).

Much of the natural topographic relief of the urbanised sections of Majuro atoll has been greatly altered by anthropogenic development. Historically, the area contained a number of smaller islands which have subsequently been connected by causeways and land reclamation. The total land area of the D.U.D. area has increased significantly over the past 40 years as a result of development within the coastal zone (Ford 2011). The majority of the urban shoreline, both ocean- and lagoon-facing, has been armoured using a variety of engineering structures (Maragos 1993) and the surrounding reef impacted by pollution (Osawa et al. 2010) and mining (Ford et al. 2012). Atoll Islands are dynamic landforms, which have been shown to adjust to elevated water levels by changing planform configuration (i.e. island shape, size and position) and increasing elevation of island margins (Kench and Cowell 2001; Webb and Kench 2010). However, unlike the shorelines of unmodified reef islands, the hardened shoreline of Majuro is geomorphically inert, unable to dynamically adjust to changing boundary conditions. Despite the high level of anthropogenic modification, the island is still characterised by higher elevations on the ocean side of the island dipping towards the lagoon coast.

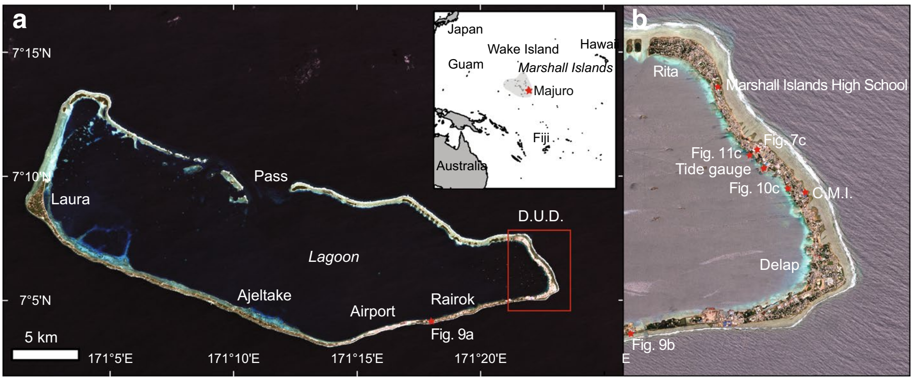

Fig. 1 **a** Majuro Atoll within the Marshall Islands, **b** D.U.D. area of Majuro Atoll

2.1 Regional sea level

The tidal regime of Majuro is semi-diurnal, with pronounced diurnal inequalities and a spring tide range of approximately 1.6 m. The highest annual tides typically occur between January and March and are commonly referred to as 'king tides'. Majuro has a lengthy and largely complete sea-level record collected since 1968. The record is a function of two separate series collected by the University of Hawaii Sea Level Center (UHSLC) between October 1968 and December 1999 and by the Australian National Tidal Facility from June 1993 until present (Fig. 2a). The combined tide gauge record has a sea-level rise rate of 3.3 ± 0.6 mm year^{-1} (two standard deviations) between October 1968 and December 2015, similar to the global sea-level rise rate from satellite altimetry since 1994 (3.4 ± 0.4 mm year^{-1}, http://www.sealevel.colorado.edu), and higher than the previous Majuro tide gauge estimate of 2.8 mm year^{-1} between October 1968 and December 2001 (Church et al. 2006). The El Niño Southern Oscillation (ENSO) has a significant control on interannual sea-level fluctuations in the region, with the Marshall Islands experiencing low sea-level anomalies during the El Niño phase of ENSO and high anomalies during the La Niña phase (e.g. Chowdhury et al. 2007).

2.2 Typhoons and swell waves

The Marshall Islands are east of the most active concentration of typhoons within the western tropical Pacific, which is located between the Philippines and Guam (Camargo et al. 2007). Despite the relatively low frequency of tropical storm and typhoon activity in the Marshall Islands, a number of catastrophic typhoons have been documented in Majuro and surrounding atolls (Blumenstock 1958; Spennemann and Marschner 1995; Wells 1951). During El Niño conditions, westerly wind bursts and typhoon generation typically occur farther south-east in the western tropical Pacific than normal (Camargo and Sobel 2004), potentially increasing storm impacts at the Marshall Islands during this phase of ENSO.

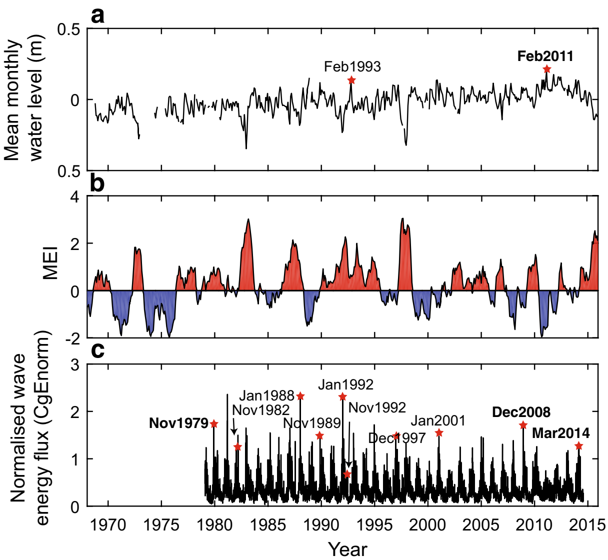

Fig. 2 **a** Mean monthly sea level at Majuro, **b** multivariate ENSO index, **c** normalised wave energy flux (CgE$_{norm}$). Stars indicate inundation events outlined in Table 1

The Marshall Islands are exposed to ocean swell generated remotely in the south and north Pacific during the respective winter seasons (Genz et al. 2009). Wave heights are generally greatest in the north and east of the RMI. At Majuro, waves are generally from the northeast quadrant and average 1.6 m (Bosserelle et al. 2015).

The shallow reefs surrounding the islands provide considerable protection from wave-driven inundation by attenuating incident swell wave energy. The reefs tend to be exposed at low tide and submerged at high tide. The bulk of incident swell energy attenuates at the reef edge due to wave breaking, with additional turbulent bore and bottom friction dissipation occurring on the reef flat (Lugo-Fernández et al. 1998). Waves that reach the shore are comprised of small swell waves below a depth-limited breaking parameter, reformed waves and long-period infragravity (IG) waves. In addition, wave-driven setup causes water levels over the reef to rise by ~ 0.2 times the breaking wave height (Becker et al. 2014). The depth-limited swell and reformed waves, the IG waves and the wave setup all contribute to wave-driven inundation in Majuro (Ford et al. 2012; Merrifield et al. 2014).

