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ORIGINAL PAPER

Coastal flooding in the Maldives: an assessment of historic events and their implications

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Abstract With many inhabited islands only at about 1 m above mean sea level, the Maldives is among the nations most threatened by coastal flooding and sea level rise. However, the understanding of recent coastal flood events in the Maldives is limited and is important to understanding future flood threats. This paper assesses (1) the sea level and wave climate of the Maldives, (2) the sea level and wave conditions during recent coastal flood events, and (3) the implications for flood management and future research. The analysis uses observed still water levels (1987–2015) and hindcast wave conditions (1979–2015). Two significant flood events on 10–13 April 1987 and 15–17 May 2007 are examined in detail. This shows that coastal flooding in the Maldives occurs due to multiple interacting sources. These include long-period (up to 20 s) energetic waves generated in the Southern Ocean combined with spring tides. Wave run-up (mainly wave set-up) appears an essential mechanism for a flood, but is currently poorly quantified. However, as sea levels continue to rise the conditions that produce a flood will occur more frequently,

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suggesting that flooding will become common in the Maldives. This analysis is a starting point for future research and highlights the need to continue research on flood sources, pathways and receptors, and plan adaptation measures. Priorities include monitoring of waves, sea levels and flood events, and a better understanding of set-up (and other shallow water processes over reefs).

Keywords The Maldives · Sea level rise · Coastal flooding · Swell waves · Run-up · Set-up · Climate change adaptation

1 Introduction

Hundreds of millions of people are presently exposed to the effects of extreme sea levels and coastal floods (e.g. Lichter et al. 2010; Hinkel et al. 2014). Over the past decade, major storm surge events have caused extensive human and economic losses, whilst there may also be substantive losses from more frequent smaller coastal floods that are under-reported (Sadoff et al. 2015). Floods have always been a hazard to low-lying coastal populations (Kron 2013); but it is increasingly recognised that the number of people exposed to floods is growing due to various factors such as coastal population growth (Neumann et al. 2015) and sea level rise (Church et al. 2013). Tide gauge records indicate a global average sea level rise of 1.7 ± 0.2 mm year^{-1} from 1900 to 2010, whilst satellite altimetry data indicate a higher rate of 2.8 ± 0.8 mm year^{-1}, over the period 1993–2010 (Church et al. 2013). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Church et al. 2013) concluded that over the remainder of the twenty-first century it is ‘very likely’ that mean sea levels will increase at a greater rate than previous observations. It is hoped that the ‘Paris Agreement’, a commitment by 195 nations to stem global average temperature increases to well below 2 °C (compared to pre-industrial levels) (United Nations 2015), can limit the rate of this rise, but some rise in sea level is inevitable due to the ‘commitment to sea level rise’, which arises because of the long timescale of the oceans response to atmospheric temperature rise (Nicholls and Lowe 2004; Church et al. 2013).

The threats of climate change and sea level rise (SLR) to small islands have been recognised since the late 1980s and have been reiterated in every IPCC assessment (e.g. Pernetta and Sestini 1989; Pernetta 1992; Tegart et al. 1990; Nurse et al. 2014). The most vulnerable islands are coral atolls, which are especially susceptible to the effects of SLR and other environmental changes (e.g. coral bleaching due to high sea surface temperatures, periodic flooding). Global analyses suggest that island regions will experience the largest relative increase in flood risk due to SLR in the coming century (Nicholls et al. 1999; Nicholls 2004) and low-lying atoll nations appear to be consistently vulnerable across a wide range of scenarios (Nicholls and Tol 2006). Many small islands in the Indian and Pacific oceans are low-lying at only 4 m or less maximum elevation above sea level (e.g. Kench et al. 2003). This includes whole nations such as the Maldives, Tuvalu and Kiribati. Hence, it is apparent that small island states and low-lying atoll island regions have high vulnerability to SLR and climate change, and they will have to be ‘early adaptors’ to survive (Betzold 2015).

This paper considers sea levels, waves and coastal flooding in the Maldives, situated in the Indian Ocean, which is the lowest nation in the world (Fig. 1). The land area in the

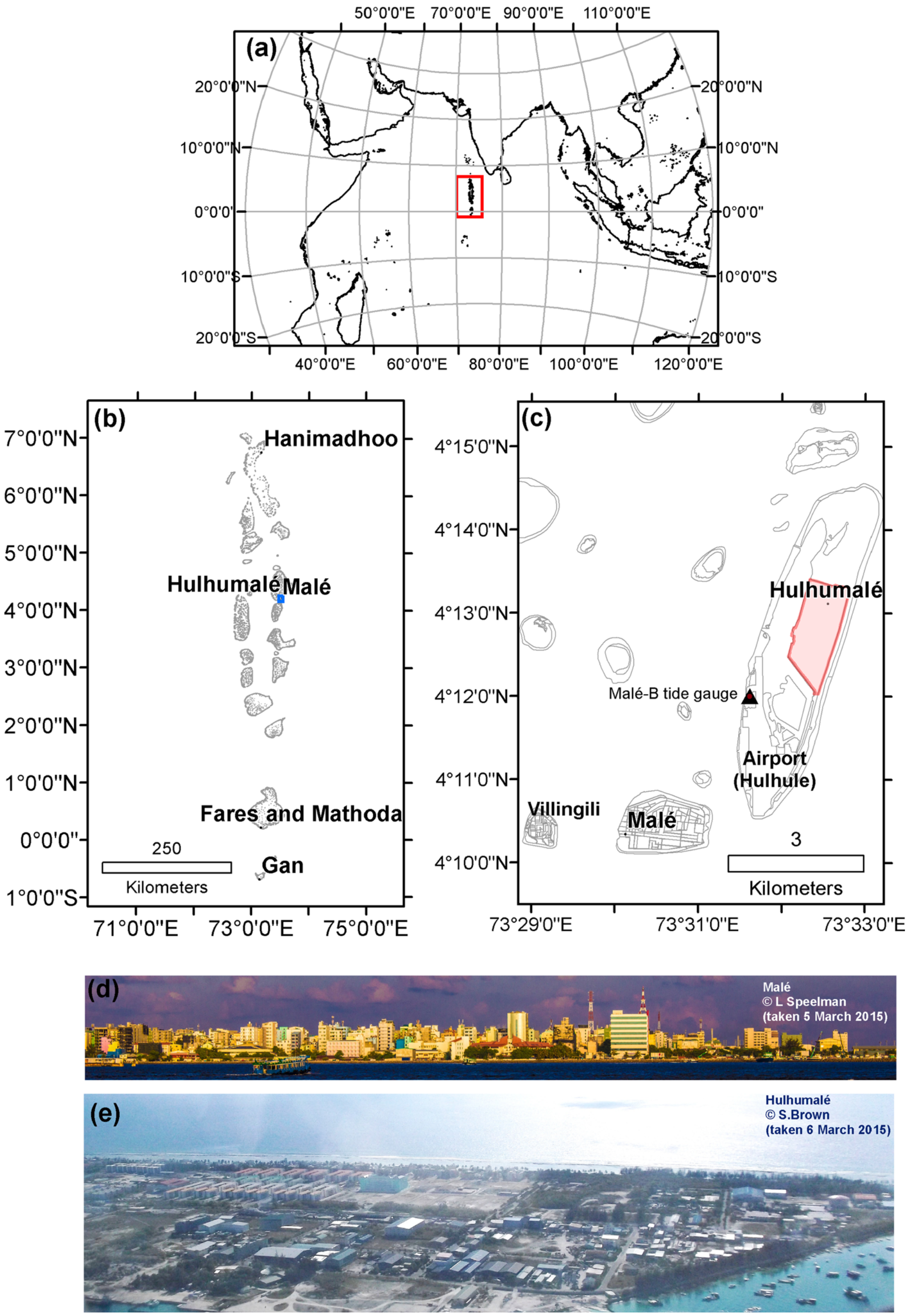

Fig. 1 Location maps **a** global view, the Maldives highlighted by the *red box*, **b** national view, **c** locations mentioned including the capital Malé, **d** view of southern Malé taken from a boat and **e** view of the artificial island Hulhumalé which is currently being developed to alleviate population pressure on nearby Malé

Maldives is relatively small (298 km^2), although the islands span 860 km north to south and up to 100 km west to east, covering a total area of approximately 107,500 km^2. Most of the land lies at $\leq$1 m above mean sea level (MSL)—refer to Appendix 1. The Maldives consists of approximately 1200 islands with the population of 325,000 located on 198 of these islands. In 2015, the nation had an annual population growth rate of 2% (World Bank 2015). More than 100,000 people live on the capital city of Malé, and this urban population is expected to continue to grow substantially in the future due to continued internal migration (Speelman 2016). Approximately 100 islands are dedicated to tourist resorts, the biggest source of income for the country.

