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Estimation of Wave Run-up in the Northern Indian Ocean using WAM model

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ABSTRACT: The aim of this study is to estimate the wave runup on selected beaches around the northern Indian Ocean. The runup has been estimated using ERA-Interim, which is the latest global atmospheric re-analysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF uses the global Wave Model (WAM) model to calculate two dimensional wave spectra. The distances between the model grid points and the beaches have been calculated by a great circle calculator. The beach slopes have been calculated by Google Earth for all locations, except Maldives beach, which was assumed as an imaginary beach because the method of calculating the slope could not be used there. The significant wave height as well as the peak wave period at the grid points is assumed to be the same at the beach. The most frequent estimated runup is between 0.5 m and 1.0 m, which is produced by swell coming from the southern Indian Ocean for all locations except Sri Lanka, India and Maldives shores, where the most frequent runup value is less than 0.5 m. Generally, the largest wave heights are wind sea and the longest wavelengths are swell. The mean elevation of the runup for all locations is 56 cm. It is comparable to the measured values obtained by (Stockdon et al., 2006) at several beaches in USA and the Netherlands who found the mean value of dissipative sites to be 84 cm for all experiments.

Keywords: wave runup, Swell, Wind speed, Northern Indian Ocean

1 INTRODUCTION

The vertical displacement in wave runup consists of two components: Elevation of the mean water level above the still water level, which is called the wave setup, and the fluctuations of that mean, which is called the swash (Ruggiero et al., 2004), the swash is given at times of extrema and the difference between the runup and the setup values. Based on statistics, extreme wave runup R2 is the value of R that will be exceeded 2% of the time. The lowest vertical displacement below the still water level is called wave rundown (Gourlay, 1992).

1.1 *The area of study*

The North Indian Ocean covers two interacting regions affected by wave climate:
1. The Equatorial region that extents to about 5 to 8ºN, which is dominated by local wind forcing.
2. The Arabian Sea, which is dominated by strong southwesterly winds blowing during the summer monsoon (Kantha et al., 2008). The locations at which the runup wave study will be focused. At each location, a statistical analysis of extreme wave runup is made, which is based on 21 years of six-hourly wave height and period data. The locations were selected because of their small beach slopes in order to investigate the condition of the ratio (ξ), of beach slope to square root of wave steepness which must be smaller than 0.3 to be considered as a dissipative wave runup. Google Earth was used to get the beach slope (β). Then tan β (see Table 1) was calculated. The beach slope for Maldives is considered as an imaginary beach since where we were not able to use this method to estimate its beach slope. According to Riyaz (2009), the Maldives islands are small and rarely reach more than 2.5 m above sea level, therefore, they are at risk of flooding, tsunamis, and sea level changes.

2 DATA AND METHODS

The data of wave height, the period and the surface wind have been collected from seven grid point locations near shores in the northern Indian Ocean. The wave height and period values are combined for swell and wind sea. The total wave height is the square root of the sum of the squares of the separate trains:

$H_{total} = \sqrt{H^2 swell + H^2 wind}$

The corresponding shore points (beaches) are selected because they represent different locations and different gentle beach slopes, except the beach on the Maldives, which is assumed as an imaginary beach. The dataset in this study by ERA-Interim, which is the latest global atmospheric re-analysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) in collaboration with many institutions.

The ERA-Interim software covers the period from 1 January 1989 until 31 December 2009 every six hour. The analysis provides the global surface wind, and the two wave parameters significant height and peak period (Kulseng, 2010). The horizontal resolution of the wave model in ERA-Interim is 110 km (Dee et al., 2011).

Table 1. Name of beaches locations, its latitude and longitude, the slope of the beaches, the directions of the beaches, model grid point position (latitude and longitude), the corresponding wave forecasting distance from grid points to the beaches, and direction from beaches to the grid points, this table contain for all location except Maldives beach is just an imaginary beach.

