Oceanologia 65 (2023) 503—516

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.journals.elsevier.com/oceanologia

ORIGINAL RESEARCH ARTICLE

Remotely induced storm effects on the coastal flooding along the southwest coast of India

P.S. Swathy Krishna [a,b], **Valliyil Mohammed Aboobacker** [c], **Madipally Ramesh** [a,b,*], **L. Sheela Nair** [a]

[a] *National Centre for Earth Science Studies, Thiruvananthapuram, Kerala, India*
[b] *Cochin University of Science and Technology, Cochin, Kerala, India*
[c] *UNESCO Chair in Marine Sciences, Environmental Science Center, Qatar University, Doha, Qatar*

Received 9 January 2023; accepted 29 March 2023
Available online 18 April 2023

KEYWORDS
IASO swells;
ERA5 winds;
Indian Ocean;
Kerala coast;
Coastal inundation;
Wave runup

Abstract The southwest coast of India is exposed to long-period swells propagated from the South Indian Ocean during pre- and post-monsoon seasons. Although swells from the Southern Ocean and Atlantic Ocean were identified in the North Indian Ocean, their existence and impact along the southwest coast of India were not well investigated. On 19 March 2019, the Valiyathura-Shangumukham coastal stretch along the southwest coast of India experienced an unexpected coastal inundation without having a prompt forecast/warning, and not induced by a storm/cyclone in its vicinity. The present study investigates the causative forces of this inundation and estimates the wave runup and inundation. The study reveals that an unusual swell system was developed in the Indian-Atlantic-Southern Oceans (IASO) interface during 10—12 March and propagated towards the southwest coast of India. The measured wave spectra off Varkala clearly depicts the presence of long-period swells (T_p>18 s), which dominantly occurred as single-peaked. Wave modelling has been carried out to characterize the wave transformation associated with the "IASO interface swells" along the southern Kerala coast. A wave runup of up to 0.93 m height and a coastal inundation of up to 83 m onshore have been estimated during this event.

* Corresponding author at: National Centre for Earth Science Studies, Thiruvananthapuram, Kerala, India; Cochin University of Science and Technology, Cochin, Kerala, India.
E-mail address: ramesh.madipally@ncess.gov.in (M. Ramesh).

Peer review under the responsibility of the Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

https://doi.org/10.1016/j.oceano.2023.03.003

1. Introduction

Swells play a major role in the distribution of energy from the deep ocean to nearshore regions and contribute to wave-induced coastal dynamics as they interact with wind seas, tides and currents (Hanley et al., 2010). Waves in the North Indian Ocean (NIO) are generally dominated by the swells propagated from the South Indian Ocean (SIO) during pre- and post-monsoon seasons (Anoop et al., 2015; Sashikant et al., 2013). However, local wind seas induced by sea breeze often superimpose with these swells and result in complex sea states during pre-monsoon seasons (Glejin et al., 2013; Piyali et al., 2019; Vethamony et al., 2011). In the Arabian Sea (AS), southwest monsoon (SWM) winds and tropical cyclones generate high swells (Aboobacker et al., 2011a). Long-period swells from far SIO and the Atlantic Ocean were also identified in the AS (Samiksha et al., 2011). The AS also experiences the northerly shamal and makran swells during pre- and post-monsoon seasons (Aboobacker et al., 2011b; Aboobacker and Shanas, 2018; Anoop et al., 2020).

Long-period swells generated by tropical or extra-tropical storms cause flooding along the coasts in different parts of the world (Andrew et al., 2015; Kurian et al., 2009a). Along the SW coast of India, the relative narrowness of the continental shelf and a near perpendicular orthogonal of swells enhance the wave setup and increase the swell heights compared to the other coasts of India (Remya et al., 2016). In low-lying areas, the combination of long-period swells and spring tides can contribute to nuisance flooding (Hamed et al., 2015). There were such incidents occurred along the Kerala coast on a few occasions (Kurian et al., 2009b). For example, high swells that occurred in May 2005 have marooned almost all the low-lying areas of the Kerala coast and the southern coast of Tamil Nadu. The coastal floods that occurred at Chavakkad in September 2021, at Alappuzha in September 2015, and at different parts of the Kerala coasts in April 2018, were a few other incidents as reported by the news media. Recently (May 2021), cyclone Tauktae caused severe flooding at Thiruvananthapuram, the southern tip of the Kerala coast. Most of these events are associated with an initial receding of coastal waters, followed by strong swells, called Kallakadal (Kurian et al., 2009b). During the Kallakadal of May 2005, the Adimalathura coast, near Thiruvananthapuram was inundated about 500 m inland (Kurian et al., 2009b).

When waves approach the coast, most of the energy dissipates across the surf zone by breaking. A part of this energy is converted into potential energy and makes a runup on the beach (Stockdon et al., 2006). The swash is dominated by incident energy on reflective beaches, and more extreme wave runup occurs for swells with wavelengths between 500 m and 800 m (Abdalazeez Ahmed, 2012). Highly reflective beaches have a slope between 4° and 10° with medium sand grains (Scott et al., 2011). The Kerala coast has been distinctively classified into high-energy, medium energy and low-energy regions, depending upon the beach face and grain size distributions (Kurian, 1987). The southern Kerala coast falls under high-energy coast, and the impact of flash flood events along this coast is relatively higher (Ramesh et al., 2022).

The number of flooding events along the Kerala coast is increasing year by year, and most of the events were not given proper scientific attention (Sachin et al., 2014). Future projections indicate that extreme wind speeds and wave heights in the SIO are increasing towards the end of the century (Krishnan et al., 2022). The connectivity of flash floods with SIO swells is somewhat known (Remya et al., 2016). However, this needs to be further elaborated on the context of swells generated at an interface between the Indian, Atlantic and Southern Oceans (IASO). The present study aims to fill this gap by exploring swell generation regions in the IASO interface, which propagate towards the NIO and impact the southern Kerala coast. Flooding of March 2019 has been investigated by identifying causative remote storms, swell generation, and propagation, and analyzing the nearshore wave regime including wave runup. The study also emphasises the importance of continuous monitoring and prediction of distant storms and corresponding swell propagation, which contribute significantly to the pre-monsoon coastal flooding.

2. Study area

Kerala is an Indian coastal state located at the southwest of the subcontinent with a coastline of 590 km distributed across 222 coastal villages with an average population density of 2,262 people per square kilometre (Sachin et al., 2014). Nearly 40% of the population lives within 25 km of the coast and as the sea level rises, low-lying land areas and small islands could shrink due to flooding and coastal erosion, forcing large-scale migration inland. Thiruvananthapuram coast is located at the extreme south of Kerala coast. Figure 1 shows the study region that extends from Kanyakumari in the South to Varkala in the North covering approximately 120 km alongshore. The Valiyathura is in the middle, and Shangumukham is 2.4 km north of it. The Thiruvananthapuram coast is a high-energy coast, where the shelf gradient is 33.33×10^{-3}, the highest along the SW coast of India (Kurian, 1987; Ramesh et al., 2022). The mean grain size here is around 0.30 mm. The annual mean wind speed is around 4.3 m/s along the Thiruvananthapuram coast and 5.0 m/s in the offshore region (Abdulla et al., 2022). This region experiences a maximum H_s of around 6.0 m and 2.0 m during SW monsoon and during fair-weather seasons, respectively. Whereas the mean H_s are around 3.0 m and 1.5 m during SWM and fair-weather seasons, respectively (Baba and Joseph, 1988).

3. Data and methodology

3.1. Wind data

This study utilises the ECMWF Reanalysis v5 (ERA5) winds over a semi-global domain (0°—120° E, 90°S—30°N) covering the Indian Ocean and part of the Southern, Atlantic and Pacific Oceans to evaluate the storm events which cause the flash floods off Valiyathura. These winds are also used as the surface forcing in the wave simulations. The ERA5 winds are extracted for every 1 hour on a 30 km × 30 km spa-