The Maldivian atolls are already threatened by erosion and periodic flooding from the sea (e.g. Jameel 2007). Like many low-lying islands they are susceptible to inundation from energetic swell (long-wavelength wind waves), which can propagate thousands of kilometres across ocean basins (Munk et al. 1963; Harangozo 1992; Hoeke et al. 2013). However, detailed research on the causes of coastal flood events in the Maldives has been limited. A notable flood event was the swell wave floods of 10–13 April 1987 which displaced over 300 people, and affected 16 islands with the severest impacts in Malé (e.g. JICA 2001). This event triggered debate about whether the event was a realisation of climate change and SLR (e.g. Harangozo 1992; Pernetta 1992; Church et al. 2006). Subsequently, defences were upgraded in the 1990s, particularly around Malé (Naylor 2015). The 26 December 2004 Indian Ocean tsunami over washed many islands (Fritz et al. 2006) with over 80 people killed and 100,000 people affected across the nation (Richmond and Gibbons 2005). This was a seismically generated event rather than tidal-meteorological flooding, although it emphasised the vulnerability of the islands. During 15–17 May 2007, energetic swells from the Southern Ocean flooded 88 islands across 18 atoll districts. Over 1600 people were evacuated from their homes (approx. 500 housing units were damaged), but fortunately there were no recorded fatalities.

Despite its high vulnerability, the Maldives lacks a detailed and up-to-date scientific assessment that considers sea levels, waves and coastal floods. An assessment of these mechanisms is an important first step to understand adaptation management needs, and to provide specific guidance to plan research and monitoring requirements to support this activity. Thus, the overall aim of this paper is to assess the oceanographic sources of coastal flooding in the Maldives, and consider their present and future implications given SLR. The specific objectives are to analyse:

1. The general characteristics of the oceanographic sources of flooding around the Maldives: waves, tide, surges and mean sea level;
2. Previous coastal flood events—particularly the two largest known events (occurring in 1987 and 2007) and investigate their driving mechanisms, relative sea level conditions, and consequences; and
3. The implications of these results for future coastal flooding and adaptation, including recommendations for monitoring and future research.

The structure of this paper is as follows: Sect. 2 summarises the data and methods; Sect. 3 assesses the sea level and wave climate, Sect. 4 analyses the coastal flood events and their sources, Sect. 5 discusses the results and their implications, and conclusions are given in Sect. 6.

2 Data and methods

The main data used to determine the characteristics of sea levels and waves that can cause coastal floods, comprised sea level and wave time series, and a synopsis of relevant information extracted from existing literature. The sea level data were recorded at three tide gauges across the Maldives and wave data from a hindcast time series (since, to our knowledge, no wave buoy data are publically available).

Observed sea levels are available for three stations (Gan, Malé, Hanimaadhoo–locations shown in Fig. 1) at hourly frequency from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/datainfo/). The sea levels at each gauge were separated into: mean sea level (MSL), astronomical tide and non-tidal residual (NTR) components. The MSL component (indicative of seasonal, inter-annual and longer-term change) was derived using a 30-day running mean of the observed sea level time series, and the tidal component was estimated (minus the 30-day mean) using the T-Tide harmonic analysis software (Pawlowicz et al. 2002). Analyses were undertaken for each calendar year with 67 tidal constituents. The NTR was calculated by subtracting the MSL and tidal component from the total measured sea level. The NTR primarily contains the storm surge component, which represents sea level forcing due to changes in atmospheric pressure and wind. The skew surge was also calculated for each high water event. This is the difference between the observed elevation of high water and the corresponding predicted high water, and can quantify the contribution of surges to extreme sea level events (de Vries et al. 1995; Horsburgh and Wilson 2007).

Wave hindcast data were used from WAVEWATCH III (WW3), an ocean surface wave model developed at the National Oceanic and Atmospheric Administration–National Centers for Environmental Prediction (NOAA–NCEP) (Tolman 2002, 2009). The WAVEWATCH III® hindcast covers the entire globe, and outputs from model v2.22 are available for the Indian and Southern Ocean at 3-h temporal resolution, from a 30-arc-minute global grid. Details of the wind forcing and bathymetry are available at http://polar.ncep.noaa.gov/waves/implementations.shtml. The data span the period 1979 to 2015. Grids for 1979–2006 were downloaded from http://polar.ncep.noaa.gov/waves/nopp-phase1/ and 2006–2015 were downloaded from http://polar.ncep.noaa.gov/waves/ensemble/download.shtml. Significant wave height (H_s), wave period and direction were extracted at the data points shown in Appendix 3 and also plotted over the Indian Ocean domain to illustrate swell propagation on a wider scale. A limitation to this model is that the physics does not cover conditions where waves are severely depth-limited. Furthermore, the model is applied on spatial scales larger than 1–10 km, outside the surf zone and not in the coral reef environments that surround the Maldives. More detailed descriptions of the model and its governing equations are given in Tolman (2002).

In this paper, we discuss the effects of shallow water processes upon flooding. Wave run-up broadly describes the projection of water above the still water level. The upper limit of run-up is defined by swash, superimposed on set-up which is the super-elevation of mean water level at the coast caused by breaking incident waves. Set-up is the most frequently referred to component of run-up on reef coastlines, and as with surge and tide, set-up appears as a slowly varying change in sea level to an observer (e.g. Gerritsen 1981; Dean et al. 2005). Set-up is regarded as a key coastal flood mechanism in the Maldives and other ocean islands (e.g. Harangozo 1992; Gourlay 1996; Hoeke et al. 2013, 2015). In an attempt to amalgamate wave height and period (linked to set-up), wave power was calculated since this can indicate the transport of energy by waves, which is known to be proportional to wave set-up in reef environments (e.g. Gourlay 1996). These time series aim to compare events, but we acknowledge the coarse resolution wave data and lack of tools (to assess run-up on coral reef coastlines), and we cannot accurately calculate the vertical displacement (above tide and surge) of water level at the coast. Therefore, the literature was also reviewed to provide a synopsis of run-up, including set-up, relevant to this case study. Details of the formula that were used are provided in Appendix 2.

3 Sea level, wave climate and floods

This section describes the first objective, which is to assess the characteristics of sea level (tide, surges and mean sea level) and waves around the Maldives. Coastal flood events are discussed briefly in the context of the causative mechanisms and are described in more detail in the next section.

3.1 Tides and surges

The first sea level component analysed is tides. Due to its open ocean location, the Maldives has relatively small tides (Fig. 2). The mean spring tidal ranges at Gan, Malé and Hanimaadhoo are 0.96, 0.76 and 0.70 m, respectively (Woodworth 2005). The tidal regime is semi-diurnal with strongly diurnal inequalities: the two high tides and two low tides are of different heights. On springs the larger of each day's two tidal high waters is approximately 0.25 m higher than the smaller tidal high water of the day, and approximately 0.1 m larger on neaps. Storm surges are also small in the Maldives (e.g. Titus 1989; Woodworth 2005; Church et al. 2006), with none across the data larger than 0.25 m, whilst skew surges have not exceeded 0.15 m. The lack of evidence of large surges is consistent with the islands location near the equator (the 5° latitude zone is generally regarded as the approximate limit to tropical storms). It has elsewhere been hypothesised that larger surges of up to 1 m may be possible in the northern islands of the Maldives (DIRAM Team and

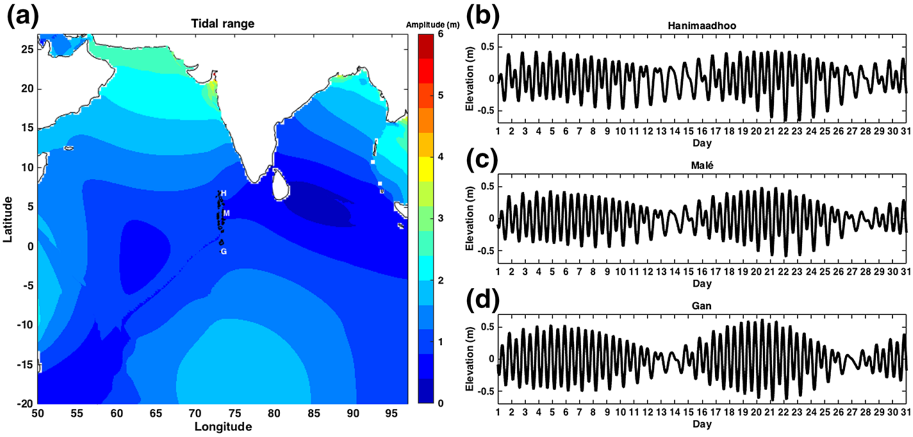

Fig. 2 Tides in the Maldives: **a** with a view to the surrounding Indian Ocean, **b** at the northernmost tide gauge Hanimaadhoo, **c** Malé, **d** at the southernmost gauge at Gan. The *tides* shown are for March 2007. The tidal data were generated by Oregon State University (OSU) Tidal Inversion Software (OTIS) Egbert and Erofeeva (2002)

UNDP Maldives 2007): the northernmost atoll Ihavandhippolhu (at 7°) is potentially exposed to cyclones.

