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# Superimposed wind-waves in the Red Sea

P.R. Shanas, V.M. Aboobacker*, M.A. Albarakati Alaa, M. Zubier Khalid

*Faculty of Marine Science, Department of Marine Physics, King Abdul-Aziz University, P.O. Box 80207, Jeddah 21589, Saudi Arabia*

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ABSTRACT

The waves in the Red Sea are associated with the prevailing wind systems, frequently in combination with regional and local wind conditions. Measured waves from a buoy located in the central Red Sea show the presence of multi-directional waves; those propagated from distant areas in the northern Red Sea as well as those generated locally within the central Red Sea. On a diurnal cycle, superimposition occurs that leads to an increase in significant wave height and decrease in mean wave period. Monthly features of superimposed waves have been analysed based on a correlation analysis. The analysis has been further extended to the entire Red Sea by implementing a third generation spectral wave model, WAVEWATCH III. Monthly and spatial variability of the superimposed and non-superimposed have been discussed. The waves at 58% area of the Red Sea are dominated by unidirectional waves, while the 28% area is dominated by superimposed waves and 14% area has nearly the same contribution of two wave systems.

## 1. Introduction

The Red Sea lies in a narrow, elongated rift valley between Africa and the Arabian Peninsula, approximately 2250 km long and maximum width around 350 km. The waves in the Red sea have unique characteristics unlike the other Seas in the world. It has been assumed that distant swells (from the Arabian Sea) have no significant role in the Red Sea wave characteristics, because of the narrow strait and topographic features at the south of the Red Sea. The open boundary at the south usually keeps with zero energy for the Red Sea wave model (Ralston et al., 2013). The wave characteristics in the Red Sea depends upon the prevailing wind systems, especially on the seasonal reversal (Clifford et al., 1997; Patzert, 1974; Sofianos, 2003; Sofianos and Johns, 2002). The wind and waves during summer (May–Sep) are predominantly from the northwest (NW) / north-northwest (NNW) direction throughout the Red Sea. During winter (Nov–Mar), the wind and waves are from the NW/NNW in the northern Red Sea (north of 20°N) and between southeast (SE) to south (S) in the southern Red Sea (below 17°N); these two regions are separated by a convergence zone (around 18°N), where the wind blows as easterlies. In addition, the mountain gaps along both sides of the Red Sea enhance the wind flow across the longitudinal axis of the Red Sea. The Tokar Gap wind jet is developed at 18°N over the Sudan coast of the Red Sea, which blows with a speed exceeding 15 m/s more frequently during summer (Jiang et al., 2009).

The wind wave characteristics in the Red Sea were studied based on satellite observations and numerical modelling (e.g., Metwally and Abul-Azm, 2007; Saad, 2010; Langodan et al., 2014, 2015; Ralston et al., 2013). Metwally and Abul-Azm (2007) implemented the WAVEWATCH III (WW3), a third generation spectral wind-wave model, for the first time in the Red Sea and established a wind-wave atlas by hindcasting the wind-waves for about 16.5 years, forced with National Centers for Environmental Prediction (NCEP) winds. Saad (2010) made an attempt to improve the accuracy of wave hindcasting in the Red Sea using the third generation model WAM forced with European Centre for Medium-Range Weather Forecasts (ECMWF) winds. Further attempts were made to understand seasonal and monthly characteristics of the wind-waves in the Red Sea (Langodan et al., 2015, 2014; Ralston et al., 2013). The convergence zone develops around 18°N during winter due to the convergence of the NNW and SSE winds, which is highly sensitive to the overall atmospheric conditions, thereby model-derived wave patterns forced by various wind fields show large variability (Langodan et al., 2014). Since the convergence zone in the Red Sea is a unique feature, the physical aspects of the relevant wave evolution and propagation are different from the commonly used schemes (Langodan et al., 2015). During summer, the strong westerly Tokar gap winds prevail in the central Red Sea, especially during Jul and Aug, which has significant impact in modulating the wind-wave conditions in the Red Sea (Langodan et al., 2014; Ralston et al., 2013). Wave-energy potential in the Red Sea have been assessed considering long-term wave hindcasting (Aboobacker et al., 2017; Langodan et al., 2016). Seasonally, the winter prevails for higher wave power (up to 6.5 kW/m). Regionally, the central Red Sea has the highest wave energy potential. Inter-annual variability in wave

