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RESEARCH ARTICLE

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Wave climate projections along the Indian coast

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Abstract
Future changes in wave climate will influence the marine ecosystem, coastal erosion, design of coastal defences, operation of near- and off-shore structures, and coastal zone management policies and may further add to the potential vulnerabilities of coastal regions to projected sea level rise. Many studies have reported changes in the global wave characteristics under climate change scenarios, but it is important to project future changes in local/regional wave climate for smooth implementation of policies and preventing severe coastal erosion and flooding. In this study the regional wave climate along the Indian coast for two time slices, 2011–2040 and 2041–2070, is reported using an ensemble of near-surface winds generated by four different CMIP5 general circulation models (GCMs), under RCP4.5 scenario. Comparison of the wave climate for the two time slices shows an increase in wave heights and periods along much of the Indian coast, with the maximum wave heights increasing by more than 30% in some locations. An important finding is that at most locations along the east coast, wave periods are expected to increase by almost 20%, whereas along the west coast an increase of around 10% is expected. This will alter the distribution of wave energy at the shoreline through changes in wave refraction and diffraction, with potential implications for the performance and design of coastal structures and swash-aligned beaches. Furthermore, the computations show material changes in the directional distribution of waves. This is particularly important in determining the longshore transport of sediments and can lead to realignment of drift-aligned beaches, manifesting itself as erosion and/or siltation problems. This study is a preliminary contribution towards regional climate projections for the Indian Ocean region which are needed to plan and mitigate the impacts of future climate change.

KEYWORDS
climate change, coastal vulnerability, dynamical projections, Indian coast, surface ocean waves, wave climate variability

1 | INTRODUCTION

Knowing the wave climate is crucial for a variety of applications, such as ocean wave research, coastal morphodynamics, navigation, and the planning of marine operations and offshore and coastal structures (Hisaki, 2018). Available evidence, for example in situ measurements and remotely sensed recordings, has increased to the extent that we can characterize the variability in surface ocean wave characteristics like wave heights, periods, and directions in addition to their means. Changes in wave conditions are likely to drive alterations to the equilibrium and variability of shoreline orientation and shape. The other major impacts of changing wave climate are the disturbed coastal ecosystem (Hoegh-Guldberg and Bruno, 2010), altered nearshore coastal processes (Zacharioudaki and Reeve, 2011; Chowdhury and Behera, 2017), variable loading on offshore structures (Weisse *et al.,* 2009; Kamath *et al.,* 2017), and altered ocean–atmosphere coupling and feedback, influencing the entire climate system (Cavaleri *et al.,* 2012). It is possible that a changing atmospheric climate will cause a change in oceanic response, and regional variations in the former are likely to be reflected in the latter. Global-scale studies, while giving a good indication of general trends, are unable to resolve the spatial variability in regional wave climate. Coastal zone management policies require accurate measures of wave climate to effectively incorporate the thresholds for coastal and offshore infrastructure management. Therefore, there is a need to project future regional wave climate and assess the impacts of its change. Progress on this topic has been reported for regions like northeast Atlantic Ocean (Izaguirre *et al.,* 2011; Aarnes *et al.,* 2017), northwest Mediterranean Sea (Casas-Prat and Sierra, 2013), North Sea (Groll *et al.,* 2014), northeast Atlantic Ocean and the Mediterranean (Perez *et al.,* 2014), West European Seas (Zacharioudaki *et al.,* 2011), East China Sea (Li *et al.,* 2016), among others, and all have noted strong regional deviations from projected global trends. In this study, we use general circulation model (GCM) wind output to simulate surface ocean waves along the Indian coast and present the mean wave climate at selected locations for a better understanding of the wave parameters for effective coastal zone management.

In recent years, studies have revealed that the Indian Ocean (IO) has a much larger impact on the global wave climate than previously thought (Schott *et al.,* 2009). After the severe El Niño event of 1997, which caused hundreds of thousands of deaths, population displacement, forest fires, severe droughts, and flooding in many of the IO rim countries, it was recognized that there were several other unusual conditions taking place in tropical IO which might have worsened the effects of El Niño. The global- and regional-scale seasonal variations in the wave climate are a result of the interaction of the IO with the atmosphere. The Asian monsoon is the strongest of these interactions and generates seasonal variations in ocean currents (Schott *et al.,* 2009). Hisaki *et al.* (2016) reported that the ocean environment along the coasts is affected by the presence of such currents. Also, the annual mean winds on the equator are westerly in the IO region (Xie *et al.,* 2002), unlike other oceans. All the above-mentioned phenomena indicate that the IO responds differently to the respective influences of inter-annual and seasonal climate events and there is a need to study the response of the IO to changing wave climate, separately.

Past wave climate can be analysed using observations (which are sparse in time and space) or by wave modelling. But, to project future waves, future wind conditions are necessary. In this approach, the projected winds derived from GCMs or regional climate models (RCMs) are used to force a wave model. However, according to McSweeney *et al.* (2015) it is important to select appropriate climate model(s) and representative concentration pathway (RCP) scenario(s) in order to generate projections that are policy-relevant and manageable to develop, analyse, and disseminate. It was concluded in Chowdhury and Behera (2018) that RCMs fail in providing acceptable wind inputs for wave simulations over the IO. It is well known that the nearshore wave climate along the Indian coast is heavily influenced by the seasonal monsoon winds and the strong swells arriving from the southern IO (SIO; Aboobacker and Shanas, 2018). According to Mawren and Reason (2017), tropical storms are generated in the southwest IO during the post-summer monsoon season, which in turn reaches the Indian coast as swells. Thus, wave simulations using RCM (South Asia domain) winds do not give satisfactory results along the Indian coast. Therefore, we used an ensemble of GCM winds from the RCP4.5 emission scenario to simulate future wave climate in the IO.

