Can we extrapolate climate in an inner basin? The case of the Red Sea

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Abstract

We examine the possibility of making useful climate extrapolations in inner basins. Stressing the role of the local geographic features, for a practical example we focus our attention on the Red Sea. We observe that in spite of being an enclosed and relatively small Sea, its climate conditions are heavily affected by those of the larger neighboring regions, in particular the Mediterranean and the Arabian Seas. Using existing high-resolution information of the recent decades, we use both reasoned extrapolation and knowledge of, past and future, longer term general climatic information to frame what is presently possible to assess for the Red Sea. Specifically, the northern part, influenced by the Mediterranean Sea, shows a clear decreasing trend of both the meteorological and wave conditions in the recent decades. However, within a longer span record of 100 years, this decrease appears to be part of a 70-year cycle, which may be overturning, partly at least, in the coming decades. These trends are consistent with the expectations inferred from regional climatic indices, such as North Atlantic Oscillation and Atlantic Multidecadal Oscillation. No similar long term trend has been found for wave, hence implicitly the wind, conditions in the southern part of the basin. As expected, some correlation exists with the typical patterns of the Indian Ocean, but without any specific indication of a future trend. We suggest that, suitably adapted for the specific local conditions and dominant patterns, similar correlation and physical patterns may exist in several of the enclosed areas of the world, opening the possibility of exploring their possible trends in the future decades.

Keywords: Winds, Waves, the Red Sea, Climate change, Climate projection
1 - The basic question

The ever increasing measurement capabilities, particularly from space, coupled with the high quality of the present meteorological models, provide a solid background of the Earth present climate. For instance, global meteorological models, together with various satellite observations, produce a fairly accurate distribution of different weather parameters such as temperature, wind speed, ocean surface waves, etc, in the form of both analyses and short-to-medium range forecasts. For the details of the skill of meteorological models, see the statistics of the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, U.K.) at http://www.ecmwf.int/en/forecasts/charts and of the National Center for Environmental Prediction (NCEP) at http://polar.ncep.noaa.gov/nwps/. The reliability of present climate simulations, in particular for temperature, are also outlined in the latest IPCC report at https://www.ipcc.ch/report/ar5 and the annual reports of the American Meteorological Society at AMS (Blunden and Arndt, 2017).

We are specifically interested in wind and waves; these two are strictly related and as such often modeled in a fully coupled system as at ECMWF (IFS Documentation CY43R3, 2017). The results from these models are very satisfactory, as evidenced by the statistics available at the websites (http://www.ecmwf.int/en/forecasts/charts). Although with somewhat decreased accuracy, the results are still satisfactory in the enclosed basins; in particular, the general patterns are well reproduced and the possible biases are mostly limited to about 10%, or less (see Cavaleri et al., 2018). There is a strong influence of orography in these basins that drastically affects the features of the local wind and wave fields. The specific example where we focus our attention in this paper is the Red Sea.
A big burst to the knowledge in these enclosed seas has followed the availability of various reanalyses, both global and then regional, providing a long-term perspective of those areas of interest for a few decades of the recent past. In general, and more so in specific areas, a strong push to wind and wave studies has been supported by the obvious engineering implications.

With the growing interest in climate, the reanalyses have provided a clear perspective of how the situation has evolved in the recent decades. The much used example is ERA-Interim (henceforth ERA-I, see Dee et al., 2011), extending from 1979 to 2019, now substituted by the more recent ERA-5 (Hersbach et al., 2016; Adrian Simmons, 2018) that however was not available when this work was initiated. With its T256 spectral resolution (approximately 80 km), this dataset has provided both a detailed climate variability of the last forty years and the initial and boundary conditions for parallel regional high resolution studies over specific areas. A much longer step into the past has been taken with ERA-20C (Poli et al., 2016), a reanalysis of the entire 20th century. A recurrent problem practically in all the reanalyses is a bias related to the increasing volume of available, hence assimilated, measurements in time. This is mostly pronounced during the era of satellite observations, creating temporal inhomogeneities (Kistler et al., 2001). The philosophical approach of ERA-20C was rather different. Focusing on climate variability, hence not on the specific details and to avoid the problem, ERA-20C assimilated only data uniformly available throughout the century.