3.2 Mean sea level

The third main component of sea level assessed is MSL, which during storm events has a smaller effect upon sea level height than tides and surges, but has a notable signal over periods of months to years (c.f. Pugh 2004; Woodworth 2005). We do not assess mechanisms for regional or local sea level change, but calculate the trends at the tide gauges. Natural ocean variability (and monthly to decadal effects on sea level) has already been noted by previous authors, associated with regional weather patterns (e.g. El Niño-Southern Oscillation, the Asian–Australian monsoon, North Pacific Decadal Oscillation) (Woodworth 2005; Church et al. 2006). As shown in Fig. 3, month-on-month changes to the (30-day running averaged) MSL are of the order of several cm at the Gan and Malé gauges. There is higher variability further north at Hanimaadhoo (of up to 0.11 m), consistent with the winter (December to March) wind-driven mass redistribution that can cause significant sea level increase around the northern Maldives (Han et al. 2010). An earlier study of sea level in the region (Church et al. 2006) determined upward trends of 8.4, 3.7 and 4.4 mm year^{-1} for the tide gauge records at Gan, Malé and Hanimaadhoo, respectively—although the records at that time were <10 years long, and therefore deemed unrepresentative of longer trends. Church et al. (2006) generated a 52-year (January 1950

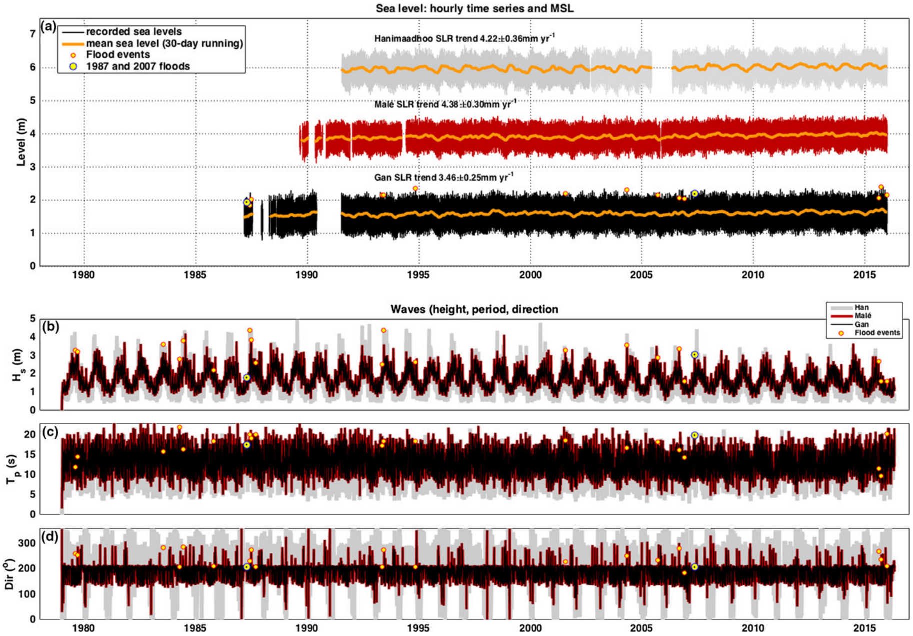

Fig. 3 **a** The available sea level time series for the 3 tide gauges showing observed levels, 30-day running mean sea level (*orange*) and the linear trend across each record; **b** significant wave height time series from WAVEWATCH III—the flood events in Table 2 are shown by *yellow* markers on the highest values associated with each event, and the *green* markers are the April 1987 and May 2007 severe events; **c** wave period; **d** wave direction

Table 1 Top 10 high waters since 1987 in the Maldives (note that the sea level is provided to 3 decimal places to differentiate the ranking positions)

Rank HW	Date–time	Sea level (m)	Tide (m)	Skew surge (m)	MSL (m)	Wave power at HW (kW)
(a) Gan—where (for this longest of tide gauge records in the Maldives) wave power is also provided, and the maximum high waters of the 1987 and 2007 floods						
1	27/10/15 21:00	2.420	0.66	0.04	1.71	22
2	26/10/15 20:00	2.404	0.62	0.07	1.72	11
3	29/09/15 22:00	2.402	0.65	0.03	1.72	18
4	28/10/15 22:00	2.397	0.65	0.04	1.71	22
5	28/09/15 21:00	2.384	0.65	0.01	1.72	10
6	27/09/15 21:00	2.368	0.60	0.05	1.72	12
7	28/09/15 09:00	2.366	0.58	0.06	1.72	13
=8	03/11/94 21:00	2.360	0.66	0.06	1.64	23
=8	06/05/12 09:00	2.360	0.63	0.04	1.69	19
=8	19/08/12 10:00	2.360	0.58	0.08	1.70	12
13,168	10/04/87 19:00	1.840	0.39	-0.05	1.51	23
9124	11/04/87 20:00	1.940	0.45	-0.02	1.51	24
7055	12/04/87 20:00	1.990	0.49	-0.01	1.51	22
5912	13/04/87 09:00	2.020	0.53	-0.02	1.51	20
940	15/05/07 08:00	2.177	0.56	0.01	1.60	43
751	16/05/07 09:00	2.189	0.59	-0.01	1.60	38
1105	17/05/07 09:00	2.168	0.59	-0.03	1.60	50
Highest wave power coincident with a known high water						
12,000	24/06/2014 19:00	1.870	0.21	0.00	1.66	63
(b) Malé						
1	28/10/15 21:00	2.592	0.51	0.08	2.00	
2	29/10/15 22:00	2.581	0.48	0.10	2.00	
=3	18/04/03 09:00	2.576	0.55	0.05	1.97	
=3	04/06/08 09:00	2.576	0.50	0.05	2.03	
5	07/05/12 09:00	2.572	0.52	0.03	2.02	
6	15/10/08 21:00	2.571	0.52	0.08	1.97	
=7	05/06/08 09:00	2.569	0.48	0.07	2.03	
=7	28/10/11 21:00	2.569	0.54	0.06	1.98	
9	27/10/11 21:00	2.568	0.55	0.04	1.98	
10	23/07/13 09:00	2.563	0.50	0.04	2.03	
332	16/05/07 08:00	2.458	0.51	-0.02	1.96	
(c) Hanimaadhoo						
1	29/04/02 09:00	1.745	0.58	0.06	1.11	
2	23/12/14 21:00	1.706	0.57	0.03	1.11	
3	03/01/14 21:00	1.704	0.60	0.02	1.09	
4	23/12/10 21:00	1.703	0.54	0.06	1.10	
5	11/02/13 20:00	1.698	0.57	0.02	1.11	
6	18/01/95 21:00	1.695	0.50	0.10	1.10	
=7	18/06/07 09:00	1.689	0.54	0.13	1.01	
=7	28/04/02 08:00	1.689	0.57	0.11	1.01	

Table 1 continued

Rank HW	Date–time	Sea level (m)	Tide (m)	Skew surge (m)	MSL (m)	Wave power at HW (kW)
=7	21/01/11 21:00	1.689	0.55	0.10	1.04	
10	15/06/14 09:00	1.684	0.52	0.06	1.11	
14	17/05/07 08:00	1.676	0.52	0.06	1.10	

to December 2001) reconstructed time series, which determined rates of approx. 1 mm year^{-1} at the same sites. Woodroffe (2005) used geological evidence to infer a net increase of up to 6 mm over the 20–30-year period up to 1989 (in the southern Maldives), which was consistent with the reconstructed time series (over that period) of Church et al. (2006).

In our analysis, we find upward trends in MSL. For the Gan record (1989–2015), SLR is 3.46 ± 0.25 mm year^{-1}; for Malé (1991–2015) 4.38 ± 0.36 mm year^{-1}, and at Hanimaadhoo (1992–2015) is 4.22 ± 0.36 mm year^{-1} (the latter tide gauge was moved in 2002 which may affect the accuracy of this rate). There is some evidence for an increase in extreme HWs over time. For example, at Gan, 7 out of the top 10 ranked HWs occurred in the year 2015, and almost half of the top 30 ranked HWs also occurred during that year (Table 1). However, the period of extreme high waters of September–October 2015 at the southern gauges also coincides with peak lunar nodal (astronomical tide) modulation (refer to Haigh et al. 2011).

3.3 Waves

Ocean wave conditions are the main control upon wave energy and approach at the outer margins of the atolls (Pernetta and Sestini 1989), and coastal flooding at islands in the Maldives has primarily been associated with extreme wave events (e.g. Harangozo 1992). The April 1987 Maldives floods, for example, were associated with long (>15 s) period waves (Harangozo 1992). Wave climate in the vicinity of the Maldives is influenced by both local and distant waves from all directions. Sabique et al. (2012) determined that Southern Indian Ocean swells play an important role in determining the Northern Indian Ocean wave climate.