3 Data sources and methodology

In order to generate a chronology of inundation events at Majuro, we adopted a mixed-methods approach to identify and verify periods of inundation between February 1979 and October 2015. Our approach incorporated field observations made by the lead author during three inundation events (February 2011, June 2011 and June 2013), the analysis of observed and modelled oceanographic and meteorological conditions and through content analysis of academic literature, government documents and popular media publications related to inundation events.

3.1 Physical data sets

The physical data sets examined here include sea level from tide gauges, and wave data were obtained from wave model hindcasts. The two tide gauges in the lagoons of Majuro and Kwajalein atolls provide the only long-term records of ocean conditions in the Marshall Islands. Both tide gauges are largely sheltered from oceanic waves. The Majuro tide gauge record provides a near-continuous record of sea level at Uliga dock on the east side of the lagoon (Fig. 2a). Data are available at hourly intervals since 1968 and more recently at 6-min and 1-min intervals. Surface winds are obtained from the Australian Bureau of Meteorology (BOM) weather station collocated with the Majuro tide gauge.

To characterise ocean waves, we use a wave model hindcast (1979–2010) of global conditions at 0.4° resolution generated using WAVEWATCH III™ (WW3), forced by the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) wind data set (Durrant et al. 2013). The hindcast has since been extended until June 2014. To provide a measure of the relative energetics of offshore wave conditions, Hoeke et al. (2013) normalised wave energy flux by the 99th percentile of the 1979–2010 wave energy flux record from the WW3 hindcast (CgE_{norm}). We calculate CgE_{norm} from the hindcast time series at two locations, one north (7.6N, 171.6E) of the atoll and one to the south (6.4N, 170.8E) (Fig. 2c). Given the quality of the CFSR winds used to force the WW3 wave model, it is likely that wave conditions during energetic storms are underestimated (Cox et al. 2011).

3.2 Descriptions of inundation within secondary sources

Newspaper and popular media reports from a two-week period after possible inundation events were inspected for inundation reports. We searched for secondary material describing inundation for the 20 most energetic events within the CgE_{norm} record and 20 highest hourly water-level events from the tide gauge record. For the 1979 event the Pacific Daily News, published in Guam, provided the most complete coverage of the event. For all other events, the Marshall Islands Journal, a weekly newspaper published on Majuro, was the primary source. Additional published material related to the inundation of Majuro was located using a variety of sources, including: a list of FEMA disaster declarations and keyword searches within ProQuest, Google Scholar and Google web search using the terms *Majuro flooding* and *Majuro inundation*. Where reports of inundation were found through these searches, physical data from the reported time of the event were extracted from wave and tide records. Once published materials were identified for a particular event, a content analysis was undertaken of these secondary source materials. The content analysis involved searching within published material for descriptions of the events, including identifying areas most impacted, the degree of impact and any references to prior inundation events.

Our chronology spans a 36-year period across which there has been increasing academic interest and popular media coverage of climate change issues in Marshall Islands. As such, it is likely our chronology is unavoidably biased towards coverage of recent events. It is likely that a number of minor inundation events, the likes of which receive media coverage today, would have received scant attention in the 1970s and 1980s. As a result, the chronology is not intended to provide a faithful time series of all inundation events which would be necessary to isolate temporal trends with respect to frequency and magnitude of inundation. However, despite the potential for a recent bias within the chronology, the ability to ground-truth physical data sets which are either coarse resolution (i.e. the WW3 wave model) or point measurements within sheltered settings (i.e. tide gauge records) improves the utility of the chronology and provides a local context to meteorological and oceanographic data sets.

We developed and applied an integrated approach to classifying inundation events based on the areas of impact and characteristics of the processes driving inundation. Firstly, events are divided into those which impact lagoon- or ocean-facing shorelines based on descriptions contained within secondary sources. We further classify events impacting ocean-facing sections into three classes based on the area of wave generation identified from WW3 and records of tropical storms, being, (1) north Pacific (IA), (2) south Pacific (IB) and (3) tropical storms and typhoons (II). Impacts from far-field swell events (IA and IB) can be largely attributed to swell generated either in the north or in the south Pacific, whereas the impacts from tropical storms and typhoons are a function of local-generated swell, barometric setup, storm surge and strong local winds.

Inundation events impacting the lagoon are classified into three classes, being (1) still water (III), (2) swell penetration into the lagoon (IV) and (3) locally forced waves (V). Still-water events are classified based on tide gauge records, observations and published reports which all reveal extreme high water levels and little indication of wave forcing. Swell penetration events are characterised based on extreme high water levels comprised of tidal components as well as long-period (> 12 s) surges, which appear to be generated outside of the lagoon and propagate into the lagoon over the northern fringing reefs. Locally forced waves (V) are classified based on meteorological observations, reports and photographs during the 2015 event which suggested waves were short period (< 10 s) and generated within the lagoon by bursts of wind from the west.

4 Historic inundation of Majuro

We have detected more than eighteen unique inundation events between 1979 and October 2015, three of which occurred between July 2014 and October 2015, beyond the wave hindcast record (Table 1). In some cases (i.e. November 1979 and December 2008), inundation occurred, followed by another period of inundation several days later. We consider these sequential occurrences of inundation as single events. In addition, between July and October 2015 there were a number of periods of inundation associated with a prolonged anomalous westerly winds. Here too, we consider these sequential inundation events as a single event, despite intermittent calm periods. Six of the eighteen events are associated with tropical storms (TS) or typhoons. Most reports of damage from inundation events are associated with the D.U.D. area of Majuro, which is the most densely populated section of the atoll. The concentration of reports within the D.U.D. area is likely a function of both the exposure of this section of the atoll to swell out of the north-east quarter as well as the higher levels of development. Four events (June 1994, June 2011, June 2013 and October 2014) have reports of inundation along the southern rim of the atoll, with three of these events overwashing the airport (June 1994, June 2013 and October 2014). Six events have reports and documentation of inundation along the lagoon-facing shorelines, areas which are generally sheltered from the full effect of ocean waves. We further examine six inundation events which we classify by their drivers and inundation outcomes.

