1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

The climatology of the Red Sea – Part 2: The waves

Sabique Langodan¹, Luigi Cavaleri², Angela Pomaro², Yesubabu Vishwanadhapalli³, Luciana Bertotti² and Ibrahim Hoteit^{1,*}

¹King Abdullah University of Science and Technology (KAUST), Physical Sciences and Engineering Division, Thuwal 23955-6900, Saudi Arabia

²Institute of Marine Sciences, Venice, Italy

³National Atmospheric Research Laboratory (NARL), Gadanki- 517 112, Andhra Pradesh, India.

*Corresponding author: Ibrahim Hoteit, King Abdullah University of Science and Technology (KAUST), Physical Science and Engineering Division, Thuwal 23955-6900, Saudi Arabia. E-mail: ibrahim.hoteit@kaust.edu.

Abstract

The wave climatology of the Red Sea is described based on a 30-year hindcast generated using WAVEWATCH III configured on a 5-km resolution grid and forced by Red Sea reanalysis surface winds from the Advanced Weather Research Forecasting (WRF) model. The wave simulations have been validated using buoy and altimeter data. The four main wind systems in the Red Sea characterize the corresponding wave climatology. The dominant ones are the two opposite wave systems with different genesis, propagating along the axis of the basin. The highest waves are generated at the center of the Red Sea as a consequence of the strong seasonal winds blowing from the Tokar Gap on the African side. There is a general long-term trend toward lowering the values of the significant wave height over the whole basin, with a decreasing rate depending on the genesis of the individual systems.

Key Words: The Red Sea, Wave climatology, Red Sea waves, Long-term climatological change

1. Introduction

Accurate knowledge of ocean surface weather conditions, particularly wind and wave , is important for a broad range of applications ranging from scientific studies, to engineering applications and industrial developments. While global studies (e.g., Hermer et al., 2010; Gulev and Grigorieva, 2004) provide an overview of the general wave climate, regional studies, such as Patra and Bhaskaran (2016) for Bay of Bengal, Gulev and Hasse (1999) for North Atlantic, Sasaki (2014) for North Pacific, and Casas-Prat and Sierra (2013) for Mediterranean, investigate the waves climate and their trends over specific regions. Despite being one of the important world's shipping routes, the Red Sea remains to be explored in terms of wind-wave climatology. Detailed understanding of the wave variability in the Red Sea will be very beneficial for various maritime activities in the basin. Because of the scarcity of the measured data in this region, a long-term high-resolution (spatial and temporal) wave hindcast is required for a comprehensive characterization of wind and wave variability in the Red Sea. This study brings out the detailed wave climatology of the Red Sea based on a 30-year hindcast generated using WAVEWATCH III configured on a 5-km resolution grid and forced by Red Sea reanalysis surface winds from the Advanced Weather Research Forecasting (WRF) model.

2. The Red Sea

The Red Sea is an elongated basin covering the area between 12°-30° N and 32°-43° E (see Figure 1). The basin has 2,250 km long, extending from the Suez and Aqaba narrow gulfs in the North to the southern strait of Bab el-Mandeb, and connecting the Red Sea with the Indian Ocean. The geological genesis has established both the submerged and external characteristics. The overall average depth is 490 m, with a maximum depth below 2,000 m.