The generated high resolution regional reanalyses based on global reanalyses provide a comprehensive view of how, among other parameters, wind and waves have evolved in the last decades. Following the present arguments on climate, the question is to infer, if possible, how the climate in these inner basins is going to evolve in the near future. On one hand this could be done by downscaling the various global projections, derived, under different hypotheses, from the
numerous climate models. See in this respect the IPCC 2013 Fifth Assessment Report (https://www.ipcc.ch/report/ar5/). Granted the differences among the projections, well discussed and used by Conte and Lionello (2013) who focused their attention on the Mediterranean Sea, the approach of downscaling specific scenarios may become questionable when we focus on inner basins with very small spatial dimensions like the Red Sea, where the details of the orography play a fundamental role in shaping the relevant details of the local climate.

While in this paper we report our results for the Red Sea, we stress that our main message is meant to be in the methodology we have followed. In the present specific case we have used a local high resolution hindcast coupled with a more extended, both in time and space, information to better understand, where possible, the large scale patterns that somehow determine the boundary conditions for the ensuing local details. Both large and small scales are required to derive, where and when possible, the long term evolution of local (relatively speaking) details. Our examples and results concern the Red Sea, but, mutatis mutandis, the same principle may be applied for any similar basin or problem.

The manuscript is structured as follows. In Section 2 we briefly describe the area of interest and its characteristics. The available information are outlined in Section 3. The analysis is focused on the wave spectrum (Longuet-Higgins et al., 1963; Holthuijsen, 2007), a variable not commonly used until recently that in turn outlines the whole distribution of the sea surface energy. Waves have two favorable characteristics for climate analysis: they are the integrated effect of winds over the propagation domain, and their different signals superimpose without canceling each other. In the Red Sea, this reveals the influence of three meteorological sources. The first one dominates the northern part and is largely influenced by the Mediterranean activity (E1). The second is influenced by the winter monsoon and its specific characteristics over the Arabian Sea (E2). The
third one is driven by continental winds and linked to the summer monsoon (E3). These three systems seem to be responding differently to the long-term climate variations (Langodan et al., 2018). The possible projections via the data presently available are presented in Section 4. Here we highlight the possible changes in climate in the near future, but stressing the possible uncertainties and the related reasons. Particularly, the wave activity of the northern wave system (E1) shows a decreasing trend, which is consistent with the decreasing trend in wind speed over the area, and also correlated with the more general NAO trends. In turn, the analysis of the longer time series (100 years from ERA-20C), while consistent with these trends, suggests that they are part of a longer cycle, spanning about 70 years, which may be overturning in the coming decades. These results are summarized in Section 5 where, beside the specific area of present interest, we try to frame a general philosophy for approaching similar problems in other areas of the world.

2 – The area of interest

A thorough description of the Red Sea wind and wave characteristics is provided by Langodan et al. (2014, 2015, 2018, henceforth L14, L15 and L18 respectively) out of which we summarize here the information relevant for the present study.

The Red Sea (see Figure 1) is a slightly more than 2000 km long basin, located between Africa and Asia, extending in a rather straight North-North-West to South-South-East direction (NNW to SSE; henceforth the four cardinal directions North, East, South and West will be indicated as N, E, S and W, respectively). It has an average width of 180 km with 355 km at its widest span. At North the Red Sea is closed with the Suez and Aqaba gulfs, and at its southern end it is connected to the Arabian Sea via the Bab-el-Mandeb strait with a curved geography that blocks Indian Ocean waves from entering the basin. Therefore, the waves in the Red Sea are locally
generated and thus strictly related to the local winds. Moreover the basin is a deep sea, at least from the wave point of view (i.e. more than 200 m, so that waves do not feel the bottom), except on the coastal areas fringed by shallow corals.

The orography bordering the Red Sea is very important in determining the local wind and wave climate. The basin is bordered on both sides by mountains, which largely determine the local wind and waves in two different opposing ways. On one hand, the winds, and the associated waves, are channeled along the main axis of the basin (roughly in 330°-150° direction), with two main opposite flow directions. The winds from N to S (along the basin axis) are due to meteorological inputs from the Mediterranean Sea. Following L14, L18, we refer to this system as E1. On the other hand, the high Somali and Ethiopia plateau bordering the Gulf of Aden and the cited orography of the strait are instrumental in channeling the Arabian Sea NE monsoon winds into the Red Sea, blowing in the NNW direction. In winter (from October to April) this condition leads to a wind and wave system (named as E2) opposite to E1. These two confronting systems lead to some interesting possible interactions at various latitudes of the Red Sea (see L15 for a full discussion). A rather different situation is connected to the strong transversal winds that in summer blow down the Tokar Gap (African side, see Figure 1) across the Red Sea (referred to as E3, following L18).