We present physical data in time periods that overlap with the observed inundation events described above. Average and maximum wind speed in the 7 days prior to inundation are provided in Figs. 3 and 4 and provide an indication of the likely location of the generation of remote offshore waves. Similarly, Fig. 5 presents the maximum CgE_{norm} 7 days before and after reported inundation. The CgE_{norm} record is extended beyond the reported date of inundation to account for the possibility that the inundation reports might not necessarily be coincident with the most energetic conditions during the event and as some secondary reports of inundation have unclear timing.

4.1 Inundation Classes I and II: inundation due to storms at ocean-facing island sections

A well-known driver of inundation for low-lying islands and atolls is typhoons, tropical storms (e.g. Blumenstock et al. 1961; Spennemann 1996) and remotely generated swell waves (e.g. Hoeke et al. 2013; Merrifield et al. 2014). Wave-driven inundation in Majuro exhibits different characteristics based upon whether the storm waves originate in the north Pacific (Class IA) or south Pacific (Class IB). Half of the 18 distinct inundation events catalogued here fall into Class IA (5) or Class IB (4). Inundation due to typhoons and tropical storms (Class II) has been well documented in the literature and account for an additional three inundation events of those catalogued here.

Table 1 Chronology of inundation events at Majuro Atoll between 1979 and 2015

Start date	Class	Description	Max water level (m)	Hs (m)	CgE_{norm}	References
11/25/1979	IA	Waves overwashed island causing significant damage in the D.U.D. area. Est. $26 m damage at Majuro	0.91	3.56	1.65	Spennemann (1996), Ginoza (1979a), Ginoza (1979b)
11/25/1982	II (Typhoon Pamela)	Damage to buildings and crops in Majuro. Unclear of wind versus wave damage	0.66	3.84	1.33	Typhoon Pamela headed for Lae (1982)
01/08/1988	II (TS Roy)	Damage to some buildings, high surf, ship broke free of mooring in Majuro lagoon	N/A	4.99	2.32	FEMA declaration DR809, Wright (2006), Storm slams Ebeye (1988)
11/17/1989	IA	Wave damage to building at Marshall Islands High School (Oceanside, Rita, D.U.D.)	1.19	3.59	1.50	Surf pounds MIHS (1989)
01/07/1992	II (TS Axel)	Strong winds, overwash in D.U.D. area and Long Island area. Rubble deposited on airport runway	0.71	5.18	2.28	FEMA declaration DR932, Typhoon batters Majuro (1992), Spennemann (1996)
11/17/1992	II Typhoon (Gay)	Strong winds, large waves in Majuro lagoon, boats broke free of moorings	0.91	3.05	0.82	Night in the storm: Much more than they bargained for (1992)
02/07/1993	III or IV	Reports of flooding along lagoon shoreline Majuro, some in D.U.D., flooding at the airport	1.10	3.10	0.93	Record tide of 6.6 ft. (1993)
06/08/1994	IB	Impacts along southern rim of Majuro. > 100 houses damaged or destroyed, debris on to airport.	0.71	2.71*	1.07*	FEMA declaration DR1040, Johnson (1994)
12/10/1997	II (Typhoon Paka)	Est. $1 m damage at Majuro	0.54	4.11	1.34	Kabua (1997)
01/13/2001	IA	Roads covered in debris, plants killed, shops boarded up. 'Worst flooding since the early 1990s'	1.03	3.76	1.48	Peter et al. (2002), Vander Velde (2003)
12/08/2008	IA	Considerable overwash and inundation of ocean-facing sections of the D.U.D. area	1.06	3.50	1.70	Hoeke et al. (2013), Vainerere (2008)
02/18/2011	III	Minor flooding of low-lying lagoon-facing sections	1.34	1.98	0.38	High tide hits (2011)
06/29/2011	IB	Minor overwash of southern section of Majuro	0.96	1.85*	0.53*	Ford et al., (2012)

Table 1 (continued)

Start date	Class	Description	Max water level (m)	Hs (m)	CgE_{norm}	References
06/24/2013	IB	Overwash of southern section of Majuro, airport wall damaged, debris on runway	1.01	1.95*	0.51*	Pope (2013), Johnson (2013)
03/02/2014	IA and IV	Inundation of lagoon- and ocean-facing sections of D.U.D.	1.16	3.17	1.26	Tidal flooding in Marshall Islands has caused widespread damage, (2014), Lewis (2015), OCHA (2014)
10/08/2014	IB	Inundation of southern rim, including the airport	1.06	N/A	N/A	Southern edge of Majuro inundated with water (2014)
01/21/2015	IV	Inundation of lagoon shoreline, in D.U.D. and near airport	1.09	N/A	N/A	Johnson (2015)
July–October 2015	V	Short-period waves in the lagoon, causing boats to break free of moorings, destruction of coastal structures and inundation along lagoon shoreline. Occurred several times over ~ 4 months	N/A	N/A	N/A	Storm Damage (2015), Tony's house hit by savage storms (2015), Chunks fall off Majuro (2015)

TS tropical storm

Wave parameters from WW3 hindcast are extracted from 7.6N, 171.6E, except for southerly swell events, marked by *, which are extracted from 6.4N, 170.8E. No WW3 data are available beyond July 2014