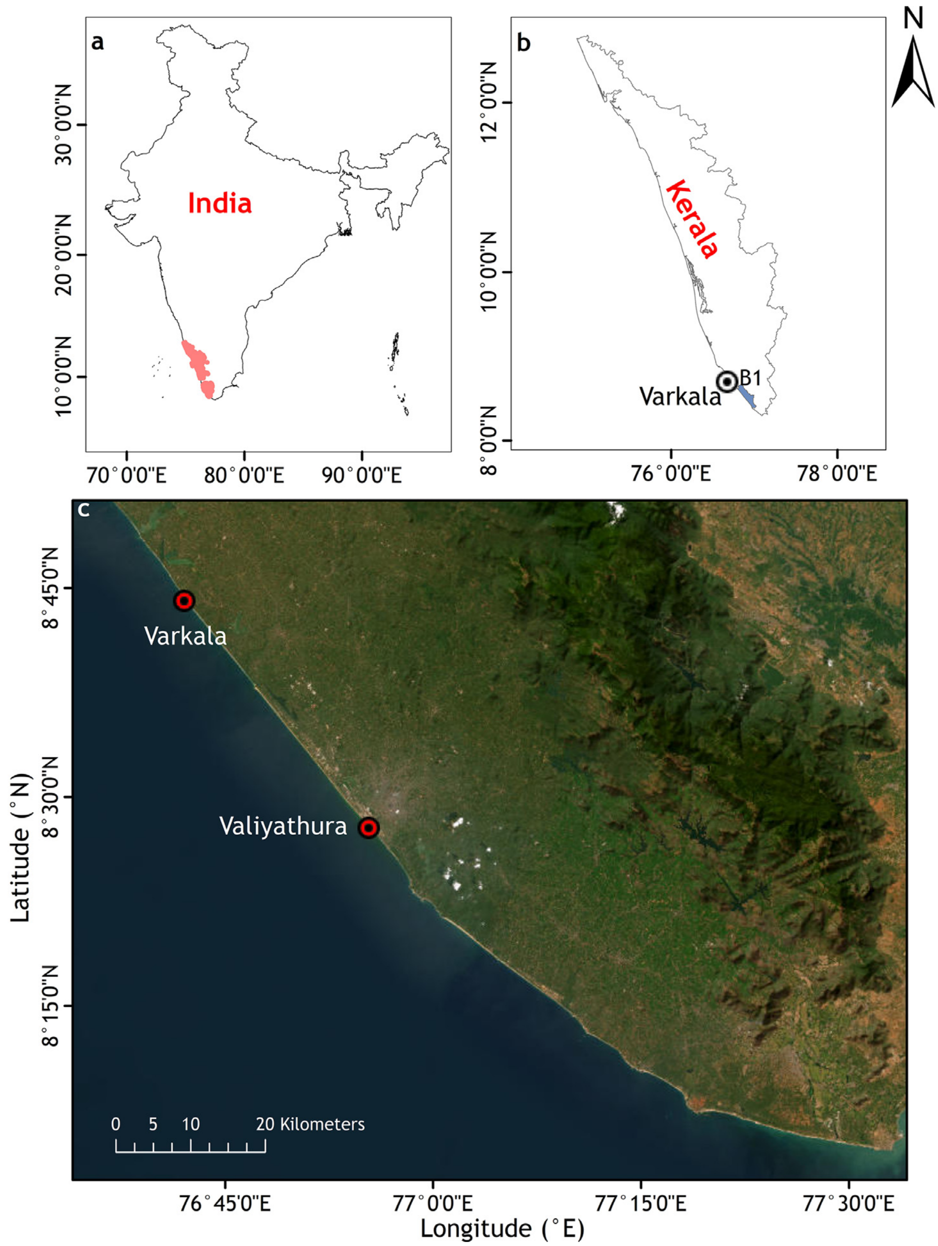


Figure 1 Location map of the study area: a) India sub-continent, b) SW coast of India with buoy location (B1), and c) Thiruvananthapuram coast. Shangumukham is 2.4 km north of Valiyathura.

tial resolution during March 2019 (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). The ERA5 winds are found satisfactory for the global ocean modelling (Parsons et al., 2018). Recent studies on the wind-wave characteristics over the Indian ocean has made use of ERA5 datasets and are validated with measurements (Aboobacker et al., 2021; Mahmoodi et al., 2019; Parsons et al., 2018; Sreelakshmi and Prasad, 2020a, b). The ERA5 waves are also extracted for every 1 hour on a 55 km × 55 km spatial resolution during March 2019 for the spatial wave data analysis.

3.2. Wave measurements

The present study analyses the measured wave spectra and integral parameters along the Thiruvananthapuram coast. A directional wave rider buoy (DWR-MKIII) developed by Datawell BV, Netherlands, was deployed at 15 m depth off Varkala during 01—22 March 2019 (Figure 1b). The DWR is provided with the HF link facility for online transmission with wave data output rate of 1.28 Hz for distances up to 50 km over the sea. The heave range of the buoy is −20 m to +20 m with a resolution of 1.0 cm. The range of frequency in the spectra is 0.01—0.58 Hz (wave period between 1.6 s and 100 s), and the directions are from 0° to 360°. Continuous wave data for every 30 minutes with a sampling period of 20 minutes were collected.

3.3. Wave modelling

The wave runup calculations require fine-resolution wave data close to the shore. Therefore, numerical wave

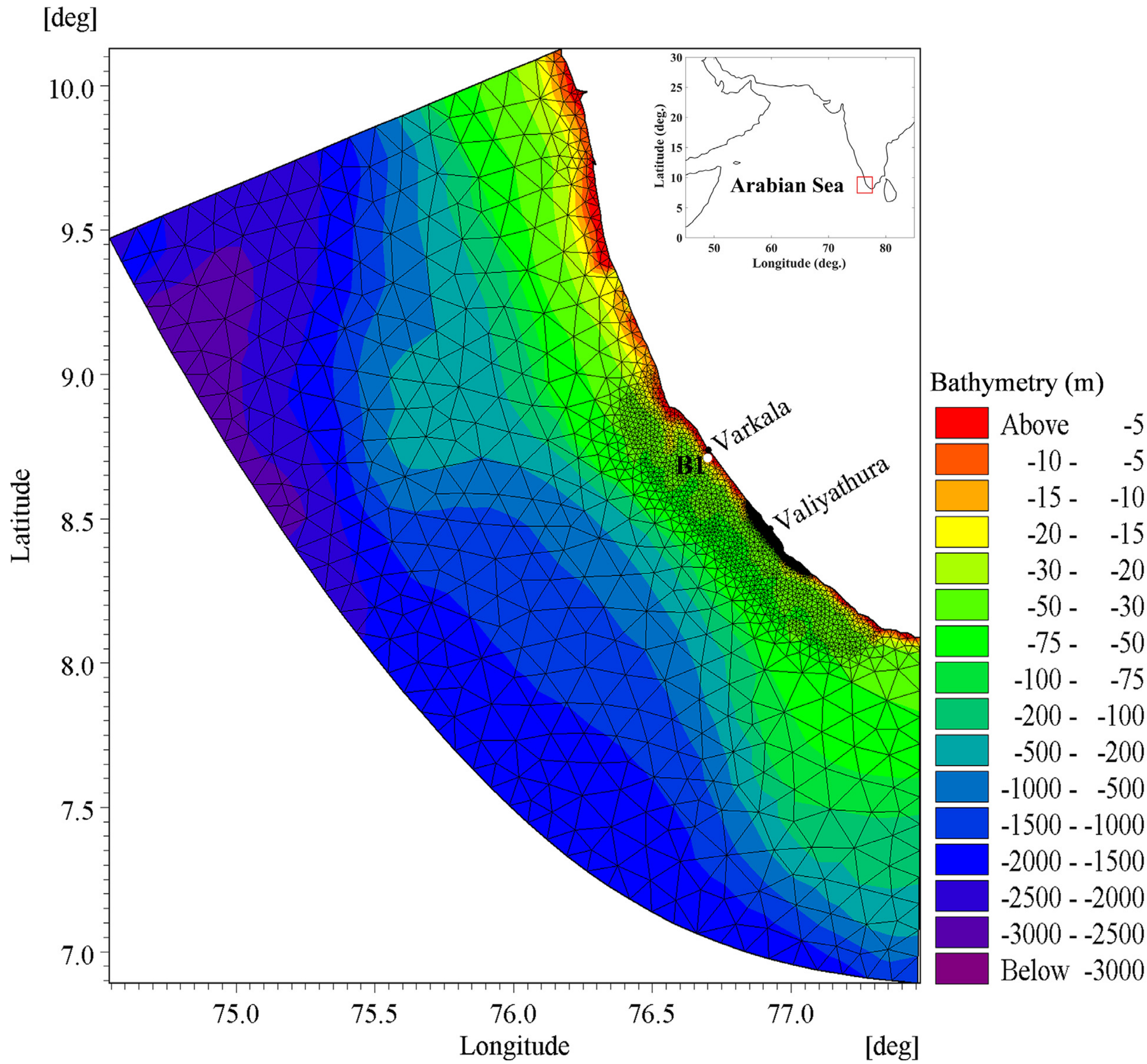


Figure 2 Model domain, bathymetry and flexible mesh used for wave simulations off the Thiruvananthapuram coast. B1 is the wave measurement location. Valiyathura is the region where the flash floods occurred on 19 March 2019.

simulations have been carried out along the Thiruvananthapuram coast to resolve the shallow water effects and to extract the nearshore wave parameters (at 5 m depth) for the wave runup calculations. For this purpose, a local model has been set up using MIKE 21 — Spectral Waves (DHI, 2019). The model domain extends 220 km in the north-south axis covering the entire Thiruvananthapuram coast and has a width of 199 km in the north and 133 km in the south (Figure 2). 1 arc-minute resolution ETOPO1 data (Amante and Eakins, 2009) along with digitized hydrographic charts available at National Centre for Earth Science Studies (NCESS) has been used to generate the model bathymetry. A variable resolution mesh has been adopted for the proper representation of deep, intermediate, and shallow waters. The mesh size in the outer region is around 6—7 km (side of the triangle), while that in the intermediate zone is around 1.4 km and that at the Valiyathura coast is around 300 m. The ERA5 winds have been used to force the surface boundary, while the wave parameters extracted from ERA5 waves have been applied as the boundary conditions all along the 3 open boundaries. The simulations have been carried out in March 2019.

The wave model has been tuned with different values of coefficients such as dissipation due to bottom friction (S_{bot}), white capping dissipation coefficient (C_{dis}) and wave breaking parameter (γ). Earlier studies used C_{dis}, and γ as calibration parameters in the nearshore wave simulations along the SW coast of India (Nair et al., 2011, 2013; Parvathy et al., 2014). Kurian et al. (2009a) applied varying bottom friction estimated using mean grain diameter (D_{50}) ranging from 0.00025 m to 0.0003 m for the wave simulations along the southern Kerala coast. In the present study, a better calibration has been obtained when $C_{dis} = 2.6$ and $\gamma = 0.5$. We used $D_{50} = 0.0003$ obtained from field investigations to calculate the bottom dissipation.

