Short-term Spectral and Statistical Analysis of Sea Surface Elevation Data from buoys located in the Greek Seas

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Abstract
Sea surface elevation is of great interest due to its impact on every-day activities such as tourism and shipping as well as the information it provides for various scientific fields. As Greece has its main socio-economic activities along its coastline, data that focus on the condition of its' marine state are of significant importance. The Poseidon Marine Monitoring Network of HCMR has been used in order to monitor, forecast and provide information about sea conditions, with the use of offshore located buoys. For this research, sea surface elevation data from 5 buoys in the Aegean and Ionian Seas were analyzed, both statistically and spectrally using a script in MATLAB's Toolbox WAFO (Wave Analysis for Fatigue and Oceanography) that was developed. The records covered a sampling period of 17mins (i.e., 1024 sec), repeated every 3hours and with a sampling frequency of 1 Hz. For this analysis, the waves were defined as consecutive down-crossings of the sea surface elevation at the mean sea level (i.e. 0 m). The following wave characteristics were calculated: wave steepness (S), wave height (H), wave period (T), crest amplitude (A_c), trough amplitude (A_t), crest front period (T_{cf}) and crest back period (rear) (T_{cb}). From the analysis, the following results were provided for the Aegean and Ionian Seas: For the North Aegean, $\bar{H} = 0.63 - \text{m}$, $\bar{T} = 4.20\text{s}$, $H_{1/3} = 0.99\text{m}$, $T_{1/3} = 5.43\text{s}$, $H_{m_0} = 1.06\text{m}$ and $T_{m_{02}} = 3.98\text{s}$. For Central Aegean: $\bar{H} = 0.67\text{m}$, $\bar{T} = 4.06\text{s}$, $H_{1/3} = 1.04\text{m}$, $T_{1/3} = 5.34\text{s}$, $H_{m_0} = 1.11\text{m}$ and $T_{m_{02}} = 3.8\text{s}$. For South Aegean, $\bar{H} = 0.58\text{m}$, $\bar{T} = 4.11\text{s}$, $H_{1/3} = 0.9\text{m}$, $T_{1/3} = 5.42\text{s}$, $H_{m_0} = 0.98\text{m}$ and $T_{m_{02}} = 3.8\text{s}$. For the North-East Ionian Sea, $\bar{H} = 0.57\text{m}$, $\bar{T} = 4.45\text{s}$, $T_{max} = 10.048\text{s}$, $H_{1/3} = 0.89\text{m}$, $T_{1/3} = 6.14\text{s}$, $H_{m_0} = 0.988\text{m}$ and $T_{m_{02}} = 4.14\text{s}$. For the East Ionian Sea, $\bar{H} = 0.70\text{m}$, $\bar{T} = 4.79\text{s}$, $H_{1/3} = 1.10\text{m}$, $T_{1/3} = 6.36\text{s}$, $H_{m_0} = 1.20\text{m}$ and $T_{m_{02}} = 4.51\text{s}$. The correlation between statistical and spectral wave characteristics had values of r-square approximately 0.9. Future work will include a more detailed analysis of sea surface elevation, to obtain information about characteristics of wind waves and swell, as well as, a relation of maximum values of wave height with potential extreme events.

Keywords: Sea surface elevation, Greek Seas, WAFO, Spectral Analysis, Statistical Analysis, Wave Characteristics

1. Introduction
The Greek coastline extends more than 15.500 km and is characterized as a dynamic and variable marine system where more than 30% of the population, 80% of industry and 90% of tourism are based at near shore locations, making coastal evolution of rather great importance (Soukissian et al., 1999). It is connected with the Marmara Sea via the Dardanelles Strait, the Black Sea via the Bosporus Strait and the Mediterranean Sea via Crete-Karpathos-Rhodes-Turkey (southeast) and Crete-Kithira-Peloponnese (southwest). The irregular bathymetry, the complex coastline morphology and the numerous islands lead to uncertainties in forecasting / simulating the wave state in the Aegean (Poulos et al., 1997). Low swells, short fetches and durations and generally mild annual wind conditions, describe the Aegean (Soukissian et al., 2009). The Ionian Sea is located at the west of the Greek mainland, including the Hellenic

Trench that hosts the deepest basins in the Mediterranean Sea. To the north communicates with the Adriatic Sea through the Otrando strait and to the south with the central Mediterranean. Therefore, the Ionian Sea is associated with long fetches, intense storm events and swells. In contradiction to the Ionian Sea, the Aegean Sea is characterized by channeling effects that could intensify wind speed and related wave height, resulting eventually in extreme weather and wave phenomena. The tidal range in the Aegean and the Ionian seas, as parts of the eastern Mediterranean sea are of the order of centimeters (Tsimplis, 1994) that is considered negligible.