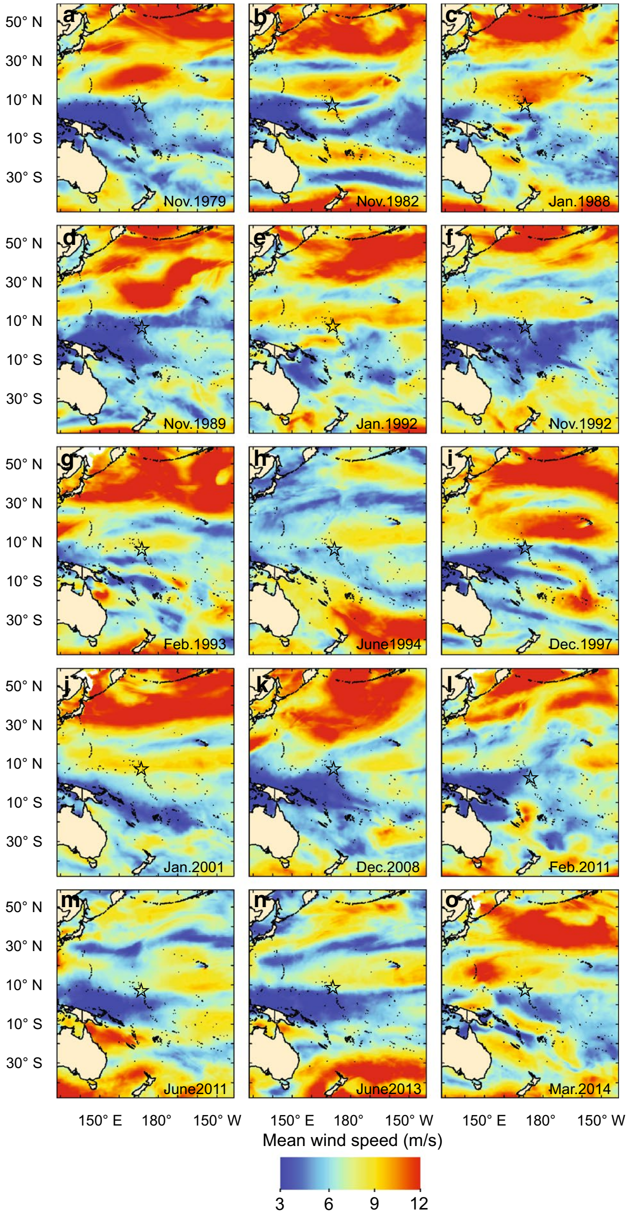

Fig. 3 Mean wind speed during the 7 days prior to inundation events. Data sourced from Durrant et al. (2013) who utilised the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) wind data set

4.1.1 November 1979: Class IA

In late November and early December of 1979, waves overwashed and inundated large sections of Majuro. The first inundation occurred between 9 and 10 am local time on 26

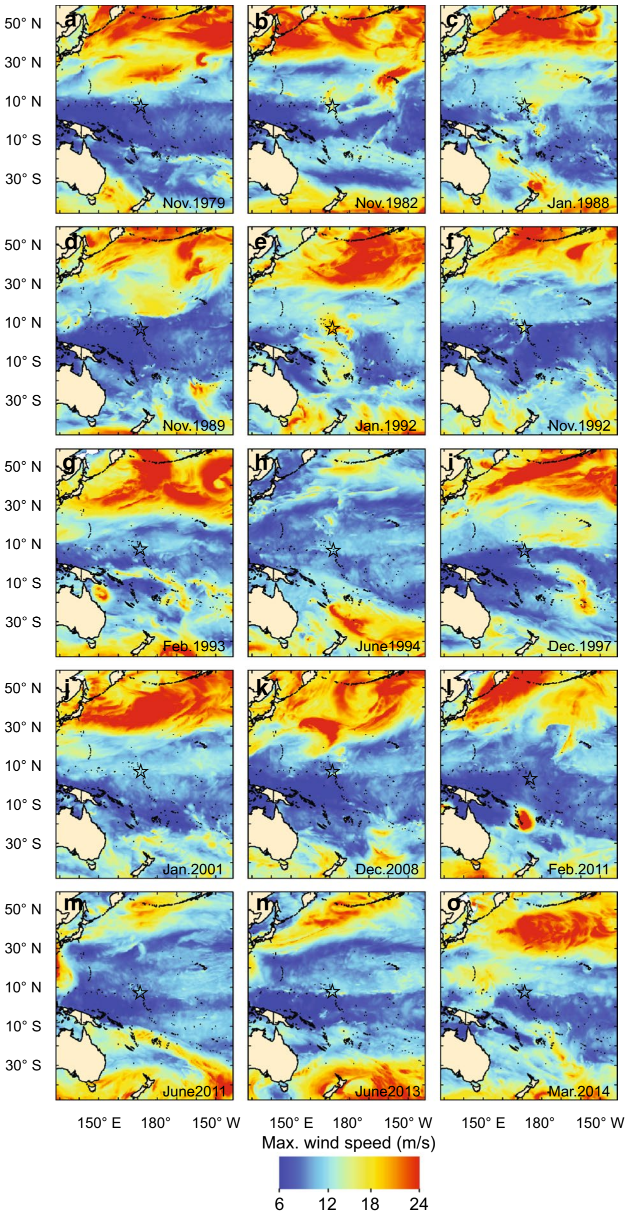

Fig. 4 Maximum wind speed during the 7 days prior to inundation events. Data sourced from Durrant et al. (2013) who utilised the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) wind data set

November 1979 and was followed by subsequent inundation that evening and the following 2 days (Fig. 6) (Ginoza 1979a). Local government reports indicated waves were between 15 and 20 ft. and resulted in 10 ft. waves overwashing the island and inundating 80% of the D.U.D. area (Padden 1979; Ginoza 1979a) (Fig. 7). Winds in Majuro were relatively light