2.1 The wind

57 The Red Sea is surrounded by a topography that determines much of its wind characteristics. The
58 high mountains on both sides of the Red Sea constrain the winds to blow along the axis of the
59 basin. The dominant wind blows from northwest throughout the year over the northern Red Sea
60 and Gulf of Suez, frequently extending to the southern strait. This wind is generally related to
61 Mediterranean storms reaching the most eastern part of this basin. From May to October,
62 northwest winds dominate the whole basin. During winter months (November to February), the
63 northeast monsoon blows intensively over the Arabian Sea. In the Gulf of Aden, high mountains
64 on both African and Arabian sides deviate the monsoon winds to blow through the Bab el
65 Mandeb strait, leading to a southeast wind in the Red Sea. These southeast winds converge with
66 the dominant northwest winds over the northern part of the Red Sea to create a convergence area
67 centered around 18° N, known as the Red Sea Convergence Zone (RSCZ). The topographic
68 features surrounding the basin, with larger and smaller valleys cutting across the bordering
69 mountain ridges, leads to typical local winds relevant for characterizing the local wind regimes.
70 In summer (from May to September), the most relevant one is the wind blowing through the 110
71 km wide Tokar Gap located around 18° N on the African side. The wind blowing through the
72 Tokar Gap is a synoptic-scale wind forcing regime associated with the Indian summer monsoon,
73 further enhanced by the strong land-sea breeze (Jiang et al., 2009; Davis et al., 2015; Yesubabu
74 et al., 2016). Finally, some narrow valleys on the Arabian side in the northern Red Sea lead to
75 occasional localized jets. In a companion paper, Langodan et al. (2017, henceforth L1) provide a
76 detailed description of the general wind patterns in the basin, discussing different characteristics
77 of the various wind systems in terms of their climatology and their possible long-term trends.
78 To have a complete picture over the whole year, we emphasize that we have stressed the winter
79 and summer conditions because it is during those two periods that intense phenomena occur in

the Red Sea. The two intermediate transient seasons, spring and fall, are with milder wind systems. Though wind bursts arrive from the Mediterranean during those periods with a lower intensity compared to the winter, they do not meet with the southeast monsoon connected wind and waves.

2.2 The waves

In this paper we are concerned with the climatology of the waves in the Red Sea and, as expected, these react according to the wind patterns described in the previous section. The four dominant wave systems are (see Figure 1 and also Table 1):

1 – Waves generated by the northwest winds that propagate in the southeast direction, frequently reaching the Bab el Mandeb strait. These waves are marked as E1.

2 – Opposite to E1, waves propagating in the northwest direction from the Bab el Mandeb strait. These waves are generated by the northeast monsoon winds and marked as E2.

3 – Waves generated by the Tokar Gap winds. On average, these waves are the most intense events in the Red Sea, marked as E3.

4 – Locally generated waves by the mountain gap jets in the northern part of the Arabian Peninsula, marked as E4. These waves are hardly relevant, being also often masked by the E1 system.

In the winter months, an interesting interaction takes place between systems E1 and E2. Langodan et al. (2015) provide a detailed description of this situation and its implications. In this period the systems E1 and E2 are active at the same time with almost equal wavelengths. These wave fields are created by two different systems and, as specified, they occur in winter: the monsoon connected southeast wind generates a wave field that extends much towards the north

and a storm pulse enters from the Mediterranean Sea creating a cold front advancing along the Red Sea. This leads to very peculiar situation of the encounter of two opposite wind, and active wave systems. The convergence at the center of the Red Sea causes a full reversal of the winds coming from the north, which in turns causes warmer air from the south to slide on top of the colder air from the north. This leads to an area of cloudiness and drizzle in the middle of the otherwise sunny zone. On the surface, the convergence of the northwest and southeast wind systems lead to a unique situation of opposing wind-wave systems. Langodan et al. (2015) have shown how the usual wave model physics (see, e.g., Cavaleri et al., 2007) do not well describe the evolution of waves under this situation. They have proposed a correction term to the wind input and white-capping terms, somehow generalizing the standard formulation. This term has not been used in the present 30-year hindcast because not sufficiently tested under all possible conditions. Physically relevant, the implications of the “encounter” condition, limited in space and time, is marginal for the overall statistics.

Complementing the L1 companion paper on the wind climatology, in this paper we report the corresponding results for wind-waves in the Red Sea. Towards this aim, Section 3 describes the modeling system, the general hindcast procedure, and the data generated for the analysis. Section 4 offers a description of the wave climatology of the Red Sea, focusing on both the statistical aspects and the physics behind it. Taking advantage of the 30-years of the wave hindcast, in Section 5 we explore the presence of possible trends in time. Given that the waves are an integrated effect of the driving winds in space and time, the information provided by waves has a more general significance than the one reported by wind in the companion L1 paper. All our results are discussed and summarized in the last Section 6.

Considering the companion paper (part 1) on wind climatology, dealing obviously with wind, in this paper we encounter the problem of two opposite conventions for direction: coming from for wind (meteorological one) and flowing to for waves (oceanographic one). Following the suggestion of one anonymous reviewer, we considered using the same convention for both wind and waves. We feel that such a solution would not be physical (e.g., a south coming wind creates waves that, important for waves they propagate, are flowing north). We address, as well as we could, the problem being as explicit as possible by referring most of the time to the E1, E2, E3, E4 systems defined above and represented in Figure 1.