In the different world climates it is relatively common to find areas characterized by strong gradients, e.g. of temperature or characteristics of the storms. Possibly the most classical example is the Mediterranean Sea, squeezed between (on its northern side) the relatively cold and stormy Europe, and (at South) the tropical and arid African continent. As such these areas, and specifically the Mediterranean Sea, are very sensitive to even small changes in the climate system. Several authors, see among others Giorgi and Lionello (2008), have framed well the situation pointing out
the possible progressive shift northwards of the European storm belt. A similar situation with a strong geographical gradient exists over the Red Sea, enclosed between (extending from) the Mediterranean Sea to the north and the much warmer Arabian Sea in the south. This makes the Red Sea, or at least some of its mentioned wind and wave systems, very sensitive to even small changes of climate. It is of interest to identify and enlighten the less immediate and more significant large scale changes. We are not attempting at addressing such a huge task in this paper; instead, we endeavor the first step toward this assessment by exploring the capability of hinting to the possible future scenario of the Red Sea on the basis of the available data.

3 – The available information

Our basic information is the extensive hindcast of the wind and wave conditions described in L18. This hindcast is possibly the best information presently available for the Red Sea. Starting from ERA-I as initial and boundary information, a two-step nested domain, respectively at 30 and 10 km resolution, has been used for daily 36 hours runs using an assimilative Weather and Research Forecasting (WRF) model (Shamarock et al., 2008). The first 12 hours were considered as spin-up, and the remaining 24 hour simulations have been saved as the hourly wind fields. The wind fields are then used to drive an uninterrupted high resolution (0.05°) run of the WAVEWATCHIII (WW3 – ST4 version) wave model (Tolman, 2014; Ardhuin et al., 2010) from 1979 till the present. Compared to the available measured data, L18 report best-fit slopes, bias, rms error and scatter indices of 0.99, -0.07, 1.63, 0.31 for wind speed $U_{10}$ (ms$^{-1}$), and 1.01, 0.03, 0.24, 0.26 for significant wave height $H_s$ (m). These values are amply suitable for a climatological analysis. A key characteristic of the L18 analysis of the wave results is the use of the wave spectral partition approach to derive different wave systems. Portilla-Yandún et al. (2015) and Portilla-Yandún (2018) provide a full description of the approach. Here we report the details required for
a full appreciation of the results.

In a complex environment such as the Red Sea, the “significant wave height” is hardly a sufficient information to derive large-scale climate features as it accounts for a general superposition of different wave systems with different geneses, e.g. systems E1, E2, E3 mentioned in the previous section. The full two-dimensional spectrum available as the regular output of any advanced wave model (as the WW3 used in the cited Langodan et al. papers) is the best variable to work with. At each given time and position, the spectrum reproduces the distribution of wave energy among the different frequencies and directions (the interested reader can find all the information on Holthuijsen, (2007)). The partition technique (Portilla-Yandún et al., 2015) allows to logically separate the spectrum into different sections, each with its dominant own frequency and direction clearly associated to its specific origin. The key point of the L18 analysis is that the “climatological” one, i.e. the estimate of the trends and their possible reasons, is done on the single partitions, hence systems E1, E2, E3, each one arguably dependent on a different phenomenology.

Figures 2, 3 and 4, explain and summarize well the situation. Figure 2 shows the yearly variability of the partial wave energy ($\propto H_s^2$). The three columns are for the northern, central and southern regions of the Red Sea, respectively (see in this respect Figure 1). The first row refers to the total energy, the second one to system E1 (waves moving from N to S), the third one to E2 (from S to N), the fourth one to E3 (the transversal system from the Tokar Gap). In L18 a fourth system of wind and waves have been identified, associated with the secondary transversal winds, hence waves, from the eastern side of the basin. We will neglect this system in our discussion as its energy is negligible compared to E1 and E2. Intentionally, we use energy as so doing the contribution from the different systems can be added to obtain the overall values in the top panel.
Together with the Red Sea geometry in Figure 1, a detailed analysis of the figures in rows 2 to 4 clarifies the overall phenomenology. System E1 is very active in the northern part of the basin, extending with progressively decreasing intensity till its southern section. The opposite happens from S to N with system E2, which propagates less effectively with distance. E2 exhibits a seasonality associated to the winter NE monsoon in the Arabian Sea. The Tokar Gap winds, system E3, are present only in summer and in the central part of the Red Sea. All this makes it clear how a long-term climatological analysis is only possible after identifying the relevant systems in the basin, their meteorological origins and distributions.