Figure 3c, d, f shows the WAVEWATCH III time series of wave height, period and direction at the three sites. Annual patterns of wave height reveal the effects of the two monsoon periods, which are marked by strong seasonal reversals in wind direction confined to a narrow range of wind angles (Kench and Brander 2006). Towards the middle of each year, there is an increase in wave heights with the highest waves occurring from June to August, due to the effects of the Indian monsoon in the northern part of the Indian Ocean. During the summer or ‘northeast monsoon’ (December to March), waves are generally smaller than the middle of the year, despite locally stronger winds. There are some large wave events and floods in the central and northern Maldives at the onset of the northeast monsoon—for example, the swells which recently impacted the northeast Maldives were considered ‘normal’ for that time of year (late December 2015) (Maldives Independent 2015c). These floods were also associated with high tide levels.

Table 2 A catalogue of coastal flood events recorded in the Maldives 1966–2015, from various sources including the Detailed Island Risk Assessment of Maldives reports (UNDP 2007); and the associated sea level and wave conditions at Gan (the highest values associated with the dates available are provided)

Date of event	Source	Description	Highest HW (m)	Peak Hs (m)	Peak T (s)	Peak 12 h power (kW)	HW at peak power (m)	Direction of peak power (°)
5 July 1966	DIRAM Team and UNDP Maldives (2007)	No details available—these coastal floods reported to have affected southern islands (Viligili, Feydhoo, Thinadhoo)	N/A					
24 August 1975								
7 May 1978								
8 August 1979			N/A	2.71	11.09	30	N/A	147
17 September 1979				2.72	11.01	29		149
14 July 1983				3.03	11.02	32		135
6–7 April 1984				2.79	21.75	48		202
6–7 June 1984				2.29	15.65	35		196
14–15 October 1985				2.21	17.32	36		212
10–13 April 1987	Harangozo (1992), Naylor (2015), Pernetta (1992)	Most damage was at Malé and floods reportedly impacted 16 islands across 13 atolls. Impacts to 300 people, 200 houses. Reportedly caused $6 million damages to sea walls around the city and the airport and an outbreak of Cholera. The poor state of defences and low-lying reclaimed land were to blame for the flooding of Malé	1.94	1.82	17.59	23	1.71	211
2–3 June 1987	DIRAM Team and UNDP Maldives (2007)	Details unavailable		2.15	20.13	35		209
28 June 1987			1.84	3.21	19.22	60		194

Table 2 continued

Date of event	Source	Description	Highest HW (m)	Peak Hs (m)	Peak T (s)	Peak 12 h power (kW)	HW at peak power (m)	Direction of peak power (°)
9–10 September 1987			2.01	2.62	19.91	45	1.48	202
June–July 1988 (unspecified dates)	Pernetta and Sestini (1989), JICA (2001), ADRC (2005)	A period of flooding with dates unspecified. It was reported that high waves and sea level damaged houses, structures and coastal areas. Widespread flooding was reported on islands in the south (ADRC (2005). Pernetta (1989) reported this as a 'July 1988 high water situation at Thulhaadhoo' (located on the outer western Maldives, towards the northern central part of the country)—and that it was caused by south-westerly waves of up to 2.5 m high and with periods of 12–15 s, accompanied by high tide and south-westerly wind. Damage was reportedly enhanced by lack of beaches and presence of vertical low sea walls	Morning of 30 June-1 July HWs of 2.15–16 m, coincident with wave power 34–37 kW. Also over the two days 19–30 July HW reached 2.14 m, wave power 18 kW.					
September 1988 (unspecified date)	JICA (2001)	Details unavailable	26–27 September HW as high as 2.2 m, with wave power >22 kW					
June–July 1991 (unspecified dates)	DIRAM Team and UNDP Maldives (2007)	Details unavailable	14–15 July HW as high as 2.20 m, coincident with wave power 35 kW					
8 May 1993			2.16	2.62	15.85	25	1.33	194
5 June 1993			2.15	3.61	18.46	60	1.22	207
6 November 1994			2.35	2.63	17.45	38	1.50	201

Table 2 continued

Date of event	Source	Description	Highest HW (m)	Peak Hs (m)	Peak T (s)	Peak 12 h power (kW)	HW at peak power (m)	Direction of peak power (°)
20 July 2001			2.20	3.29	17.72	55	2.20	204
June–July 2003 (unspecified dates)			Morning of 31 July HW 2.24 m, coincident with wave power 34 kW					
3–5 May 2004			2.31	2.83	16.72	43	2.11	208
June–July 2005 (unspecified dates)			Morning of 22 July HW 2.24 m, coincident with wave power 40 kW					
18 September 2005			2.16	2.89	17.35	46	1.05	201
June 2006 (unspecified date).			Morning 27 June HW 2.19 m, coincident with wave power 26 kW.					
4 September 2006			2.07	2.20	11.79	25	1.62	166
30 November 2006			2.04	1.26	15.18	14	1.84	203
15–17 May 07	DIRAM Team and UNDP Maldives (2007); Reliefweb (2007b, c)	In the Maldives these floods affected 1649 people on 88 islands across 18 atolls; over 500 housing units damaged and four people injured. The waves started during the morning of 15 May 2007 and 'intermittently re-occurred for two days'. Waste disposal areas and septic tanks were damaged, and the water table was contaminated by saltwater, resulting in a shortage of clean drinking water in some locations	2.19	3.05	19.74	45	1.49	210

Table 2 continued

Date of event	Source	Description	Highest HW (m)	Peak Hs (m)	Peak T (s)	Peak 12 h power (kW)	HW at peak power (m)	Direction of peak power (°)
11–12 August 2015	Maldives Independent (2015a)	Flooding event in the northeast of Malé with the eastern waterfront flooded to 0.5 m. Pumping was required to remove the water. Flooding affected the outer road, cafés and restaurants. Swells were not reported further south. Associated with strong winds. Reporting suggested that the flooding and swells happen every year but this event was worse than usual in Malé, and a month earlier than usual	2.07	2.28	11.58	24	1.96	146
27–30 September 2015	Maldives Independent (2015b)	Waves combined with high tides caused minor flooding in 5 southern islands (Gaafu Alif and Gaafu Dhaal atolls and Kolhufushi Island in Meemu atoll. The flooding did not cause severe damage and were not as bad as predicted	2.40	1.61	6.37	12	2.37	154
28 December 2015	Maldives Independent (2015c)	Swells hit Komandoo Island (northeast Maldives) around 2:00 am. The water seeped 300 feet [91 m] through the island from the northeast side. No houses were damaged. Floodwater reached 3 homes, but the water was kept at bay with sandbags	2.15	1.20	20.33	19	2.04	212

Note that atolls are actually atoll districts (currently there are 189 islands, 19 atolls and 2 cities in the Maldives, although administrative districts have changed under different government regimes)

For much of the year, swell is a principal factor in determining the wave climate of the northern Indian Ocean (Sabique et al. 2012), and the wave period time series appears more chaotic than wave height (Fig. 3d). This is partly because swell waves reach the Maldives throughout the year, generated from low-pressure systems persistently passing through the 'Roaring Forties' (between latitudes 40° south and 50° south). Late April–early May marks the onset of the 'southwest monsoon' season where despite locally calm and dry weather, stronger winds are generated thousands of kilometres south and southwest of the Maldives, which can generate large and long-period waves. This consistent high-period swell wave activity from the southern Indian Ocean occurs between March and November, and during this period, the Maldives often experiences larger waves (and minor flooding) from further afield, known locally as 'Udha' (DIRAM Team and UNDP Maldives 2007). As discussed in the next section, two severe flood events occurred during this period: 10–13 April 1987 and 15–17 May 2007.

3.4 Shallow water wave processes

Of the processes linked to extreme sea levels in reef lagoon environments, wave set-up has been found to be the largest component of extreme water levels for other island case studies with fringing reef morphology (e.g. Hoeke et al. 2015). Set-up tends to vary according to wave steepness and the type of foreshore over which waves are breaking. Set-up at coasts has been regarded approximately as 10 to 20% of deep water wave height (e.g. WMO 1998; Holden 2008), with reefs potentially forcing higher set-up values, of up to a third of incident wave height (Munk and Sargent 1948; Hoeke et al. 2013). The coast at the city of Malé fits criteria for relatively large wave set-up, having a narrow reef with smooth flat and steep fore slope (Quataert et al. 2015). Hence, given that wave heights of over 3 m occur, it is plausible that wave set-up at Maldivian reefs could reach 0.3–1 m. As discussed in the following section, peak set-up must have reached even higher levels to explain the depth of floods in the extreme circumstances of the 1987 and 2007 events. Further to set-up, the filtering and dissipation of incident swell on coral reef platform generates infra-gravity waves which can be 20–60% of the deep water wave height (Longuet-Higgins and Stewart 1964; Guza and Thornton 1985).