3.4. Beach slope

The beach slopes at Valiyathura and Shangumukham coast are measured by field surveys using clinometer compass (McFall, 2019). The compass has been placed at the mid-water line during low tide, to measure the foreshore slope of the beach. Three field surveys are conducted in March 2019, to characterise the beach slopes.

3.5. Wave runup computations

The wave induced maximum water elevation on the foreshore is estimated as the extreme wave runup using both wave (H_s and T_p) and beach slope (β) (Torres-Freyermuth et al., 2019). The amount of runup is the extreme vertical height above still water level that the rush of water reaches. It is affected by wave set up and swash (Stockdon et al., 2006). The wave set up is the elevation of the mean water level (MWL) above the still water line due to onshore mass transport by the action of waves. We find that the selected coastal stretch, namely Shangumukham to Valiyathura along the Thiruvananthapuram coast is a dissipative beach based on the Irribarren number (ξ) and foreshore slope β, which are collectively defined as:

$$\xi = \tan\beta/\sqrt{H_b/L} \quad (1)$$

where L is the wavelength and H_b is the breaker wave height.

The estimated β and ξ for the Thiruvananthapuram coast are 0.034—0.047 radians and 0.20— 0.27, respectively. When $\beta <$ 0.1 radians and ξ <0.3, the runup is independent of β (Stockdon et al., 2006). Thus, runup can be approximated to Equation (2) as follows:

$$R_{2\%} = 0.043(H_s L)^{1/2} \quad (2)$$

Based on this approximation the wave runup along the Thiruvananthapuram coast has been estimated.

4. Results and discussion

4.1. Spectral variability in response to remote storms

The waves measured from 1 to 22 March 2019 indicate that the H_s are moderate except on a few occasions (Figure 3). Interestingly, the highest H_s occurred in two instances — one with a lower T_p (about 9 s on 6 March) and the other with a relatively higher T_p (around 20 s on 18 March). The corresponding mean wave directions are 200° and 210°, respectively. The former is associated with a wind sea-dominated sea state, while the latter is associated with a long-period swell-dominated sea state. Typically, there are three sea states along the west coast of India: wind sea-dominated, swell-dominated and co-existence of wind seas and swells in nearly equal proportion (Aboobacker et al., 2011a; Rashmi et al., 2013). The presence of two wind sea components from two different directions along with a distant swell (Aboobacker et al., 2014) and two swell components from different directions along with wind seas (Anoop et al., 2020) were also identified along the west coast of India.

The measured 1D spectra measured highlights typical and peculiar spectral characteristics (Figure 3). Generally, they are a combination of single-peaked and multi-peaked spectra during the measurement period. The spectra on 06 March reveal the co-existence of a swell and a wind sea, during which the H_s is above 1.0 m. The frequencies corresponding to the primary and secondary peaks are 0.11 Hz (swell) and 0.24 Hz (wind sea), respectively. The generation area of the swell present here could be the tropical/subtropical SIO as the peak swell period is only around 9s, during which the peak swell direction was 180°. This is a potential swell generation area during the pre- and post-monsoon season as evidenced by Aboobacker et al. (2011a). The peak wind sea direction was around 305°, which is due to a sea breeze. Sea breeze activity is prominent along the SW coast of India during the pre-monsoon season (Aparna et al., 2005). Although wind sea energy varies, the influence of sea breeze is evident in the wave spectra in variable frequencies throughout the measurement period.

On 09 March, the spectrum is single-peaked consisting of a dominant SIO swell from 195° having a peak frequency of about 0.095 Hz, during which the energy in the wind sea region is very low. The absence of wind sea peak here is associated with low/no wind conditions (at 12 AM), which is apparent from the diurnal patterns of the coastal winds along the southwest coast of India during the pre-monsoon season (Aboobacker et al., 2021, 2014).

On 16 March, the region experienced two major swell components; primary swell was from 195° with a frequency of about 0.08 Hz and the secondary swell was from 185° with a frequency of about 0.11 Hz. This is a mixed sea state with swells from far and near regions of the SIO. In the following days (17 and 18 March), the primary peak has been shifted to a relatively lower frequency region with a narrow spectral band having a peak frequency of about 0.05—0.055 Hz, and the energy in the secondary swell peak has been gradually weakened. During these days, the primary swell directions were shifted to 210°, while the secondary swells remained at 180—185°. This brings the possibility of longer swells propagating from a region farther than the swells generated in the preceding days. On 19 March, the secondary swell peak has been disappeared, while the primary peak (from 210°) remained in the lower frequency region with a peak frequency of about 0.065 Hz. These swells have had a higher celerity in absence of muti-frequent and multi-directional waves. In the nearshore waters, especially in the breaker zone, the transformation of kinetic energy to potential energy yields to higher wave heights along with strong elliptical/linear motion for the particles under the waves. On a flatty beach, this may lead to considerable wave runup and coastal inundation. The influence of these longer swells has been gradually weakened and the spectra started to retain the pre-existing conditions in the following days, as seen from 20 to 22 March.

4.2. IASO interface swells

The swells present along the west coast of India are predominantly propagated from the SIO (Aboobacker et al., 2011a; Remya et al., 2016). Although swells from the Southern Ocean (SO) and Atlantic Ocean (AO) are present in the NIO (Alves, 2006; Samiksha et al., 2011), their impact along the

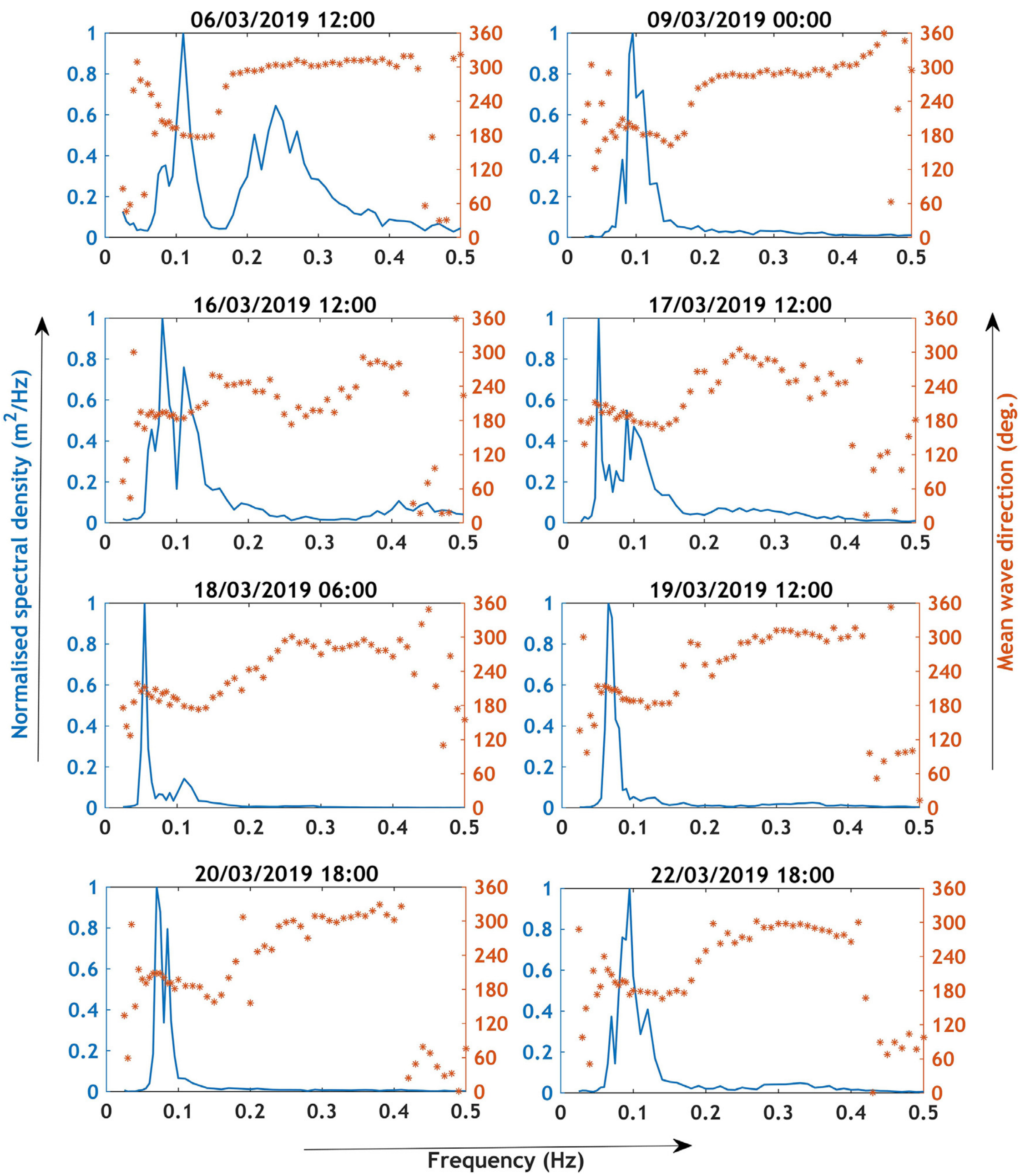


Figure 3 1D wave spectra and corresponding MWD during different wave conditions.

west coast of India has not been well-investigated. Here, the genesis of distant swells has been analysed with reference to the spectral variability of Varkala. The ERA5 winds show that the IASO interface experiences large storms, out of which a few storms generate S/SSW/SW winds (Figure 4), which can generate swells from the respective directions and propagate towards the west coast of India. The IASO interface winds from S/SSW/SW directions are evident during 10—12 March 2019, which was initially formed in the AO-SO interface, and ultimately the system has made an eastward propagation to the IO-SO interface with considerable spatial enhancement. The wind speeds during this event are of the order of 15—25 m/s. The storm has been weakened in the successive days, and the southerly wind components were disappeared. There have been two tropical cyclones formed in the SIO during the study period: (i) Idai developed east of Madagascar (10—14 March 2019) and (ii) Savannah developed southeast of Indonesia (14—21 March 2019) with maximum wind speeds of about 195 km/hr and 165 km/hr, respectively (https://tropic.ssec.wisc.edu/storm_archive/2019/storms/tracks/). Compared to the IASO interface winds, the impact of these cyclones is limited to relatively small regions.