L18 provides a keen analysis of the trends eventually present in the different systems of the basin. The results, for each month of the year, are prescribed in Figure 3, which plots the trends for different percentiles of the distributions (50, 75, 95, 99%) for the different systems and different zones. The distribution of the panels is similar to the one of Figure 2. The circles identify the results whose significance is higher than 90%.

We recognize at once the diffused decrease of energy of the E1 system (waves from N to S), more marked in the northern zone directly exposed to the meteorological pulses from the Mediterranean, less so moving S where on the other hand the energy is lower (see Figure 2). There is also a, more limited, tendency to a decrease of the high percentiles of E2 (associated to the NW winter monsoon), quite evident in the southern zone and in the early months of the year when (see Figure 2) these winds are stronger. Only a limited negative trend was detected, concerning Tokar Gap winds (E3).

Given that Figure 2 deals with overall energy, the question that naturally arises is whether the decreases seen in the figure are due to lower wind speeds, hence wave heights, or to a decreased
number of meteorological events that generate particular wind/wave systems. This is clarified in Figure 4 where one can see that indeed, (only the significant results are shown) mainly for E1, but also for E2, the number of events per year shows a marked decrease.

4 – What we can say about the future of the Red Sea

The data and trends outlined in the previous section suggest a clear decrease in the number and intensity of the events entering the Red Sea from the Mediterranean since 1979. A milder decrease of the stronger events is present in the S to N systems associated with the NW monsoon in the Arabian Sea, and only minor changes are seen in the Tokar Gap wind. The question is what can we project for the relatively near future, say order of 20-40 years?

The natural thing would be to extrapolate the trends to the future, accepting some confidence limits for the specific values, to be then complemented with some large scale information. As summarized by Giorgi and Lionello (2008) and Conte and Lionello (2013), there are several studies concerning the future of the Mediterranean Sea climate. Basically the prospect is a progressive dominance in the North Atlantic of the pressure pattern corresponding to NAO, hence a decrease of the storms entering from the Atlantic directly into the Mediterranean basin. Such scenario is consistent with the decreasing trends of E1 shown in Figure 3. While it is possible to look for a correlation with NAO and the other various climatic indices to deduce the information related to the large-scale dynamics, we try to analyze the problem keeping a keen eye on the physical aspects of the situation.

An increased NAO value comes also with a northward shift of the Atlantic storm track, a finding that Giorgi and Lionello (2008) extends with their simulation till 2050. Indeed this is the order of magnitude of the future predictions where we feel we can also argue based on the results
derived from the available data. An increase of the NAO index corresponds, in general terms, to a strengthening of the Azores high pressure system, with a consequent decrease of the number of storms entering the Mediterranean from its W side. However, it is significant that a decreased, but still appreciable, correlation exists between NAO and the E1 system in the Red Sea also in these apparently unfavorable conditions. The reason is that, if not extreme, this situation corresponds to a northerly flow over the eastern part of the Mediterranean basin (Ulbrich et al., 2012). This latter situation is still favorable to northerly inputs of fresh air in the northern part of the Red Sea, generating the E1 system. All this is confirmed by plotting (see Figure 5) the correlation between NAO (retrieved from https://climatedataguide.ucar.edu) and the energy of the E1 system at a series of points along the axis of the basin. The distributed correlation over a full range of percentile values supports the physical relationship between these two variables. Note its higher values with increasing fetch, hence in the coastal part of the basin. Previous studies also confirm that the Red Sea basin is largely affected by climatic conditions that prevail over the North Atlantic Ocean (Papadopoulos et al., 2013; Abualnaja et al., 2015; Yao and Hoteit, 2018; Krokos et al., 2019). Therefore, the future climate of the Red Sea partially appears as a delicate balance between the effect of the northerly shift of the storm belt and how frequently the Azores high geometry favors these impulses.