* Corresponding author.
*E-mail addresses:* shanaspr@gmail.com (P.R. Shanas), vmabacker@gmail.com (V.M. Aboobacker), alaa7@yahoo.com (M.A.A. Alaa), khalid.zubier@gmail.com (M.Z. Khalid).

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power was identified, which is closely related to the global climatic features. Fery et al., (2015, 2012) investigated the influence of wave growth formulations on the model results along the Jeddah coast, and identified the periodic patterns in the waves on the shorter and longer time-scales. Zubier et al. (2009) inferenced that the spectral wave model SWAN is suitable for the operational wave forecasting in the Red Sea, however, the high resolution atmospheric models should be customized to improve the accuracy of predictions.

The wave models provide reasonably good predictions upon proper treatment of source functions and input data. Accuracy of wind-wave predictions has been improved due to the implementation of recently developed physics source schemes in the wave model. For instance, Langodan et al. (2015) made an effort to improve the accuracy of wave predictions in the Red Sea, suggesting modifications in the wave dissipation terms. Even though the wave modelling studies (Langodan et al., 2015, 2014; Ralston et al., 2013; Saad, 2010) have given an overall idea of the seasonal wave characteristics in the Red Sea, there is still room for improvements in understanding the waves on a finer temporal scale (say, diurnal variability). The interaction of multi-frequency (or multi-directional) waves by the presence of the sea/land breezes and/or young swells is yet to be understood. The coastal breeze generated by the temperature gradients between the sea and adjacent desert shows diurnal variations leading to sea breeze – land breeze system (Pedgley, 1974).

The interaction of multi-directional waves usually results in superimposition that leads to complex sea states. For instance, the local wind seas superimpose over the swells along the west coast of India during pre-monsoon season (Vethamony et al., 2012). Major swells along the west coast of India are "old", which are mostly propagated from the south Indian Ocean (Aboobacker et al., 2011a, 2013; Remya et al., 2016; Sabique et al., 2012; Samiksha et al., 2012; Vethamony et al., 2012; Kumar et al., 2013; Kumar and Anjali, 2015). Since the Red Sea is a semi-enclosed basin, "old" swells are negligible and the "young" swells developed within the Red Sea can interact with the dominant wind seas. This requires special attention as the difference between the wind sea and swell periods in the Red Sea is not sufficiently large. The major limitations in studying the diurnal variability in the Red Sea are the lack of measured wind and wave data. In the absence of measured winds, the global data sets such as Climate Forecast System Reanalysis (CFSR) and ECMWF are useful to describe the wind characteristics in this region, even though the spatial and temporal resolutions are coarse. The only measured wave data available is from a buoy off Thuwal (north of Jeddah) in the central Red Sea (Fig. 1). The hourly CFSR winds and the waves measured off Thuwal have been analysed to study the diurnal variability and the characteristics of the multi-directional waves present in this region. The study further extended to the entire Red Sea by hindcasting the wind-waves for a period of one year using a third generation spectral wave model, WW3. The domain covers the entire Red Sea and part of the Gulf of Aden with the geographical extension 32–44°E and 10–30°N (Fig. 1). The wave model results have been validated with the measured waves off Thuwal as well as with the satellite data during Dec 2009–Nov 2010.

## 2. Available data

Wind and wave data used in this study are described in the following sections.

