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Time series analysis on marine wind-wave characteristics using chaos theory

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ABSTRACT

This paper discusses an attempt to identify the chaotic behavior of the dynamic system of wind-wave characteristics including significant wave height, wave period and wave direction in southern, central and northern regions of the Caspian Sea. Surrogate data method and spectral analysis are utilized to detect the nonlinearity and aperiodicity of the time series. The delay embedding theorem of reconstructing the phase space is applied to identify characteristics of the time series dynamic system. The false nearest neighbor analysis along with the correlation dimension estimation indicate the presence of high dimensional chaotic behavior with dimensions of the chaotic attractors at the range of 5.91, 6.30 and 7.55 for the significant wave height series and 6.59, 7.64 and 7.87 for the wave period for the southern, central and northern parts of the Sea. Higher correlation dimension of the northern station could be related to the physical characteristics of the sea bathymetry. However, the estimated correlation dimension indicates the low choaticity of the wave direction set (3.65, 3.70 and 3.77). Positive Lyapunov exponents obtained for all 9 data series prove the exponential divergence of the trajectories which support the presence of chaos in the wind-wave characteristics.

1. Introduction

Waves are produced by forces that disturb a body of water (e.g., gravitational pull of the sun and the moon, underwater earthquakes and landslides, the movements of boats and swimmers, etc.), though, the vast majority of sea waves are generated by wind. In coastal/marine engineering profession, wind-waves are the most important phenomenon to be considered among the other potential factors affecting marine and coastal activities like construction, maintenance, transportation, fishing, etc. However, wind waves have very complex natures and are highly irregular with respect to their height, direction, amplitude and period (Yilmaz, 2007). Hence, marine and ocean wave parameters such as significant wave height and average wave period are necessary elements in ocean engineering operations. However, the significant wave height is possibly the most important parameter. Significant wave height is defined as average height of the highest one-third waves in a wave spectrum over a time period. Another important factor on the wind-wave characteristics is wave period. Stationary structures such as offshore installations, the wave direction may also become important. (Ozger, 2010; Vanem and Walker, 2013).

There are several different ways for modeling and predicting wind-wave characteristics, such as statistical techniques (Reikard and Rogers, 2011), discrete spectral approach (Yilmaz, 2007). Stochastic simulation (DelBalzo et al., 2003; Agrawal and Deo, 2002), numerical methods (Galanis et al., 2011) and data driven models (Ozger, 2010; Deka and Prahlada, 2012).

Recently, the use of soft computing techniques for modeling time series processes has been given a special interest (Zounemat-Kermani et al., 2013). In the field of ocean engineering, many data driven models have been proposed for simulating and forecasting wave parameters so far. Especially, soft computing techniques such as artificial neural networks (Deo et al., 2001; Zamani et al., 2008), neuro-wavelet model (Deka and Prahlada, 2012), fuzzy-wavelet model (Ozger, 2010), genetic programing (Londhe, 2008; Gaur and Deo, 2008) and fuzzy logic (Kazeminezhad et al., 2005; Sylaios et al., 2009) have been used for this purpose.

In addition, advances in chaos theory offer new methods to handle time series data, such as hydrological time series (Ng et al., 2007; Dhanya and Kumar, 2010). This attitude assumes that the underlying mechanism of the data is dimensional and deterministic in spite of its stochastic nature. However, nonlinear analysis should be used to verify and provide evidences towards determinism or stochasticity of the dynamic system.

To the knowledge of the authors, related studies to chaotic time series analysis and wave characteristics are quite scarce. Sannasiraj et al. (2004) reported an enhancement in tidal prediction accuracy in a deterministic model using chaos theory. The tidal prediction was carried out using a three dimensional baroclinic model and, error

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correction was instigated using a stochastic model based on a local linear approximation. Babovic et al. (2005) used the local model approximation as a powerful tool in the forecasting of chaotic time series and has employed it for wave prediction in a forecasting horizon from a few hours to 24 h. Domenicoa et al. (2013) investigated chaos and reproduction in sea level variations. In their study, the state space reconstruction of the unknown underlying process was directly employed from time series data, through Takens delay embedding method.

This study presents nonlinear analyses for determination of chaotic behavior of wind-wave characteristics such as significant wave height, mean wave period and wave direction in the Caspian Sea. Three hourly wave characteristics were obtained for three distinct parts of the northern, central and southern Caspian Sea from Jan-1992 to Aug-2003 in reference to the results of Iranian Seas Wave Modeling (ISWM) project including wave simulation based on 12 yearly ECMWF (European Center for Medium Range Weather Forecast) wind field. The organization of this paper is as follows. In Section 2, a brief review of the study area and data set is presented. Section 3 addresses the applied methods including phase space reconstruction, method of surrogate data, spectral analysis, correlation dimension and Lyapunov exponents. Section 4 deals with the application and results of the chaos identification methods to wave data. An attempt is then made in Section 5 to discuss the important results of this study and eventually the conclusion remarks are addressed in Section 6.