3. The modeling system, the hindcast and the data available

We first provide a brief description of the 30-year hindcast of the driving wind fields. For a more complete description, the reader is referred to the companion L1 paper. The detailed description of the modeling systems is discussed in Langodan et al. (2016, henceforth L2).

The Advanced Weather Research and Forecasting model (WRF, see Shamrock et al., 2008) was implemented with two, two-way nested domains, with a high-resolution 10 km inner domain centered on our area of interest, the Red Sea (Yesubabu et al., 2016). The simulations were reinitialized daily from the ERA-Interim reanalysis (see Dee et al., 2011) and the available observations were assimilated at 6-hour intervals. The outputs were made available at hourly intervals. The quality of the generated wind fields was verified versus buoy and scatterometer measured data. L2 reports low bias (-0.07 m s^{-1}) and root-mean-square (rms) errors (1.03 m s^{-1}), making the data suitable for forcing the wave model in the Red Sea.

The 30-year hourly wind fields have been used as input to force the third generation WAVEWATCH III wave model (version 4.18 and package ST4, Tolman, 2014). The model was implemented on a regular latitude-longitude grid with 0.05° resolution. We used 29 frequencies,

starting from 0.05 Hz with 1.1 geometric progression and 36 equally spaced directions. The integrated parameters, such as significant wave height H_s , mean and peak periods T_m , T_p , and mean direction θ_m , were saved at hourly intervals.

The outputs were validated versus buoy and altimeter data. The buoy (WMO 23020, location is marked in Figure 1) was deployed from October 2008 till May 2010. All the available altimeter (ERS-1, ERS-2, Jason1, Jason2, GFO, Envisat, Cryosat2, Altika) data were used ($\sim 4 \times 10^5$ collocated points), as derived from the GlobWave database (<http://www.globwave.org>). Table 2 reports the general performance of the wave model when compared to these data (only buoy observations were available for wave period and direction). Bias and scatter index are respectively defined as

$$\text{bias} = \frac{1}{n} \sum_i (M_i - O_i)$$

where M_i and O_i represents the model data and observations, and

$$\text{Scatter Index} = \frac{RMSE}{\bar{O}}$$

where $\bar{O}$ is the average value of observations, and RMSE is defined as $\sqrt{\frac{\sum_i (M_i - O_i)^2}{n}}$.

In general, the errors (which include also the instrument errors) are small enough to be confident about the derived general climatology. A particularly large value is found in the directional rms error. This points to the frequent superposition of different, possibly opposite, wave systems (at the buoy position) and the consequent sensitivity of the direction. This likely leads to an increased error compared to errors in the case of single systems. The associated very small bias

suggests again good confidence in the overall results, especially to investigate long-term statistics.

To summarize, we have available 30 years of wave data at a resolution of 0.05° in space and one-hour in time. This corresponds to more than 2.6×10^5 data (for H_s , T_m , T_p , θ_m) per grid point. We used this information to derive the wave climatology of the Red Sea.

4. The wave climatology

For the Red Sea wave climatology, we first provide a general overview of the wave conditions related to the winds described in L1. Then we highlight the spatial and temporal differences between three areas, respectively northern, central, and southern (for convenience henceforth N, C, S) parts of the Red Sea. The two dash lines in Figure 1 split the basin accordingly. While some characteristics are common throughout the basin, each of these three areas has specific characteristics that will be soon detailed.