While all this is certainly a valid working hypothesis, details and quantification may need other pieces of information. A first question concerns the trends reported in the previous figures. While a linear fit is an obvious first attempt, a careful analysis of the related time series reveals other possibilities. Out of the 30-year hindcast, in Figure 6 we report (panel a) the monthly and smoothed (5-month moving mean) thirty year time series of the wind speed in the northern part of the Red Sea (mean and 95% percentile) and (panel b) the monthly frequency of occurrence
(number of hours) in each month during which the E1 wave energy was larger than its overall 95% percentile. Consistent with the results summarized in Figure 3, Figure 6 suggests also a tendency to decrease (more evident in the moving averages) and a flattening of the trend in the last decade.

One of the recurrent characteristics of climate is the presence and superposition of cycles with different periods. To explore this possibility we use the long term information derived from ERA-20C (see Section 1). The corresponding results in the Red Sea are outlined in Figure 7. Although coarser compared to the 30-year hindcast, the span of more than a century could provide useful information. Figure 7a shows how the wind speed (yearly values) varied in the northern and overall Red Sea together with the evolution of the Atlantic Multidecadal Oscillation (AMO, retrieved from https://climatedataguide.ucar.edu), a natural long-term oscillation defined by SST anomalies over the north Atlantic with a periodicity of 60-80 years (Schlesinger and Ramankutty, 1994). We performed a singular spectrum analysis (SSA) to identify the major modes of oscillations from wind and AMO. SSA is considered as a robust method to identify the dominant modes of variability that represent low frequency signals in a time series (Ghil et al. 2002), and has been used to identify the long-term variability of the Mediterranean Sea (Marullo et al., 2011).

It appears that the first two modes of SSA account for almost 58% of the total wind variability over the Red Sea, which matches the one present in the first two modes of AMO as shown in Figure 7b. These results strongly suggest that the long term variability of wind over the Red Sea is related to the changes in the AMO signals with a 30-35 year shift that could also be interpreted as an inverse phase relationship. Apart from an obvious tendency to an increase at the end of the series (Figure 7a), that we will soon discuss, the decrease of wind speed evident in the period of hindcast (1985-2015) corresponds to a part of a longer cycle. Interesting enough, this also corresponds to a cycle of the air temperature (Figure 7c), which relates to the AMO in a more
A similar cycle is found also in sea surface temperature (data of the Hadley Centre for Climate Change, U.K., https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html) in the Red Sea (Krokos et al., 2018). A ~70-year oscillation of North Atlantic origin is reported also in the coral oxygen isotope record from the northern Red Sea (Felis et al., 2000). Finally we stress that the 70 year or so oscillations of the AMO index extend in the past till 1870 revealing two full cycles till today. A similar periodicity of about 70 years linked to the AMO was also reported in the sea surface temperature of the Mediterranean Sea (Marullo et al., 2011).

For its importance we first discuss the positive trend of the wind speed in Figure 7a. One of the characteristics of the ERA-20C is an apparent progressive increase of the world surface wind speeds. Although only surface information has been assimilated, it is generally assumed that the increased number of ship reports and their quality have led in time to an increase of the general surface model wind speeds (see Bridget et al., 2008, for a general discussion on this problem). Given this general characteristics, even if we choose to ignore this increase to focus our attention on the “70 year cycle” seen in Figure 7b, it is clear that the recent period 1985-2015 was characterized by a general decrease of the wind speeds. Note in particular how the minor rebound of the last ten years fits well with the flattening of the decrease pointed out above in Figure 6. Therefore, acknowledging the cycle present in Figure 7, it is rational to expect an increase of the E1 wind speeds, hence wave heights, in the next 30-40 years.

Neglecting the secular trend, the oscillations of the wind speeds are of the order of ±0.10 m s⁻¹. The 30-year simulation in L18 shows an average 6-7 m s⁻¹ wind speed in the northern Red Sea. So the ±0.10 m s⁻¹ corresponds to ±1.5%, i.e. between 2 and 3% in wave height. However, L18 reported in their Figure 5 about 0.80 m as typical (mean) Hₜ in the area, whose 3% would be
~2 cm. This is substantially lower, although of the same order of magnitude, of the $H_s$ decrease, between 5 and 6 cm, derived over a 30 year period from the long term hindcast (Figure 3).

Our tentative conclusion (and we believe it would be difficult to say anything more elaborate with the data and knowledge presently available) is that in the long term the northern shift of the storm belt will dominate the situation, with a decrease of the winds in the Mediterranean Sea and of the northerly ones in the Red Sea. However, although not fully explained, the variability that emerges from what appears a robust correlation with the AMO index suggests that long term oscillations may be superimposed. Their present phase is such that in the relatively near future (20-30 years) there can be, if not an increase, at least a slow-down of the rate of decrease experienced during the 30 year hindcast period.