It is evident from ERA5 waves (Figure 5) that strong southerly swells developed in the AO-IO interface (around 10°E) started to make a clear presence in the SIO on 11 March as it propagates towards the north. The swell generation area has been further shifted towards the east according to the propagation of the storm system, while the southerly swells continued to develop and propagate

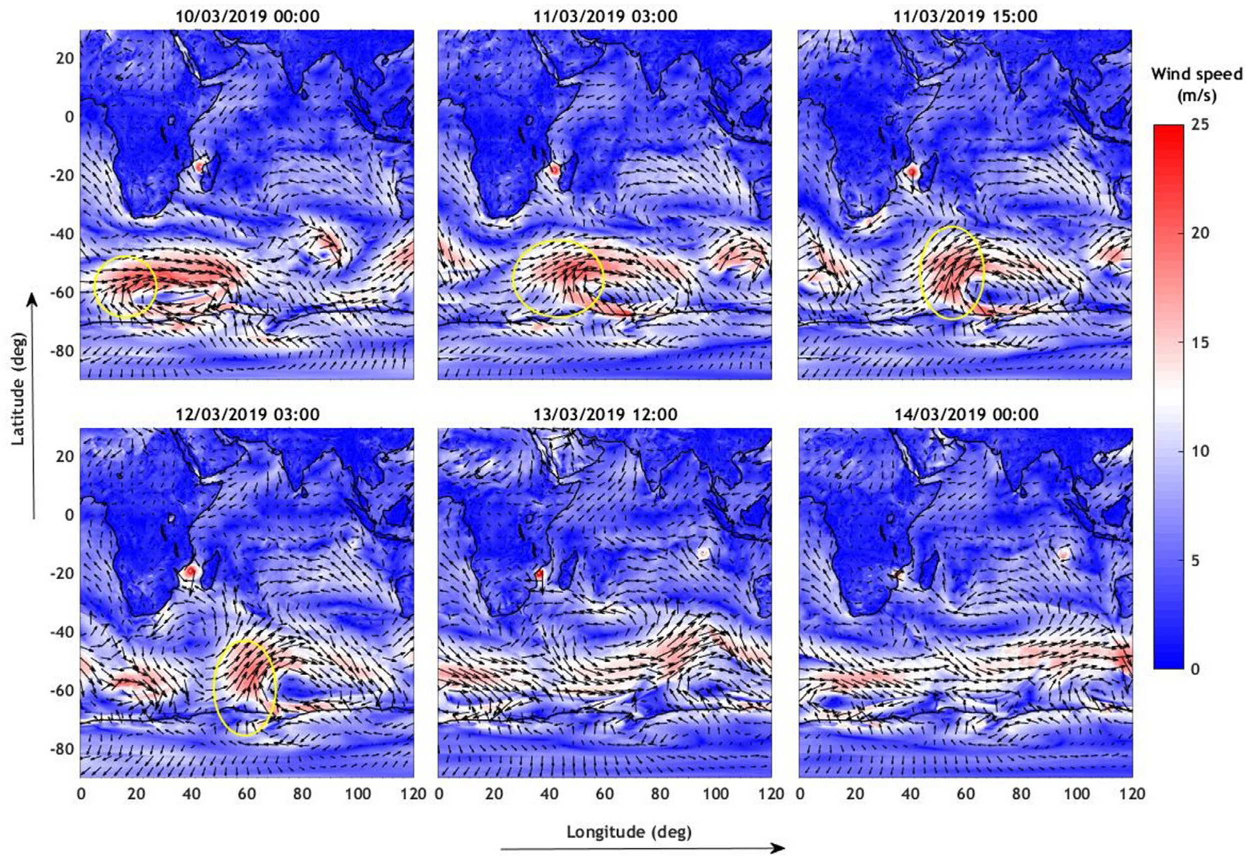


Figure 4 Snapshots of ERA5 winds during 10—14 March 2019.

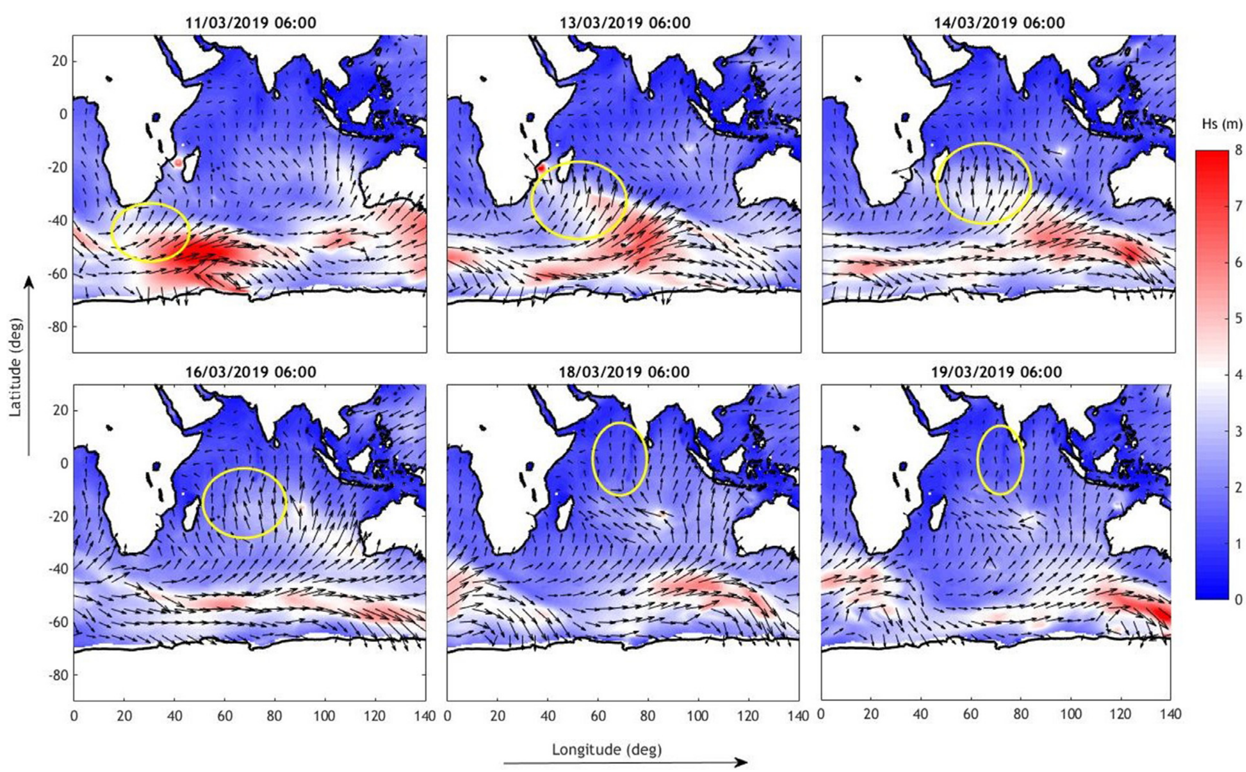


Figure 5 Snapshots of ERA5 wave heights and directions during 10—14 March 2019.