Operational oceanography provides the necessary information in order to describe the marine state of the Greek Seas but also to accurately adapt to potential changes. Wave records that are gathered by offshore buoys, give information about significant wave height, period, direction (swell and wind-wave) and variation of sea surface elevation. For this study, sea surface elevation data from 5 Sea-Watch buoys installed by HCMR in offshore locations (Figure 1), were statistically and spectrally analyzed. To statistically interpret wind waves in deep water, it is assumed that the sea surface elevation is a stationary, Gaussian process is taken (Longuet-Higgins, 1952). The authors would like to note that due to the hydrodynamic characteristics of the buoys, steep waves tend to be flattened in time records, i.e. a buoy seems to linearize the waves (Casas-Prat and Holthuijsen, 2010). In addition, there can be uncertainties in buoys measurements due to potential dragging or swerving around the 3-D peaks of waves.

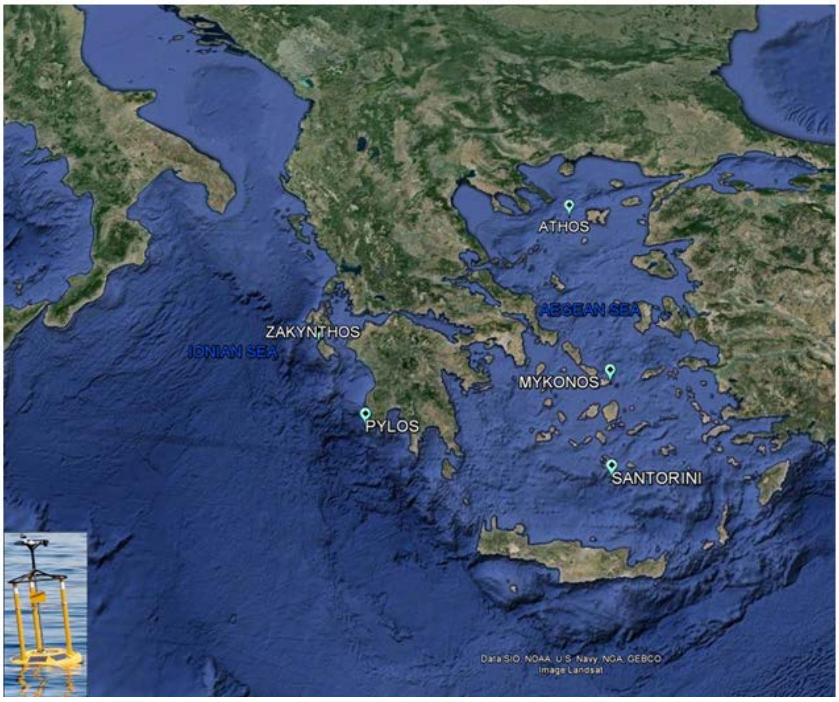

Figure 1: Sea Watch Buoys Locations

The scope of this work is to provide sufficient information about wave characteristics such as wave height, crest - trough amplitude, wave period etc. in various regions of the Aegean and the Ionian Seas and to relate statistical with spectral wave characteristics.

2. MATERIALS AND METHODS

2.1. Data Collection

The data used in this study were obtained by 5 offshore buoys (Figure 1, Table 1) located in North Aegean (Athos), Central Aegean (Mykonos), South Aegean (Santorini), North-East Ionian Sea (Zakynthos) and East Ionian Sea (Pylos). The recording period of the buoys for wave data is of 17 min (i.e. 1024sec) with recording intervals of 3 hours and sampling frequency of the sea surface elevation measurements of 1 Hz.