We add a final comment regarding the air (Figure 7c) and sea surface temperature trends (not shown) in the northern Red Sea. It is clear that the air temperature depends on (is an inverse function of) the intensity and number of the cold (respect to the Red Sea area) northerly inflows. Therefore the last 30 year decrease in wind speed in Figure 7b corresponds to the increase in temperature in Figure 7c. Although as part of a more complex process involving the whole basin, the water too cools down during these northerly flows. This implies an increased evaporation rate leading, among other things, to the deep water formation that characterizes the northern Red Sea (Cember, 1988, Manasra et al., 2004, and Yao and Hoteit, 2018). Therefore a decrease of the northerly flows has a direct relationship with the formation and circulation of the Red Sea deep water.

We have also explored the possible future characteristics of the E2 system. Since the wind that blows towards N and waves in the southern Red Sea depend on the winter monsoon, we have
also examined the reported trends in the Arabian Sea. Both ERA-20C and ERA-Interim (see Figure 8a, b) suggest a positive trend in the Arabian Sea that however is not reflected as a corresponding trend in the Gulf of Aden (Figure 8c). In contrast, the high winds in the Gulf (here we consider the winter monsoon) show an, albeit limited, tendency to decrease. It is straightforward to link this decrease to the decrease of the E2 system higher percentiles seen in Figure 3. However, these trends may not persist for two reasons: 1) the winter monsoon, as its correspondent summer one, is a highly discussed subject (see, among many others, Rajeevan et al., 2012) and there is no consensus about its future trends, 2) as Figure 8 clearly shows, also given the strength of the monsoon, there is no simple direct link with the detailed characteristics of the southern surface winds in the Red Sea because of the orographic channeling due to the Ethiopian plateau that leads to the E2 wind and wave system. The E2, connected to the monsoon phenomenon, is expected to exist with random variability and an intensity that will depend on the characteristics of the monsoon.

5 – General Discussion

The general question we started from is how feasible is to forecast the wind and wave climate in an inner basin for the forthcoming few decades. We purposely focused on the inner seas because their climate is often strongly linked to their geography, and as such, potentially dependent at a critical level on details of the general pattern. This often makes their forecast much more challenging and uncertain than the deriving global fields. As an example, we have investigated the Red Sea, a long and narrow peculiar basin somehow linking the Mediterranean climate to the Indian Ocean. These two different environments, with fully different phenomenology and climate, both input their influence on the opposite ends of the basin. How far we can go with our projections depends on the dominant phenomenology. In the northern Red Sea, the inputs depend on the storm
track in the Mediterranean. With the present climatic trend, it seems likely to find in the future a
northward shift of the storm belt, with a reduced Mediterranean activity. However, also with an
increased atmospheric pressure on the western side of the basin, northerly cold inputs are expected
to find their way towards Sinai and the Red Sea. The balance among the various possibilities is
very delicate. In the long term, if the present climate trends continue, the northerly storm events
will decrease in number and strength. In the southern end, everything depends on the monsoon,
and we do not know much about the long-term variability of the monsoon system. The more so
because the strength of the monsoon is not the only controlling factor, but slight changes of
directions or interactions with the Ethiopian plateau will impact their role in establishing the
southern winds in the Red Sea.

Mutatis mutandis, analogous different arguments are likely to hold for most of the inner
basins. When discussing climate, we are used to observe Earth on a global scale and we tend to
select for our attention the dominant patterns. While this is certainly relevant for the overall
perception of the climate problem, our daily life happens on a much smaller scale, and it is often
at this scale that relevant information are needed. As we have shown with an example, this may
be, and mostly is, not straightforward and a careful analysis is required.

A final comment is due on the scale of the global changes. What is implicit in all our above
arguments is that future changes will be of the same order of magnitude of the changes we have
witnessed in the recent past. However (see again the cited latest IPCC report), there are substantial
indications that the possible future climatic changes could be of a different, i.e. much larger, order
of magnitude. The rapid melting of the northern polar ice cap is expected to change substantially
the meteorological patterns, and the consequent local changes could, and most likely will, be well
beyond the ones we have discussed on the base of a supposedly slowly changing situation. While
the climatic projections try, and up to a certain level succeed in, modeling this future, facing a completely new situation raises question marks on our present capabilities to accurately project our future climate.