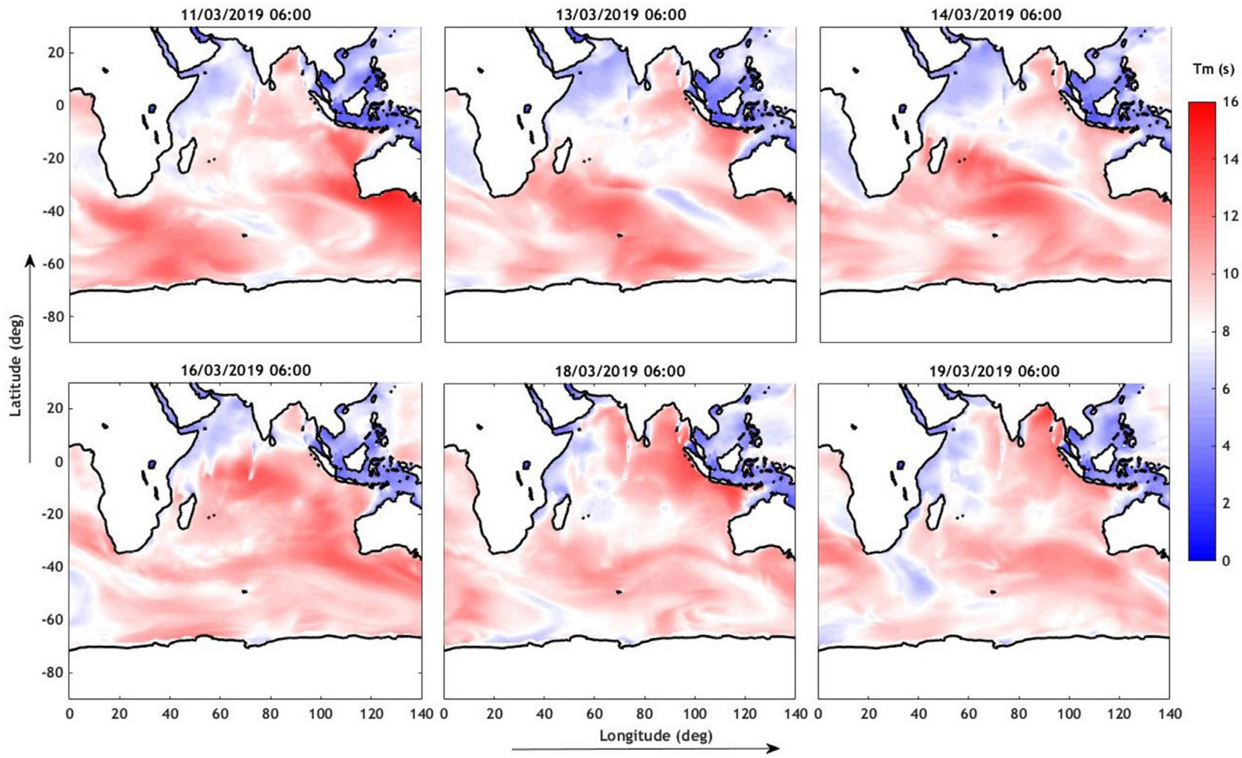


Figure 6 Snapshots of ERA5 mean wave periods during 10—14 March 2019.

through the SIO. On 13 March, these swells reached around 30° S, east of Madagascar, with H_s up to 5.0 m. Although the energy has been gradually attenuated, the swells continued to propagate and reached the AS on 17 March. This has prevailed until 19 March. The wave spectra measured off Thiruvananthapuram indicates the presence of these swells during 17—19 March having peak energy in the very low-frequency region (Figure 4). Since these swells are generated in the IASO interface and propagated towards the NIO, we hereby named them as "IASO interface swells".

The ERA5 mean wave periods (T_m) clearly substantiates the propagation of IASO interface swells through the SIO and NIO. It was not only propagated up to the west coast of India but also identified along the head of BoB (Figure 6). The T_m of the IASO interface swells reach above 12 s in the AS and BoB. A rough estimation of the propagation duration of the swells considering the distance between the storm area and the coast, and the wavelength indicate that the swells generated at around 10°E, 65°S can take at least 7 days to reach the Thiruvananthapuram coast. Thus, the swells generated on 10 March have reached on 17 March. This indicates, the swells reached along the Thiruvananthapuram coast during 17—19 March are dominantly from far distance including AO and SO, which has a higher celerity. When these high wavelength approaches a flat and reflective beach, the possibility of wave runup is high. The wave measurements indicate that the T_p along the Varkala coast increases from about 12 s to 20 s from 17 to 19 March, during which the MWD has been changed from about 200° to 210°, a clear shifting of swells from SIO origin to IASO interface origin (Figure 7). This is a peculiar feature considering the pre-existing wave conditions in this region. Although H_s is not very high (about 1.0 m) during this event, the longer period and corresponding celerity of the IASO interface swells along with the flat beach topography of Valiyathura-Shangumukham stretch together caused the flash floods.

4.3. Model validation

The model results have been validated against the measurements at B1. Figure 7 shows the time series comparison of H_s, peak wave period (T_p) and mean wave direction (WMD) between the model and measurements during 01—22 March 2019. The model parameters have reasonable match with measured values with estimated correlation coefficients of 0.85 and 0.92 for H_s and T_p, respectively. The scatter indices of H_s and T_p are 0.15 and 0.19, respectively, while the bias is 0.01 m and 0.17 s, respectively. The root means square errors for H_s and T_p are ± 0.15 m and 2.23 s, respectively. The model wave direction has a perfect match with the measurements, except on a few occasions. It has a bias of less than 4°. These comparisons are consistent with the earlier modelling attempts along the southwest coast of India utilizing MIKE 21 SW (Parvathy et al., 2014; Remya et al., 2012), Wavewatch III (Samiksha et al., 2011) and SWAN (Amrutha et al., 2016) Figure 8.

4.4. Nearshore wave transformation and wave runup

4.4.1. Wave transformation

The results of the validated wave model are utilized in this subsection to investigate the nearshore wave transformation and to estimate the wave runup. During the event on 18-19 March, waves approached the coast with a max-

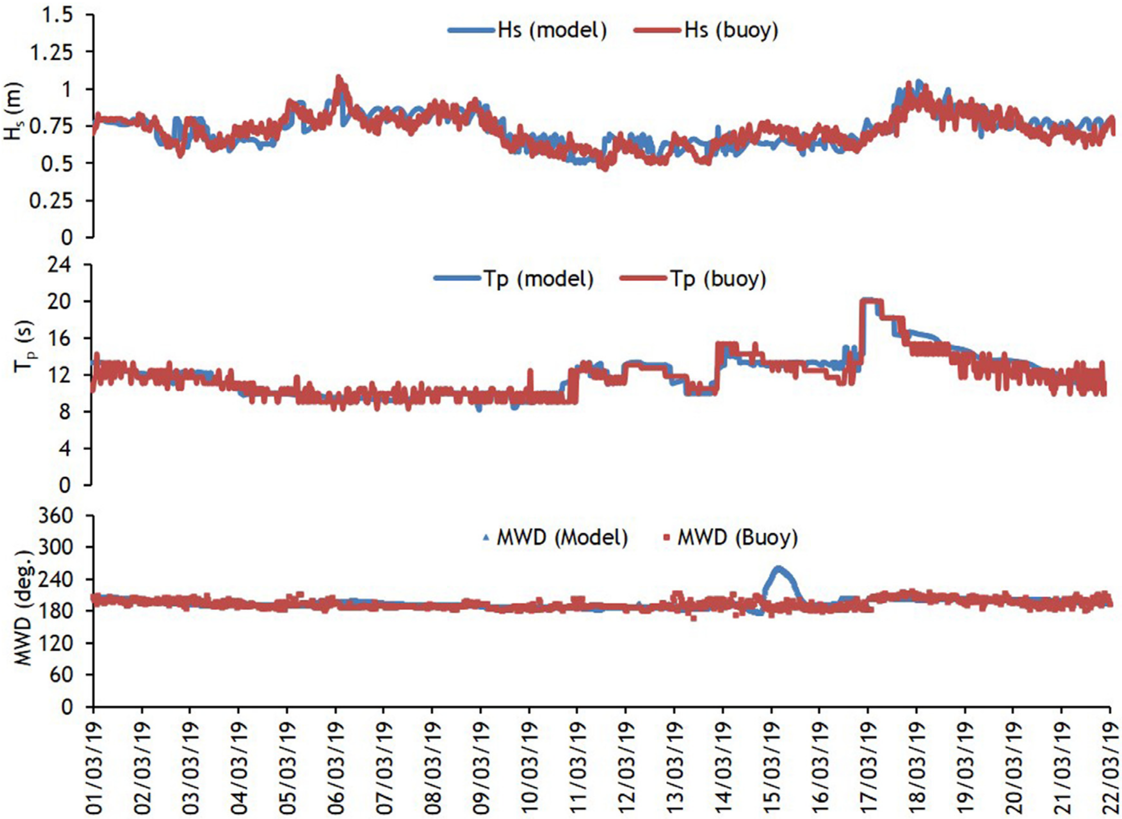


Figure 7 Comparison of measured and modelled significant wave height, peak wave period and mean wave direction off Varkala during 01—22 March 2019.

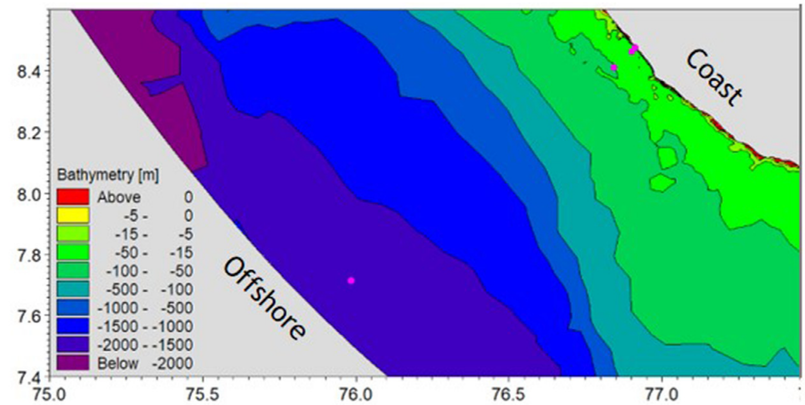
imum wavelength of 600 m. Thus, the deep, intermediate, and shallow waters can be defined with respect to the depth as d>300 m, 30<d<300 m and d<30 m, respectively. During fair weather season, the wave breaker depth along this coast was around 5—7 m with a breaker height of 1—1.5 m (Swamy et al., 1979). The bottom attenuation resulted a decrease in wave height when the waves were propagated from 1600 m to 50 m and 15 m depth contours, which is consistent with earlier observations along the Thiruvananthapuram coast (Parvathy et al., 2014). As obvious, there are no significant changes in T_m between the depths. The wave refraction enables a shore normal propagation in the nearshore waters, with a shift of around 20—25° from the deep-water waves. The dominant wave direction along the Kerala coast during fair-weather season varies between northwest and southeast (Hameed et al., 2007). During 14—16 March, the waves were approaching from the W. The boundary data applied (ERA5 waves parameters) in the local model also reveals a W/WNW component on the northern boundaries, however, they were not present in the southern regions. The wave model results indicate that this has been propagated towards the coast. The W/WNW component could be due to the effect of sea breeze, which are predominant along the Kerala coast during March (Abdulla et al., 2022).