Table 1: Characteristics of the Sea Watch Buoys and their mooring locations

	Athos	Mykonos	Santorini	Zakynthos	Pylos
Coordinates	24.7226°E 39.9635°N	25.46631 °E 37.51831 °N	25.49568 °E 36.26111 °N	20.61035 °E 37.9541°N	21.60889 °E 36.83105°N
Depth (m)	220	140	320	313	1670
Diameter (m)	1.74	1.74	1.74	1.74	1.74
No. of Records	8705	7464	4308	6333	6078
Period	2006-2010	2007-2011	2001,2008	2007-2011	2007-2011

Prior to the analysis of the sea surface elevation, the data were analytically examined and filtered to discard erroneous values and outliers, following two basic criteria: (1) the record is of the nominal length (Holthuijsen, 2007); and (2) there were no linear trends in the record. In the case of erroneous measurements found in a record, then the relevant heave time series was rejected.

2.2. Methodology

According to Pierson (1952) and Longuet –Higgins (1952), free sea-surface elevation at a fixed position of the free sea surface can be modeled as a zero-mean, stationary, ergodic and Gaussian linear process. The stochastic representation of sea surface elevation record at one location as a function of time η(t), with duration D, can be analyzed as a sum of a large number of harmonic wave components (a Fourier series) as follows:

$$\eta(t) = \sum_{i=1}^{N} a_i \cos(2\pi f_i t + \alpha_\iota)$$

where, a_i and α_ι the amplitude and phase of each frequency $f_i = i/D$.

A wave is considered as the surface elevation between two consecutive downward zero-crossings of the elevation as shown in Figure 2 (Haring et al., 1976). Furthermore, waves cannot be negative, while sea surface elevation can be (Holthuijsen, 2007).

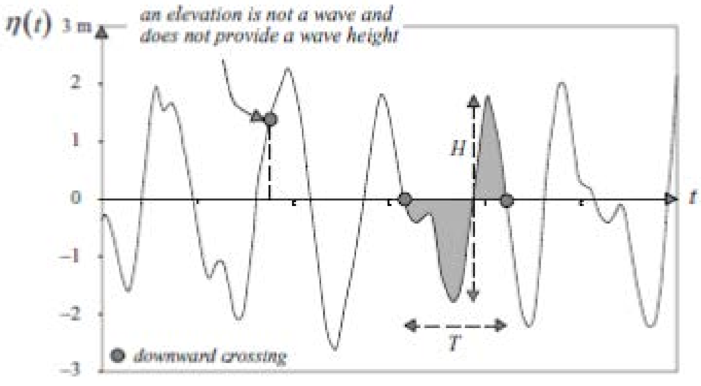

Figure 2: Down-crossing waves in a sea surface elevation SSE time-series (Holthuijsen, 2007)

Moreover, all of the spectral characteristics were determined by spectral analysis per record. The spectrum $E(f)$ was estimated as follows:

$$E(f) \approx \overline{1/2a_j^2}/\Delta f$$

The spectral moments were calculated using the relationship:

$m_n = \int_0^{\infty} f^n E(f)\, df$, for $n = \cdots, -3, -2, -1, 0, 1, 2, 3$

with m_n the nth-order moment of $E(f)$.

Therefore, the significant wave height and period of a record can be spectrally estimated as:

$$H_{m_0} \approx \sqrt{m_0}\,,$$

$$T_{m_{02}} = \sqrt{\frac{m_0}{m_2}}$$

with m_0 and m_2 being the zeroth and second order moment, respectively.

Waves can be characterized by their individual height and period. As wave height H is defined as the vertical distance between the highest and the lowest sea surface elevation considering that there can be multiple wave heights in a sea surface elevation record (Figure 2). Thus, in a wave record with N waves, the mean wave height $\bar{H}$ is:

$$\bar{H} = \frac{1}{N}\sum_{i=1}^{N} H_i$$

with i the number of the wave in the record (i.e., i = 1 is the first wave in the record, i = 2 the second, etc.). The statistical significant wave height $H_{1/3}$ is defined as the mean of the highest one-third of waves in the wave record:

$$H_{1/3} = \frac{1}{N/3}\sum_{j=1}^{N/3} H_j$$

where, j is the rank number of the wave, based on wave height (i.e., j=1 is the highest wave, j=2 is the second-highest wave, etc).