Location	Lat/Long beach	Beach slope	Exposure	Lat/Long grid points	Distance km	Direction to grid points
Oman	18°41'57" 56°45'08"	0.23	E	18.5N 57.0E	34	SE
Somalia	5°23'12" 48°33'35"	0.46	E	0.5N 49.0E	65	SE
Sri Lank	7°47'16" 81°38'37"	0.23	NE	8.0N 81.5E	28	NW
Goa	15°14'34" 73°55'21"	2.30	W	14.5N 74.0E	82	S
India	19°53'11" 72°40'54"	2.30	W	20.0N 27.5E	22	NW
Pakistan	25°28'03" 66°18'02"	0.29	S	25.0N 66.0E	60	SSW

2.1 *Wave runup equation*

The vertical displacement in wave runup R_2 consists of two components Wave setup $<\eta>$ and Swash S:

$$R_2 = <\eta> + S/2 \tag{1}$$

Where swash $S = (S_{inc}{}^2 + S_{IG}{}^2)^{0.5}$

A better linear relation that combines $<\eta> + S/2$ and R_2 has been derived from Stockdon's et al (2006) experiment. Then the Equation (1) becomes

$$R_2 = 1.1\ (<\eta> + S/2) \tag{2}$$

When the Irribaren number, $\xi_o > 0.3$, then the general formula of non-dissipation wave runup has been written as

$$R_2 = 1.1(0.35\ \beta_f(H_oL_o)^{1/2} + [H_oL_o(0.56\ \beta_f^2 + 0.004)]^{1/2}/2) \tag{3}$$