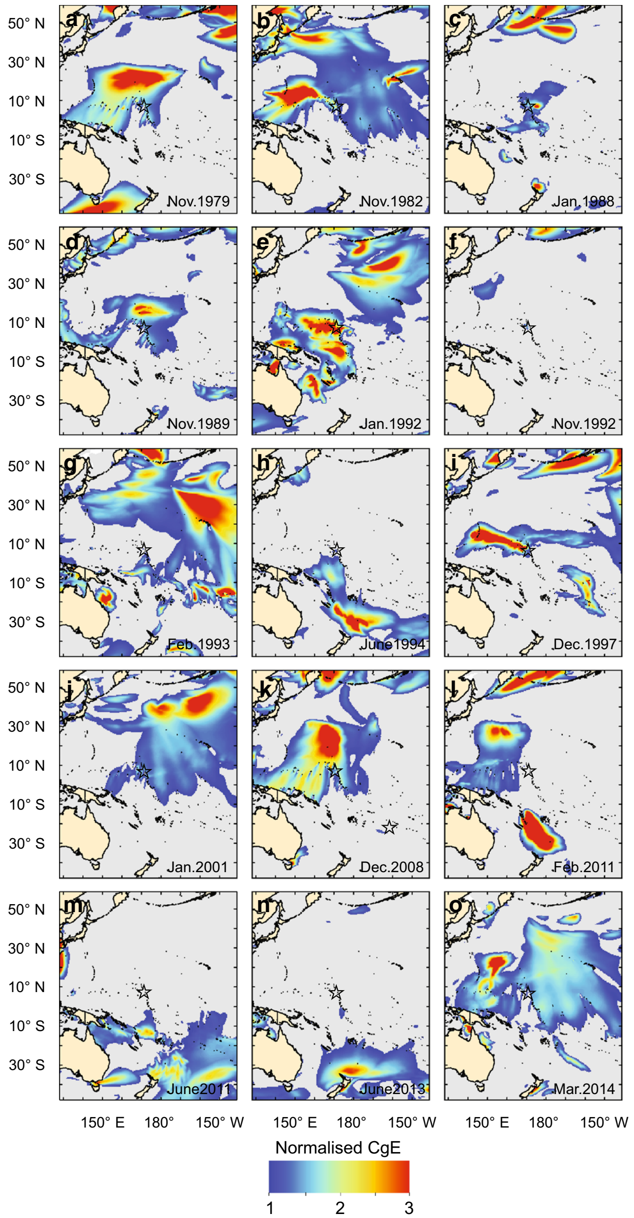

Fig. 5 Wave energy flux normalised by the 99th percentile of wave energy flux (CgE_{norm}). Data sourced from Durrant et al. (2013). *Note* Only areas with $CgE_{norm} > 1$ area shown for clarity

during the event, not exceeding 5 ms^{-1} prior to or during the inundation (Fig. 6). Strong winds to the north of the Marshall Islands were responsible for the generation of large waves which propagated south and drove the inundation (Fig. 5). During the first inundation, the maximum significant wave height was 3.56 m, with a peak period of 15 s and CgE_{norm} of 1.65 (Fig. 6).

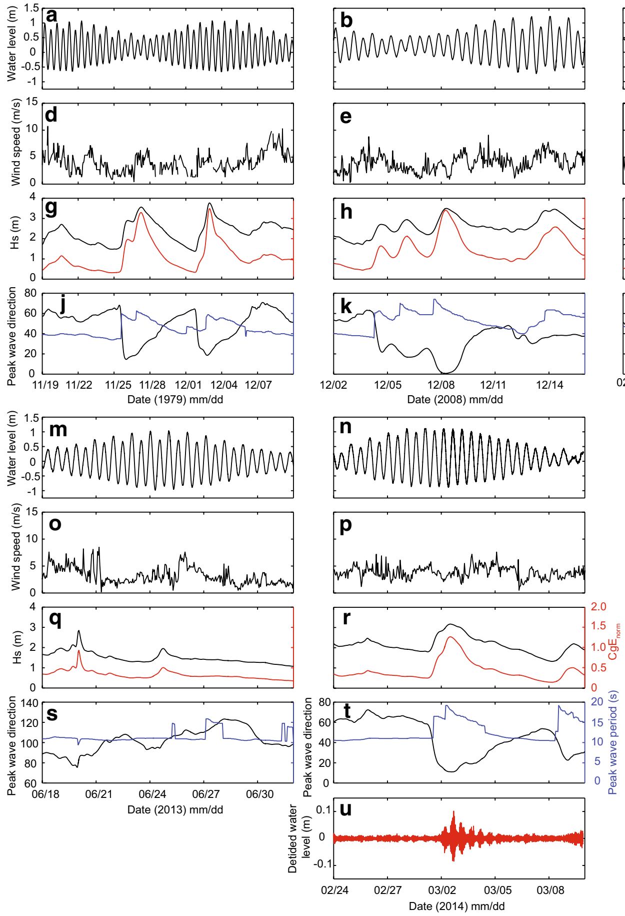

Fig. 6 Sea-level, wind and wave conditions during the November 1979, December 2008, February 2011, June 2013 and March 2014 inundation events. Water-level measurements are from the University of Hawaii Sea Level Center. Surface winds between 2008 and 2014 are provided by the Australian Bureau of Meteorology station at the tide gauge, 1979 observations are from the National Weather Service at Majuro airport. Wave parameters from WW3 hindcast (Durrant et al. 2013) are extracted from 7.6N, 171.6E, except for the June 2013 southerly swell event which are extracted from 6.4N, 170.8E

Within the lagoon, the maximum water level during the time of the first inundation was less than 0.65 m above MSL, ~ 0.5 m below typical spring tide levels (Fig. 6a). In early December 1979, additional wave-driven inundation was reported in the D.U.D. area of Majuro (Hoversten 1979). Wave conditions during the second inundation were similar to the first inundation (Fig. 6); however, the second inundation occurred during higher tidal conditions, ~ 1.0 m above MSL. The November 1979 event was one of the most financially costly natural disasters of modern times in the RMI, causing damages estimated in 1979 currency to be over $26 million (Ginoza 1979b). The densely populated D.U.D. area on the eastern side of the atoll was most severely impacted, with widespread damage to infrastructure and utilities reported (Padden 1979) (Fig. 7). An estimated 5000 people were relocated to Rairok on the southern section of the atoll and housed in temporary accommodation (Spennemann 1996).

4.1.2 December 2008: Class IA

In early December 2008, a low-pressure system which initially developed at approximately 25°N and 144°E tracked east-north-east across the Pacific (Ward 2009). The depression travelled south-west, midway between Wake Island and Utrik Atoll, ~ 950 km north-north-west of Majuro and tracked west where it was eventually upgraded to typhoon status (Ward 2009). Hoeke et al. 2013 provide a detailed reconstruction of the meteorological and oceanographic drivers of the December 2008 event. Strong winds associated with the depression generated large, long-period swell waves which propagated southward and were responsible for the inundation of numerous islands within the western Pacific region (Hoeke et al. 2013) (Figs. 6, 8). Within Majuro, the primary inundation occurred on 09 December 2008, coinciding with the afternoon high tide (0.68 m), with further inundation reported on 15 December 2008 (Vainerere 2008). Offshore waves were 3.50 m in height with a peak period of 16 s and CgE_{norm} of 1.70 during the first inundation (Fig. 6). Impacts were most acute along the ocean-facing shoreline of the D.U.D. area; where despite no reported casualties, over 300 people were displaced as a result of damage to housing and coastal defences (Majuro flooded for third time in one week 2008).