In addition, mean wave period $\bar{T}$ is defined as the time interval between one zero-down crossing and the next one (Figure 2), while the statistical significant wave period $T_{1/3}$ is defined as the mean period of the highest one-third of waves in the wave record:

$$\bar{T} = \frac{1}{N}\sum_{i=1}^{N} T_i\,,$$

$$T_{1/3} = \frac{1}{N/3}\sum_{j=1}^{N/3} T_j$$

In order to obtain the aforementioned parameters, an algorithm based on WAFO toolbox of Matlab (Brodtkorb et al., 2000) was developed and implemented (see flow chart in Figure 3).

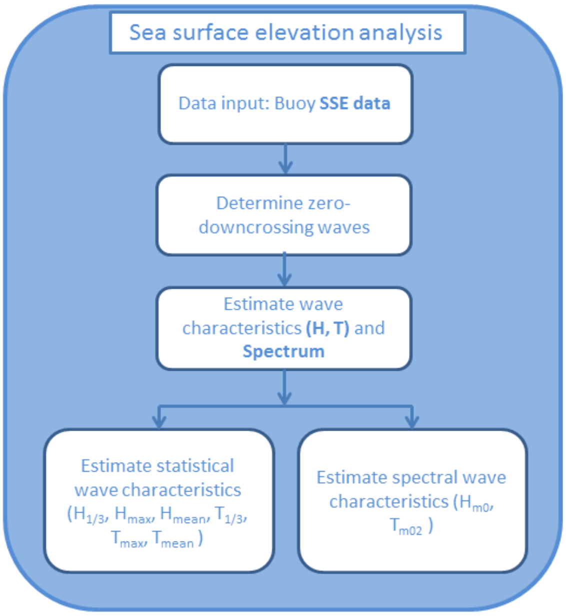

Figure 3: Basic structure of the algorithm used

All the input records were in form of time-series, i.e. one column was time (1-1023 sec) and the second column was the sea surface elevation. Every record was de-trended in order to exclude any linear trends. Afterwards, mean sea level was considered to be at 0 m and down crossing waves are determined. The spectrum was estimated per record and spectral characteristics, such as H_{m_0}, $T_{m_{02}}$ were calculated. Additionally, from the determination of waves, individual wave heights and periods are estimated while from those characteristics, the statistical wave properties of $H_{1/3}$, H_{mean}, H_{max}, $T_{1/3}$, T_{mean} and T_{max} were also calculated.

3. Results and Discussion

North Aegean

The sea surface elevation record that included the maximum wave height for Athos buoy is shown in figure 4, along with the wave spectrum and line plots of wave height and wave period, according to the number of waves. From the sea surface elevation plot, the combination of the variation of frequency and the peaks of the spectrum from the spectral plot can help to describe the marine state during the record period (i.e. fully developed sea, narrow spectrum etc.). Moreover, the plot of wave height and period against the number of waves reveals whether these two parameters relate well, or not. In this case, the spectral plot gives a wave peak period of $T_p = 10.24s$, while the maximum wave height in the same record was 9.103 m.

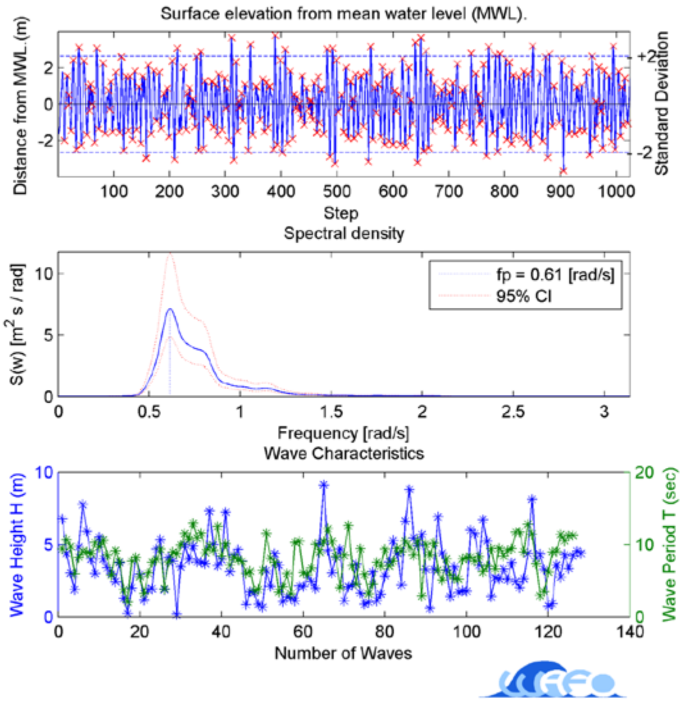

Figure 4: Sea surface elevation (SSE) record, spectrum and wave height-period plots against number of waves for the Athos buoy.