When $\xi_o < 0.3$ the dissipative runup may be calculated as

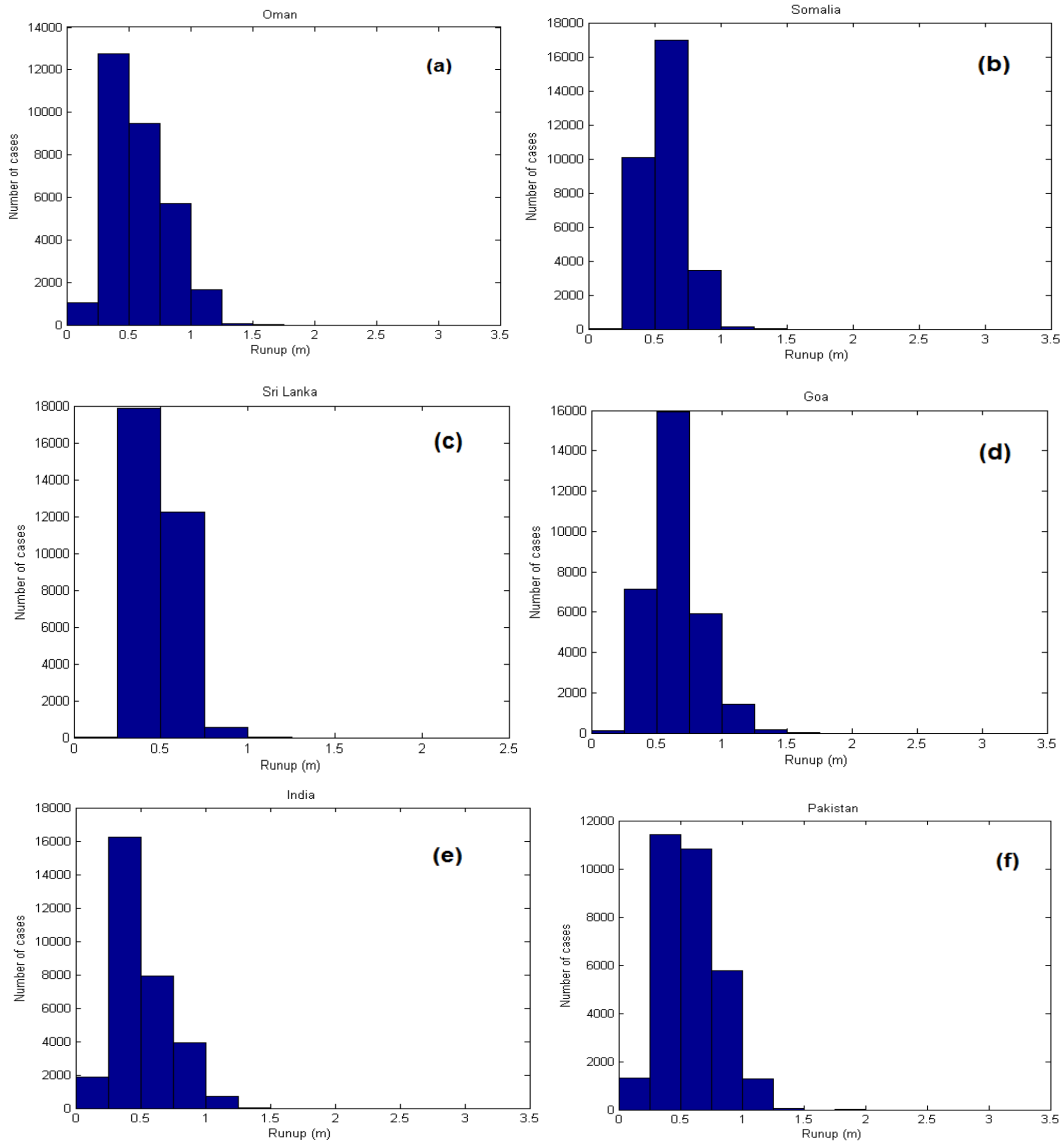
$$R_2 = 0.043(H_oL_o)^{1/2} \tag{4}$$

3 RESULTS

3.1 *Frequency distribution of runup*

The frequency distribution of the estimated runup at the shore in Oman (Figure 1a) reveals that in 49% of the cases the runup is between 0.5m and 1.0m, while the highest number of cases of wave runup at the shore in Somalia, 66%, occurs between 0.5m and 1.0m (see Figure 1b). At Sri Lanka shore, Figure 3c shows that in most cases, 52%, wave runup is less than 0.5m. The estimation of wave runup at the shore in Goa reveals that 71% occur between 0.5 and 1.0m. At the shore in India, Figure 1d, most number of cases, 59%, runup is less than 0.5m. While at the shore in Pakistan, Figure 1e shows that 53% of the cases runup is between 0.5 and 1.0m. Figures 1g1 and 1g2 demonstrate that at an imaginary dissipative beach when the Iribarren number $\xi < 0.3$ in Maldives 58% of the cases runup is less than 0.5m, while on a non-dissipative beach with the Iribaren number equal to 0.3. 58% of the cases runup is between 0.5 and 1.0m.

Summary: Generally the highest number of cases of estimated wave runup lies between 0.5m and 1.0m for all locations except Sri Lanka, India and Maldives (dissipative runup) shores where it is less than 0.5m (see Figures 1e and 1g).



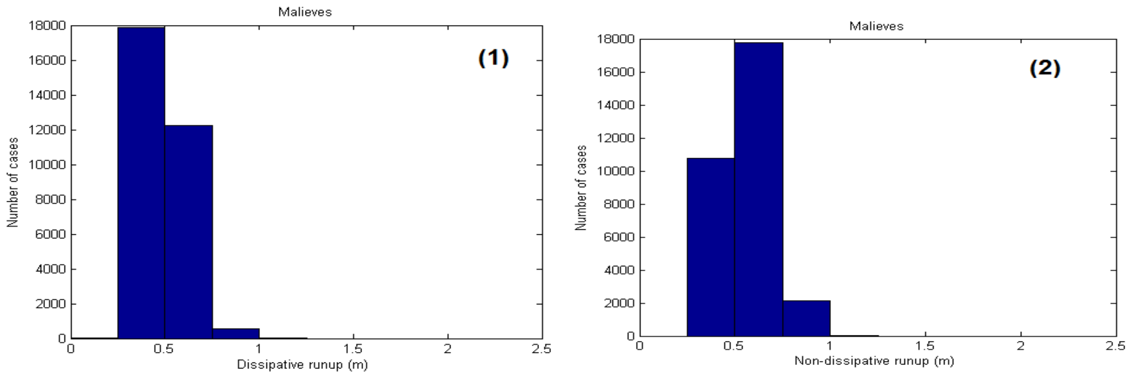
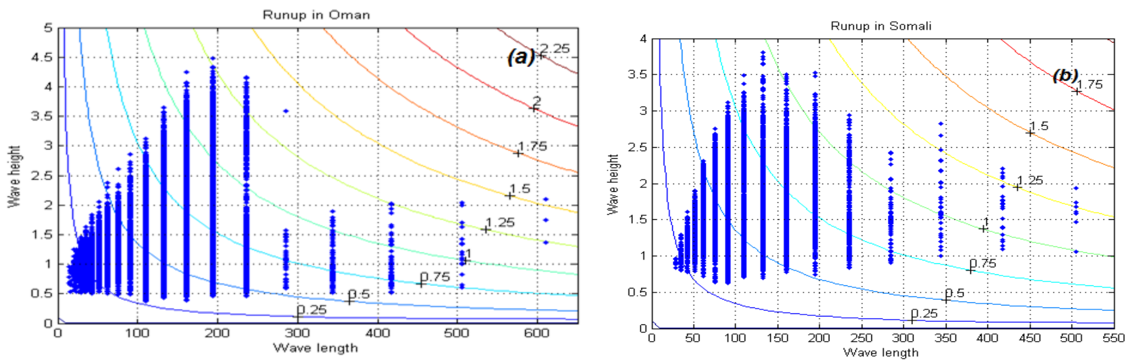