In the design of coastal defence and offshore structures, ocean waves are usually characterized by significant wave heights (H_s). Other important wave parameters are the mean wave direction (θ_m) and mean wave period (T_m) which are important in determining the response of beaches and coastal structures to the incident wave conditions. Therefore, in this study we provide the time slice averaged mean of H_s, T_m, and θ_m, and maximum wave height ($H_{\max}$) values for the two selected time slices. For the sake of simplicity in discussing these time slices repeatedly in section 3, we are considering the first time slice of 2011–2040 as "near-term" and the second time slice of 2041–2070 as "mid-term." These values are computed at spatial as well as selected point locations along the Indian coast for a better understanding of the coastal wave climate and for a better local coastal zone management practice.

1.1 | Wave climate in IO region

The IO region may be subdivided into two main water bodies, the northern IO (NIO) region and the SIO region, based on its spread over both hemispheres. Furthermore, the Indian subcontinent divides the NIO into the Arabian Sea (AS) on the west and the Bay of Bengal (BoB) on the east. The ocean–land interaction that exists in the NIO due to the presence of the Indian subcontinent influences the wave climate in this region. The west coast of India experiences an annual monsoon from June to September (JJAS) which is called the southwest monsoon, and the east coast experiences a monsoon between October and December (OND) which is called the northeast monsoon. Most of the wave activity in the AS is driven by the monsoon winds. The BoB, on the other hand, experiences higher cyclone frequency than AS, which determines most of the wave climate in this region. Aboobacker *et al*. (2011) noted that the central west coast of India is also influenced by the presence of shamal winds, which are seasonal winds that occur during winter (November–March) and summer (June–August) months. These are northwesterlies that lead to changes in wave climate along central west coast of India by increasing wave heights (Aboobacker and Shanas, 2018). The swells travelling from SIO also play important role in determining the wave climate of the NIO and regional wave climate along Indian coast.

The wave climate of the IO is a combination of waves from many geographic areas and different atmospheric driving phenomena. As such, it is not straightforward to predict how climate change will affect the future wave climate. Also, for the future projection of coastal processes like sediment transport and their impact on shoreline evolution, coastal inundation, ecosystem management practices, and offshore structure design, it is necessary to study the changes in future wave climate on a regional/local scale. Studies on future changes in wave parameters along the Indian coast are currently lacking, which is primarily the motivation for this study. The main aim of this study is to provide the coastal community with a robust future projection of wave parameters along the Indian coast for better management and planning purposes. The projected wave parameters can be used as an input to the compound coastal inundation models and the projected wave directions can be used to investigate the future of sandy beaches in terms of sediment transport.

2 | DATA AND METHODOLOGY

In this study, we used a third-generation spectral wave model MIKE21 (DHI) to simulate the wave climate over the IO region (http://manuals.mikepoweredbydhi.help/2017/MIKE_21.htm). MIKE21 is an operational wave simulation model of the Danish Hydraulic Institute and has been extensively validated for wave simulation (Sørensen *et al.,* 2004; Venugopal and Smith, 2007; Remya *et al.,* 2012; Chowdhury and Behera, 2018). The numerical model simulates the time evolution of the wave spectrum over a spatial grid by solving the wave action conservation equation with an implicit, cell-centred finite volume method. The model is based on an unstructured flexible mesh which allows simultaneous computation at regional (coarser) and local (finer) scales, in which time integration is performed using the fractional step approach. In the fully spectral formulation, the source functions are based on the WAM Cycle 4 formulation (Komen *et al.,* 1994). The source term for depth-limited wave breaking is based on the formulation by Battjes and Janssen (1978). The spectral wave model is applied over the IO region ranging from 30°N to 40°S and 20° to 110°E with variable resolutions (coarser $0.75 \times 0.75°$ in deeper ocean to finer $0.25 \times 0.25°$ in coastal regions). This model produces phase-averaged wave parameters as output for the computational area. In this study, we have assessed only changes in integrated wave parameters: H_s, $H_{\max}$, T_m, and θ_m.

The spectral wave model is forced with 3-hourly meridional (north–south) and zonal (east–west) components of the GCM near-surface (10 m height) wind outputs pertaining to the RCP4.5 scenario. The RCP4.5 is an intermediate "stabilization without overshoot" pathway in which radiative forcing is stabilized at approximately 4.5 W/m^2 after 2100 (Moss *et al.,* 2008). Whenever multiple GCM runs with different initial conditions were available, only outputs from the r1 (first GCM run) simulation were used. In this study, we used an ensemble of wind outputs obtained from GCMs (listed in Table 1) as according to Donat *et al.* (2010) an ensemble mean is more robust than output from a single model. Winds from different GCMs have variable grid resolution. To get information on the same grid, we considered two options: dynamically downscaling GCM winds, which is computationally very demanding, and interpolation. Here we chose interpolation to a finer resolution of $0.5 \times 0.5°$ using bilinear interpolation method.

The GCMs used to obtain the ensemble in this study belong to the Coupled Model Intercomparison Project 5 (CMIP5). CMIP5 data sets are archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). Here we used four GCMs as listed in Table 1. There is a lack of sufficient literature discussing the performance of downscaled winds in generating waves in the IO

TABLE 1 List of GCMs considered for obtaining ensemble GCM wind output

CMIP5 GCM	Resolution (°) (lat × lon)
NOAA Geophysical Fluid Dynamics Laboratory, United States (GFDL)	2.5 × 2.0
Institut Pierre Simon Laplace, Paris, France (IPSL)	2.5 × 1.25
Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO)	1.8 × 1.8
Centre National de Recherches Meteorologiques, France (CNRM)	1.4 × 1.4

region. There are, however, papers available that discuss the other significant climate variables, like Indian summer monsoon propagation; for example, Sabe*erali e*t al. (2015) found that IPSL and GFDL show greater skill in simulating propagation characteristics of the Indian monsoon. Therefore, Chowdhury and Behera (2018) performed an evaluation test of the GCMs listed in Table 1 to analyse how they behave during wave simulation over the IO region. The authors concluded that the ensemble derived from these GCMs was efficient in capturing the seasonality in IO wave climate along with capturing the annual trends.