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**Data Availability**

The regional reanalysis used in this study could be requested from the corresponding author. All climate indices including Atlantic Multi-decadal Oscillation (AMO) and North Atlantic Oscillation (NAO) are retrieved from National Center for Atmospheric Research (NCAR) climate data guide (https://climatedataguide.ucar.edu/). The global reanalysis ERA-Interim and ERA-20c are retrieved from ECMWF archives.
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Figures captions

Figure 1 – The Red Sea. The topography is shown by the color shades. The dashed lines split the basin into three zones. The arrows indicate the main winds blowing in the basin. The small panel frames the position of the basin within a larger geographical area.

Figure 2 – Single columns for the north, central, and south zones in Figure 1. The four panels in each column respectively report (from top) the total wave energy throughout the year, and the energy of the E1, E2 and E3 systems. 95 percentile, mean, running averaged mean, and 5 percentile are shown. Each row shows how the energy of each system varies throughout the basin (Derived from L18).

Figure 3 – The energy value trends for each month of the year are presented with the same logical distribution as Figure 2. The trends of the 99, 95, 75, 50 percentiles are shown. A circle indicates that the result is statistically significant at more than 90% (Derived from L18).

Figure 4 – Trend in the number of events for each month of the year. The results are shown only for the months where a sufficient number of data is present – E1 in the north, E2 in the south, and E3 in center. The results of the 99, 95, 75, 50 percentiles are shown. A circle indicates that the result is statistically significant at more than 90% (Derived from L18).

Figure 5 – Correlation, all along the Red Sea, between NAO and the energy of the E1 system for different percentile values. A circle indicates that the result is statistically significant at better than 90%.

Figure 6 – Hindcast wind speed in the northern Red Sea. a) The two plots show the mean and 95% percentile. b) 95% percentile of the monthly number of hours the E1 system was blowing
(wind from N to S). For each plot, monthly values, running averages and quadratic fits are shown.

Figure 7 – Wind speed and air temperature anomaly in the whole (RS) and northern Red Sea (NRS) resulting from the 100 year hindcast of the ERA-20C reanalysis of ECMWF along with the AMO index. a) Yearly values of wind speed. b) dominant spectral modes of winds plotted in upper panel (a). c) Same as upper panel a, but for air temperature.

Figure 8 – Surface wind speed considering only the winter months DJF. a) Arabian Sea from ERA-20C, b) Arabian Sea from ERA-Interim, c) Gulf of Aden from ERA-Interim.
Figure 1 – The Red Sea. The topography is shown by the color shades. The dashed lines split the basin into three zones. The arrows indicate the main winds blowing in the basin. The small panel frames the position of the basin within a larger geographical area.
Figure 2 – Single columns for the north, central, and south zones in Figure 1. The four panels in each column respectively report (from top) the total wave energy throughout the year, and the energy of the E1, E2 and E3 systems. 95 percentile, mean, running averaged mean, and 5 percentile are shown. Each row shows how the energy of each system varies throughout the basin (Derived from L18).
Figure 3 – The energy value trends for each month of the year are presented with the same logical distribution as Figure 2. The trends of the 99, 95, 75, 50 percentiles are shown. A circle indicates that the result is statistically significant at more than 90% (Derived from L18).
Figure 4 – Trend in the number of events for each month of the year. The results are shown only for the months where a sufficient number of data is present – E1 in the north, E2 in the south, and E3 in center. The results of the 99, 95, 75, 50 percentiles are shown. A circle indicates that the result is statistically significant at more than 90% (Derived from L18).
Figure 5 – Correlation, all along the Red Sea, between NAO and the energy of the E1 system for different percentile values. A circle indicates that the result is statistically significant at better than 90%.
Figure 6 – Hindcast wind speed in the northern Red Sea. a) The two plots show the mean and 95% percentile. b) 95% percentile of the monthly number of hours the E1 system was blowing (wind from N to S). For each plot, monthly values, running averages and quadratic fits are shown.
Figure 7 – Wind speed and air temperature anomaly in the whole (RS) and northern Red Sea (NRS) resulting from the 100 year hindcast of the ERA-20C reanalysis of ECMWF along with the AMO index. a) Yearly values of wind speed. b) dominant spectral modes of winds plotted in upper panel (a). c) Same as upper panel a, but for air temperature.
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