Figure 2 provides the general distribution of the mean and maximum significant wave height, in the summer (panels a and b) and the winter months (panels c and d), respectively. In these figures, the color bars represent different parameter ranges and for each point, the maximum refers to the highest value in the whole 30-year time series. The general distribution of mean H_s values in most parts of the basin in summer manifests the dominant role of the meteorological inputs from the Mediterranean Sea. The exception is the most southern part of the basin, suggesting that these impulses are in general not strong enough to reach this area (more than 2000 km away from the northern end). Note that the highest waves in the basin are produced by the Tokar Gap winds in summer. An interesting oceanographic detail is the different positions of the two larger waves areas in panels 2a and 2b. The reason is the different behavior of fetch-limited wind-generated waves under a compact jet that expands with decreasing wind speeds

189 while funneling out to the sea. In “normal” conditions, the expansion is more limited and
190 dependent on both wind speed and fetch; a maximum wave height is reached at a certain distance
191 from the coast. In contrast, particularly in strong wind cases, the waves grow correspondingly
192 faster and the peak is reached sooner, i.e. for a shorter fetch, the rapid wind speed decreases with
193 distance because of the wider expansion of the jet. Another factor could be the occasional
194 encounter between a northerly storm (cited above) and the Tokar Gap winds. The latter situation
195 is practically a daily event in summer over the central part of the basin.

196 The major difference between summer and winter is the presence, in the latter, of high waves in
197 the most southern part of the Red Sea. These are generated by the northeast monsoon connected
198 southern winds, which prevail throughout the season but without reaching extreme values. This
199 leads to relatively high waves in Figure 2c compared to the maxima in Figure 2d. In the
200 southeastern Red Sea, the waves are significantly attenuated by the islands, in particular coral
201 reefs. This also results in a well-defined preferential flux of energy along the main axis of the
202 Red Sea, with swell characteristics most of the time as a consequence of the frequent propagation
203 of waves from the north (E1).

204 For a more integral view, we show in Figure 3 the statistical distribution of H_s in the cited three
205 areas of the basin (see Figure 1). In area N, the waves height range between one and two meters,
206 with the highest waves generated by the frequent northerly storms. Areas C and S are
207 progressively more concentrated on the relatively low wave heights, less than one meter.
208 However, for the highest range (> 2.25 m), more occurrences are observed in area C, as a result
209 of the occasionally very strong Tokar Gap winds, especially when superimposed to a northerly
210 event.

211 A much more illustrative representation of the wave conditions in the Red Sea is given in Figure
212 4, where we plot the variability of the 95th and 5th percentiles (the upper and lower borders of the
213 grey area), the daily mean, and the corresponding 31-day running average of waves in the three
214 zones N, C and S. Although the waves in N exhibit some variability throughout the year, the
215 maxima (95th percentile) are relatively more observed within the first part of the year (January-
216 March), but without being much different from the other periods. A minimum in the 95th
217 percentile is reached in the summer months, due to both reduced activity in the Mediterranean
218 Sea, and to the absence of the, albeit small, waves from the south during this period. The
219 prominent feature of area C is the intense waves generated by the Tokar Gap winds in summer.
220 Otherwise the wave climate in this area is dominated by the superposition of waves coming from
221 north and south. The noticeable feature in S is related to the northeast monsoon period, from
222 October to April. The means and the 5 percentiles are consistent, of course at a reduced level,
223 with the 95 one. The partial exception is the summer Tokar Gap values in C, the largest increase
224 of the maximum values (95 percentiles) representing the peculiar physics (may be related to the
225 non-linearity) of these events in the most intense cases.

226 The characteristics of winds associated with the four dominant meteorological systems, hence
227 waves, appear more clearly in the time series of the monthly values, respectively for 95th, 50th
228 and 5th percentiles as shown in Figure 5. Consistent with Figure 4, the N waves are very
229 irregularly distributed throughout the year. Although the highest waves are observed in winter,
230 the summers too show high waves in the time series, not much different from the winter periods.
231 The yearly cycle is more evident in C and S. The differences between the 95th and 50th
232 percentiles in C are the characteristic of a temporary phenomenon. The Tokar Gap wind blows
233 only for part of the day, preferably in the morning hours, which explains this large difference. In

S waves, the difference between the 95th and 50th percentiles is rather variable (note the high 50th percentile values in 1999 and 2002), reflecting the variable characteristics of the monsoon from year to year.

Another basic feature of the wave characteristics in the three zones emerges from their H_s - T_m statistical distributions as shown in Figure 6. The two dotted lines correspond to the 1/15 and 1/25 wave slopes. The first value of the isolines is higher than usually found in deep waters because we have used T_m instead of T_p . This choice was mandatory due to the mixed character of the waves, wind-sea and/or swell, in parts of the basin. Isolines are at ratio of 2, geometric progression starting from 0.025.