From Table 2, it can be seen that at North Aegean, more than 50% of mean wave heights H_{mean} are among 0 to 0.5 m with the 45% of these waves having mean periods T_{mean} of 3.5-4 sec. The same analysis for maximum wave heights shows that 37% of the waves are in the range of 1-2 m of which 62% have periods from 6.8-8.5 sec.

Table 2: Counts of mean wave height $(\bar{H})$ and period $(\bar{T})$ for Athos Buoy

				$\bar{H}$				
$\bar{T}$	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	Total
2.5-3	238							238
3-3.5	1308	16						1324
3.5-4	1989	417						2406
4-4.5	727	1364	10					2101
4.5-5	87	870	287					1244
5-5.5	10	172	574	38				794
5.5-6		23	158	213	2			396
6-6.5			18	89	43			150
6.5-7				16	23	3		42
7-7.5			1		4	3		8
7.5-8							1	1
8-8.5							1	1
Total	4359	2862	1048	356	72	6	2	8705

The correlation among the spectral and statistical parameters in the case of Athos buoy reached 0.99 for $H_{1/3}$ and H_{m_0} and 0.95 for $T_{1/3}$ and $T_{m_{02}}$.

Central Aegean

In the case of the Central Aegean, the spectral plot (Figure 6) gives a wave peak period value (T_p) of $5.761\ s$ and maximum wave height of 8.19 m.

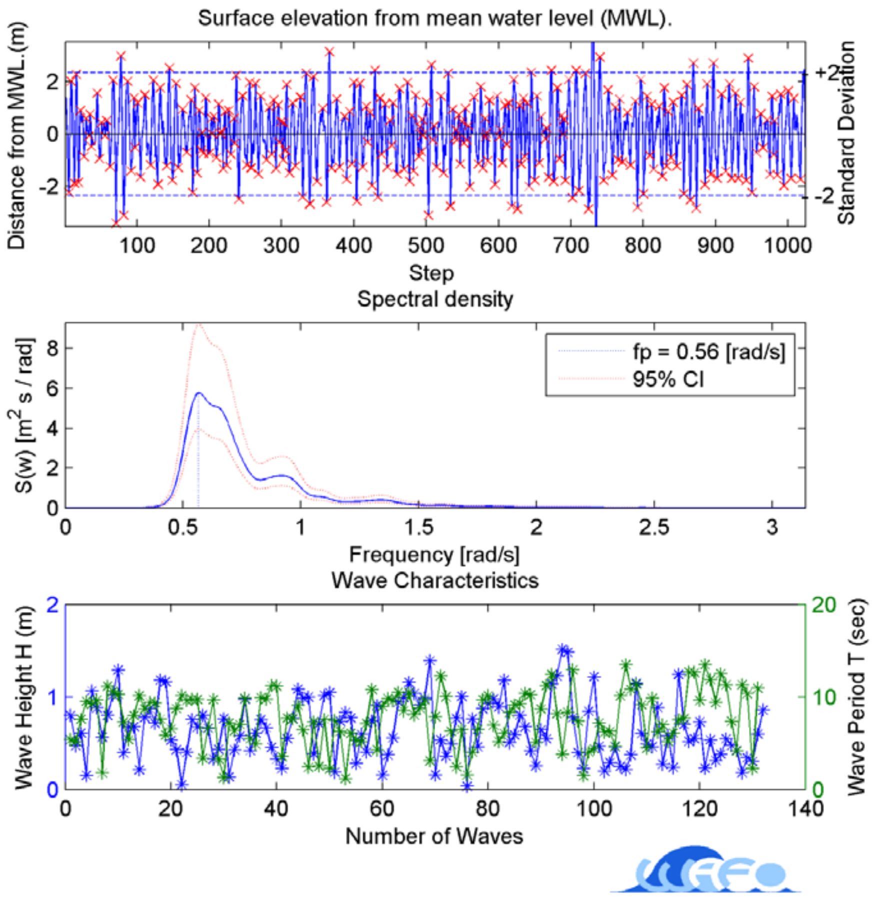

Figure 5: Sea surface elevation (SSE) record, spectrum and wave height-period plots against number of waves for the Mykonos buoy.