2.1 | Model evaluation

Daily wave data obtained from the model simulations are compared to observation data from two different buoys, one each in deep water (AD07) and shallow water (Ratnagiri WRB) conditions (Table 2). The selection of buoys was made so as to test the model's ability in simulating surface ocean parameters in both deep and shallow water. The comparison is carried out for the years 2010 (Ratnagiri WRB) and 2016 (AD07). We selected these years for comparison because the buoys have the greatest number of JJAS (monsoon) data available in 2010 (Ratnagiri WRB) and 2016 (AD07). It is crucial to have enough observation data from JJAS months because the NIO region is most influenced by the monsoon winds, and hence we can test the model's ability in capturing the seasonality in wave climate.

We forced the MIKE 21 wave model with ensemble winds for the future climate and selected the years: 2010 and 2016 for model evaluation (depending on maximum data availability during JJAS months). The results of this comparison are shown in Figure 1 and summarized in Table 2. Significant wave height and wave period are compared. From Figure 1, it can be seen that the simulated H_s and T_m are in good agreement with the observed data. Correlations between simulated and observed data exceed 0.9 for H_s and 0.7 for wave period. Apart from the point data evaluation, we also evaluated time-slice-averaged spatial data over the study domain. We compared the historical time slice average (1979–2005) mean wave climate (significant wave height, mean wave direction, and mean wave period) obtained from our model with ERA-Interim reanalysis data and derived the spatial bias (Figure 2). We observed that ensemble GCM show a medium negative bias in significant wave heights along the east coast of India and a strong negative bias in SIO. This bias is attributed to the reduced intensity of storminess within most of the CMIP5 models. Ensemble GCM-simulated mean wave period is consistently over predicted in most of the IO region. The overpredicted wave periods are dominant in the swell generation regions of the SIO. A weak bias, however, is observed along the Indian coast. Mean wave directions across the IO region show eastwards zonal distribution of waves. The ensemble GCM-forced wave simulation shows minimum bias in the coastal regions of India and the west IO region.

3 | RESULTS AND DISCUSSION

In this section, we present the major wave parameters for the near-term and mid-term climate scenarios. Here, interest is in the synoptic scale; hence, the results were extracted at various locations along the Indian coast at approximately 100–150 km apart. However, for even geographic representation, one location was considered along each of the nine coastal states of India, namely Gujarat (location 1), Maharashtra (location 2), Goa (location 3), Karnataka (location 4), Kerala (location 5), Tamil Nadu (location 6), Andhra Pradesh (location 7), Odisha (location 8) and West Bengal (location 9) (Figure 3). The figure also shows the buoy locations (AD07 and Ratnagiri WRB) that were used for evaluating the wave model. Apart from presenting wave climate changes at the selected locations along the Indian coast, we also present spatial maps of the IO region depicting the projected changes in mean wave parameters for the two time slices (2011–2040 and 2041–2070) as compared with their means derived from the historical period (1979–2005) (Figure 4).

The H_s and H_{max} values for the two time slices were extracted at the selected nine locations and are shown in Figure 4a,b. The near-term average means of H_s and H_{max} at location 1 are 1.5 and 3.5 m, respectively, whereas they are expected to increase by as much as 0.5 m during the later period (2041–2070), indicating increased wave activity

TABLE 2 Comparison between model data and buoy observations for H_s and T_m: The mean of observed data (X_{obs}), the mean of simulated data (X_{model}), the bias (model data minus observed data), the correlation coefficient (r), and root-mean-square error values are given below

	Significant wave height					Wave period				
Buoy	X_{obs} (m)	X_{model} (m)	Bias (cm)	r	RMSE	X_{obs} (s)	X_{model} (s)	Bias (s)	r	RMSE
AD07 (Jan 1, 2016 to Dec 31, 2016)	1.36	1.70	12.5	.94	.38	5.2	5.8	0.55	.76	.67
Ratnagiri WRB (Jan 1, 2010 to Dec 31, 2010)	0.89	1.20	31.0	.84	.42	2.8	4.45	1.5	.70	.72