A slight increase in H_s has been identified when the wave approaches the shore (from 15 m to 5 m). This increment was more pronounced during 18—19 March when IASO swells were present. In addition, the T_m on these days were the highest (10—12 s) of the month. This high T_m indicates that the long-period swells from the IASO interface have approached the shore without considerable interference of locally generated wind seas. The presence of local wind seas generally reduce T_m of the total waves compared to the independent swell T_m (Vethamony et al., 2011). Thus, the persistent higher T_m with an increased wave setup in the shallow waters of Valiyathura-Shangumukham stretch over the fully developed beach have made the runup easier than the other adjacent regions.

4.4.2. Coastal inundation and morphological changes

The study area is part of a straight coastal belt in which the 2.4 km stretch between Shangumukham and Valiyathura has got particular attention in this study. The beach is relatively wider at Shangumukham while the beach slope is relatively small at Valiyathura. Sea-level rise, anthropogenic activities and geomorphological changes by the wave action together contribute to the long-term erosion along the coast. It makes the coast more vulnerable to sudden floodings and inundation.

During 17—19 March 2019, the Valiyathura and Shangumukham coasts were heavily affected by wave runup, wave breaking and inundation. The coastal inundation was evident from the field visits immediately after the event (Figure 9). The beach survey along the Shangumukham coast reveals that the beach is dissipative with slopes ranging between 2° and 6° before the event. On 05 March, it was a fully developed beach with a beach width of 52 m (with a berm at the landward side) and an extended mild slopy beach up to 75 m. This has been altered by the wave



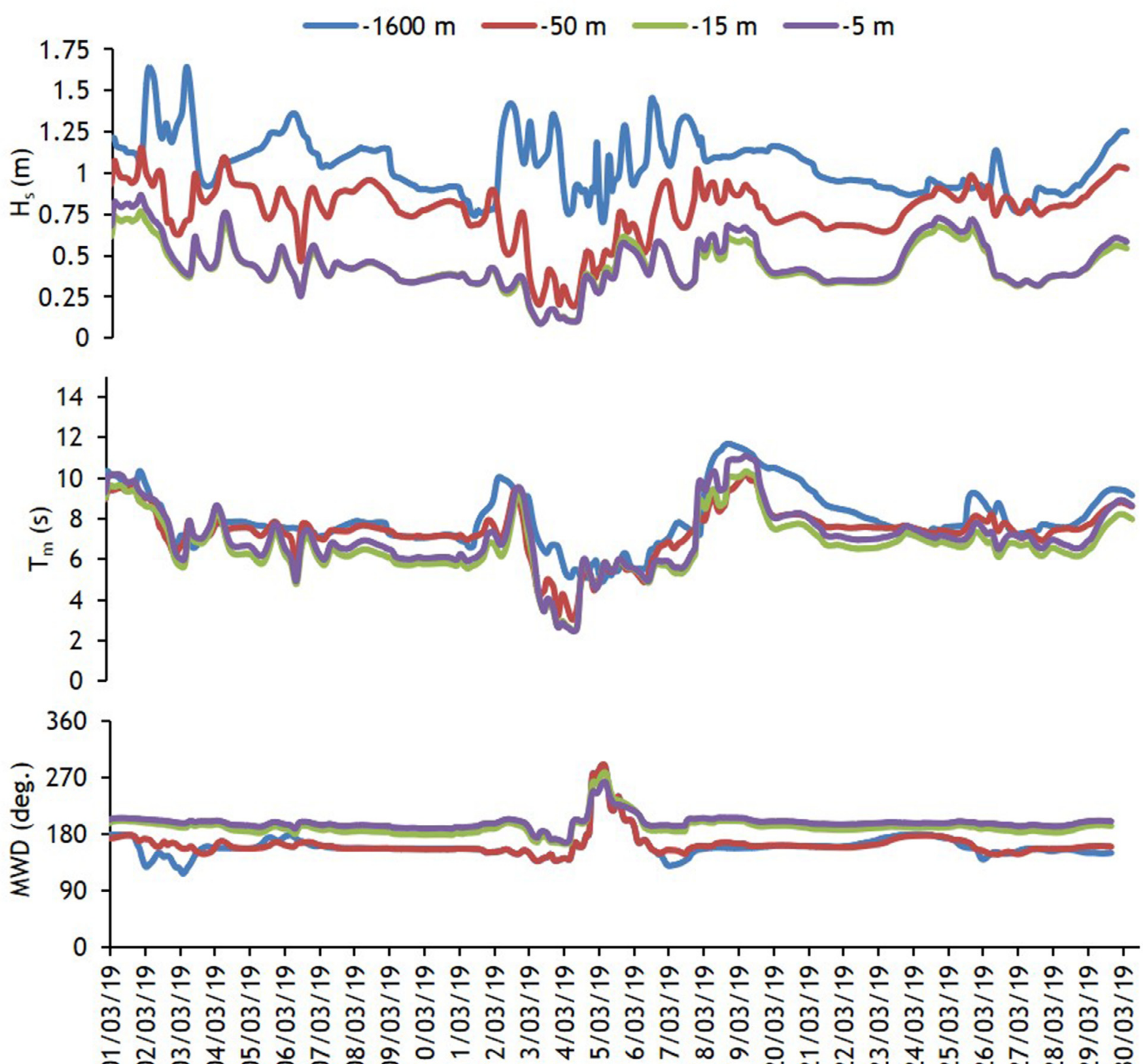


Figure 8 Wave transformation: Spatial variations of bathymetry (contour plot) in the top panel including the extraction locations; changes in wave parameters from the deep ocean (1600 m) to nearshore (5 m) across Valiyathura coast in the bottom panel.

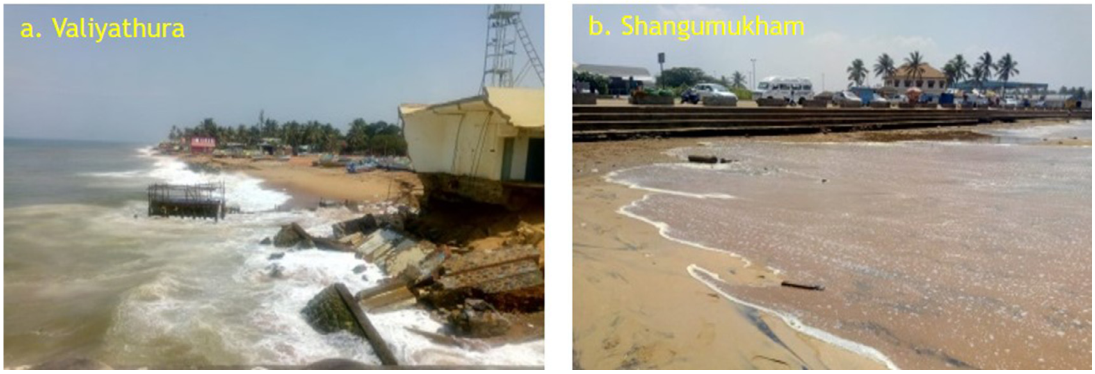


Figure 9 Field photographs of Valiyathura — Shangumukham stretch during the event on 18 March 2019.

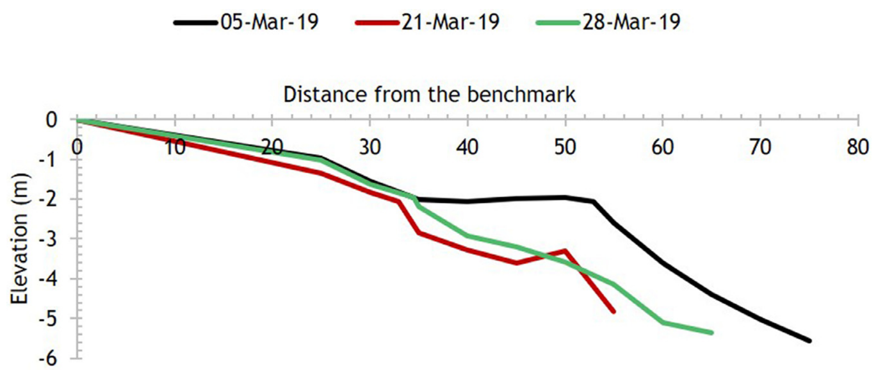


Figure 10 Beach profiles at Shangumukham coast during March 2019.

activity that occurred on 18—19 March. The beach face has turned flat, the fully developed flat beach was extended up to 80 m, and the beach slope was modified with a steep foreshore slope of about 10°. A mean grain diameter (d_{50}) of 0.41 mm observed during this period indicates the presence of relatively fine sand. The water was inundated by almost 80 m up to the permanent benchmark of the survey (steps) (Figure 10).

The post-event scenario indicates that the foreshore slope has been decreased from 10° to 6° with the berm shifted towards the seaside within a week time. Compared to 05 March, a significant erosion was occurred due to the flood event with a beach loss of 20 m. The flooding normally reduces the capacity of the beach acting as a natural barrier against erosion (Miguel et al., 2021). Kurian et al. (2009a) identified similar erosion by the effects of southerly swells, which generated a southward alongshore current, gets amplified and enabled a wave setup during event. The post-flood profile (28 March) at the Shangumukham coast indicate that the beach has started to retain the pre-existing condition (Figure 10). The characteristics of the inundation occurred due to these long-period swells are quite different from those that occurred due to the cyclonic activity (Gayathri et al., 2017; Rao et al., 2020), on which the coast re-building may take a longer duration.

