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Wave statistics in the Adriatic Sea based on 24 years of satellite measurements

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ABSTRACT

Based on a database of sea state parameters in the Adriatic Sea, wave statistics has been developed at three different geographic locations along the busy Adriatic shipping route. The underlying database consists of a systematic numerical hindcast calibrated by 24-year satellite measurements and represents the most comprehensive data source of wave parameters available for the region. Joint probability distributions of significant wave heights and peak spectral periods are derived, thus enabling extreme sea states to be determined. Furthermore, waves have been evaluated with respect to the well-known dominant wind patterns in the Adriatic and compared to the Tabain's spectrum, a single parametric spectral description developed for local conditions and widely used in engineering practice. Statistics for three geographical locations are compared with one another as well as with data from other available references. These long-term statistics and regression equations developed can be used not only for fatigue and extreme wave loads of ships, offshore installations and renewable energy devices intended for the Adriatic Sea, but also for planning and carrying out various marine operations in that specific environment. At the end of the study, some consideration is given to the effects of climate changes on the variability of sea states in the Adriatic.

1. Introduction

The Adriatic Sea is a semi-enclosed body of water connected to the Mediterranean Sea through the Otranto Strait at its southeast. Located between parallel mountain ranges of the Apennines (west) and the Dinarides (east), it experiences a specific wind-wave climate with strong winds of limited fetch. Considering its enclosed nature, a rich commercial activity poses a significant associated risk to its fragile ecological system. Therefore, a better understanding of the wave climate in the Adriatic is required to support sustainable and ecologically friendly shipbuilding, maritime, offshore, mariculture, renewable energy, (nautical) tourism and related industries. Wave climate is important also for planning and decision-making in the event of a marine accident (Parunov et al., 2017). Up-to-date, statistical analyses of waves in the Adriatic Sea have been mostly based on gathered visual observations and occasional buoy measurements.

Specifically for seagoing vessels, an adopted approach for seakeeping response analysis is based on wave energy spectrum description (Ochi, 1978). For the Adriatic Sea, naval architects use a formulation given by Tabain (1997), which is a one-parameter wave spectrum (dependent only on significant wave height, *Hs*). The Tabain's spectrum is derived by modification of the well-known JONSWAP spectrum. Although of great importance to the maritime sector in the Adriatic region, the Tabain's spectrum is derived mostly from observations and a limited number of measurements and therefore needs to be compared with recently acquired data.

The northern part of the Adriatic Sea (the Gulf of Venice) has relatively shallow waters and mild bottom slopes, while its southern part reaches maximum water depths of up to 1200 m. Dominant wind events that cause surface waves in the Adriatic are *bura* (N-NE to E-NE, Italian *bora*), *jugo* (E-SE to SS-E, *sirocco* family) and *maestral* (W-NW to NW). *Bura* and *jugo* reach storm conditions and can cause extreme wave occurrences, while *maestral* is of milder character and important for recreational sailing, due to its predictive nature, especially during summer months (Katalinić et al., 2015). A maximum wave height of 10.8 m was recorded as the highest maximum wave in the Adriatic during an event of *jugo* wind, while theoretical predictions of the most probable extreme significant wave heights for 20 and 100 year return periods read 7.20 and 8.57 m respectively (Leder et al., 1998). *Bura* (N-NE to E-NE) is the strongest wind by its intensity, blowing over the Dinaric Mountains

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which shape its focus points across the Adriatic. By nature, it blows in gales of more than 20 m/s (72 km/h) and the fastest recorded wind impact of *bura* is 68 m/s (245 km/h) in the mid-Adriatic coast line where the Velebit Mountain forms a funnel. The main limitation for the development of *bura* wind waves is its relatively short fetch. *Jugo* blows along the Adriatic (E-SE to SS-E) and usually develops for several days until reaching its maximum speed. Waves, already formed, enter through the Otranto Strait's southern boundary and develop further along the Adriatic reaching a more developed sea state and longer waves than those of *bura,* which are inherently steeper and shorter. In storm conditions *jugo* can reach speeds up to 30 m/s (over 100 km/h) (Katalinić et al., 2015).

Nowadays, there are two relevant wave atlases available and applicable for the Adriatic: MedAtlas (Cavaleri, 2005) and WorldWaves atlas (Barstow et al., 2003). Both databases are obtained by hindcasting using numerical wave modelling, calibrated against satellite and wave buoy measurements. This study is based on data from the WorldWave atlas, gathered during the last two decades up to recent dates. Statistical analysis of wave parameters is done for three representative geographical locations chosen in the northern, central and southern Adriatic Sea, located along the main longitudinal shipping route.