3.5 Coastal floods

Table 2 provides a collation of coastal flood events (i.e. listed as caused by large waves, tide or surge) from various sources, including media sources found online, and a series of reports (the 'detailed island risk assessment in the Maldives'–DIRAM) commissioned in 2007 by the Government of Maldives (DIRAM Team and UNDP Maldives 2007). Most records lack detail such as the source and pathways of flooding, severity of impacts, or duration. They indicate that minor flood events are common throughout the Maldives, with at least 30 flood events in 50 years, including the two large events in 1987 and 2007 already mentioned. Locally they have been accepted as resulting from waves generated during the onset of southwest monsoon season and are regarded as being almost annual, often during the months of May–June. Impacts from these events tend to be restricted to within 20 m of the shoreline, with flood depths of <1 m, mainly affecting reclaimed areas and causing minor crop damage (DIRAM Team and UNDP Maldives 2007). The flood event, water level and wave data (Fig. 3) indicate most events have coincided with the mid-year wave height maxima, and are associated with wave periods of 10–20 s, with (often Southern Ocean generated) waves of a south-westerly and sometimes westerly

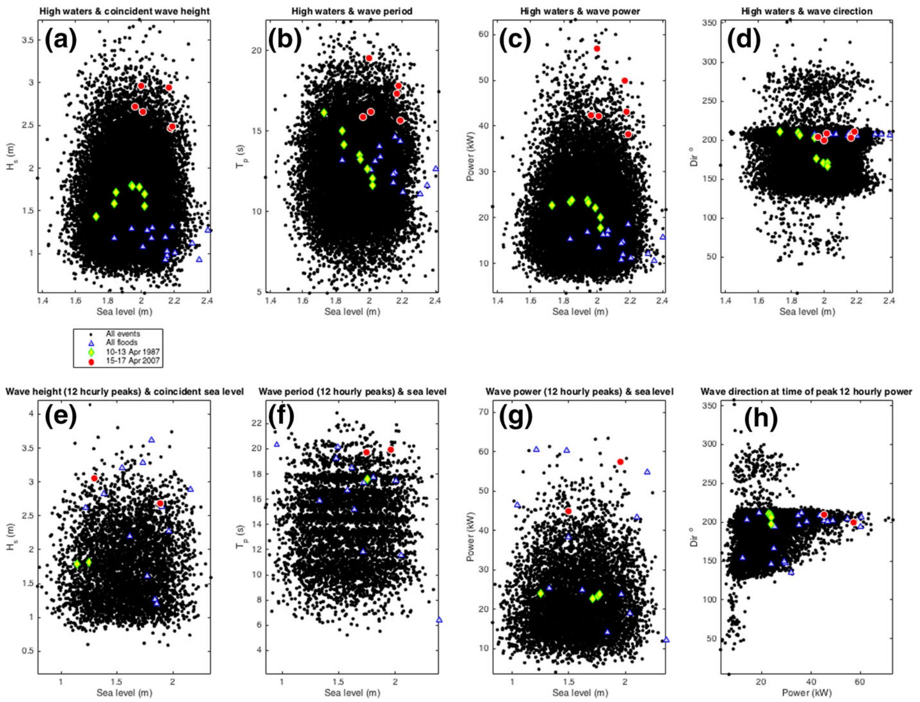

Fig. 4 For the data at Gan 1987–2015: **a**–**d** Scatter plots of twice daily high water values against simultaneous wave height, period, run-up and power values (interpolated), and **e**–**h** 12-h wave peaks and simultaneous sea level values (hourly data, interpolated to the wave height, period, power peaks) and wave direction at time of peak power. In each case, the 1987 (*yellow dots*) and 2007 (*red*) events are *highlighted*, and the flood events for which specific dates are available, listed in Table 2

direction. However, flood events in August and September 2015 were not so much linked to wave period, rather high tides and (more locally generated) wave heights. All of the flood events for which there is a specific date (five of the entries in Table 2 do not have a date or time, only a month and year) are associated with spring tides.

3.6 Summary

From a simple frequentist approach, the record of events in Table 2 (31 incidences of flooding from 1966 to 2015) together suggests that minor coastal floods occur about every 1.6 years and that severe floods (namely those of April 1987 and May 2007) can be expected approximately every 20 years. This approach is overly simplistic (e.g. due to limitations in reporting affecting the sample size, and also changing human and physical factors over time). Also there is a lack of sea level and wave data to verify conditions associated with many of these floods. As shown in Fig. 3b and c, all the flood events are associated with relatively extreme wave conditions and, as indicated in Fig. 3a, are associated with high spring tides—the exception is the 1987 event which was between neaps and springs. At Gan, the highest sea level during the 15–17 May 2007 floods was a high spring tide, only ranked 751 out of 18,627 HWs from April 1987 to December 2015, whilst the highest HW during the April 1987 event is ranked 5912 in this data set. The 15–17 May 2007 sea levels are prominent within the tide gauge records at the northern

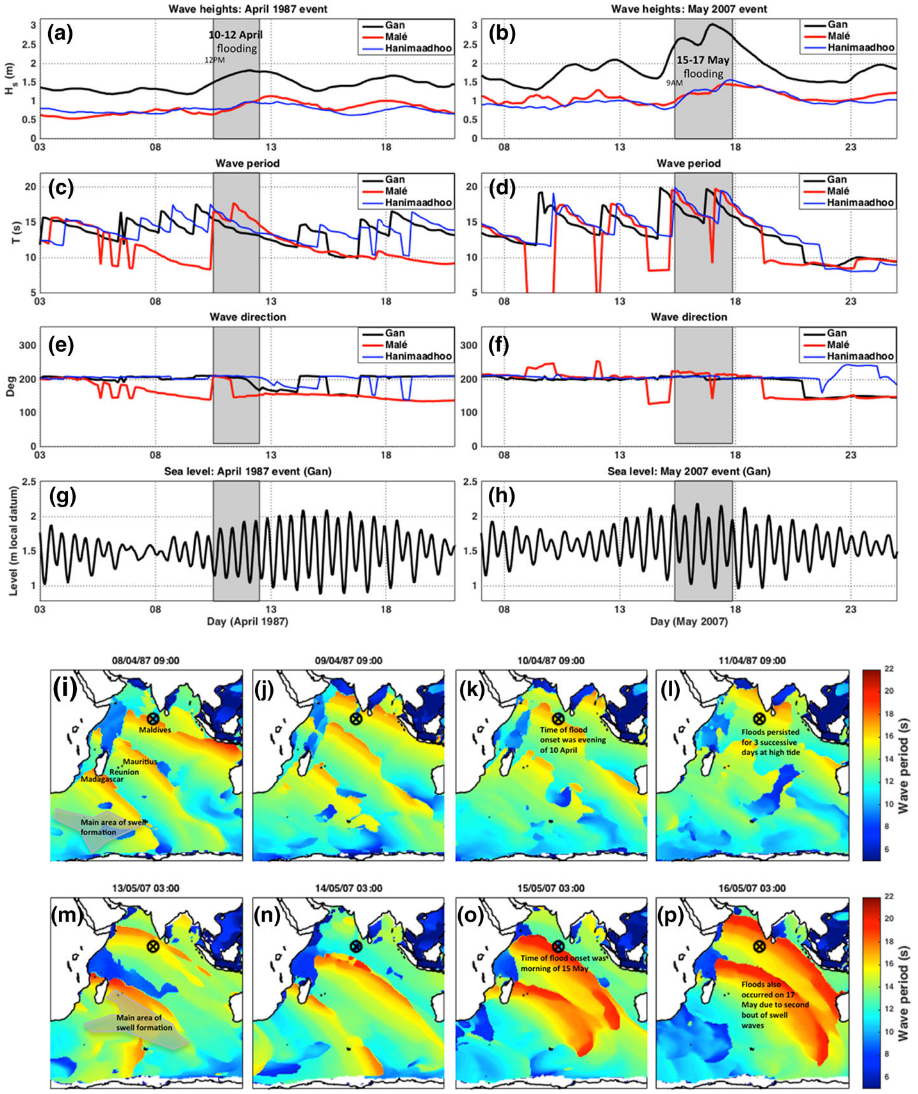

Fig. 5 **a** and **b** are the wave heights associated with the 1987 and 2007 Maldives flood events; **c** and **d** show the wave period; **e** and **f** the direction; and **g** and **h** the corresponding sea levels observed at the tide gauges (note that wave data were extracted from the WAVEWATCH III hindcast. **i** to **l** are snapshots of swell period as the waves propagated the Indian Ocean during the April 1987 floods and **m** to **p** for the May 2007 event. The observed flooding onset in each event is represented by the third snapshot from the *left*. The wave height extracted from the WAVEWATCH III data for the 1987 event is smaller to that noted in Harangozo (1992), which indicated that deep water H_s reached 3 m

gauge, Hanimaadhoo, where the 17 May ranks 14th (only 7 cm below the highest HW). At Gan, the highest recorded HW of 27 October 2015 is not known to have caused flooding (and was 23 cm higher than the highest HW of May 2007 and 40 cm higher than the highest HW of April 1987). None of the known flood events were associated with the largest sea level, wave height or period. As outlined by other authors, the effect of wave run-up (primarily there has been reference to the set-up component) is likely to be large relative to sea level variation. The small tides and surges of the Maldives also indicate that MSL (and hence mean SLR) exerts a relatively large influence on extreme HWs. The two major flood events are now considered in detail.

