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Sea breeze-induced wind sea growth in the central west coast of India

V.M. Aboobacker[1], M. Seemanth[2], S.V. Samiksha, K. Sudheesh, Jyoti Kerkar, P. Vethamony*

CSIR-National Institute of Oceanography, Dona Paula, Goa 403004, India

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ABSTRACT

Fine resolution wind data is required in wave models to study the interaction between wind seas generated by coastal winds, and swells. In the present study, a mesoscale model, MM5, which is capable of reproducing fine details of sea breeze characteristics, has been used to simulate winds along the central west coast of India during pre-monsoon season, and these winds are used in the wave model. Our analysis shows that sea breeze induced wind seas are generated roughly around 210 km off Goa in the northwest direction, and grow progressively while propagating towards the coast. Relationships between wind speed and wind sea height have been derived, and they fairly explain the generation of wind seas by the sea breeze system. Since, the land breeze is weak and available fetch is very limited, the land breeze has no significant effect on wind sea generation from the northeast direction.

1. Introduction

The sea breeze circulation system – a common mesoscale meteorological phenomenon – has a profound effect on the meteorology and oceanography of coastal areas (Simpson, 1994). It occurs along about two-thirds of the earth's coastline, especially in the tropics and sub-tropics (Sonu et al., 1973). The sea breeze system begins at some distance offshore from the coast and expands further offshore (Laughlan, 1997). As the intensity of the wave activity depends on fetch length, the seaward extent of the sea breeze is important for wind sea generation. Aparna et al. (2005) studied the seaward extent of sea breeze along the west coast of India utilising QuikSCAT scatterometer winds (Ebuchi et al., 2002), and found that the maximum seaward extension is about 180 km off Goa, the central west coast of India. However, due to constraints in temporal and spatial resolutions, QuikSCAT winds are not useful to study the sea breeze characteristics very close to the coast. Moreover, fine resolution winds are necessary to model the waves, and understand the effect of land-sea breeze on wind-sea generation in the coastal regions (Vethamony et al., 2011). Earlier, Dhanya et al. (2010) modelled the land-sea breeze circulation along the central west coast of India using the mesoscale model, MM5, which was developed by the Pennsylvania State University/National Centre for Atmospheric Research (PSU/NCAR). It provides fine details of winds in reasonable temporal and spatial resolutions (Grell et al., 1994).

Theoretical study and experimental verification of wind wave generation and evolution focus generally on ideal conditions of steady state and quiescent initial background, of which the ideal fetch-limited wind wave growth is an important benchmark. In the study of ocean surface wind stress, the growth function expressed as the dimensionless dependence of wave variance on wave frequency is invoked to make comparison among different expressions of the drag coefficient or dynamic roughness (e.g., Pierson and Moskowitz, 1964; Toba et al., 2001; Jones and Toba, 2001; Hwang, 2005). Wave growth data are usually reported at 10 m elevation, serving as the scaling wind velocity; several growth functions are proposed. The discrepancies in the proposed functions are due to stability conditions and combination of field and laboratory data in some of the analyses (e.g., Hasselmann et al., 1973; Kahma and Calkoen, 1992, 1994; Young,1999), the spatial variability of the wind field caused by the proximity of land (Dobson et al., 1989; Donelan, 1979) and the difference in wave development stages in individual data sets (Hwang and Wang, 2004). After sorting out the stability conditions, excluding laboratory data from the analysis, and using the average wind speed between measuring stations as the scaling wind velocity, Kahma and Calkoen (1992, 1994) found that many of the discrepancies could be reconciled.

Waves along the west coast of India have been studied using measurements and models by several researchers (for example,

* Corresponding author. Tel.: +91 832 2450473; fax: +91 832 2450608.
E-mail addresses: vmabacker@gmail.com (V.M. Aboobacker), seemanth.m@gmail.com (M. Seemanth), vsamiksha@nio.org (S.V. Samiksha), sudheesh@nio.org (K. Sudheesh), jyoti2317@gmail.com (J. Kerkar), mony@nio.org (P. Vethamony).
[1] Presently at Tropical Marine Science Institute, National University of Singapore, 18, Kent Ridge Road, Singapore 119227.
[2] Presently at Space Applications Centre, Ahmedabad, Gujarat 380015, India.

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Kurian and Baba, 1987; Baba et al., 1989; Chandramohan et al., 1991; Kumar et al., 2000; Samiksha et al., 2012; Vethamony et al., 2014; Rashmi et al., 2013; Aboobacker et al., 2013). Measured wave energy spectra off Goa (part of the central west coast of India) show the presence of two different wave systems – wind sea and swell, during pre-monsoon season (Vethamony et al., 2009); they superimpose with pre-existing swells and generate diurnal variations in the wave parameters(Vethamony et al., 2011). Swells observed off Goa are primarily from SSW/SW direction generated in the south Indian Ocean. Sea breeze activity is predominant during pre-monsoon season (Aparna et al., 2005), and this influences the wave characteristics off Goa (Neetu et al., 2006). The present study aims at understanding the role of sea breeze in the generation and growth of wind seas along the central west coast of India. We have utilised Mesoscale Model (MM5) winds along the central west coast of India during May 2005 to reproduce wind seas off Goa using the model, MIKE21 SW.

