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A high-resolution assessment of wind and wave energy potentials in the Red Sea

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HIGHLIGHTS

- Wind and wave energy assessment for Red Sea is performed based on reanalysis data.
- Wind and wave energy in the Red Sea is dependent on seasonal variations.
- Detailed analysis of energy variation in the northern, central and southern Red Sea.
- Monthly variability suggests that peak power seasons vary in different areas of the Red Sea.
- The Red Sea is rich in wind energy; but seasonality is the key factor determining the harvesting.

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ABSTRACT

This study presents an assessment of the potential for harvesting wind and wave energy from the Red Sea based on an 18-year high-resolution regional atmospheric reanalysis recently generated using the Advanced Weather Research Forecasting model. This model was initialized with ERA-Interim global data and the Red Sea reanalysis was generated using a cyclic three-dimensional variational approach assimilating available data in the region. The wave hindcast was generated using WAVEWATCH III on a 5-km resolution grid, forced by the Red Sea reanalysis surface winds. The wind and wave products were validated against data from buoys, scatterometers and altimeters. Our analysis suggests that the distribution of wind and wave energy in the Red Sea is inhomogeneous and is concentrated in specific areas, characterized by various meteorological conditions including weather fronts, mesoscale vortices, land and sea breezes and mountain jets. A detailed analysis of wind and wave energy variation was performed at three hotspots representing the northern, central and southern parts of the Red Sea. Although there are potential sites for harvesting wind energy from the Red Sea, there are no potential sites for harvesting wave energy because wave energy in the Red Sea is not strong enough for currently available wave energy converters. Wave energy should not be completely ignored, however, at least from the perspective of hybrid wind-wave projects.

1. Introduction

Increasing awareness of the adverse effects of fossil fuel consumption on climate change has significantly contributed to the push toward developing alternative renewable energy sources. Ocean energy is considered to be a major renewable energy resources, among which ocean waves and offshore winds are the most evident. Intensive efforts have been expended on developing wind and wave energy harvesting technologies (see Hau [1] and McCormick [2] for more details). Because huge infrastructure investments are required to extract energy from wind and waves, careful analysis of the wind and wave climates is a necessary step for selection of suitable sites. This analysis should be conducted based on the climatology of wind and waves in terms of their power, rather than on standard characterization (i.e., mean and extremes) commonly employed in ocean/coastal engineering applications (e.g., offshore and coastal structures, navigation, etc.) [3]. In general, energy resource assessment involves identification of optimal locations with maximum potential for harvesting wind and wave power based on an investigation of the variability of wind and waves at all scales (diurnal, seasonal and inter-annual).

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Characterization of both wind and wave power has been carried out at the global (e.g., [4–6]) and regional scale (e.g., [3,7–17]). Zheng et al. [4] provides an overview of offshore global wind energy evaluations and Reguero et al. [5] presented the seasonal and inter-annual variability of global wave power resources. Sempreviva et al. [7] and Pontes [8] offered an assessment of renewable energy resources across the European seas from offshore winds and waves, respectively. Several other regional resource assessment studies such as Ashtine et al. [9] for Ontario and Great Lakes, Rusu and Soares [10] for Azores islands, Dvorak et al. [11] for California and Kim et al. [12] for Korean peninsula present a comprehensive evaluation of available renewable energy potentials over their respective regions. Zheng and Li [14] and Zheng et al. [15] also provide a detailed assessment of wind and wave energy resources in the South China Sea.

While the global studies provide a general assessment of potential wind and wave energy sites across the ocean, regional studies are usually focused on areas with high wind and wave energies. Regional studies are commonly based on local wind and wave models because of their capability to simulate offshore fields at high spatial and temporal resolutions [9]. A minimum of ten years of climate information is needed to assess potential wind and wave energies in a given region [18]. Because long-term measurements are required for reliable energy assessments, numerical model outputs are the main source of information in regions where long-term, in-situ observations are not available (e.g., [9,10–12,17,19–21]). However, there has been little effort to characterize wind and wave energies in areas with low-energy conditions, especially in enclosed seas ([3,8,15,16]). Although such areas are often characterized by low energy production rates, they have practical advantages in terms of implementation, operation, and maintenance of energy converter devices [22]. With its long and narrow basin, the Red Sea is one area where few alternative energy studies have been conducted. Despite the perception that the Red Sea does not produce enough wind or wave energy for harvesting, there are some areas where seasonal systems produce sustained wind speeds greater than 10 m s^{-1} [23].