Figure 1. Histogram of runup (m) at the shore in (a) Oman (b) Somalia (c) Sri Lanka (d) Goa (e) India (f) Pakistan. Histogram of runup (m) at the shore in Maldives: (1) Dissipative runup and (2) Non-dissipative runup.

3.2 *Runup as a function of wave height and wave length*

Figure 2a shows the runup as a function of wave length and wave height at the shore in Oman. Runup more than 1.25 m is produced by wind waves with heights between 3.5 to 4.5 m and wave lengths between 200 to 300m. Values more than 1.25 m also occur for swell with height 2.0 m and wave lengths longer than 500 m. The maximum runup value (> 1.5 m) is generated by a long swell of about 600 m. In Figure 2b At Somalia's shore runup more than 1.0 m is generated by wind waves with wave heights between 2.5 to 3.5 m and wave lengths between 150 to 250m. Runup more than 1.0 m occurs for swell with wave heights around 2.0 m and wave lengths longer than 280 m. Ten cases of extreme runup larger than 1.25 m occur for swell waves longer than 340 m. At Sri Lanka's shore, Figure 2c shows two cases of extreme wave runup larger than 1.5m which occurs at long wave length, most of the extreme wave runup occurs for swell between 500m to 800m wave length. At Goa shore, in Figure 2d runup more than 1.5 m is produced by wind waves for high wave heights between 4.0 to 6.0 m and wave lengths between 200 to 300m. The extreme values of wave runup are only at high wave height and medium wave length and therefore due to wind. Figure 2e at Indian shore, runup more than 1.25 m occurs with wind waves for high wave height between 3.0 to 4.5 m and wave lengths between 200 to 300m. Runup more than 0.75m occurs for swell with wave heights between 0.5 to 1.0 m, and wave lengths between 400 to 600m. Figure 2f shows, at the shore in Pakistan, two cases of the extreme values of wave runup more than 1.75m at swell waves longer than 700m. At Maldives shore Figure 2g shows the runup is dependent of long swell wave more than wind speed.

Summary: Generally the extreme runup is generated by swell of long wave lengths. The highest wave heights do not affect the extreme runup. Locations at high latitude: Oman, Goa and Pakistan (see Figures 4a, 4d and 4f) have higher wave heights than the other locations due to the monsoon, especially the summer monsoon.