4 The April 1987 and May 2007 flood events

This section focuses upon the second objective, to assess the historic coastal flood events in the Maldives, with emphasis upon the causes and characteristics of the flood events of 10–13 April 1987 and 15–17 May 2007. These events stand out due to the volume of news they generated and the number of people affected over a widespread area. April 1987 caused more intense damages as it impacted the capital city of Malé and the airport, and 300 people. The 2007 event affected a wider area and >1600 people, but without impacts reported for the capital or airport.

Figure 4a–d shows the wave conditions (height, period, power, direction) that coincided with high waters at Gan, and the red and yellow dots highlight the 1987 and 2007 events (with the triangular markers showing other floods listed in Table 2). Figure 4e–h shows, respectively, the wave parameter peak values over a 12-h window, plotted against the coincident hourly sea level value. Dots lying further to the upper right of each plot indicate more extreme combined (wave and sea level) conditions. The April 1987 event in each case stands out less than the May 2007 event amongst the population of events. The 2007 event appears most extreme (in relation to other events) when one of the wave power peaks (of 17 May) coincided with a large sea level (Fig. 4g). These plots show that the peak of wave power was from (approx.) 200° (south-southwest) direction in both of the larger events and that there have been more powerful wave events, including the most powerful recorded being from this direction (Fig. 4h). The time series of data associated with the 1987 and 2007 events and maps of the swell are shown in Fig. 5.

During the 10–13 April 1987 event, flooding on Malé started on the evening of the 10 April, local time (Maldives is UTC + 5 h) (Harangozo 1992) and persisted for 2–3 days. The United Nations reported of this event: ‘Serious damage to the entire archipelago of the Maldives following the highest tidal waves experienced for years on 11 April 1987’ (Reliefweb 1987). A non-tidal water level anomaly in a harbour in north Malé which reached 0.15 m was associated with wave set-up further afield, and persisted until the evening of the 13 April, with flooding over three successive days at high tide (Harangozo 1992). This event is most noted for flooding of the south Malé reclaimed area and adjoining Hulhule airport (e.g. Naylor 2015). The floods reportedly impacted 300 people and 200 houses in Malé, and 16 islands in the surrounding area (Reliefweb 1987)—further detail is not readily available, only that various tourist resorts were affected as well as atolls to the south (Pernetta and Sestini 1989). There were $6 million (about $20 million in today’s values) damages to sea walls around the city and the airport. The event was exacerbated by reclamation on the islands which created new areas vulnerable to flooding (Edwards 1989; Pernetta 1992). The ‘Malé Land Reclamation Project’ comprised mining activities that lowered the remaining reef by half a metre and extended land closer to the edge of the Malé reef (closer to deeper water). The low-lying reclaimed land was the worst affected area, with 60 hectares of landfill inundated and approximately 300,000 m^3 of fill washed away by the floods (Edwards 1989). Sea walls at that time were not robust with sections missing (JICA 2001; NDA 2005).

Published literature suggests that this swell came from a storm off Australia (e.g. Harangozo 1992; McLean 2009). Other sources suggest the swell was generated between 4 and 7 April 1987 by a storm in the southern Indian Ocean, which sent long-period swell 4500 km towards the Maldives (Naylor 2015). The latter description is more in agreement with the analysis of the WAVEWATCH III data presented here (Fig. 4i–l). Swell had been propagating from the Southern Ocean for several days, but wave heights notably increased from the 10 April around Gan. Skew surges were relatively small (<3 cm) during 10–13 April (and hence are not discussed further). Wave heights assessed around the Maldives by other authors using altimetry data and hindcast methods have indicated 15–16-s wave period and deep water significant wave height (H_s) of up to about 3 m (Goda 1988; Jensen 1991; Harangozo 1992). Nearshore breaker heights were likely to have been much larger; data and observations suggest that upon reaching Malé on April 10 the swells' maximum height was 5 m (Harangozo 1992; Naylor 2015). The event occurred during a period between neap and spring tides (Fig. 5g). It was speculated that set-up on the south coast of Malé was around 0.6 m (Harangozo 1992) although to account for the observed flood levels, set-up may have actually reached 1.25 m, which would also have been further accompanied by transmitted and infragravity waves (Gourlay 1996). Following the 10–13 April 1987 event and its flood impacts, sea walls were built around the entire perimeter of the capital Malé and a breakwater to the south which took 14 years to construct at a cost of $63 million, 99% paid for by aid from Japan (Pernetta 1992; BBC 2004).

The 15–17 May 2007 flood event was caused by two separate bands of long-period (swell) waves from two consecutive storms (e.g. WMO 2007; ESA 2007; McLean 2009; Samiksha et al. 2012)—as indicated in Fig. 4m. These swells were generated in a similar area of the southern Indian Ocean to the 1987 event. Intense storms south of South Africa started on the 8 May with a central pressure of 945 hPa and gale force winds (reaching speeds of 175 km/h) which extended over an area 1200 km wide (MMS 2007). In the swell generation area on 10 May 2007, wave hindcast and altimeter data indicated waves were >15 m high (Samiksha et al. 2012). The swells hit La Reunion Island on the 12 May and then the islands of Rodrigues and Mauritius (3000 km southwest of the Maldives), killing 6 people. The path of the swell around this time is shown in Fig. 4k. The waves propagated 5600 km to the Maldives where flooding is likely to have occurred on two separate days, starting during the morning of the 15 May (Fig. 4o) and also on 17 May (WMO 2007; Reuters 2007). The swells approached the archipelago from the southwest and the most severely impacted islands were those located in the west and south. After impacting the Maldives, the swell caused damage in Indonesia and Thailand (Reliefweb 2007a). Wave direction 15–17 May was 213°–225° with a persistent wave period of 18–20 s. The constancy of wave direction, height and period was highlighted for the 1987 event as an important mechanism for maintaining the set-up levels in the lagoon, which were initiated by waves breaking on the reefs (Gourlay 1996; Harangozo 1992), and appears also to have been a feature of the 2007 event. The event coincided with the middle of the spring tidal cycle (Fig. 4h). Peak H_S at Gan reached 3.05 m (at midnight 17 May). The entire island of Fares (located at the south facing rim of the Huvadhu Atoll) was flooded on 17 May 2007, and nearly one-third of Maathoda flooded as the swell 'washed ashore in a south-westerly direction' (LHI 2015). It was described how 'water crept in slowly' before receding with the tide (BBC 2004).

The data presented in the previous section indicate that many other swell events combined with high tides may have occurred since April 1987, but the adaptation following that event has so far been largely effective. The May 2007 swells flooded more places and people, likely accounted for by the longer period waves (20 s, compared to 16 s in 1987), whilst still water levels were 10–20 cm higher. The 30-day running MSL was approximately 0.1 m higher during May 2007 than during April 1987, largely accounted for by mean SLR.

5 Discussion

The third objective is to discuss coastal flood events and their implications, as well as recommendations for monitoring and future research.

The biggest floods of 1987 and 2007 are associated with coincidently energetic long-period, powerful waves and high sea levels (Fig. 4f, g). Both of these large events comprised prolonged swell conditions (Fig. 5), and Harangozo (1992) and Gourlay (1996) previously suggested the importance of persistent wave (direction and swell) to promoting high set-up in the lagoons. This may be due to importance to set-up levels, and/or cumulative volume of overtopped water, and beach and/or defence erosion. Long-period swell in other coastal environments is known to cause greater run-up comparable to shorter-period (locally generated) waves (Mason et al. 2008; Palmer et al. 2014); although the Maldivian coast has small tidal (and surge) sea level variations, distinguishing extreme events is complex because of the dynamics of shallow water processes. The coarse