In N, the distribution of waves reflects the basic local feature of a wind-sea. A slight prominence in the upper left of the distribution represents some low waves coming from large distance, i.e., low wave heights with relatively large periods coming from the southern Red Sea (E2). This feature is more evident in C, due to the waves coming from both north and south. Moreover, the distribution extends towards the high values (Tokar Gap waves, E3). The influence of the waves propagating from north (E1) is much more evident in S, with the large bump of low wave heights and larger periods.

The above frames well the main characteristics of the wind-waves in the Red Sea. However, with the exception of what can be seen in Figure 5, we do not have information about how these characteristics change in time. This is discussed in the next section.

5. The climatic trends

Similar to the discussion of Figure 3, we begin with an integral view showing the statistical distribution of the significant wave height for the first (1985-1994) and last decades (2005-2014)

of the studied period (Figure 7). We stress that the results for the intermediate decade are fully consistent with the ones we report here. We chose to discuss only the extreme decades to obtain larger quantities and put more emphasize on differences. We use a logarithmic scale for a better representation of the differences in the higher H_s range (2-4 m). This comparison clearly indicates a general shift of the wave heights towards lower values. Otherwise discrepancies in the higher value range are not significant because of the limited number of samples.

As a further step toward understanding the change in wave climate, Figure 8 provides the spatial distribution of the trend (cm y^{-1}) of a) the full time series ($\sim 2.6 \times 10^5$ data for each point of the basin), b) the monthly maxima (360 data), c) the monthly 90th, and d) 50th percentiles. Again there is an obvious decreasing trend of the wave height and its distribution is reflected throughout the basin. It is also noticeable from Figure 8 that the rate of decrease is consistent with, if not proportional to, the H_s distribution.

To further explore these results and to understand the rate of decrease of the dominant wave systems, we have evaluated the trend in the H_s for the three N, C, and S areas. We have first used the Mann-Kendall approach (Mann, 1945; Kendall, 1975), then quantified the trend using the Sen (1968) method. Pomaro et al. (2017) provide a full description of the procedure.

Evaluating the trend in H_s for each month from January (1) till December (12) emphasize the possible seasonality and the genesis of these trends. The results are shown in Figure 9 for the 99th, 95th, 75th, and 50th percentiles. A circle indicates those with greater than 90% significance. As expected, the trends are almost everywhere negative; the only exception being the 99th percentile result for September in C. Though the decrease is very diffused, very clear patterns emerge. For example, the decrease in the first months of the year are more pronounced in C than in N (and only mild in S). These indicate a reduced intensity of the Mediterranean intrusions

(E1), which prevent the storm from reaching the southern Red Sea. This is confirmed from the trends at S and it seems proportionally more marked for the higher percentiles, indicating most severe events. With the exception of the 99th percentile of the waves in C in September, there is no significant trend in this period, which cannot be interpreted in a specific direction.

The above results have the limitation of not specifying which wind system is behind the observed trend. For this purpose, and focusing on the E1 and E2 systems (see Table 1), we have repeated the analysis, but considering separately the south (E1) and north (E2) going systems. More specifically, we have considered the time series of wave data whose mean flow direction is within a 90° sector centered about the Red Sea main axis, respectively between 112.5° and 202.5° for south going waves (referred as D1), and between 292.5° and 22.5° for north going waves (referred as D2). It is evident that D1 and D2 are likely to be similar to E1 and E2. The corresponding results are given in Figures 10 and 11, respectively. A decreasing tendency in the intensity of the E1 system is evident in D1. For instance, as already pointed out, the strong decrease in S during February points to a progressively reduced capability of the E1 system to extend up to the most southerly part of the basin. Partially, this trend is also noticeable in December, at least clearly observed in C. In contrast, the indications are scarcer for D2 as shown in Figure 11. Note that a missing value in the plot means that there were not enough data to compute a meaningful statistics for that particular month. There is no observed significant trend in the data, except for wave heights in the last months of the year, related to the northeastern monsoon generated waves.