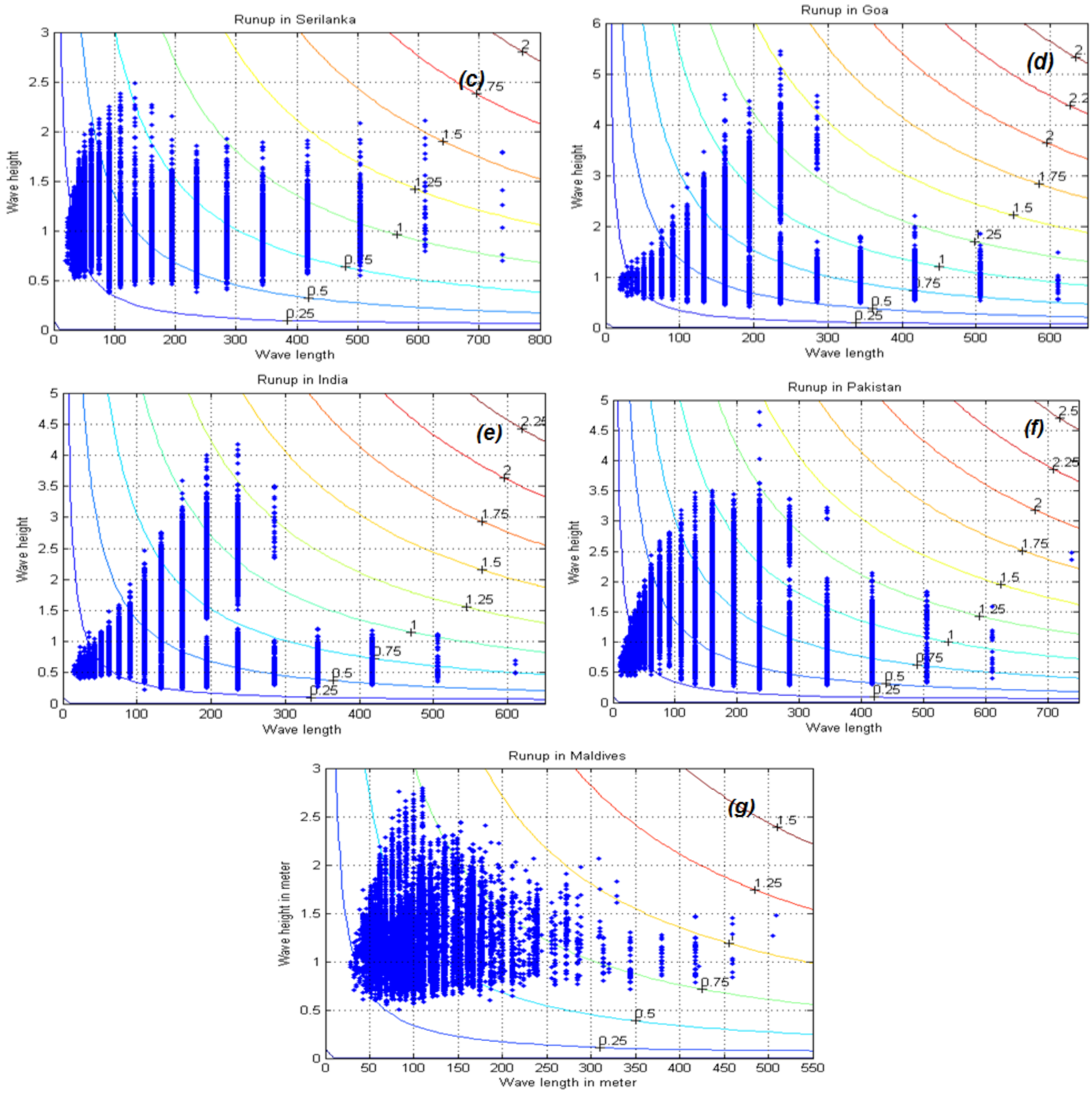


Figure 2. Wave runup as a function of wave height and wave length at: (a) Oman, (b) Somalia, (c) Sri Lank, (d) Goa, (e) India, (f) Pakistan and (g) Maldives. The contour lines are given by the runup formula for dissipative beaches.

4 DISCUSSION

The frequency distributions of estimated wave runup at the shores reveal that more than half of the time runup is less than 0.5–0.75m. Wave height values become higher at high latitudes (Oman, Pakistan, and Goa) and decrease towards the Equator (Sri Lanka, Maldives and Somalia). The highest runup is generated at medium wind speed. This suggests that swell strongly contributes to generate extreme runup. The methods, which we have used, contain some uncertainty because we do not involve the wind direction; we just assume that the wave height and the period at the grid point are the same at the beach. We also neglected the tidal effect. We assumed that the slope is not changing from sea to the beach. We took the imaginary beach slope in Maldives at two cases investigating two conditions: Dissipative, when the Iribarren number is less than 0.3, and a non-dissipative beach with Iribarren number equal to 0.3.

5 CONCLUSION

We estimated runup on gentle beaches for seven locations in the northern Indian Ocean covering the period from 1 January 1989 to 31 December 2009 every six hour. The most frequent estimated wave runup ranges between 0.5 and 1.0 m. In general, long swell is the dominant factor of runup. The wave height depends on locations, it increases with latitude.

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