4.1.3 June 2013 event: Class IB

In late June 2013, southern sections of Majuro Atoll were overwashed and inundated by waves. In places waves were observed to have propagated across the entire island, ultimately passing into the lagoon. No warnings of likely inundation were issued in Majuro prior to the first inundation; however, islands in the south Pacific as far north as Tuvalu (8°S and 179°E) were advised of potential high surf conditions. (Damaging waves expected in the Pacific this weekend 2013.) Swell waves were generated by storm activity several days earlier in the Tasman Sea between New Zealand and Australia (Figs. 3n, 4n, 5n) (June 2013 New Zealand Storm 2013). The first inundation occurred in the early hours of the morning local time starting approximately 1 h before the highest tide of the month (24 June 2013) (Fig. 6). At the time of inundation, Majuro was experiencing spring tides, with levels up to 1.01 m above MSL (Fig. 6). These levels, while relatively high, were not unusual, with predicted tidal levels 6 cm higher in January 2013. Wave model outputs indicate the inundation occurred at the coincidence of spring high tide and the arrival of swell waves, which were not particularly large (1.94 m). Observations along the southern rim of the atoll indicate groups of larger waves appeared responsible for periods of inundation and arrived every 10–15 min.

Minor damage was reported to houses along the southern rim of the atoll from Delap to Ajeltake. Large quantities of organic and inorganic debris were deposited on the island and made the road impassable in places for several hours (Fig. 9). In several places, small coral boulders (~ 50 cm diameter) were deposited on the island some distance from the shoreline (Fig. 9). The most disruptive impacts of the wave inundation were to the airport, where waves overtopped a revetment and toppled a vertical wall (Fig. 9). As a result, waves washed on to the runway through the breach in the wall, reaching the centreline of the tarmac. Large quantities of sand and gravel were deposited on the tarmac and runway flanks. Airport operations were suspended for several hours until the runway was cleared. During

Fig. 7 **a**–**c** Impacts of the 1979 inundation event within the D.U.D. area of Majuro. **d** Temporary accommodation on the southern rim of Majuro to house displaced residents. Photographs **a**–**c** Courtesy of Dr. Dirk Spennemann, photograph **d** Trust Territory of the Pacific archives, Hamilton Library, University of Hawai'i

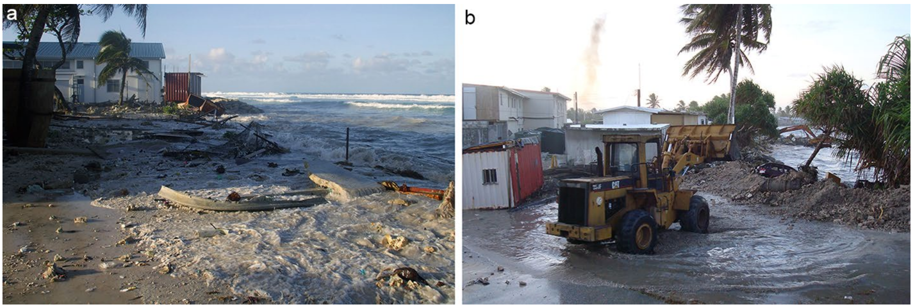

Fig. 8 **a** and **b** Impacts of wave inundation along the north-east shoreline of the D.U.D. area during the December 2008 event. Photographs courtesy of the Marshall Islands Journal

the considerably lower evening high tide, waves were again observed breaching coastal defences at the airport necessitating further clean-up of the runway.

4.2 Inundation Classes III, IV and V: lagoon inundation

Despite typically being a lower energy environment than the open ocean, a number of factors have been shown to elevate water levels within atoll lagoons increasing inundation

Fig. 9 Impacts of the 25 June 2013 wave-driven inundation event: **a** ponded water and mix of organic and inorganic debris deposits on southern Majuro, **b** sand, gravel and coral boulders deposited on sections of southern Majuro, **c**–**f** damages to coastal protections and subsequent inundation and debris deposition at Majuro International Airport

risk, including tsunami (Ford et al. 2013), elevated sea levels due to ENSO variability (Chowdhury et al. 2007), swell waves infiltrating the lagoon (Aucan et al. 2012) and locally generated waves (Kench et al. 2006b). The lagoon shoreline within urbanised sections of Majuro has been engineered to reflect the lower energy setting, with less robust structures used for armouring than along the ocean-facing shoreline (Fig. 10). A number of historic inundation events have involved lagoon-driven processes, whether exclusively inundating lagoon-facing sections (i.e. February 2011) or coincident with overwash and inundation of ocean-facing sections of the island (i.e. March 2014).

4.2.1 February 2011 event: Class III: still-water inundation

As a result of La Niña conditions during February 2011, mean monthly sea level was at record levels at the Majuro tide gauge (Fig. 2a). The maximum recorded hourly water level at Majuro during spring high tide was 1.35 m above MSL, occurring on 18 February 2011 (Fig. 6c). Surface winds during the February spring tide period were relatively light, averaging 3.8 ms^{-1}. Offshore wave heights were < 2 m and CgE_{norm} was < 0.5 indicating conditions outside of the lagoon were relatively calm. No in situ or modelled data on wave conditions within the lagoon are available; however, visual observations indicate the lagoon was calm, with low wave heights (Fig. 10). During the event, local residents were observed deploying sandbags along lagoon front property, while seawater entered the storm water network and flooded land some distance from the lagoon. In numerous places, the road flooded for approximately 1 h either side of high tide. Observations made between the D.U.D. area and the airport indicate that water levels in excess of ~ 1.25 m tended to inundate the more low-lying sections of the island along the lagoon coast.

4.2.2 March 2014 event: Class IV: swell penetrating into the lagoon (see also Class IA)

In early March 2014, large areas of D.U.D. were inundated with approximately 940 people evacuated to shelters in local schools and churches (Johnson 2014). Overwash and inundation were also reported at Kwajalein Atoll, ~ 500 km west-north-west of Majuro (Cheriton et al. 2016). Reports and photographs from the event indicate that inundation was driven by overtopping of both lagoon- and ocean-facing shorelines. Winds were relatively light at Majuro during the event averaging 3.9 ms^{-1}. Offshore wave heights peaked at 3.17 m, with

Fig. 10 Threatened, low-lying housing and infrastructure along the Majuro lagoon shoreline during the February 2011 still-water inundation. Photographs **a**–**c** are within the D.U.D. area, photograph **d** is the road running East–West along the airport boundary. Photographs **a**–**c** courtesy of Nick Wardrop, photograph **d** authors own

a maximum CgE_{norm} of 1.26. Inundation was a result of the coincidence of large, long-period swell from the north which peaked during the monthly spring tide which reached 1.16 m above MSL. Interestingly, photographs and video footage during the event show low amplitude surge within the lagoon (Fig. 11). Given winds were light and from the east it is unlikely that the surges along the lagoon shoreline of the D.U.D. area were generated within the lagoon. Water levels sampled at the tide gauge every 1 min show a marked oscillation that is tidally modulated, with the height greatest at high tide and largely absent at low tide (Fig. 6u). Due to the 1-min sampling, it is not possible to fully establish the size of the waves and mechanism producing the waves; however, the tidal modulation of the surge suggests the energy source is offshore swell waves that propagate into the lagoon through a deep channel as well as shallow passages between islands on the north rim of the atoll. More energy would enter over the shallow passages at high tide, likely explaining the higher observed energy levels in the lagoon during high tide.