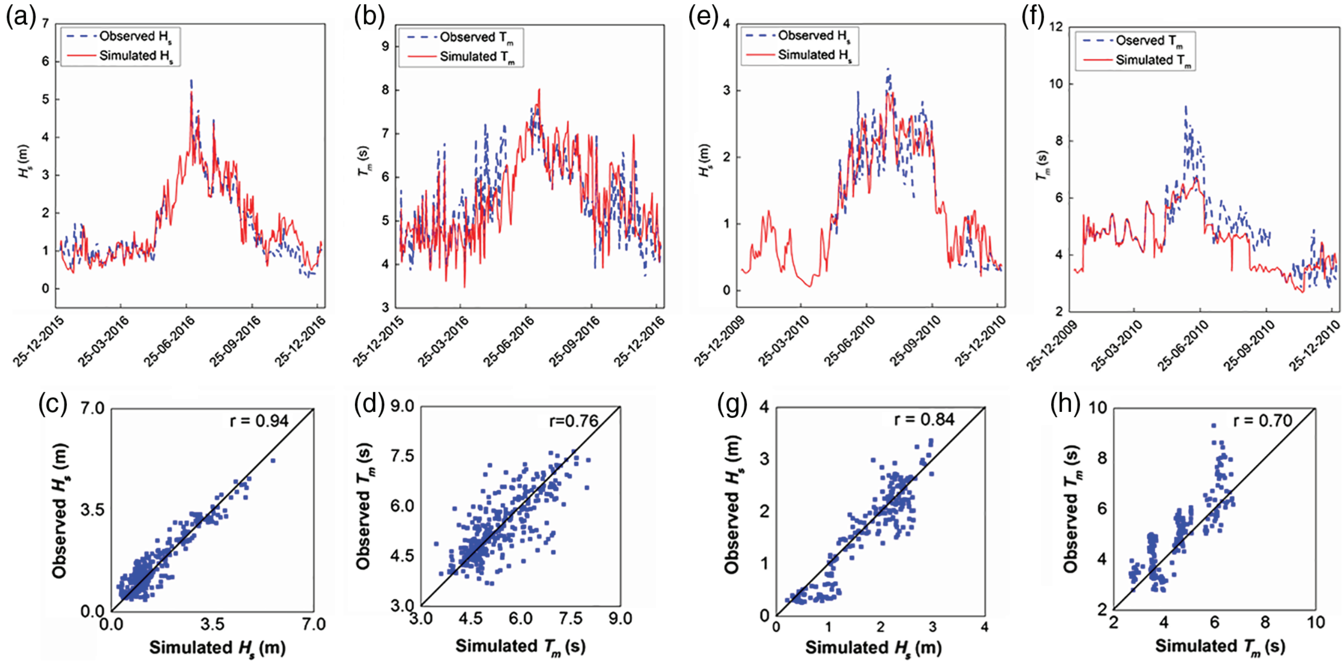

FIGURE 1 (a–d) Comparison between model data and AD07 buoy observations during Jan 1, 2016 and Dec 31, 2016, and (e–h) comparison between model data and Ratnagiri WRB observations during Jan 1, 2010 and Dec 31, 2010

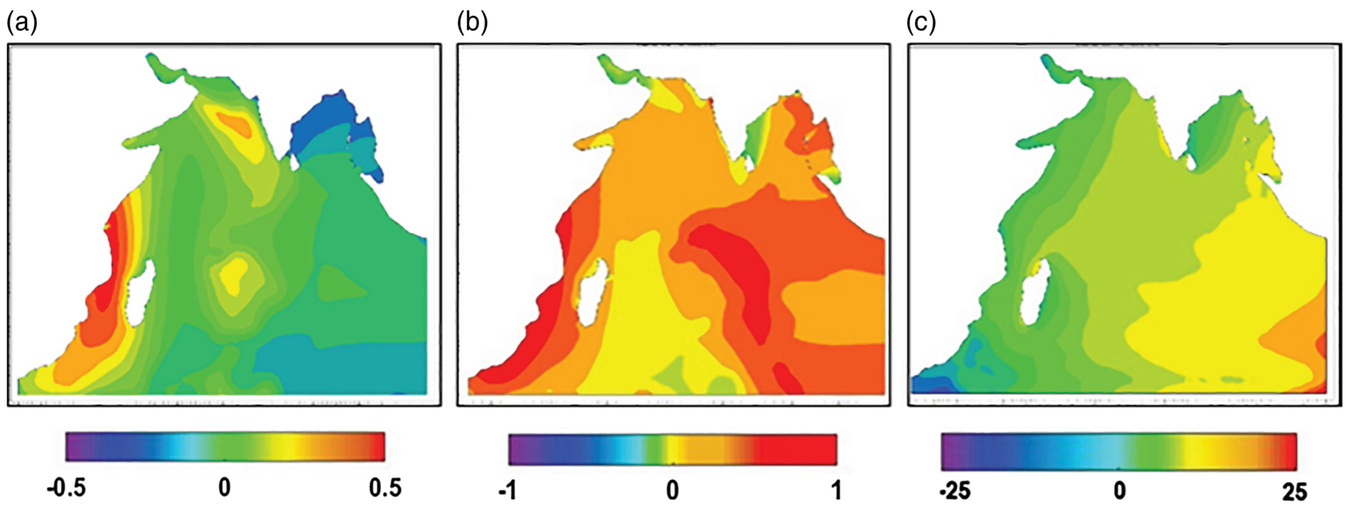

FIGURE 2 Bias in annual (a) significant wave height (m), (b) mean wave period (s), and (c) mean wave direction (degree) for the period 1979–2005 (ensemble GCM vs. ERA-Interim)

towards the mid to end of century. The expected percentage increase in H_s and H_{max} along Gujarat coast (location 1) is 15%. The mean H_s at location 2 during the near-term is 1.3 m, which increases moderately and reaches 1.5 m during 2041–2070. The H_{max}, on the other hand, increases rapidly between the two time slices and reaches to almost 2.8 m from 2.1. The percentage increase in H_s and H_{max} along Maharashtra coast is observed to be 15 and 35% respectively. A higher percentage change in mean H_{max} value of 30% is observed along the Goa coast. Both H_s and H_{max} are observed to increase along Karnataka coast between the time slices (by almost 20 and 30%, respectively). Kerala coast will experience increased H_s (by 0.1 m) and H_{max} (by 0.8 m). Tamil Nadu coast shows minimal increase in H_s (8%) and H_{max} (16%) between the periods. Wave activity at location 7, along Andhra Pradesh, also increases by as much as 18 (H_s) and 25% (H_{max}). Odisha coast (location 8) shows an increase in wave activity due to H_s and H_{max} by 15 and 25%, respectively, as we move into the later time slice. West Bengal coast (location 9) also shows increase in both mean H_s

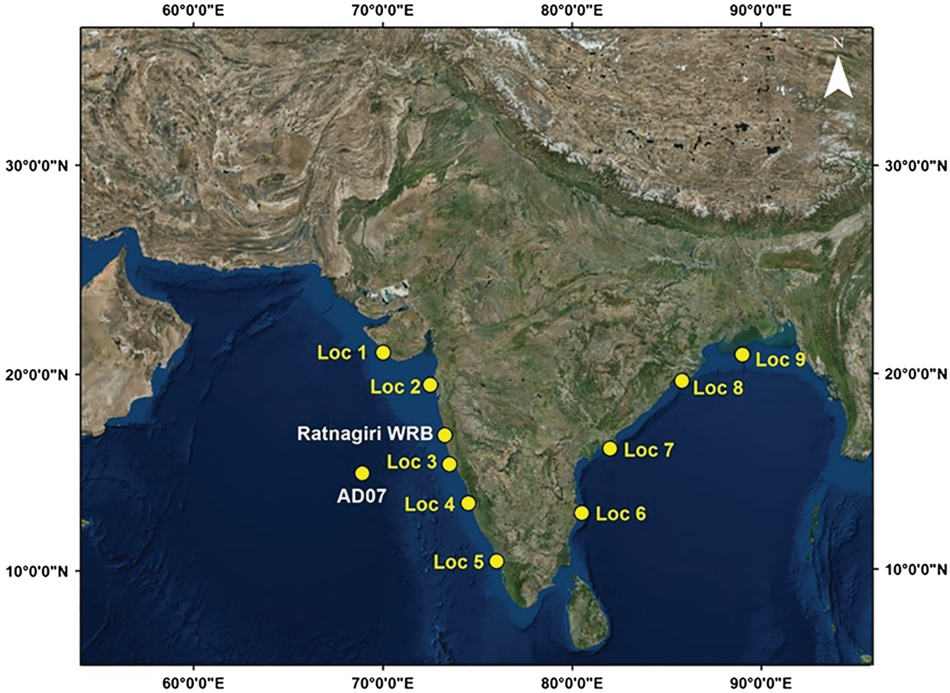

FIGURE 3 Selected representative locations along Indian coast for computation of mean wave characteristics