4.4.3. Wave runup

The wave runup is higher in a mild slopy beach that results in greater landward inundation during high waves (Gayathri et al., 2017). Here, the runup exceeded by 2% of the waves ($R_{2\%}$) is estimated corresponding to the daily H_{max} for March 2019 on the Shangumukham beach (Figure 11). This shows that the highest values are obtained during 18 March compared to the pre- and post-event scenarios. On 18 March, the $R_{2\%}$ has reached 0.93 m with H_{max}= 1.37 m and T_p= 18.5 s. On the following day (19 March) it was 0.8 m with H_{max}= 1.7 m and T_p= 17 s. However, the $R_{2\%}$ corresponds to the highest H_{max} (2.11 m) was only 0.59 m, which was occurred during 13 March with T_p below 15 s. This shows that the T_p has more dependency on the runup rather than the H_{max} and the persistence of long-period swells of above 18 s for more than a day has resulted in the coastal flooding along the Valiyathura-Shangumukham coastal stretch.

The highest wave runup along the Indian coasts occurred during 2004 tsunami. It went up to 4.17 m height along the coast of Tamil Nadu and inundated 238 m inshore (Seelam et al., 2005). The runup varied along Kerala coast due to the influence of bottom topography in channelising the tsunami waves. The runup height was 3.5 m along the north Kerala coast and 5.0 m along the south Kerala coast (Narayana et al., 2007). Generally, the increased runup variability is attributed to low frequency wave which dominates the swash (Torres-Freyermuth et al., 2019). Therefore, under long-period swell dominant conditions, the swash has contributed to the high wave runup on 18—19 March. The IASO swells reached the Thiruvananthapuram coast on 17 March (Figure 4). As the swell activity continued, the wave setup increased and accordingly the runup has reached to

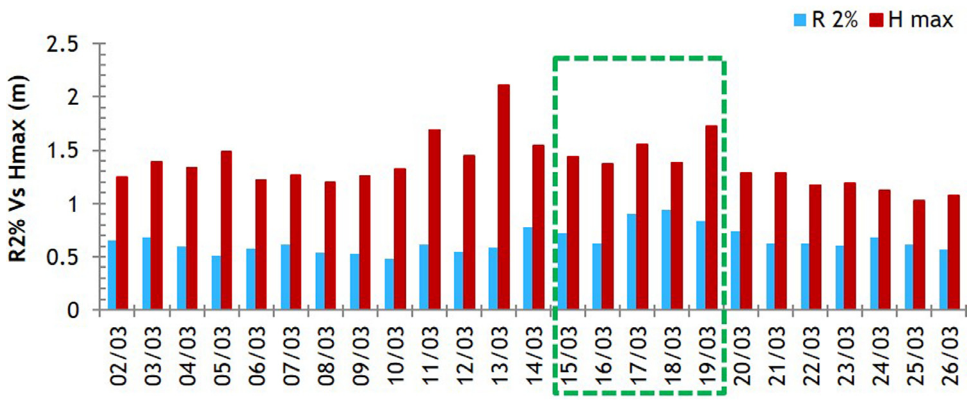


Figure 11 Wave runup along Shangumukham beach.

a height of 0.6 to 0.89 m along the Shangumukham coast on 18 March. It is further developed to 0.93 m on 19 March which contributed to the flooding and inundation over the Valiyathura-Shangumukham stretch.

5. Conclusions

The coastal inundation that occurred along the Valiyathura-Shangumukham stretch during March 2019 was investigated through the analysis of ERA5 winds and waves over a global domain, fine-scale modelling for the Thiruvananthapuram coast and estimation of wave runup and inundation for the affected region. The study identified that a storm system was developed in the Indian-Atlantic-Southern Oceans (IASO) interface during 10—12 March 2019, from where the southerly components generated high swells having significant wave heights of the order of 6.0—8.0 m and propagated towards the North Indian Ocean. These swells have a clear incidence along the southwest coast of India as evident from the measured spectra. The arrival time of the swells estimated (~7 days) was matched well with the low-frequency spectra measured off Varkala. The high celerity of these waves along with the presence of a fully developed/reflective beach made a quick runup of waters towards the shore, which caused an inundation of up to 83 m with a runup height of up to 0.93 m.

There were several wave runup events occurred at different parts of the southwest coast of India in the past; most of them were associated with long-period swells during fair-weather seasons (pre- and post-monsoon seasons). A few of them were investigated in relation to the Kallakadal phenomena, which are somewhat predictable considering the recent advances in wave forecasts in the country. However, the wave runup event of March 2019 was not expected as there were no high swell forecasts or warnings related to it. Our analysis indicates that this event is a localised effect of a remote forcing, originating from the IASO interface. Similar events were often ignored as the swell heights were not very high along the southwest coast of India, but their celerity does an impact. A more detailed understanding of the IASO interface swells including their climatological features is our future scope. This will help to better assess the forecasts and provide early warnings to the public.

Acknowledgements

The authors would like to thank Mr Sarankumar S.G., Mr Akhildev S., Dr Prasad R., Dr Anoop T.R., Dr Glejin J. and Ms Amrutharaj V., for their valuable support during fieldwork and laboratory analysis. The authors would like to extend their gratitude towards the Director, NCESS and the Ministry of Earth Sciences for extending their support and funding for the research. The second author acknowledges the support of the UNESCO Chair in Marine Sciences at Qatar University, funded through the project, QUEX-ESC-QP-TM-18/19-01.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

P.S. Swathy Krishna: Conceptualization, Investigation, Methodology, Software, Formal analysis, Validation, Writing — original draft, Writing — review & editing. **Valliyil Mohammed Aboobacker:** Conceptualization, Investigation, Formal analysis, Writing — original draft, Writing — review & editing. **Madipally Ramesh:** Software, Data curation, Formal analysis, Visualization, Resources, Writing — original draft, Writing — review & editing. **L. Sheela Nair:** Project administration, Resources, Supervision, Writing — review & editing.

References

Abdalazeez, A., 2012. Wave runup estimates at gentle beaches in the Northern Indian Ocean. Faculty of Mathematics and Natural Sciences, Geophys. Inst., Univ., Bergen, 31. https://doi.org/10.13140/RG.2.2.29367.55207

Abdulla, C.P., Aboobacker, V.M., Shanas, P.R., Vijith, V., Sajeev, R., Vethamony, P., 2022. Climatology and variability of wind speeds along the southwest coast of India derived from CFSR winds. Int. J. Climatol. 42. https://doi.org/10.1002/joc.7767

Aboobacker, V.M., Shanas, P.R., 2018. The climatology of shamals in the Arabian Sea part 2: surface waves. Int. J. Climatol. 38, 4417—4430. https://doi.org/10.1002/joc.5677

Aboobacker, V.M., Rashmi, R., Vethamony, P., Menon, H.B., 2011a. On the dominance of pre-existing swells over wind seas along the west coast of India. Cont. Shelf Res. 31 (16), 1701—1712. https://doi.org/10.1016/j.csr.2011.07.010

Aboobacker, V.M., Vethamony, P., Rashmi, R., 2011b. "Shamal" swells in the Arabian Sea and their influence along the west coast of India. Geophys. Res. Lett. 38 (3), 1—7. https://doi.org/10.1029/2010GL045736

Aboobacker, V.M., Seemanth, M., Samiksha, S.V., Sudheesh, K., Jyoti, K., Vethamony, P., 2014. Sea breeze-induced wind sea growth in the central west coast of India. Ocean Eng. 84, 20—28. https://doi.org/10.1016/j.oceaneng.2014.03.030

Aboobacker, V.M., Shanas, P.R., Al-Ansari, E.M., Kumar, V.S., Vethamony, P., 2021. The maxima in northerly wind speeds and wave heights over the Arabian Sea, the Arabian/Persian Gulf and the Red Sea derived from 40 years of ERA5 data. Clim. Dynam. 56 (3), 1037—1052. https://doi.org/10.1007/s00382-020-05518-6

Alves, J.-H.G.M., 2006. Numerical modelling of ocean swells contributions to the global wind-wave climate. Ocean Model. 11, 98—122. https://doi.org/10.1016/j.ocemod.2004.11.007

Amante, C., Eakins, B., 2009. ETOPO1 1 Arc-Minute Global ReliefModel: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. https://doi.org/10.7289/V5C8276M,2009

Amrutha, M.M., Sanil Kumar, V., Sandhya, K.G., Balakrishnan Nair, T.M., Rathod, J.L., 2016. Wave hindcast studies using SWAN nested in WAVEWATCH III — comparison with measured nearshore buoy data off Karwar, eastern Arabian Sea. Ocean Eng. 119, 114—124. https://doi.org/10.1016/j.oceaneng.2016.04.032

Andrew, S., Dave, C., Helen, T., 2015. Coastal flooding in England and Wales from Atlantic and North Sea storms during the 2013/2014 winter, Weather — February. RMetS 70 (2), 62—70. https://doi.org/10.1002/wea.2471

Anoop, T.R., Sanil Kumar, V., Shanas, P.R., Johnson, G., 2015. Surface wave climatology and its variability in the North Indian Ocean based on ERA-Interim reanalysis. J. Atmos. Ocean Technol. 32, 1372—1385. https://doi.org/10.1175/JTECH-D-14-00212.1

Anoop, T.R., Shanas, P.R., Aboobacker, V.M., Sanil Kumar, V., Nair, L.S., Prasad, R., Reji, S., 2020. On the generation and propagation of Makran swells in the Arabian Sea. Int. J. Climatol. 40 (1), 585—593. https://doi.org/10.1002/joc.6192

Aparna, M., Shetye, S.R., Shankar, D., Shenoi, S.S.C., Mehra, P., Desai, R.G.P., 2005. Estimating the seaward extent of sea breeze from QuikSCAT scatterometry. Geophys. Res. Lett. 32, L13601. https://doi.org/10.1029/2005GL023107

Baba, M., Joseph, P.S., 1988. Wave climate off Cochin and Trivandrum. In: Baba, M., Kurian, N.P. (Eds.), Ocean Waves and beach processes. CESS, Trivandrum, 129—213.