The main aim of this study is to develop long-term statistics enabling prediction of extreme seas states at representative locations of three Adriatic regions, based on the acquired 24-year systematic database obtained by a satellite measurement calibration of a numerical hindcast wave model (Barstow et al., 2003). For each location, joint probability distribution of significant wave heights and peak spectral periods is established. Marginal distribution of wave heights enables to extrapolate existing data to long time periods and determine long-term extreme significant wave heights. Conditional distribution of wave periods enables predicting wave periods of such extreme sea states. Extreme significant wave heights are compared with previously published results that are mostly obtained based on incomplete wave datasets. Knowledge of the simultaneous occurrence of wind speeds and significant wave heights is used to establish a functional relationship between wind speed and significant wave heights, using regression analysis. As the swell in the Adriatic is rather low, such relationship enables quick and reliable prediction of significant wave heights solely from wind data. Database enables also to establish a relationship between significant wave height and spectral peak periods, in order to check adequacy of the single-parametric Tabain's wave spectrum, commonly used in seakeeping studies in the Adriatic. The long-term sea states are usually defined under the assumption that sea states have the same statistical distribution, i.e., the climate conditions are stationary. However, statistical approaches based on the assumption of stationarity would lead to invalid conclusions in the case of climate change. Although the present 24-year database is clearly rather short to analyse climate variability (Vanem, 2015), it has nevertheless been used to get some insight into the variation of sea state parameters in the last two and a half decades.

The paper begins with the literature review in Section 1.1, covering systematic studies of waves in the Adriatic that started in the mid-20th century, after World War II, up to the current date. The database used in the present study is described in Section 1.2. A joint probability distribution model of significant wave height and spectral peak period is developed in Section 2.2, based on Det Norske Veritas recommendations for environmental conditions and loads modelling (DNV, 2014). In Section 2.3 a regression model relating wind speed and significant wave height for two dominant wind patterns, *jugo* and *bura*, is presented. A statistical estimate of extreme sea states for various return periods is provided in Section 2.4. In Section 2.5, the peak-spectral-frequency-to-significant wave-height relation resulting from the dataset is compared with the commonly used Tabain's wave spectrum to determine its suitability. Changes of average and extreme sea states through the years, as a possible consequence of the climate variability, are analysed in Section 2.6. The paper ends with the corresponding conclusions, emphasizing the obtained results and acquired tools, and giving the geostrategic context of the Adriatic Sea.

1.1. Literature review of sea state statistics in the Adriatic Sea

First research work on wave statistics in the Adriatic Sea was performed by Tabain (1974). He used visual observations and reports from meteorological, naval and merchant ships in the Adriatic and developed a rather rough wave statistics. Considering the wind-wave specificities of the basin, he also developed a sea state scale for the Adriatic Sea and gave its relation against the WMO scale. Later on, he derived the Tabain's wave spectrum which has been commonly used for local purposes until today (Tabain, 1997; Senjanović et al., 2000).

A systematic wave statistics, based on long-term (1957–1971) visual ship observations, has been reported in the Climatology Atlas published by the Hydrographic Institute of the Republic of Croatia (1979). It contains monthly averages of wave height occurrences from basic incoming direction, represented in the form of wave roses. Although basically covering the complete Adriatic basin, it inherits all drawbacks of visual wave observations from ships: systematic underestimation of observed significant wave heights (Parunov et al., 2011) and the lack of data for highest sea states as they are avoided by ships (Guedes Soares, 1986). The accuracy of the visual wave observations has been questioned in the literature since the 1990s, especially concerning the wave period (Bitner-Gregersen et al., 2016). Parunov et al. (2011) used this Climatology Atlas to develop wave statistics in the Adriatic. They concluded that sea states with significant wave heights between 0.5 and 1 m are the most frequent in the Adriatic Sea. Sea states with significant wave heights larger than 4 m were observed quite rarely, while significant wave heights larger than 5 m were almost never encountered by merchant ships. More severe sea states, up to significant wave heights of 7 m, were recorded only by measurements from fixed offshore platforms.

More recent work includes the application of third-generation numerical wave models (e.g. WAM, SWAN …). Janekovic and Tudor, 2005 made preliminary validation of the SWAN wave model (Ris et al., 1999) for *bura* wind conditions, with wind simulation input acquired from the national meteorological organization and compared the results with wave buoy recordings. Two operational numerical wave models are available online for real-time estimation of sea states in the Adriatic. The WAM model is run by the European Centre for Medium-Range Weather Forecast (ECMWF) and the WWM II model is run, with an even higher resolution than the ECMWF's model, by a privately owned company called Gekom (www.gekom.hr). Wave climate in the Adriatic has also been examined for civil engineering purposes by Ocvirk (2010), in her PhD thesis, by application of a commercial numerical wave model, MIKE21. Bertotti and Cavaleri (2009) analysed the quality of the wind and wave predictions in the Adriatic Sea considering the corresponding analysis and forecast fields of the ECMWF up to 72 h. They used the WAM model to forecast wave fields and offered firm evidences that in an enclosed sea the capability of producing successful forecasts beyond a limited time extent is greatly reduced with respect to the oceans. Furthermore, they concluded that the reliability of the forecasts substantially decreases when dealing with meteorological events characterized by strong temporal and spatial gradients, as is typical during *bura* wind. This indicates that any wave forecast in the Adriatic Sea should be taken with great caution.

Satellite altimetry measurements have been reported in depth by Queffeulou and Bentamy (2007). Interesting conclusion from their study is that the Adriatic is the mildest sea basin in the Mediterranean, with an average significant wave height of 0.85 m, while 80% of the data are less than 1.10 m. Research on waves as a renewable energy resource, focusing on the Adriatic Sea, was performed by Liberti et al. (2013) combining both satellite measurement and numerical models, referencing also to available buoy *in-situ* measurements (RON project) along the Adriatic's west coast. They confirmed that, although the Adriatic is a low average wave power area, the wave power may reach considerable values comparable with those encountered in the more productive regions of the