(15%) and H_{max} (30%). It must be noted from Figure 4a,b that both H_s and H_{max} increase as we move into the mid-century, at all locations. The increase in wave heights at all the locations along Indian coast is probably due to the increase in swell generation in the Southern Ocean (Semedo *et al.,* 2012) and also due to the increased wind speed and its circulation in the Indian offshore region (Kulkarni *et al.,* 2016).

Although the observed increase in wave heights in the IO region matches well with the global trends as reported by Mori *et al*. (2013), the local trends at various locations (locations 1–9, in this study) may differ from global trends depending upon the local bathymetry, fetch, and wind direction. Dobrynin *et al*. (2012) reported that both wind speeds and wave heights are expected to increase in the future, especially in the Southern Ocean, hence contributing more swells to the AS and the BoB regions, which may cause increased overall wave activity along the entire Indian coast. Some early support for this trend has been provided by Patra and Bhaskaran (2016) who observed an increase in the frequency of large swells in northern BoB when comparing conditions over the last decade to those of the immediately preceding period.

We forced the wave model with hindcast winds and simulated the hindcast wave climate over the IO region (1979–2005). Then the hindcast wave climate was used as a benchmark to obtain changes in wave parameters during the two selected time slices 2011–2040 and 2041–2070. The bias in near-term and mid-term wave heights with respect to the historical period is shown in Figure 4c,d. A moderate change (~0.25–0.3 m) is observed in the IO significant wave height during the period of 2011–2040. Regions near the northwest and northeast coast of India are expected to experience severe changes in H_s (by as much as 0.5 m). However, during the mid-term period, much of the Indian coastline is expected to experience an increase in H_s by 0.4–0.5 m. Maximum wave height was observed to have increased throughout the study domain during both time slices. The H_{max} during near-term period was observed to have increased by 0.25 m in the nearshore regions of Indian subcontinent, whereas it is expected to increase by almost 0.5 m in the later period.

Seasonality in wave heights is a common phenomenon in the IO region. The maximum increase in significant wave heights is observed during the monsoon months of JJAS. We compared the significant wave heights during the months of JJAS in both time slices with the historical wave climate (Figure 4e). It was observed that the H_s was heavily influenced by the SIO swells during the monsoon months which led to increased wave heights in the nearshore regions of the Indian subcontinent. Comparing the near-term waves with historical period, we observe moderate increase in wave heights (by 0.2–0.3 m) in the nearshore region and much higher increase (0.5 m) in the deep ocean. The mid-term, however, shows a much higher increase in wave heights by almost 0.5 m throughout the domain. This indicates higher swells in the monsoon months of 2041–2070.

With changing wave climate, the wave period is also likely to change. It is observed that the wave periods are generally high along majority of the Indian coast, indicating dominance of swells travelling from SIO. Few locations in the Tamil Nadu coast, however, experience lower wave periods compared to the other locations, which is attributed