To summarize the results from this section, we have found a substantial decrease of the storms related to the intrusions from the Mediterranean Sea (E1). A possible similar tendency for the Tokar Gap waves (E3) and a much-reduced similar signal for the northeastern monsoon

connected wind generated waves (E2) are also observed. We have not explored E4, the narrow jets due waves in the northern part of the basin because of their reduced relevance, and consequent masking of the possible signal by the E1 system.

6. Summary and discussion

We summarize here the main characteristics of the wave climate in the Red Sea.

1 – Three wave systems dominate in the basin: the most prominent one occurring in the northwest (E1) and associated to the intrusion of relatively cold air from the Mediterranean Sea, the northward propagating waves (E2) forced by the orographically driven northeast monsoon winds, and the waves (E3) that follow the Tokar Gap winds through the valley in the central part of the African side. Figure 1 clearly depicts the situation.

2 – E1 occurs practically throughout the year and the intrusions of relatively cold air from the Mediterranean may have different origins in the summer and winter seasons. This wind leads to higher waves (frequently >2m) in the northern part of the Red Sea, which propagate southward with progressively decreasing height. The non-straight coasts of the Red Sea lead to shadowing areas, especially in the southern zone where the E1 waves mostly reduce to swell and exhibit a more unidirectional propagation.

3 – The E2 system, directed northwest and associated to the northeast monsoon, is present only in the corresponding period, i.e. from October to April. It does not lead to large wave heights, but to a rather consistent average value in time during the active period. The waves propagate in the basin, but their influence decreases rather rapidly moving north.

4 – The third system E3, associated with the Tokar Gap winds, generates the highest waves in the Red Sea, also because its impulses often interact with the north coming waves.

5 – A fourth wave system (E4) is associated to the narrow valley jets present in the northern part of the Arabian coast.

6 – System E1 has no specific seasonality, while systems E2 and E3 have well defined periods of action: E2 from October to April and E3 from July to September.

7 – Red Sea waves exhibit locally generated character as more dominant in the north and more seasonally in the central parts of the basin. But they are frequently a mixture of waves coming from a distance (swell from north, E1) and locally generated (from south, E2) in the most meridional part of the basin.

8 – There exists a general decreasing trend in the overall wave heights of the Red Sea. This decrease appears stronger for E1, milder for E2, and is also present in E3. The E4 signal is submerged in the E1 and, in any case, of low relative importance.

Derived from an extensive and well-verified reanalysis, the above results are robust both in their climate and trends in time (wherever significant). The local tendencies are connected to larger scale changes and the obvious example is the decrease of the northerly storms as a consequence of the progressively reduced wind (and wave) activity in the Mediterranean Sea (see, e.g., Conte and Lionello, 2013). Though it might be more difficult to study, one may also consider investigating this relationship from the other angle; once the physical connection between the systems has been established, use the acquired, or measured, information at a relatively local scale (the Red Sea in our case) to infer knowledge about the larger scales (climate). More work is still needed to understand this relationship in the Red Sea, which requires a dedicated analysis separating all the possible systems in the wind and wave fields.

Acknowledgements

346 King Abdullah University of Science and Technology (KAUST) funded this research. This
347 research made use of the resources of the Supercomputing Laboratory and/or computer clusters
348 at KAUST. Luigi Cavaleri has been partly supported by KAUST during his visits for research
349 collaborations. We express our appreciation for the extensive review of Robert Jensen and of
350 another anonymous reviewer.

References

- Casas-Prat M, Sierra JP. 2013. Projected future wave climate in the NW Mediterranean Sea. *J. Geophys. Res. Oceans*, 118: 3548–3568, doi:[10.1002/jgrc.20233](https://doi.org/10.1002/jgrc.20233).
- Cavaleri L, Alves J-HGM, Ardhuin F, Babanin A, Banner M, Belibassakis K, Benoit M, Donelan M, Groeneweg J, Herbers THC, Hwang PAEM, Janssen PAEM, Janssen T, Lavrenov IV, Magne R, Jaak Monbaliu, Onorato M, Polnikov V, Resio D, Rogers WE, Sheremet A, McKee Smith J, Tolman HL, Van Vledder G, Judith Wolf, Ian Young, WISE Group. 2007. Wave modeling-the state of the art. *Progress in Oceanography*, 75: 603-674.
- Conte D, Lionello P. 2013. Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios. *Global and Planetary Change*. 111:159-173, doi:10.1016/j.gloplacha. 2013.09.006.
- Davis SR, Pratt LJ, Jiang H. 2015. The Tokar Gap jet: Regional circulation, diurnal variability, and moisture transport based on numerical simulations. *J. Clim.* 28(15): 5885–5907, doi:10.1175/JCLI-D-14-00635.1.
- Dee D.P and co-authors, 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* 137:553–597. doi: 10.1002/qj.828.
- Gulev SK, Hasse L. 1999. Changes of wind waves in the North Atlantic over the last 30 years. *Int. J. Climatol.* 19: 1091–1117.
- Gulev SK, Grigorieva V. 2004. Last century changes in ocean wind wave height from global visual wave data. *Geophys. Res. Lett.* 31: L24302, doi:10.1029/2004GL021040.