2. Data used

Wave measurements were carried out at 25 m (B1) and 15 m (B2) water depths off Goa (Fig. 1) during May 2005 using Datawell directional wave rider buoys (Datawell, 2006). The wave rider buoy can function within −20 to +20 m of wave height, with an accuracy of 3% within the wave period range of 1.6–30 s. The direction accuracy is within 0.5–2° depending on the latitude. The wave data consists of wave energy spectra and wave parameters such as significant wave height (H_s), mean wave period (T_m) and mean wave direction (θ). Wind sea and swell parameters have been separated using the methodology given by Gilhousen and Hervey (2001) (Fig. 3), which is based on the wave steepness algorithm that partitions the wave spectrum into wind sea and swell components. The details of this methodology are discussed in our earlier study (Rashmi et al., 2013). The peak frequency (f_x), of steepness parameter (ratio between wave height and wavelength) of each frequency is calculated to estimate the separation frequency (f_s), $f_s = Cf_x$, where $C = 0.75$ is an empirically determined constant (Gilhousen and Hervey, 2001). The wind sea and swell part of the spectra have been separated using f_s, and accordingly, significant wave height, mean wave period and mean wave direction of wind seas and swells were calculated from the moments.Simultaneous wind measurements were carried out with a sampling period of 10 min using Autonomous Weather Station (AWS) of National Institute of Oceanography (NIO), Goa, installed at a height of 43.5 m at Dona Paula (Goa) coastal station (Fig. 1). These winds were reduced to 10 m height using logarithmic wind profile (Roland, 1988).

3. Simulation of winds using MM5

MM5 is a three dimensional, limited area, non-hydrostatic model designed to simulate atmospheric circulation (Grell et al., 1994). Nested model domains were selected in the Arabian Sea, covering Goa region (finest grid) with spatial resolutions of 27 km, 9 km and 3 km (Fig. 1); wind velocity vectors (u and v components) for every 1 h have been simulated, and validated with AWS measurements. Comparison between measured and modelled wind velocity vectors shows that the match is reasonably good (Fig. 2). Correlation coefficient for the zonal component is 0.86, whereas it is 0.59 for the meridional component (Table 1). If we refer to Fig. 2, we find that on an average v component is about 3 m/s and RMSE 0.69, and the error is ≈23%. In an earlier study (Dhanya et al., 2010), where MM5 model has been used, a RMSE of 1.26 m/s has been reported. The poor correlation of meridional component is mainly due to irregular topographic features of the region. Moreover, Sea breeze system along the west coast of India is mainly represented by the onshore velocity component (u-component) of wind and the model could reproduce the same reasonably good (Table 1). Also, point measurements from the AWS station cannot be truly compared with the smoothed spatial data from the model. However, we can observe main features of sea breeze (such as onset timing and maximum offshore extension) from the simulated sea breeze characteristics (Fig. 6), and these are in consistent with the earlier studies (Aparna et al., 2005; Dhanya et al., 2010).

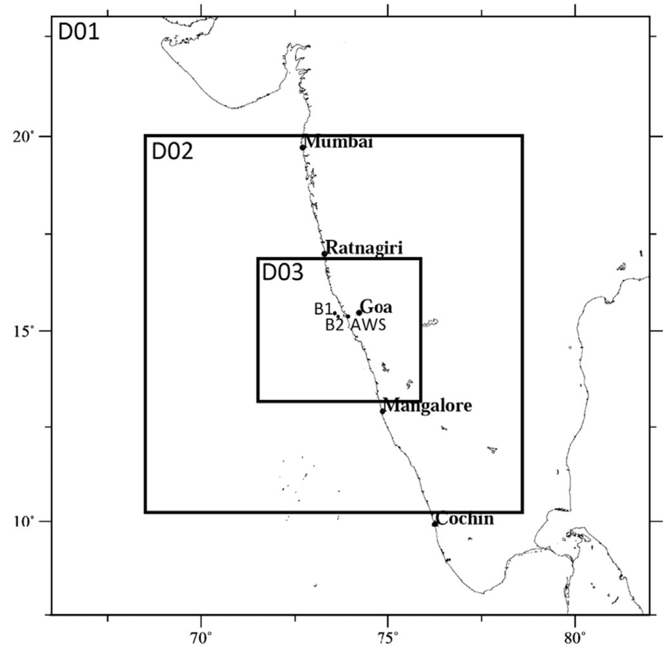

Fig. 1. Model domain used for nested MM5 simulations. Wind (AWS) and wave (B1 and B2) measurement locations are marked.

4. Wave modelling

MIKE 21 SW, spectral wave model developed by DHI Water & Environment (DHI, 2008) simulates growth, decay and transformation of wind waves and swells in offshore and shallow regions. The model considers wave growth by wind, non-linear wave-wave and wave–current interactions, dissipation by white-capping, wave breaking and bottom friction, and refraction and shoaling due to depth variations. The formulation is based on the wave action conservation equation (Komen et al., 1994; Young, 1999), where the directional-frequency wave action spectrum is the dependent variable. The discretisation of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. An unstructured mesh technique has been used on the geographical domain. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action (DHI, 2008).

MIKE 21 SW model includes two different formulations: a directional decoupled parametric formulation and a fully spectral formulation of the wave action balance equation. The first formulation is suitable only for nearshore conditions, whereas the second one is applicable to both nearshore and offshore regions. In the fully spectral formulation the source functions are based on the WAM Cycle 4 formulation (Komen et al., 1994). The source