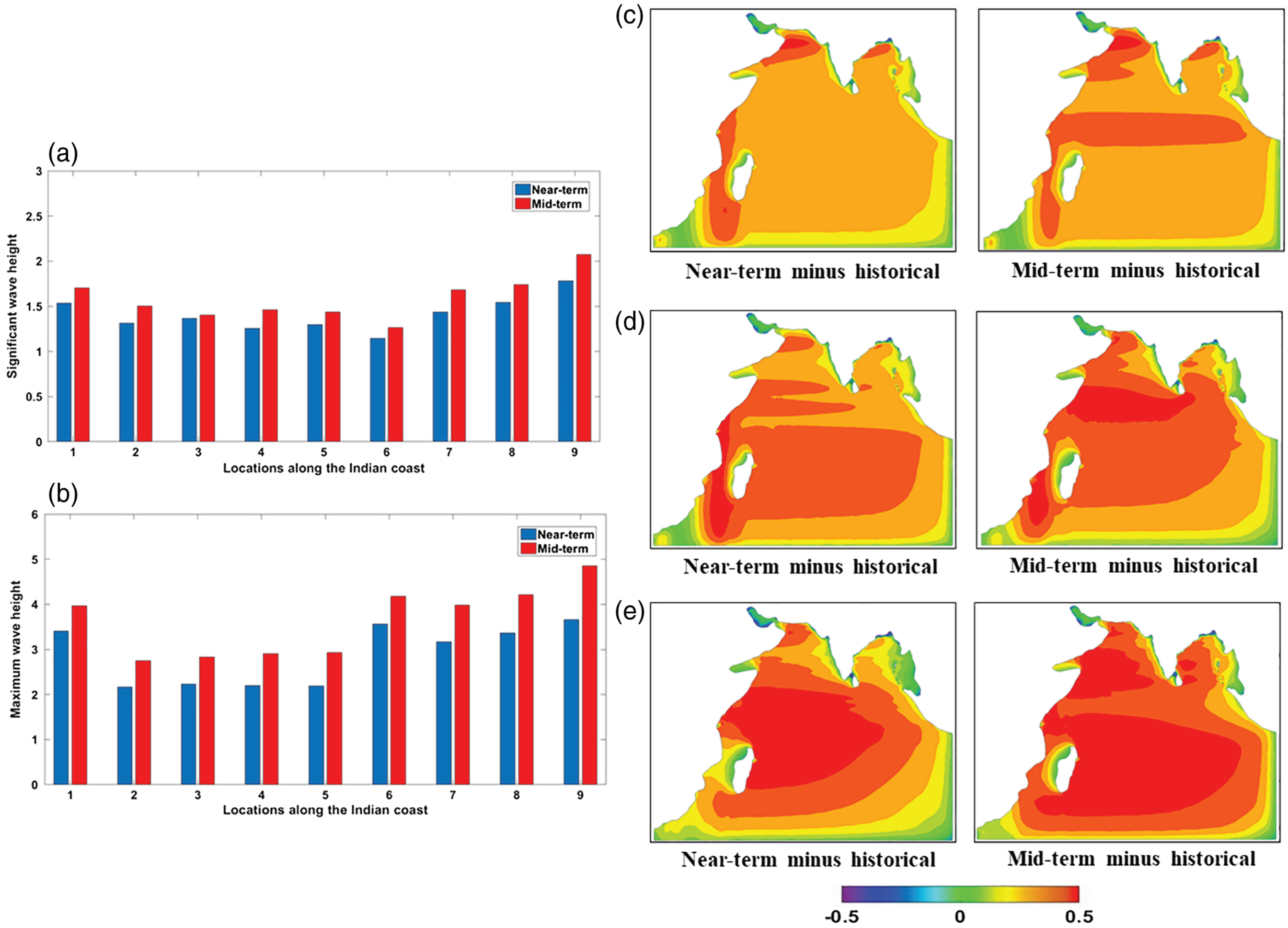

FIGURE 4 Near-term and mid-term (a) significant and (b) maximum wave heights at locations 1–9; net change (projected minus historical) in (c) annual mean significant wave height, (d) maximum wave height (e) JJAS significant wave height (m) over the IO region

to the geography at these locations that reduces the effect of swells coming from the far south, due to the sheltering effect of Sri Lanka. Hemer *et al.* (2013) suggested, on the basis of GCM wind projections, that southern extratropical winds would increase by at least 1 m/s towards the end of the century. They also pointed out increases in the northern and southern extratropical storm and trade wind belts, which implies increased energy across all wave types with consequent impact on sediment transport and other coastal processes. The increase in wind speeds would lead to the generation of larger waves in the IO region, where the swells from SIO are observed to propagate northwards into the AS and BoB basins. Our results support these findings as we observe a corresponding increase in significant wave height and mean wave period along the Indian coast. With an increase in the contribution of southerly waves to the wave spectrum of the NIO region, it is expected that the projected mean wave direction might shift to a more southerly orientation, leading to changes in longshore sediment transport and shoreline orientation.

The mean wave period values for both the time slices were extracted from the simulated results and are shown in Figure 5a. At all the locations (except 3–5), the wave period increases as we move into the mid of century. With an increase in the percentage mean wave period values, coasts of Gujarat (11%), Maharashtra (10%), Goa (10%), Karnataka (15%), and Kerala (5%) are expected to face moderate increase in mean period wave values as we move towards the mid-century. As already discussed, location 6 has lower wave periods (~6 s) compared to other locations (~8–10 s). However, it is observed that location 6 shows a higher increase in mean wave period value by almost 15%. Locations 7 (18%), 8 (12%), and 9 (16%) also show a high percentage increase in the mean wave period values. It must be noted that the increase in mean wave periods along the west coast of India is consistent throughout the coast. This increase in the mean wave periods is attributed to the combined effect of swells from the SIO and swells generated due to shamal winds. However, the comparatively higher mean wave period values along the east coast may be due to the

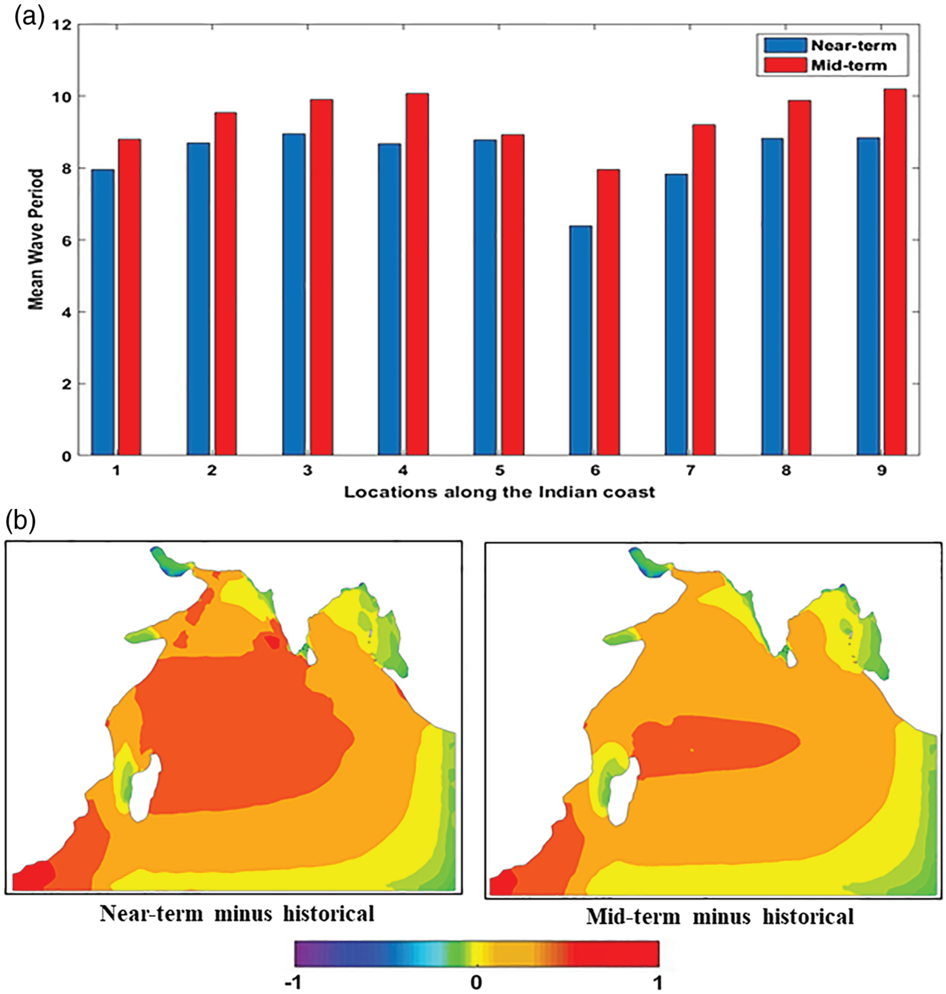

FIGURE 5 (a) Near-term and mid-term mean wave period at locations 1–9; (b) net change (projected minus historical) in mean wave period (s) over the IO region