2. Study area and data description

The Caspian Sea - the largest enclosed body of water on Earth - (which is known as the world's largest lake with a surface area of 371,000 km^2 and a volume of 78,200 km^3) is located between five countries including Iran (Fig. 1). It has three distinct parts of southern, central and northern. 60% of the sea area is shallower than 100 m which is mainly in northern part. However, there are two relatively deep basins (more than 600 m in the central region and 800 m in the southern region) in the Sea (Fig. 1-a) (Zounemat-Kermani and Sabbagh-Yzadi, 2010). Three-hour data of wind-wave characteristics including significant wave height, wave period and wave direction from Jan-1992 to Aug-2003 for three different stations, were obtained from the national Port and Maritime Organization (PMO) of Iran. The location of the southern station (which is placed on the deep part of the sea; ST1, 51.4E, 38.0N) as well as the central station (ST2, 50.0E, 42.0N) and the northern station (which is located on the shallow part; ST3, 51.0E, 46.0N) is shown in Fig. 1-b. Table 1 shows the statistical analysis of the applied data. Time dependent alterations of the significant wave height are shown in Fig. 2 for each station. It is clear from Fig. 2 that the significant wave height of the southern and central parts are higher than northern part. Fig. 3 illustrates the waverose diagrams for the three stations. Long-term distribution of wave height and direction can be clearly observed from these diagrams. The information obtained from the southern waverose in Fig. 3 describes the direction of the southern wind-waves to the north, while the northern waves have an eastern–western tendency.

3. Material and methods

Six nonlinear dynamic methods, phase space reconstruction based on Takens theory, false nearest neighbor algorithm, method of surrogate data, spectrum analysis, correlation dimension method and Lyapunov exponent method, are employed in this paper in order to investigate the chaotic behavior of the wind-wave dynamic. These methods are described in the next sections.

3.1. Phase space reconstruction, embedding dimension and time delay

Dynamics system may be stochastic, deterministic or low-deterministic (chaotic). This can be preliminary recognized by using the phase space concept. As for the time series data, the phase space reconstruction could be constructed on the basis of the Takens theorem (Takens, 1980). According to Takens theory, the dynamics of a scalar time series $\{x_1, x_2, ..., x_n\}$ are embedded in an m-dimensional phase space (m is the embedding dimension) which is defined by:

$$Y_t = \{x_t, x_{t-\tau}, x_{t-2\tau}, ..., x_{t-(m-1)\tau}\} \quad (1)$$

Table 1
Statistical analysis of the wave characteristics of the three stations.

	ST1 (southern)			ST2 (central)			ST3 (northern)		
	$H_{1/3}$	T (mean)	WD	$H_{1/3}$	T (mean)	WD	$H_{1/3}$	T (mean)	WD
Min	0.04	1.97	0.00	0.02	1.85	0.00	0.05	1.76	0.00
Max	5.92	13.26	360.00	7.29	11.66	360.00	3.11	6.93	360.00
Average	0.77	4.84	115.54	1.01	4.93	174.66	0.70	3.67	180.07
Stdv	0.57	1.47	133.08	0.72	1.29	121.66	0.47	0.84	104.84
CV	0.74	0.30	1.15	0.71	0.26	0.70	0.67	0.23	0.58

Note: $H_{1/3}$=Significant wave height; T(mean)=Mean wave period and WD=Wave direction.

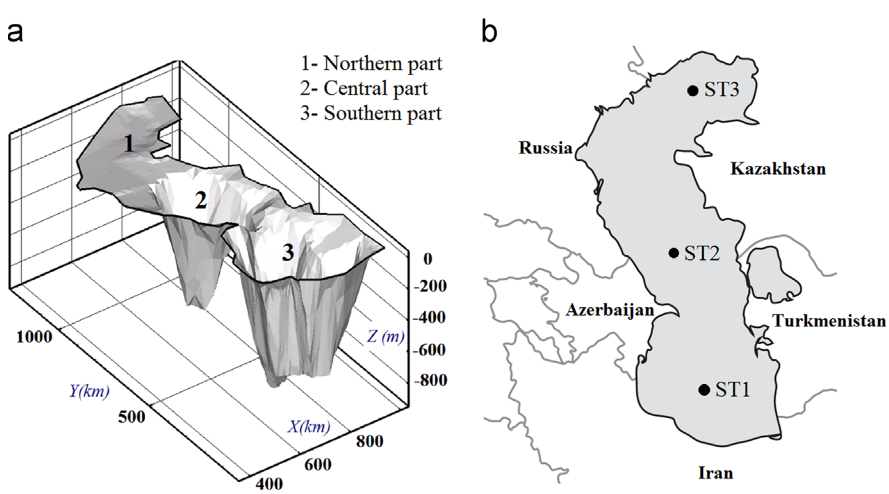

Fig. 1. (a) 3D view of the Caspian Sea bathymetry; (b) Location of three stations in southern, central and northern Caspian Sea.