Wind resource characterization is generally carried out at the height of turbine hubs (50 m, 80 m, 120 m, etc.) and most of the wind energy studies (e.g., [24]) are based on winds that are reconstructed from the surface (i.e., 10 m), assuming neutral stability conditions. Recently, Yip et al. [24] characterized wind resources in the Arabian Peninsula using reconstructed winds from the low-resolution ($0.67^\circ \times 0.5^\circ$) Modern Era Retrospective-Analysis for Research and Applications (MERRA) dataset and identified the areas with abundant wind resource. However, reconstructed winds may not provide an accurate representation of the winds over the Red Sea, where boundary-layer stratification, low-level jets (LLJs), and changing surface conditions are likely to be the dominant factors determining the weather conditions. In particular, the long and narrow shape of the Red Sea makes the local conditions very sensitive to even minor changes in the direction of the wind and wave fields [25]. Detailed analysis of wind and wave resources requires high-resolution datasets that could resolve spatial features and local circulations relevant to wind and wave power generation over the region [24]. To date, the lack of high-resolution (spatial and temporal) wind and wave information hindered the development of a comprehensive characterization of renewable energy resources from the Red Sea. This work presents the first attempt to characterize wind and wave potential energy resources over the Red Sea based on 18-year (1997–2014) high-resolution (10-km horizontal and hourly temporal resolutions) regional reanalysis generated using state-of-the-art assimilative numerical models and available observations. The long-term validated reanalysis data carries a wealth of information to elucidate the wind and wave climate in the Red Sea and describes the energy resources in the form of digital maps, providing vital information for planning and designing renewable energy extraction. By jointly considering wind and waves, our study locates potential sites for joint exploitation of offshore wind and wave energy in the region and provides a detailed analysis of their availability, while addressing seasonal and diurnal variabilities.

The remainder of the paper is organized as follows. Section 2 presents the datasets used in the study and the methodology followed for the assessment of wind and wave energies. Section 3 presents information on the wind and wave climate over the Red Sea. An assessment of wind and wave potentials is presented in Section 4. A summary of the main results and conclusions is given in Section 5.

2. Materials and methods

2.1. Study area

The Red Sea is a long basin that stretches 2250 km from the northwest to the southeast. Essentially closed at the north (except for the Suez Canal), it opens to the Gulf of Aden at the south through the narrow strait of the Bab-el-Mandeb. It has an average depth of 490 m with a maximum depth of 2300 m. The orography around the Red Sea regions consists of mountain chains of various altitudes just a short distance inland along almost the entire length of the sea. These geographical features constrain the surface winds to blow approximately parallel to the longitudinal axis of the Red Sea. In summer, from May till October, northwest winds dominate the entire basin, with speeds close to 10 m s^{-1} in the north and frequently exceeding 15 m s^{-1} [23]. During winter, typically between November and April, NW and SE winds occur in the northern and southern parts of the Red Sea, respectively. The convergence of NW and SE wind systems forms the Red Sea Convergence Zone (RSCZ) at around 18° N [26]. Night cooling on Sudan's Boma plateau and katabatic effects lead to the so-called Tokar Gap winds, blowing toward the eastern side [23,25–27]. The small and large valleys across the mountains modify the wind flow and create year-round localized weather patterns. Diurnal thermal forcing from the surface of the land drives the daytime sea breezes as well as the nighttime land breezes [23]. Moreover, local variability of the winds has strong effects on the wave fields [25,26].

2.2. Red Sea wind and wave reanalysis

The Advanced Research Weather Research and Forecasting (WRF) Version 3.6.1 model (ARW, [28]) and its WRF Data Assimilation (WRFDA) package were used in this study to generate an 18-year high-resolution reanalysis of Red Sea. ARW was implemented based on two, two-way nested domains with respective horizontal resolutions of 30 km and 10 km (Fig. 1), each with 51 vertical levels. We employed more vertical levels in the boundary layer in the atmosphere model configuration to ensure suitable representation of the fields at turbine heights. The model simulation was performed using a consecutive integration method with daily initialization. The model's physics were the same as in Jiang et al. [23] and Langodan et al. [26]. The ARW model was initialized at 1800 UTC on a daily basis with data from the European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-interim; [29]) and then integrated for 30-h using boundary conditions updated every six hours. The 6-h WRF forecast was used as a first guess to assimilate National Centers for Environmental Protection (NCEP) Atmospheric Data Project (ADP) observations in 6-hourly cycles for 24-h using a three-dimensional variational (3DVAR) approach. The full description of the PREPBUFR dataset is available at http://rda.ucar.edu/datasets/ds337.0. The outputs