increased swell activity in the entire study domain that ultimately propagates into the BoB region (Figure 5b). Hemer *et al*. (2013) also observed an increase in southern extratropical winds by almost 1 m/s towards the end of the century, which can cause increased swell activity in the IO region and BoB is known for its higher annual cyclonic activities compared to the AS. The overall increase in wave period in the northern basins of the IO region observed in this study is in general agreement with the results of Semedo *et al*. (2012), who concluded that the mean wave periods are expected to increase in the IO region towards the end of the century, especially in the swell-dominated regions.

Figure 5b shows the bias in near-term and mid-term mean wave period with respect to the historical mean wave period. Change in the mean wave period is observed to be between 0.4 and 0.5 s in much of the IO region during the 2011–2040 period. However, maximum change in wave period (~1 s) is observed during the 2041–2070 over majority of the domain, including parts of coastal India. Similar increasing trend (~1 s) in the mean wave period is observed by Hemer *et al*. (2013) in the regions of the tropical IO and eastern Pacific Ocean.

From the above discussions it is clear that the mean wave heights and periods along Indian coast are likely to increase in the future. At most of the locations, the rise in significant wave heights is expected to be around 20–30 cm. This is likely to have a wide impact across areas such as fisheries, coral reefs, longshore sediment transport rates, coastal erosion, and coastal flooding. The situation could be worse if the increased significant wave heights are accompanied with changed wave directions. A minor change in wave direction could lead to reorientation of the coast since the net longshore sediment transport rates are very sensitive to changes in wave direction. Here, we analyse the wave directions for the near and mid-terms (Figure 6).

The wave directions were analysed at each location by dividing the waves into eight sectors, N, NE, E, SE, S, SW, W, and NW. Figure 6 summarizes the results for the near- and mid-term time slices at each of the nine locations. Location 1 shows noticeable change in the future wave direction. It is noticed in Figure 6a that most of the waves in the near-term climate along Gujarat coast (location 1) are clustered from the SW direction, whereas much of the waves are directed from S-SSW as we move into future. The future waves, those directed from S-SSW, can make a significant