### 2.1. Wind data

Wind data from four different sources – ASCAT, ECMWF, CFSR and Buoy at Thuwal – have been used in this study. The CFSR winds (used for the wave modelling) have been compared with available measured winds at Thuwal. An inter-comparison of wind speeds have been also made between ASCAT (satellite data), CFSR and ECMWF winds for a longer period (1 year).

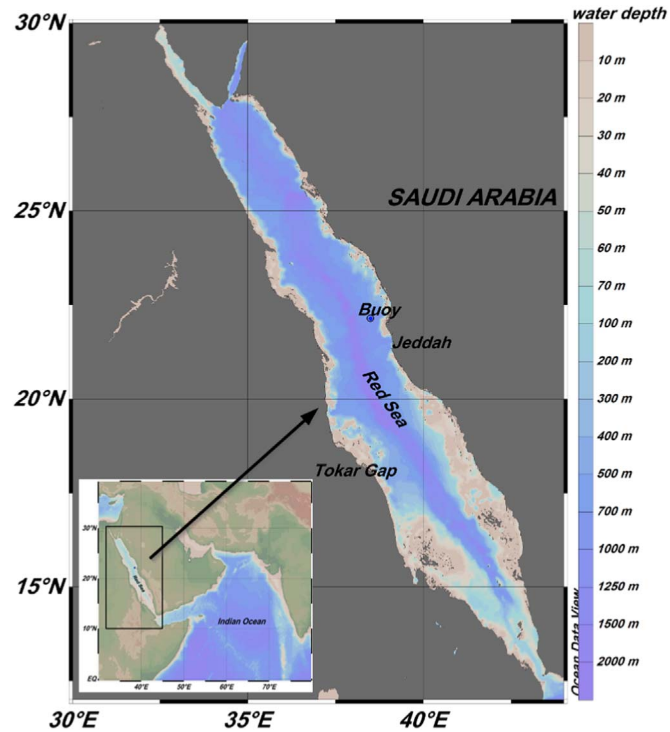


**Fig. 1.** Study area. Buoy location and Tokar Gap are marked.

#### 2.1.1. ASCAT

ASCAT is a product of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (OSI SAF), which is primarily designed to provide global ocean wind vectors for operational purposes (Von Ahn et al., 2006). It is a C-band dual fan beam radar scatterometer providing two independent swaths of backscatter retrievals in sun-synchronous polar orbit aboard the MetOp-A platform. The gridded products of the ASCAT winds have $U$ and $V$ components, available daily at every 0.25°×0.25° resolutions. Since the temporal resolution is very coarse, under-estimation of wind-wave parameters is expected upon forcing the wave model with ASCAT winds. However, the ASCAT winds can be used for the validation of global reanalysis wind fields in absence of measured wind data.

#### 2.1.2. ECMWF

The ERA-Interim wind vectors of the ECMWF is one of the most recent reanalysis wind data, which takes into account recent satellite altimeter data together with the built in ERA-40 data assimilation (Dee et al., 2011). The wind vectors ($U$ and $V$ components) are available for every 6 h at 0.75°×0.75° grids in original resolution and 0.125°×0.125° grids as downscaled since 1979 (http://www.ecmwf.int/research/era/do/get/era-interim). Here we considered the downscaled wind vectors for the analysis.

ERA-Interim wind data are well calibrated (Stopa and Cheung, 2014) and widely used for modelling purposes. For instance, these winds were validated against measurements and used to simulate the waves in the Indian Ocean using ModWAM (Samiksha et al., 2015). In the Red Sea, it was validated with winds from the a met-ocean buoy and ASCAT altimeter (Langodan et al., 2014).

#### 2.1.3. CFSR

The CFSR provides hourly wind vectors at every 0.312°×0.312° during 1979–2010 (Saha et al., 2010). The advantage of CFSR winds over the other global data sets is its fine temporal resolution, which allows capturing the extremes for some extent even though the spatial resolution is relatively coarse (Jørgensen and Nielsen, 2005). The