From Table 3, it can be noted that at Central Aegean, more than 41.33% of mean wave heights are among 0.5 and 1 m and 47% of these waves have mean periods of 4-4.5 sec. The same analysis for maximum wave heights shows that 38.55% of the waves are in the range of 1-2 m of which 22.89% have periods of 6.5-7 sec.

Table 3: Counts of mean wave height ($\bar{H}$) and period ($\bar{T}$) for the Mykonos Buoy.

	$\bar{H}$							
$\bar{T}$	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	Total
2-2.5	2							2
2.5-3	524							524
3-3.5	1371	71						1442
3.5-4	848	951						1799
4-4.5	249	1458	25					1732
4.5-5	63	510	492					1065
5-5.5	6	79	419	21				525
5.5-6		10	91	149				250
6-6.5		5	5	45	17			72
6.5-7	1		1	2	20	3		27
7-7.5					4	12		16
7.5-8						6	2	8
8-8.5							1	1
8.5-9		1						1
Total	3064	3085	1033	217	41	21	3	7464

The correlation among the spectral and statistical parameters for Mykonos buoy is 0.99 for $H_{1/3}$ and H_{m_0} and 0.97 for $T_{1/3}$ and $T_{m_{02}}$.

<u>South Aegean</u>

The spectral plot gives a wave peak period of $T_p = 8.865s$ and the relevant maximum wave height is of 7.53 m.

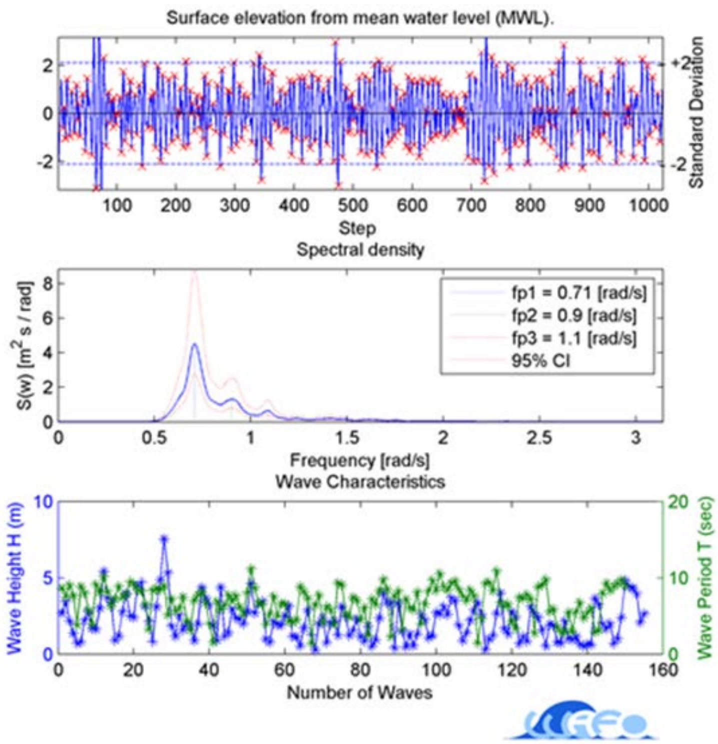

Figure 6: Sea surface elevation (SSE) record, spectrum and wave height-period plots against number of waves for the Santorini Buoy

From Table 4, it can be noted that at South Aegean, more than 51% of mean wave heights are among 0 to 0.5 m and 39.5% of these waves have mean periods of 3.5-4 sec. The same analysis for maximum wave heights shows that 56.6% of the waves are in the range of 0.4-1.4 m of which 38.9% have periods of 6-7 sec.

Table 4: Counts of mean wave height ($\bar{H}$) and period ($\bar{T}$) for Santorini Buoy

				$\bar{H}$				
$\bar{T}$	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	Total
2.5-3	103							103
3-3.5	795	10						805
3.5-4	876	387						1263
4-4.5	327	666	4					997
4.5-5	84	418	97					599
5-5.5	27	124	170	5				326
5.5-6	6	28	71	37	1			143
6-6.5	2	1	26	17	3			49
6.5-7		3	6	1	6	1		17
7-7.5			1	1	1	2		5
7.5-8							1	1
Total	2220	1637	375	61	11	3	1	4308

Once more, there is an exceptionally good correlation of 0.99 for $H_{1/3}$ and H_{m_0} and 0.96 for $T_{1/3}$ and $T_{m_{02}}$.