4.2.3 July–October 2015 event: Class V: locally forced waves in the lagoon

The 2015/2016 El Niño was among the strongest on recorded (Fig. 2b). Sea level at Majuro fell to the lowest level recorded since December 1997 (Fig. 2a). Despite the low sea level, there were a series of inundation events documented between July and October of 2015, with some causing significant damage along the lagoon shoreline (Johnson 2015). The lagoon-facing shoreline is almost entirely armoured, with development extending to the shoreline, which in some areas involves reclaimed land in the lagoon. During the 2015 El Niño, strong westerly wind events occurred that caused considerable damage to wharves,

Fig. 11 **a** Wave impacts of March 2014 event along lagoon shoreline, **b** ponded water at northern end of Rita during March 2014 event. **c** and **d** Waves impacting structures along the lagoon shoreline of Majuro during July–October 2015 westerly wind event. Photographs courtesy of Tamara Greenstone Alefaio and Giff Johnson

houses and coastal protections (Figs. 11, 12). Winds in Majuro are predominantly from the north-east (Fig. 12). However, between June and October 2015 there was a prolonged period of strong westerly winds that contributed to the build-up of the El Niño event. The lagoon-facing shoreline of the D.U.D. area has a fetch which extends up to ~ 37 km, with water depths generally > 40 m. The period of persistent strong westerlies blowing across a wide and deep fetch generated relatively large waves for what is typically a sheltered section of the lagoon. No measurements of the waves were taken, although eyewitness accounts report the waves were > 2 m in height (Johnson 2015).

5 Discussion

5.1 Inundation drivers

By generating a 36-year chronology of inundation reports, we have identified five different classes of inundation events which have impacted Majuro Atoll. These include (I) wave-driven inundation from swell generated in both the north (IA) and south (IB) Pacific Ocean, (II) storm surge and wave-driven inundation from tropical storms and typhoons and the less well-studied inundation of lagoon-facing coastal areas driven by: (III) elevated water levels during the La Niña phase of ENSO, (IV) infiltration of externally generated swell into the lagoon and (V) waves generated within the lagoon by strong local winds. The different styles of inundation have unique characteristics in terms of the drivers and spatio-temporal extent of impact. Hazard mitigation plans need to be cognisant of these different styles of inundation and tailor mitigation and adaptation plans accordingly. The classes of inundation identified at Majuro are broadly applicable to other mid-ocean atolls. However, due to spatial variations in island morphology, wave climate and atmospheric processes, the relative susceptibility of atolls to the different classes of inundation is unlikely to be homogenous.

Majuro is towards the southern and eastern limit of typhoon impact in the western tropical Pacific, particularly when compared with western Micronesia (Camargo et al. 2007).

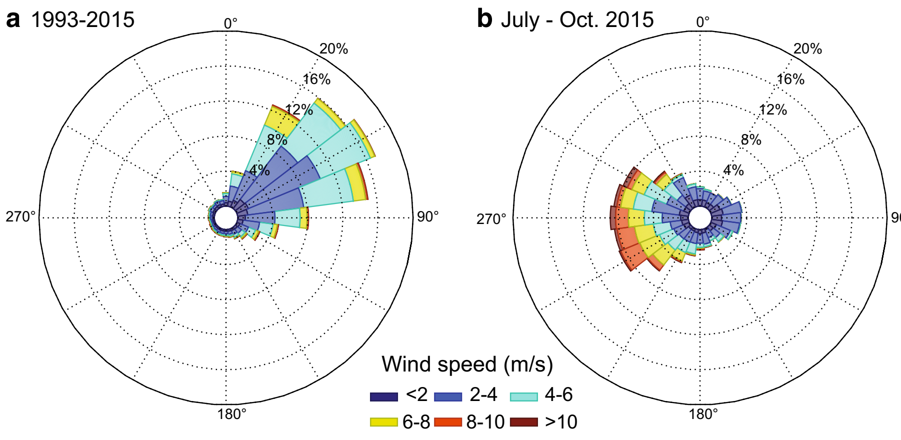

Fig. 12 Wind rose from **a** 1993 to 2015 and **b** during the July–October 2015 westerly wind event. Data obtained from the Australian Bureau of Meteorology station located on Uliga dock alongside the tide gauge

However, despite the relatively low number of tropical storm and typhoon occurrences, a number have impacted Majuro directly since 1979 along both lagoon- and ocean-facing shorelines. TS and typhoons pose the greatest potential flooding threat to Majuro due to the combined effects of wind and atmospheric pressure-driven surges and storm-driven wave overwash. However, none of the recent TS and typhoon events have had the catastrophic effects of earlier twentieth-century typhoons impacting Majuro and other atolls in the southern RMI. Typhoons in 1905, 1918 and 1958 caused considerable loss of life in the southern RMI and reportedly washed large sections of islands off the reef platform (Blumenstock 1958; Spennemann 1996). Mitigation plans and responses to storms are particularly challenging as the degree of impact is tied to the storm strength and track, with subtle changes in either changing the extent and degree of impact.

Far-field swell events are notably different from storm events in that they are not necessarily associated with strong local winds. Observations during the November 1979, December 2008 and March 2014 events indicate wind speeds were < 5.0 ms^{-1} in Majuro at the time of inundation. Likewise, a high tidal level is not a necessary prerequisite for inundation. The first inundation during the November 1979, December 2008 and June 2011 events all occurred when the high tide level was more than 0.5 m below present-day spring tide elevation. Rather, the swell waves generated by distant storms in the north Pacific were responsible for elevating water levels at the shoreline through the combination of wave setup, infragravity waves and depth-limited sea and swell waves (Merrifield et al. 2014). Unlike tropical storms, which have extreme and localised impacts, far-field swell events often drive inundation across a large swathe of the Pacific. For example, inundation from December 2008 swell event spanned much of the central Pacific from the Marshall Islands in the east to Papua New Guinea in the west (Hoeke et al. 2013).