Danish Hydraulic Institute (DHI), 2019. MIKE 21 Spectral wave Model FM User Guide. DHI, Holsholm, Denmark.

Gayathri, R., Bhaskaran, P.K., Jose, F., 2017. Coastal inundation research: an overview of the process. Curr. Sci. 112 (2), 267—278. http://www.jstor.org/stable/24912354

Glejin, J., Sanil Kumar, V., Balakrishnan Nair, T.M., Singh, J., 2013. Influence of winds on temporally varying short and long period gravity waves in the near shore regions of Eastern Arabian Sea. Ocean Sci. 9, 343—353. https://doi.org/10.5194/os-9-343-2013

Hamed, R.M., Amir, A., Brett, F.S., David, L.F., William, S., Richard, A.M., Adam, L., 2015. Increased nuisance flooding along the coasts. Geophys. Res. Lett. 42, 9846—9852. https://doi.org/10.1002/2015GL066072

Hameed, S., Kurian, N., Thomas, K., Rajith, K., Prakash, T., 2007. Wave and Current Regime off the Southwest Coast of India. J. Coast. Res. 23, 1167—1174. http://doi.org/10.2112/04-0388.1.

Hanley, E.K., Stephen, E.B., Peter, P.S., 2010. A global Climatology of wind wave interaction. J. Phys. Oceanogr. 40, 1263—1282. https://doi.org/10.1175/2010JPO4377.1

Krishnan, A., Bhaskaran, P.K., Kumar, P., 2022. Extreme wind-wave climate projections for the Indian Ocean under changing climate scenarios. Clim. Dynam. 59, 649—669. https://doi.org/10.1007/s00382-022-06147-x

Kurian, N.P., 1987. Wave height and spectral transformation in the shallow waters of Kerala coast and their prediction. Cochin Univ. Sci. Technol., Cochin, Kerala, India, 150.

Kurian, N.P., Rajith, K., Shahul Hameed, T.S., Sheela Nair, L., Ramana Murthy, M.V., 2009a. Wind waves and sediment transport regime off the south- central Kerala coast, India. Nat. Hazards 49, 325—345. https://doi.org/10.1007/s11069-008-9318-3

Kurian, N.P., Nirupama, N., Baba, M., Thomas, K.V., 2009b. Coastal flooding due to synoptic scale meso-scale and remote forcing. Nat. Hazards 48, 259—273. https://doi.org/10.1007/s11069-008-9260-4

Mahmoodi, K., Ghassemi, H., Razminia, A., 2019. Temporal and spatial characteristics of wave energy in the Persian Gulf based on the ERA5 reanalysis dataset. Energy 187, 115991. https://doi.org/10.1016/j.energy.2019.115991

McFall, B., 2019. The Relationship between Beach Grain Size and Intertidal Beach Face Slope. J. Coast. Res. 35. https://doi.org/10.2112/JCOASTRES-D-19-00004.1

Miguel, A., Jordà, G., Lionello, P., 2021. Flooding of Sandy Beaches in a Changing Climate. The Case of the Balearic Islands (NW Mediterranean). Front. Mar. Sci. 8, 2296—7745. https://doi.org/10.3389/fmars.2021.760725

Nair, L.S., Sundar, V., Kurian, N., 2011. Numerical Model Studies on the Effect of Breakwaters on Coastal Processes — A Case Study along a Stretch of the Kerala Coast, India. Int. J. Ocean Clim. Syst. 2, 291—302. https://doi.org/10.1260/1759-3131.2.4.291

Nair, L.S., Sundar, V., Kurian, N., 2013. Shore Protection for a Placer Deposit Rich Beach of the Southwest Coast of India. Int. J. Ocean Clim. Syst. 4, 41—62. https://doi.org/10.1260/1759-3131.4.1.41

Narayana, A.C., Tatavarti, R., Shinu, N., Subeer, A., 2007. Tsunami of December 26, 2004 on the southwest coast of India: Post-tsunami geomorphic and sediment characteristics. Mar. Geol. 242 (1—3), 155—168. https://doi.org/10.1016/j.margeo.2007.03.012

Parsons, M.J., Crosby, A.R., Orelup, L., Ferguson, M., Cox, A.T., 2018. Evaluation of ERA5 reanalysis wind forcing for use in ocean response modelling. In: Waves in Shallow Environments (WISE) conference, 22—26 April 2018.

Parvathy, K.G., Deepthi, G., Noujas, V., Thomas, K.V., 2014. Wave Transformation along Southwest Coast of India Using MIKE 21. Int. J. Ocean Clim. Syst. 5, 23—34. https://doi.org/10.1260/1759-3131.5.1.23

Piyali, C., Manasa, R.B., Dominic, E.R., 2019. Wave climate projections along the Indian Coast. Int. J. Climatol. 39, 4531—4542. https://doi.org/10.1002/joc.6096

Rao, A.D., Upadhaya, P., Ali, H., Pandey, H., Warrier, V., 2020. Coastal inundation due to tropical cyclones along the east coast of India: an influence of climate change impact. Nat Hazards. 101, 39—57. https://doi.org/10.1007/s11069-020-03861-9

Ramesh, M., Sheela Nair, L., Anoop, T.R., Prakash, T.N., 2022. Nearshore wave analysis from coastal video monitoring techniques at high energy micro tidal beach under sunlight dominance conditions: A case study from Valiathura beach in southwest coast of India. Reg. Stud. Mar. Sci. 51, 102205. https://doi.org/10.1016/j.rsma.2022.102205

Rashmi, R., Aboobacker, V.M., Vethamony, P., John, M.P., 2013. Co-existence of wind seas and swells along the west coast of India during non-monsoon season. Ocean Sci. 9, 281—292.

Remya, P.G., Kumar, R., Sujit, B., Abhijit, S., 2012. Wave hindcast experiments in the Indian Ocean using MIKE 21 SW model. J. Earth Syst. Sci. 121, 385—392. https://doi.org/10.1007/s12040-012-0169-7

Remya, P.G., Vishnu, S., Praveen Kumar, B., Balakrishnan Nair, T.M., Rohith, B., 2016. Teleconnection between the North Indian Ocean high swell events and meteorological conditions over the Southern Indian Ocean. J. Geophys. Res.-Oceans. 121, 7476—7494. https://doi.org/10.1002/2016JC011723

Sachin, P., Menon, A.P., Sankaranarayanan, N.R., 2014. An analysis of various coastal issues in Kerala. Int. J. Sci. Res. Educ. 2 (10), 1993—2001.

Samiksha, S.V., Rashmi, R., Vethamony, P., 2011. Wave modelling for the Indian Ocean using WAVEWATCH III. In: Proc. AOGS 2011.

Sashikant, N., Bhaskaran, P.K., Venkatesan, R., Sikha, D., 2013. Modulation of local wind-waves at Kalpakkam from remote forcing effects of Southern Ocean swells. Ocean Eng. 64, 23—35.

Scott, T., Gerhard, M., Paul, R., 2011. Morphodynamic characteristics and classification of beaches in England and Wales. Mar. Geol. 286 (1—4), 1—20. https://doi.org/10.1016/j.margeo.2011.04.004

Seelam, J., Ilangovan, D., Samiksha, S.V., Gowthaman, R., Tirodkar, G., Naik, G.N., ManiMurali, R., Michael, G.S., Raman, M.V., Bhattacharya, G., 2005. Runup and inundation limits along southeast coast of India during the 26 December 2004 Indian Ocean tsunami. Curr. Sci. 88, 1741—1743.

Sreelakshmi, S., Bhaskaran, P.K., 2020a. Spatio-temporal distribution and variability of high threshold wind speed and significant wave height for the Indian Ocean. Pure Appl. Geophys. 177, 4559—4575. https://doi.org/10.1007/s00024-020-02462-8

Sreelakshmi, S., Bhaskaran, P.K., 2020b. Wind generated wave climate variability in Indian Ocean using ERA-5 dataset. Ocean Eng. 209, 107486.

Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger Jr, A.H., 2006. Empirical parameterization of setup, swash, and runup. Coast. Eng. 53 (7), 573—588.

Swamy, G.N., Udaya, V, P., Pylee, A., RamaRaju, V.S., Chandramohan, P., 1979. Wave climate off Trivandrum (Kerala). Mahasagar- Bulletin of the national centre for Oceanography 12 (3), 127—133.

Torres-Freyermuth, A., Pintado-Patiño, J.C., Pedrozo-Acuña, A., Puleo, J.A., Baldock, T.E., 2019. Runup uncertainty on planar beaches. Ocean Dynam. 69 (11), 1359—1371.

Vethamony, P., Aboobacker, V.M., Menon, H.B., Ashok Kumar, K., Cavaleri, L., 2011. Superimposition of windseas on pre-existing swells off Goa coast. J. Marine Syst. 87 (1), 47—54.