Northeast Ionian Sea

In the case of NE Ionian Sea the spectral plot gives a wave peak period of $T_p = 8.865s$ with a maximum wave height of 11.92 m.

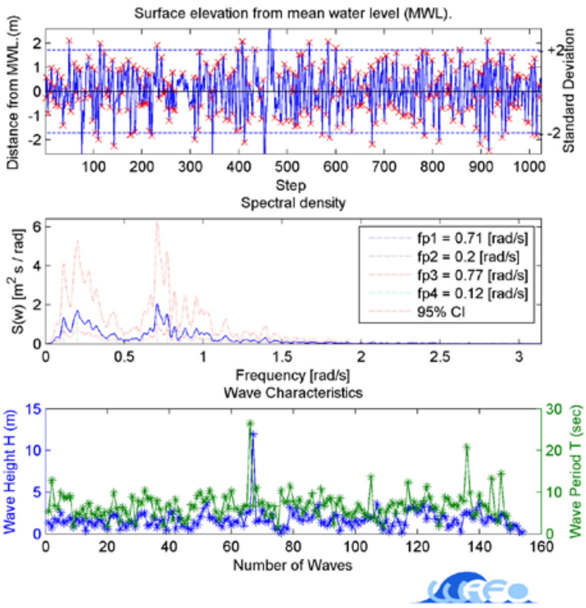

Figure 7: Sea surface elevation (SSE) record, spectrum and wave height-period plots against number of waves for the Zakynthos Buoy

From Table 5, it can be noted that at North East Ionian, more than 53% of mean wave heights are among 0 to 0.5 m and 30% of these waves have mean periods of 3.5-4 sec. The same analysis for maximum wave heights shows that 75% of the waves are in the range of 0.4-1.0 m of which 49.9% have periods of 4-8 sec.

Table 5: Counts mean wave height $(\bar{H})$ and period $(\bar{T})$ for Zakynthos

				$\bar{H}$				
$\bar{T}$	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	Total
2.5-3	189							189
3-3.5	811	5						816
3.5-4	1005	231						1236
4-4.5	834	501	2					1337
4.5-5	434	631	39					1104
5-5.5	86	544	133	1				764
5.5-6	5	253	180	7				445
6-6.5		84	139	41				264
6.5-7		12	54	42	5			113
7-7.5		1	11	20	13	3		48
7.5-8		1	1	4	4	3		13
8-8.5					2	1		3
9-9.5							1	1
Total	3364	2263	559	115	24	7	1	6333

Overall, there is a correlation of 0.99 for $H_{1/3}$ and H_{m_0} and 0.95 for $T_{1/3}$ and $T_{m_{02}}$.

<u>East Ionian Sea</u>

The spectral plot from the east Ionian Sea gives a wave peak period of $T_p = 12.84s$, while the maximum wave height is of 11.36 m.

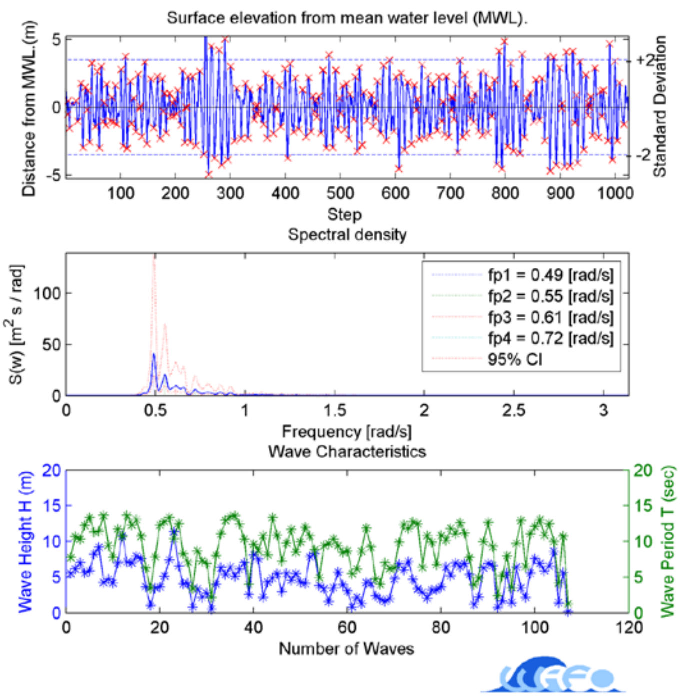

Figure 8: Sea surface elevation (SSE) record, spectrum and wave height-period plots against number of waves for the Pylos buoy.