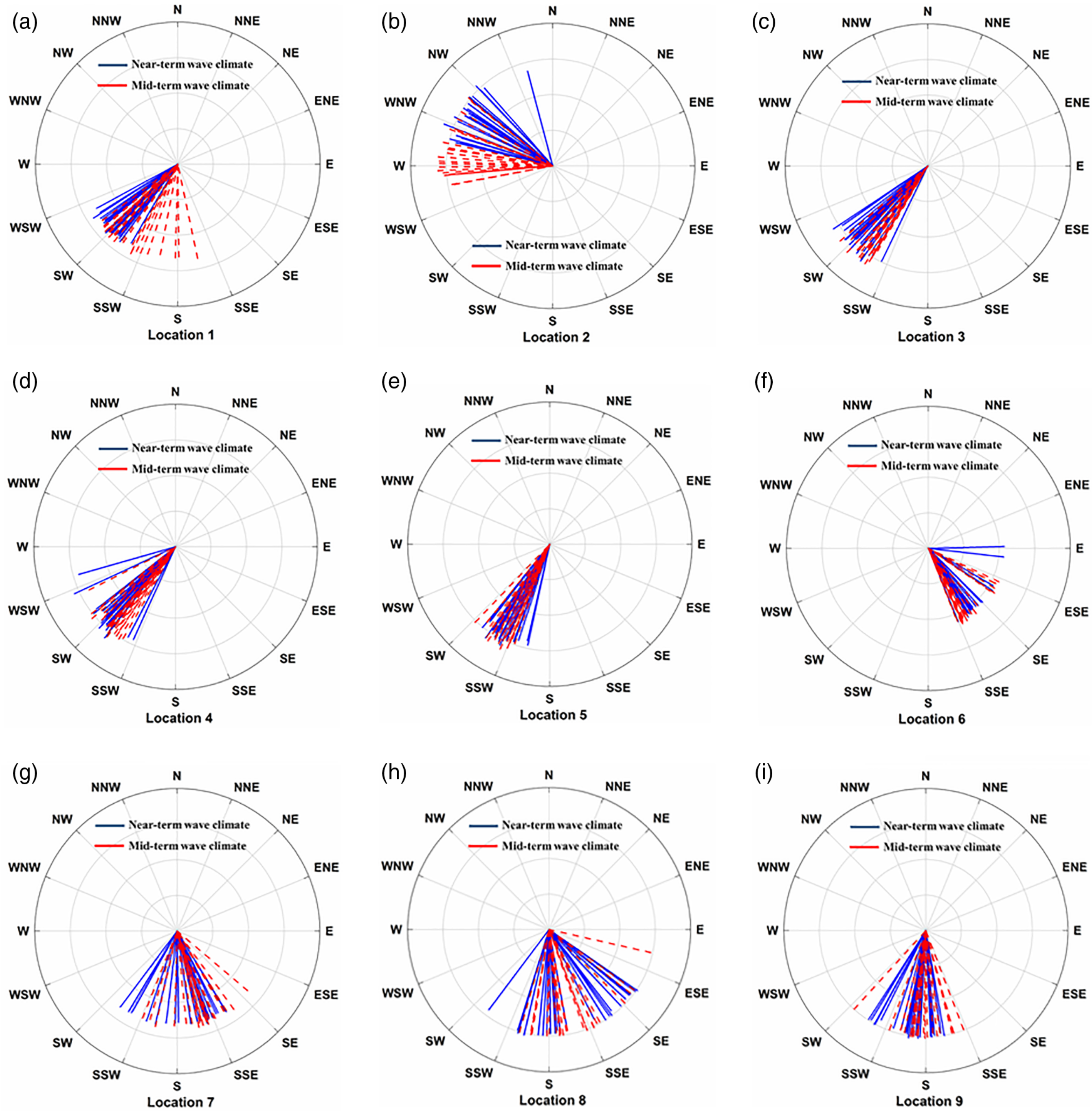

FIGURE 6 Present and future wave directions and periods at locations 1–9

difference in the direction of sediment transport and may influence orientation of coastline. Maharashtra coast (location 2), which is affected by the shamal winds, has most of the waves coming from WNW-NW in the near-term climate (Figure 6b), but in the mid-term, the majority of the waves are expected to shift towards W. This significantly reoriented wave direction (by almost 22.5°) may cause modified dynamics at the beaches and changed agitation at harbours. Future waves are expected to become more clustered along the Goa coast (location 3) coming from SW, compared to the near-term climate (Figure 6c). In case majority of the waves are focussed from a single direction, it may cause excessive erosion, leading to increased vulnerability of the coast, local sea level rise, and coastal flooding. The waves arriving at Karnataka coast (location 4) are expected to maintain the same predominant SW direction (Figure 6d). However, some waves are also seen to have shifted by almost 10° towards SSW. Kerala coast (location 5) is expected to experience clustering of waves in future as compared to the present climate (Figure 6e). Tamil Nadu coast (location 6) experiences majority of waves from the SE direction barring a few that arrives from E direction (Figure 6f). In the future, almost all the wave events are clustered from the SSE direction and none from E, causing extensive longshore sediment transport. Coast of Andhra Pradesh (location 7) is expected to experience minimum shift in wave directions in the future time slice (Figure 6g). Odisha coast (location 8) experiences a mean direction from SSE (Figure 6h), which is expected to continue in the future time slice. Similarly, the coast of West Bengal (location 9) is also expected to maintain the predominant wave direction of S-SSW in future (Figure 6i). Table 3 summarizes the changes in wave direction from present to future scenario. It is noticed that at many locations the waves show an increase in the angle of wave approach to the shoreline. If the waves change to approach closer to normal, then longshore drift is likely to reduce, and drift-aligned beaches will alter to become more swash aligned.

It is concluded that future waves would be arriving from a wider range of angles along the Gujarat and Maharashtra coasts, and more and more waves along Goa, Karnataka, and Kerala coasts would tend to cluster from SW direction. On the other hand, east coast is expected to experience more waves from S direction, indicating an increased swell activity from the SIO into the BoB region.

TABLE 3 Mean of present and future wave directions at each selected location along Indian coast

Locations	θ_m (°) (near-term)	θ_m (°) (mid-term)	Remark
1	225	202	Waves are expected to spread between S-SW in the future
2	300	290	Majority of waves are expected to shift towards W in future
3	220	225	More clustered waves expected from SSW-SW in future
4	225	215	More clustered waves expected from SW in future
5	212	210	More clustered waves expected from SSW in future
6	140	155	More clustered waves expected from SSE in future
7	160	165	Minimal shift in wave direction observed in future time slice
8	165	157	Minimal shift in wave direction observed in future time slice
9	180	195	Minimal shift in wave direction observed in future time slice

4 | CONCLUSIONS

This study provides regional wave climate projections for the 21st century covering the Indian coast obtained using an ensemble of near-surface winds produced by four different CMIP5 GCMs. The overall aim of this study was to investigate possible changes in the wave climate along the Indian coast in response to climate change. The wave climate has been analysed in terms of the phase integrated descriptors: wave height (H_s), maximum wave height ($H_{\max}$), mean wave period (T_m), and mean wave direction (θ_m). The wave climate has been calculated over two separate time slices, taken as being representative of current (2011–2040) and future conditions (2041–2070). We have presented a collective analysis of time slice average bars at point locations, spatial maps, and wave roses of present and future wave climate derived from computational modelling of wave conditions driven by surface wind projections from GCMs.

The primary findings are:

- Mean annual significant and maximum wave heights are projected to increase along much of the Indian coast. East coast is expected to experience much higher waves compared to the west coast.
- Mean wave periods are projected to increase in the future time slice, but more (by almost 10%) along much of west coast than east coast.
- Wave directions are also projected to change in the future time slice. As the mean wave direction changes in the future, waves show a tendency to cluster around one direction at few locations, reducing the directional spread of incident wave energy. Such clustering of waves and changes in direction may lead to more swash aligned beaches in the future.

To summarize, the projected changes in wave climate conditions shown here are in broad agreement with larger scale projections. Our results provide a more nuanced projection that accounts for regional variations in bathymetry and fetch length. It may be expected that the projected changes in wave climate may impact coastal and offshore activities and processes in the future climate. It is well known that surface waves influence coastal processes, coastal ecosystems, and sediment transport rates, and hence the shorelines. The movement of sediments along the shoreline is particularly sensitive to wave direction and the projected changes in mean wave direction could cause widespread realignment of beaches, leading to erosion, siltation, flooding, and disruption to coastal ecology. With changed wave directions at many locations along the Indian coast, it is now inevitable that longshore sediment transport rates and directions would change causing erosion/accretion of beaches and hence making the coastal areas more vulnerable to the impacts of climate change. Another important effect of changed wave directions would be on harbour agitation leading to reduced operational windows. Apart from damaging effects of changes in wave conditions on coastal infrastructure, the coastal ecosystem would also be under potential threat due to increased wave energy. A full assessment of the impacts of changes in wave climate on coastal sediment transport is, however, beyond the scope of this paper and is the subject of continuing research.

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