North Pacific swell events have resulted in destructive and costly impacts to urban Majuro, particularly along the ocean-facing sections within the D.U.D. area. Similarly, waves generated in the south Pacific have inundated the southern rim of Majuro on at least three occasions (June 1994, June 2011 and June 2013). The southern rim of Majuro is less-densely populated than the D.U.D. area; however, critical infrastructure including the airport, power station and fish-processing factory are located along the southern rim. Wave heights during southerly events are generally lower than during north Pacific events due to distance from the source of generation in the southern Pacific Ocean and the and blocking of waves by a number of island groups in the South Pacific. Given that waves are generated several thousand of kilometres away from the Marshall Islands, global- and basin-scale wave models such as WW3 provide several days warning of incoming swell and analysis of past events provides a coarse-resolution forecast as to the areas of Majuro most likely to be impacted. Such tools are already operational for Majuro Atoll (PacIOOS 2016).

The impacts of a number of inundation events (i.e. February 2011, July–October 2015) were most acute along the lagoon coast in the D.U.D. area. Compared to the ocean-facing coast, the lagoon coast is a sheltered, low-energy setting. However, the land adjoining the lagoon is typically lower in elevation and poorly armoured relative to the ocean-facing coast. Lagoon-driven inundation has generally received considerably less attention than wave-driven inundation of ocean-facing island sections. We have identified at least three styles of lagoon-driven inundation which have impacted Majuro. First, high astronomical tides and high sea-level anomalies during La Niña conditions, overlying a long-term sea-level rise, led to elevated water levels during a February 2011 flooding event. This type of 'still-water' inundation lacks the instantaneous destructive impacts often associated with high energy wave events. Although wave swash onto the shoreline may be weak, still-water inundation may have significant impacts as events may be long-lasting, and saltwater intrusion into the built environment may impact fresh water supplies, vegetation and sewage systems. Ocean-facing shorelines are similarly exposed to the effects of still-water inundation. However, given the lower elevation along the lagoon-facing coast it is likely that still-water inundation will impact the lagoon-facing sections of the island long before the ocean-facing sections. The likely timing of such events can be forecast several months in advance using tidal predictions and sea-level anomalies from tide gauge or satellite altimetry records. Such a first-order estimate of extreme water levels can be used in simplistic 'bath tub'-type flood models, provided topographic data are available.

Lagoon flooding also appears to have occurred during high tides when northerly swell infiltrated the lagoon, likely through the channel and across the northern rim of the atoll. No high-frequency measurements of waves within swell frequencies exist; however, infragravity period oscillations that typically accompany swell events appear in the 1-min water levels measured at the tide gauge (Fig. 6). It would appear from descriptions of the March 2014 event that surges within the lagoon during the spring high tide contributed to inundation along lagoon-facing sections of the island (Fig. 11). Further high-frequency observations of water levels within lagoons are needed to better understand the processes of swell infiltration and to develop predictive tools. Lastly, westerly wind bursts associated with an El Niño event generated local waves that impacted what are normally sheltered lagoon shorelines along the D.U.D. area. Unlike the ocean-facing shoreline, the lagoon shoreline is not perched upon a fringing reef, rather the island slopes immediately into deep water. As a result, lagoon waves impacting the D.U.D. area are not depth-limited and can break directly on to the shore with minimal loss of energy in shallow water.

5.2 Future outlook

The different styles of inundation identified in this study each present particular challenges for hazard planning, with each style having unique spatio-temporal characteristics and degrees of predictability. Climate change magnifies these challenges, with predicted changes in the frequency and strength of tropical storms, shifts in swell wave climate, and higher rates of SLR (Church et al. 2013). Of the future inundation drivers, among the most certain outcome of continued climate change is an increase in sea level, with projections for the year 2100 ranging from 28 to 98 cm above 1990 levels (Church et al. 2013). However, a high tide or high regional sea level is not necessary for inundation. Wave-driven inundation events in 1979, 2008 and 2011 all occurred when the high tide level was more than 0.5 m below present-day spring tide elevation. There are lengthy records of storm impacts in the RMI which span centuries (Spennemann 1996). In all likelihood residents of Majuro have faced regular inundation since the atoll was first settled > 1000 years ago (Kayanne et al. 2011).

There remain a number of impediments to accurately predicting the impacts of SLR on the inundation of Majuro and atoll islands in general. While it is widely acknowledged that atoll islands are low-lying, there is a paucity of topographic data sets required for inundation modelling. Variations in the topography of reef islands mean that the timing of future SLR-driven inundation can differ by decades, if not centuries even between neighbouring islands (Owen et al. 2016). In addition, high-resolution offshore bathymetry data sets are not available for the Marshall Islands, which limit the ability to model wave transformations from deep water to the shoreline. Until such high-resolution topographic and bathymetric data sets are available, predictions of inundation will continue to be coarse-scale at best.

Similarly, there are a number of unresolved feedbacks within the geomorphic and anthropogenic systems which make predicting future inundation hazards difficult. For example, the future ecological response of the fringing reef to SLR is a critical control on the height of waves reaching the island shoreline, yet this issue remains largely unresolved. Geological records show reef flats have grown vertically at rates averaging ~ 4.4 mm year^{-1} (Dullo 2005). However, whether reef flat growth can keep pace with SLR is still debated (Hubbard et al. 2014). Similarly, the geomorphic response of the islands themselves to SLR remains uncertain, with islands regularly being shown to morphologically adjust to changing boundary conditions (Webb and Kench 2010). More importantly within the context of highly modified urban settings such as Majuro are the anthropogenic feedbacks to further SLR. The coastal margins of Majuro have been extensively modified over the twentieth century, and there is little evidence to suggest such development has ceased. Given the pace of development, there is no doubt the shorelines of Majuro will continue along a trajectory of modification. The island which future extreme water levels will encounter will look considerably different to the island as it stands to today. Therefore, it is essential that such development recognises the risk of different types of inundation and develops appropriately to meet present and future inundation hazards.

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