From Table 6, it can be noted that at East Ionian Sea, more than 45% of mean wave heights are among 0 to 0.5 m and 37% of these waves have mean periods of 3.5-4.5 sec. The same analysis for maximum wave heights shows that 50.01% of the waves are in the range of 0.4-1.4 m of which 37.6% have periods of 7-8 sec.

Table 6: Counts of mean wave height ($\bar{H}$) and period ($\bar{T}$) for Pylos

	$\bar{H}$										
$\bar{T}$	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5	Total
2.5-3	15										15
3-3.5	416	1									417
3.5-4	1030	96									1126
4-4.5	723	414									1137
4.5-5	445	581	48								1074
5-5.5	123	554	207	2							886
5.5-6	16	268	318	54							656
6-6.5	1	70	215	98	9						393
6.5-7		4	59	103	42	2					210
7-7.5		2	11	39	36	11	1				100
7.5-8				8	17	10	2				37
8-8.5			1		3	11	3	1	1		20
8.5-9						3	1		1		5
9-9.5									1	1	2
Total	2769	1990	859	304	107	37	7	1	3	1	6078

Overall, there is a correlation of 0.998 for $H_{1/3}$ and H_{m_0} and 0.947 for $T_{1/3}$ and $T_{m_{02}}$.

The wave characteristics (height and period) for each region are presented synoptically in Table 7, from which it can be seen that there are not significant differences between the regions, although the relatively higher values are those from the Ionian Sea.

Table 7: Characteristics of wave state for each region

REGIONS	H_{mean} (m)	$H_{\max}$ (m)	$H_{1/3}$ (m)	H_{m_0} (m)	T_{mean} (s)	$T_{\max}$ (s)	$T_{1/3}$ (s)	$T_{m_{02}}$ (s)
North Aegean	0.63	1.65	0.99	1.06	4.20	7.66	5.42	3.98
Central Aegean	0.67	1.73	1.04	1.13	4.06	7.60	5.39	3.79
South Aegean	0.58	1.50	0.90	0.98	4.11	7.77	5.51	3.84
NE Ionian	0.57	1.50	0.89	0.99	4.45	10.03	6.14	4.14
E Ionian	0.70	1.81	1.10	1.19	4.79	8.66	6.35	4.51

On the basis of the empirical function $H_{max} = 2 * H_s$ with H_s the significant wave height (Holthuijsen, 2007) for the Greek Seas, $H_{max} \approx 1.5 * H_{m_0}$ and $H_{max} \approx 1.6 * H_{1/3}$, supporting the fact that this empirical function should not be used arbitrarily.

4. Conclusions

From the analysis of the data from the 5 buoys it is revealed that mean wave height and period vary from 0.57 m to 0.70 m and from 4.06 s to 4.79 sec, respectively, while the maximum values range from 1.50 m to 1.81 m and from 7.60 s to 10.03 s. Statistical significant wave heights range from 0.89 m to 1.10 m and periods from 5.39 sec to 6.35 sec. Moreover, spectral significant wave height values vary from 0.98 m to 1.19 m and period from 3.79 sec to 4.51 sec. The results of the spectral significant wave height and period coincide with the results of previous similar analyses such as those presented in Soukissian et al. (2007). The correlation is exceptionally good between spectral and statistical characteristics with values around 0.99 for wave height and greater than 0.95 for wave period.

Additionally, it is found that maximum significant wave height can be estimated empirically by $1.5 * H_{m_0}$ or $1.6 * H_{1/3}$. Furthermore, the authors would like to note that the analysis of sea surface elevation data can provide more details on the wave state, such as its spectral characteristics and its statistical parameters. Further work can apply directional spectrum analysis, seasonal analysis as well as extreme events identification.

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