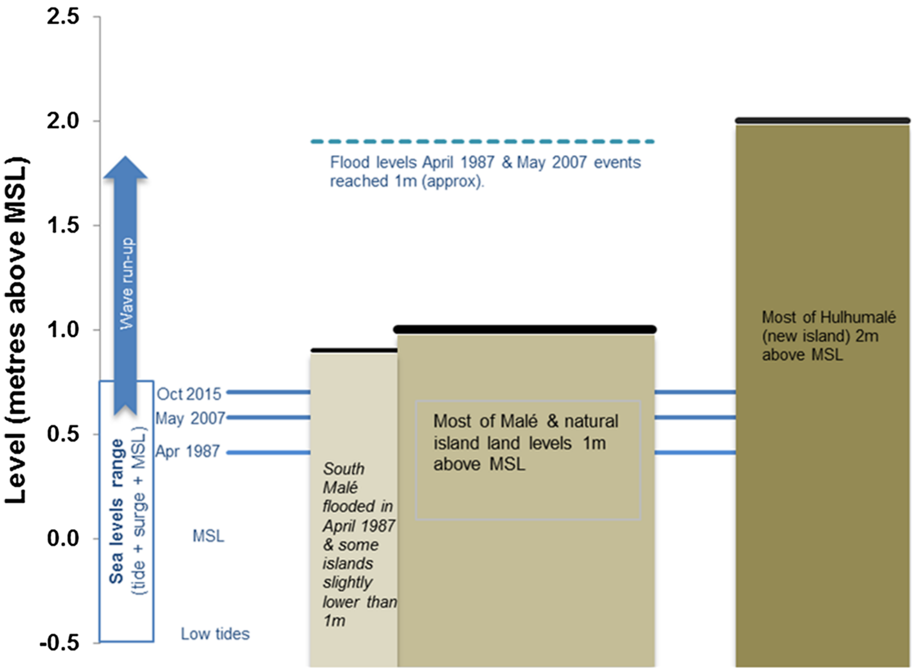

Fig. 6 Illustration of land height in relation to sea level; refer to Appendix 1 for various sources of land heights. Many of the natural islands in the Maldives are regarded as 1 m above mean sea level, which is higher than extreme sea levels caused by tides and surges, and it is the the additional effects of wave run-up that can cause flooding. The Malé sea wall and artificial island of Hulhumalé are currently higher than these extreme levels

(temporal and spatial) resolution wave time series data cannot sufficiently capture wave groups or peaks attributable to more extreme set-up and infragravity waves. Set-up is linked to (tidally influenced) water depth at reefs (Gourlay 1996; Vetter et al. 2010): at other reef islands less set-up has occurred at high tide than at low tide for a given incident wave height (Becker et al. 2014), whilst (Hoeke et al. 2013) highlighted the complex (and important) interaction between tides and set-up, and implications for inundation. It has been indicated than wave set-up at south Malé could have been 0.6–1.25 m during April 1987 (Gourlay 1996). Whilst most coastal flooding is associated with Southern Ocean swells, high tides with lesser-period waves from the opposite direction caused 'unusual' flooding at northeast Malé in August 2015, and the event during September 2015 (Table 2).

Between the 1987 and 2007 events, the Maldives experienced a significant population growth (of >100,000 people) (Speelman 2016), and current vulnerabilities to flooding have evolved from patterns of settlement, and modifications to coastlines and land cover, to support more people, at higher living standards (Naylor 2015). Coastal engineering structures were constructed in some inhabited islands as early as the 1970s, although modern-style defences were applied in the 1990s (MHE 2011)—notably the sea walls and breakwaters protecting the capital. Recent adaptation, to reduce population pressure and provide land high enough to prevent flooding, includes construction of an artificial island named Hulhumalé (e.g. Hamilton 2008a, b). This island is situated 3 km northwest of the Malé, with dimensions 0.9 km by 2 km, and constructed to approximately 2 m above MSL. Reclamation onto the original reef flat began in 1997 and the second phase was recently completed (MNA 2014). Hulhumalé has a population of 30,000, which is projected to grow as development continues. Schematically illustrated in Fig. 6, is that there is about 1-m difference between natural Maldivian island land levels and MSL (see Appendix 1), which can reduce to as little as 30 cm during high sea levels (such as those in late 2015), and was in the region of half a metre during the 1987 and 2007 floods. As already discussed, shallow water processes resulting from wave events interacting with the reef and foreshore can project water levels above the land height. The SLR rates presented in this paper indicate by the end of the century large high tides (without set-up or surge) will be at land level in many islands, which could occur sooner under more extreme projections of future SLR (e.g. Church et al. 2013). During this time, waves would increasingly be able to cause floods (c.f. Hoeke et al. 2013), and all inhabited islands will need to adapt, for example, building defences, land raising and relocation to higher areas to avoid regular inundation as well as more severe impacts during 2007-type swell events.

This paper is a first attempt to better understand coastal flooding in a remote location using freely available data (c.f. Lewis et al. 2013a). Hence, there are many potential areas of future work. To date, it seems that some islands are more susceptible to flooding than others (Shareef 2015—pers. comm.), and the reasons for this are not fully understood. A better assessment of all shallow water processes that contribute to flooding would be beneficial to account for flood risks (e.g. Lewis et al. 2013b, 2014)—there is presently a lack of simple tools to calculate run up and overtopping on coral reef coasts. Joint probability of waves and sea level occurrence in the Maldives could be applied using more sophisticated multivariate analysis methods (e.g. Wahl et al. 2012) to characterise events (e.g. by return periods), although more site- and event-specific, high-resolution analyses would be beneficial. Ideally this would include higher-resolution wave modelling, and/or numerical approaches (e.g. McCabe 2011) capable of simulating overtopping in reef-lagoon environments complemented by topographic and bathymetric data. Response of the islands and reefs to SLR (and subsequent effects on flooding) is uncertain: coral islands are well known to accrete vertically (e.g. Marshall and Jacobsen 1985; Kench et al. 2015), but there are widespread concerns that this growth will not keep pace with SLR (e.g. Woodroffe 2008), particularly given recent bleaching events. Understanding this and sediment movement could also be important for managing future risks. Changes to wave climate should be considered in future risk assessments using data such as that described by Hemer et al. (2010, 2012). WMO (2007) remarked that there was insufficient early warning for the later part of the 2007 event (on 17 May), and advice was given to install at least 3 wave buoys (hence 2 more are needed to meet this advice, in addition to a recently deployed first wave buoy in the south) to monitor ocean state in real time. Since March 2013, forecasting services have been provided by the Indian National Centre for Ocean Information Services (INCOIS) (Mallikarjun 2013). Flood warnings are issued through the Maldives Meteorological Service, and measures such as sandbags and moving items away from the coast are carried out in response (Maldives Independent 2015c). 'High wave alerts' are available 3 days in advance of an event and are usually issued when waves exceed 3 m (e.g. Mallikarjun 2013). The data presented in this paper imply that differentiating between annual type 'nuisance' flood and more severe (1987 and 2007 type) events may be challenging. Of critical important is maintenance of the tide gauges. Ideally, the sea level observations should be augmented by land-based elevation monitoring. Systematic monitoring of flood events (Haigh et al. 2011) would also enable a better understanding of conditions that cause flooding and to identify susceptible areas.

6 Conclusions

This paper assessed the sources of climate-linked coastal flooding in the Maldives, primarily focusing upon recent major coastal flood events. These coastal floods appear to occur due to composite sources and pathways, with the most extreme events of April 1987 and May 2007 linked to prolonged energetic long-period swell wave action generated in the Southern Ocean. At present, the natural islands in the Maldives are unlikely to be flooded by extreme still sea level (tide + surge + mean sea level) conditions alone; nor by extreme waves occurring on a small tide. Wave set-up (a key component of wave run-up) appears to constitute a larger contribution to coastal sea levels during flood events than exceptional tides or surges. However, the magnitude of wave set-up (and run-up in general) is poorly understood in reef settings, limiting our analysis.

The evidence presented that the worst flooding and overtopping has occurred due to combinations of moderately extreme sea levels, and extreme waves differ from how flooding and inundation in the Maldives is portrayed in the wider media which stresses mean sea level rise and does not recognise the important role of waves. Extreme wave conditions appear to be an essential mechanism of coastal floods. However, given the sensitivity to the (mainly tidally) modulated still water level, the frequency and severity of wave-induced flooding in the Maldives are likely to be highly sensitive to mean sea level rise as widely assumed. Subsequently, a key recommendation is for continued monitoring of sea levels and waves, combined with research on shallow water wave processes over reefs to better understand and predict their contribution to flooding. This will provide an improved basis for prognosis, both in the short-term and for planning adaptation for sea level rise, which is essential for the Maldives.

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Appendix 1: Selection of sources on land height in the Maldives

BBC (2004): '80% of its [the Maldives] 1200 islands are no more than 1 m above sea level'

Pernetta (1992): 'The highest point on Male is "just over" 2 m above sea level; over 85% of the original land area is <1 m above SL. No island stands more than 3 m above mean sea level and most are less than 1 m high'.

Harangozo (1992): The islands are 'mostly lying less than 2 m above MSL' and that during 1987 and 1988 experienced floods of up to 1 m in places.

Woodworth (2005): 'The islands have typical elevations of only 1–2 m above MSL'

Titus (1989): Male is 'generally about 2 m above sea level, although some of the reclaimed areas are somewhat lower'. Maldives: 'virtually the entire nation is within 4 m of sea level'.