372 Hemer MA, Wang XL, Church JA, Swail VR. 2010. Coordinated global ocean wave projections.
 373 *Bull. Am. Meteorol. Soc.* 91: 451–454.

374 Jiang H, Farrar JT, Beardsley RC, Chen R, Chen C. 2009. Zonal surface wind jets across the Red
 375 Sea due to mountain gap forcing along both sides of the Red Sea. *Geoph. Res. Letters*,
 376 36: L19605. doi:10.1029/2009GL040008.

377 Kendall MG. 1975. Rank correlation methods, 4th edition, ed. C. Griffin, 160 pp.

378 Langodan, S., Cavaleri, L., Viswanadhapalli, Y., Hoteit, I., 2015. Wind wave source functions in
 379 opposing seas. *J. Geophys. Res. Oceans*. 120: 6751–6768, doi: 10.1002/2015JC010816.

380 Langodan S, Cavaleri L, Viswanadhapalli Y, Pomaro A, Bertotti L, Hoteit I. 2017. The
 381 climatology of the Red Sea – part 1: The wind. *Int. J. Climatol.* (under review)

382 Langodan S, Viswanadhapalli Y, Dasari HP, Knio O, Hoteit I. 2016. A high resolution
 383 assessment of wind and wave energy potentials in the Red Sea. *Applied Energy*. 181:
 384 244–255, doi: 10.1016/j.apenergy.2016.08.076.

385 Mann HB. 1945. Non-parametric tests against trends. *Econometrica*. 13: 63-171.

386 Patra A, Bhaskaran PK. 2016. Trends in wind-wave climate over the head Bay of Bengal region.
 387 *Int. J. Climatol.* doi:10.1002/joc.4627

388 Pomaro A, Cavaleri L, Lionello P. 2017. Characteristics and trends of the Adriatic Sea wind
 389 waves: analysis of a 37 year long instrumental dataset. *Int. J. Climatol.* (submitted for
 390 publication).

391 Sasaki W. 2014. Changes in the North Pacific wave climate since the mid-1990s, *Geophys. Res.*
 392 *Lett.* 41: 7854–7860, doi:[10.1002/2014GL061590](https://doi.org/10.1002/2014GL061590).

393 Sen PK. 1968. Estimate of the regression coefficients based on Kendall's tau, *J. of the Amer.*
394 *Statistical Association*, 63: 1379-1389, doi:10.2307/2285891.

395 Skamarock WC, Klemp JB, Dadhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W,
396 Powers JG. 2008. A description of the Advanced Research WRF version 3, NCAR Tech.
397 Note NCAR/TN-475-STR, 113 pp. Nat. Cent. For Atmos. Res, Boulder, Colo.

398 Tolman HL. 2014. User manual and system documentation of WAVEWATCH-III version 4.18.
399 Technical Note Nr. 316, NOAA/NWS/NCEP/OMB.

400 Yesubabu V, Hari Prasad D, Sabique L, Srinivas CV, Hoteit I. 2016. Climatic features of the Red
401 Sea from a regional assimilative model. *Int. J. Climatol.* DOI: 10.1002/joc.4865
402

Figure captions

Figure 1 - The Red Sea. The two dash lines divide the basin in three logical zones where different winds and associate wave systems (arrows) dominate, albeit in different periods of the year. Note the bordering orography that strongly conditions the wind, hence waves, in the basins. The red dot shows the buoy position.