Kench et al. (2015): 'The maximum natural land levels approach 6 m above mean sea level (MSL) in places; the mean elevation of land is approximately 1 m above MSL'.

Khan et al. (2002): 'Male: >85% total land area is $\leq$1 m above SL (including most reclaimed land), max height $\sim$2 m. Maldives: 80% of the land area <1 m, max height above sea level $\sim$3 m'.

Evans (2013): Average height of the Maldives is 4 ft above sea level; the highest point (entire nation) is <8 ft (2.4 m).

Wikipedia: 'With an average ground-level elevation of 1.5 m above sea level, it is the planet's lowest country. It is also the country with the lowest natural highest point in the world, at 2.4 m'.

Henley (2008): This is the citation used within the Wikipedia post, and actually states: 'nowhere on the Maldives does the natural ground level exceed 2.3 m. Most of its land mass, which totals roughly one-fifth of Greater London, is a great deal lower than that, averaging around 1.5 m'.

UTNE (2011): 'Our islands are on average just 1.5 m above the ocean'.

UCS (2010): '80% of the Maldives are less than 1 m above sea level'.

DIRAM Team and UNDP Maldives (2007): Some islands (e.g. Viligilli which is south of Gan) are as low as 0.7 m above MSL, whilst others (e.g. Kulhudhuffushi: a northern island with >7000 inhabitants) have average elevations of 1.4 m above MSL, and with 2.5 m above MSL natural ridges. Most islands appear to be around 1 m above MSL.

Appendix 2: Methodology for wave power calculations

It is well known that wave set-up on the reef top increases with the off-reef wave power P_0 (or energy flux) (e.g. Munk and Sargent 1948). This can be expressed as follows:

$$P_0 = \frac{\rho g^2}{32\pi} H_o^2 T \tag{1}$$

Appendix 3: WaveWatch III grids and location of tide gauges

See Figs. 7, 8, 9.

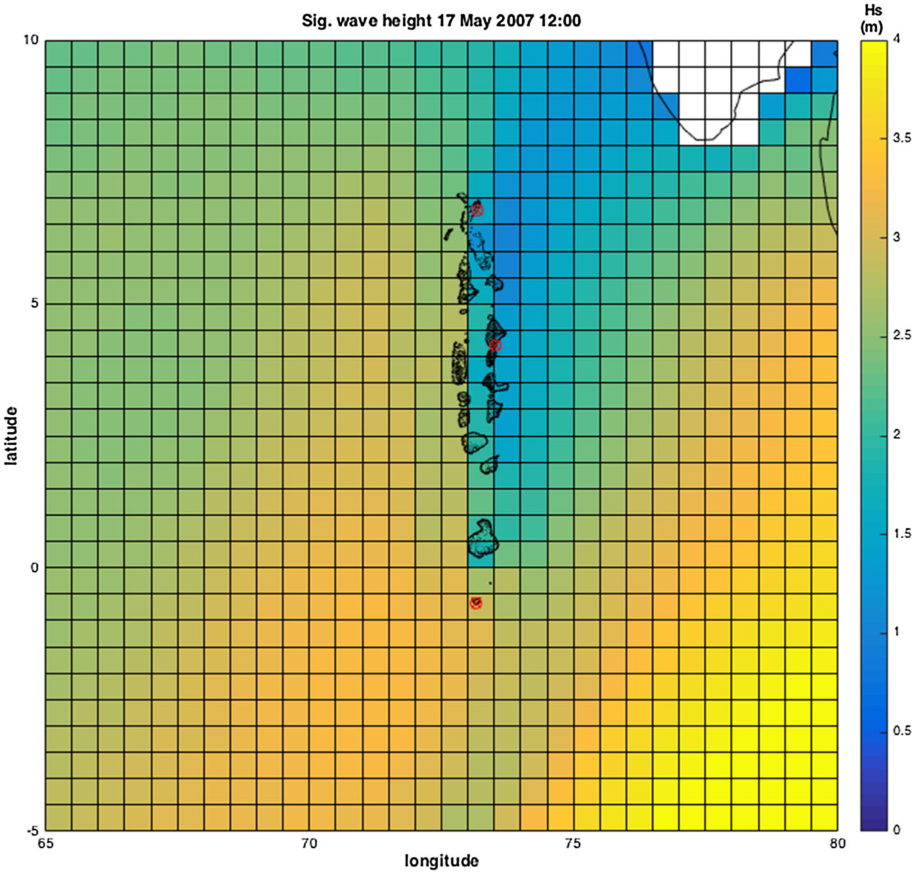

Fig. 7 Tide gauge locations (*red markers*) for which wave time series were extracted from WaveWatch III. Example image is given for significant wave heights during the 17 May 2007 event

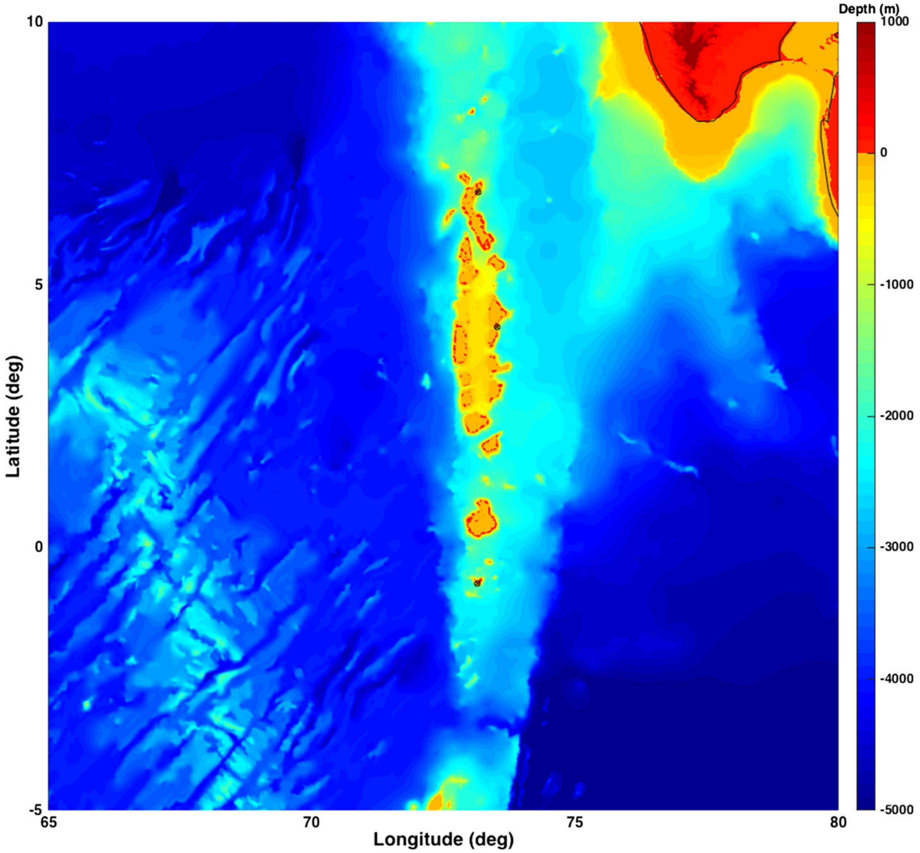

Fig. 8 Bathymetry around the Maldives and location of the tide gauge locations (*black dot markers*) (plotted from GEBCO08 grid: http://www.gebco.net/)

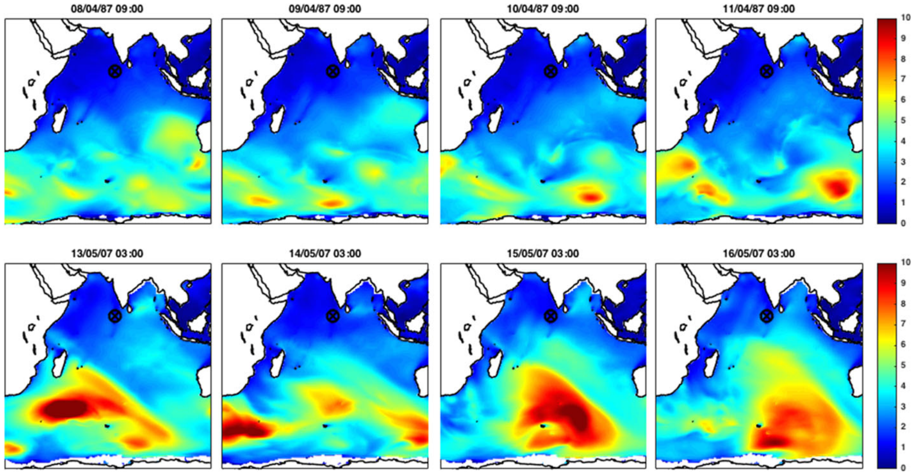

Fig. 9 Significant wave heights (in metres) in the Indian Ocean prior to and during the April 1987 and May 2007 flood events (wave period is plotted in Fig. 4 to indicate the path of the swells)

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