Figure 2 – Mean (panels a, c) and maximum (b, d) significant wave heights distribution in the Red Sea. Left and right panels are for summer and winter, respectively. The color bars represent different parameter ranges

Figure 3 – Statistical distribution of the significant wave heights in the three regions indicated in Figure 1.

Figure 4 –95 and 5 percentiles (borders of the grey area), mean and running average distribution of the daily significant wave height in the three regions indicated in Figure 1.

Figure 5 – 95, 50, and 5 percentiles of the monthly significant wave height along the 1985-2014 period.

Figure 6 – Statistical distribution of the significant wave height and mean period for each of the three regions indicated in Figure 1. Isolines are at a ratio of 2, geometric progression starting from 0.025.

Figure 7 – As Figure 3, but for the two decades 1985-1994 and 2005-2014. A logarithmic scale is used.

Figure 8 – Spatial distribution of the significant wave height best-fit slopes for a) the full time series, b) the monthly maxima, c) the monthly 90, d) monthly 50 percentiles.

424 Figure 9 - For each of the three zones delimited in Figure 1, north to south from top to bottom:
425 for each month of the year, 99, 95, 75, 50 percentiles of the long term trend of the
426 significant wave height. A circle indicates that the result is significant at the 90% level.

427 Figure 10 – As Figure 9, but for the south going waves in a 90° sector centered on the main axis
428 of the basin.

429 Figure 11– As Figure 9, but for the north going waves in a 90° sector centered on the main axis
430 of the basin.

431 **Table captions**

432 Table 1 -The main wave systems in the Red Sea and their characteristics

433 Table 2 - Performance of the wave model against buoy and altimeter measured data

434

435

436 Table 1 – The main wave systems in the Red Sea and their characteristics

Wave system	Characteristics
E1	Generated by winds blowing from the northern end towards the southern part of the basin
E2	Generated by the northeast monsoon connected winds blowing from south to north in the basin
E3	Associated to the strong winds blowing through the Tokar Gap
E4	Associated to the narrow wind jets blowing from the north Arabian side

437

438 Table 2 – Performance of the wave model against buoy and altimeter measured data

parameter	bias (m, s, °)	rmse (m, s, °)	correlation	scatter index
significant wave height	0.03	0.24	0.89	0.26
mean period	0.41	0.83	0.70	0.19
mean direction	-4.3	38.7	0.66	0.30

439

440

Figure 1 - The Red Sea. The two dash lines divide the basin in three logical zones where different winds and associate wave systems (arrows) dominate, albeit in different periods of the year. Note the bordering orography that strongly conditions the wind, hence waves, in the basins. The red dot shows the buoy position.

Figure 2 – Mean (panels a, c) and maximum (b, d) significant wave heights distribution in the Red Sea. Left and right panels are for summer and winter, respectively. The color bars represent different parameter ranges

Figure 3 – Statistical distribution of the significant wave heights in the three regions indicated in Figure 1.

Figure 4 –95 and 5 percentiles (borders of the grey area), mean and running average distribution of the daily significant wave height in the three regions indicated in Figure 1.

Figure 5 – 95, 50, and 5 percentiles of the monthly significant wave height along the 1985-2014 period.

Figure 6 – Statistical distribution of the significant wave height and mean period for each of the three regions indicated in Figure 1. Isolines are at a ratio of 2, geometric progression starting from 0.025.

Figure 7 – As Figure 3, but for the two decades 1985-1994 and 2005-2014. A logarithmic scale is used.

466

467 Figure 8 – Spatial distribution of the significant wave height best-fit slopes for a) the full time
 468 series, b) the monthly maxima, c) the monthly 90, d) monthly 50 percentiles.

469

470 Figure 9 - For each of the three zones delimited in Figure 1, north to south from top to bottom:
 471 for each month of the year, 99, 95, 75, 50 percentiles of the long term trend of the
 472 significant wave height. A circle indicates that the result is significant at the 90% level.

Figure 10 – As Figure 9, but for the south going waves in a 90° sector centered on the main axis of the basin.

476

477 Figure 11– As Figure 9, but for the north going waves in a 90° sector centered on the main axis

478 of the basin.