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Evaluation of in-situ wind speed and wave height measurements against reanalysis data for the Greek Seas

DAFNI E. SIFNIOTI[1], TAKVOR S. SOUKISIAN[2], SERAFIM E. POULOS[1], PANAGIOTIS T. NASTOS[1] and MARIA HATZAKI[1]

[1]Department of Geography & Climatology, Faculty of Geology & Geoenvironment, National & Kapodistrian University of Athens, Panepistimioupolis - Zografou, Attiki, Greece
[2]Hellenic Centre for Marine Research, Institute of Oceanography, Postal address: 46.7 km Athens-Sounion Ave, 19013 Anavyssos, Greece

Corresponding author: dsifnioti@geol.uoa.gr

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Abstract

ERA-Interim, ECMWF's reanalysis product, includes wave and atmospheric characteristics, with high temporal and spatial scale, providing more information on the marine state. Even though their assimilation process has been validated and verified in numerous studies, their performance in more local scales is still under examination. This research focuses on the evaluation of performance of ERA-Interim reanalysis datasets in the Greek Seas for wind and wave characteristics in comparison to POSEIDON buoy data. The results prove fair to good correlation for wave height (r= 0.67-0.94) and wind speed (r= 0.71-0.83) and different error statistics per sub-region. The analysis of the upper 10% (90th percentile) shows an underestimate of 10-15% for wind speed and wave height from ERA-Interim in relation to the buoy measurements. The ERA-Interim and the buoy monthly means and standard deviations are also presented and discussed according to seasonal patterns. The results of the study are compared to other researches of wave hindcasting and wind reanalysis data for the Greek Seas and globally. It is shown that ERA-Interim products could be regarded as representative for the Greek Seas, although their application should be made with caution regarding the assessment of extreme conditions (i.e. given in analyses of upper percentiles) and especially at nearshore locations due to complex coastline configuration enhanced by the great number of islands.

Keywords: ERA-Interim reanalysis products, Poseidon Buoys, Aegean Sea, Ionian Sea, Wave and Wind Characteristics.

Introduction

Long-term analysis of wave height and wind speed has become a necessity due to the variety of applications in areas such as shipping, tourism, ocean renewable energy, oceanography, coastal and offshore engineering, marine climatology, natural hazards and many others (Akpınar & Kömürcü, 2013; Tyrlis & Lelieveld, 2013; Van Vledder & Akpınar, 2015). The most commonly used wind and wave data sources are: *in-situ* instruments (e.g. buoys, recorders), atmospheric and spectral wave numerical models (e.g. WRF, WAM, SWAN), satellite altimetry (*ERS*-1, ERS-*2, Jason,* etc.) and voluntary observing ships (VOS). In several case studies, *in-situ* data covering long time periods have been used for future coupled climate scenarios as inputs (Cavaleri *et al.,* 2012; Dobrynin *et al.,* 2012; Hemer *et al.,* 2013; Khon *et al.,* 2014; Sterl *et al.,* 2012) and for trend analysis (Casas-Prat & Sierra, 2013; Gemmrich *et al.,* 2011; Gower, 2002; Martucci *et al.,* 2010; Vikebø *et al.,* 2003). However, as *in*-situ observations of offshore wind speed and wave height are temporally and spatially sparse, long term analysis of real-time data becomes limited. Reanalysis datasets can be used as an alternative data source as they are a combination of numerical models, observations and altimetry.

It should be noted though, that reanalysis datasets differ in physical, numerical and spatio-temporal resolution aspects during their assimilation processes and should be selected according to the case study characteristics (Stopa & Cheung, 2014).

ERA-Interim reanalysis dataset of ECMWF includes observations, space borne instruments as well as corrections in data assimilation (Berrisford *et al.,* 2011a, b; Dee *et al.,* 2011). Recent research studies have used ERA-Interim (after comparing them with other reanalysis datasets and *in*-situ data) for the description of regional marine characteristics (Aarnes *et al.,* 2015; Carvalho *et al.,* 2012; Liléo *et al.,* 2013; Mooney *et al.,* 2011; Shanas & Kumar, 2015; Shanas and Sanil Kumar, 2013; Stopa and Cheung, 2014, Soukissian *et al.,* 2017), for assessing seasonal cycles and teleconnection patterns (Feng *et al.,* 2014; Stopa *et al.,* 2013) and as inputs in hydrodynamic models (Martin *et al.,* 2012; Alves & Miranda, 2013; Appendini *et al.,* 2013).

The ERA-Interim dataset has been used in the area of the Black Sea for estimates of wind energy by (Akpınar & Kömürcü, 2013) and for Portugal (Carvalho *et al.,* 2014a), for evaluating wind datasets performance for the Iberian Sea (Carvalho *et al.,* 2012) and for teleconnection - seasonal pattern identifications (Carvalho *et al.,* 2014a). The wave data from ERA-Interim have been used for wave energy estimates in the Mediterranean Sea (Soukissian *et al.,* 2015). The relation of ERA-Interim wave data with North Atlantic Oscillation (NAO) in the NE Ionian Sea for the period 1979-2013 has been discussed in Poulos *et al.*(2014), whilst a long-term description of the marine state in 2 case studies in Crete from ERA-Interim and their use as climate change model inputs is discussed in Monioudi *et al.*(2014).

This research aims to compare the performance of ERA-Interim reanalysis dataset as provided by ECMWF, with in-situ buoy data of the Greek Seas for the wind and wave characteristics. This type of assessment will provide extra knowledge on the reanalysis' description of the Greek marine state and will highlight potential differences in extreme conditions and wave-wind directionality per location. This study does not use ERA-Interim as an input for hydrodynamic modelling but as a wave reanalysis dataset that contains modelled data, real time and altimetry data. It is important to mention that the POSEIDON buoy dataset have not been assimilated in the ERA-Interim datasets, nor for the wind or for the wave parameters. A discussion of previous studies with other wind reanalysis datasets and results of wave hindcasts for the Greek Seas is also presented in this research. This paper is structured as follows: Study Area: includes the characteristics and previous analyses for the case study, Materials and Methods: describes the data and the methodology used for this analysis, Results and Discussion: presents the results and discussion on the analysis, Conclusions: summarises of the main conclusions of this study.

Material and Methods

Study Area

The study area includes the Aegean Sea and the SE Ionian Sea. The Aegean Sea is connected in the northeast via the Dardanelles, the Sea of Marmaras which through Bosporus Strait communicates with the Black Sea. At the South, its border is the Island of Crete, and is connected with the Levantine Sea via the Southeast Cretan passage and to the central Mediterranean Sea through the Western Cretan passage. The SE Ionian Sea to the south of Otrando Strait is bounded to the west coast by the Greek peninsula, hosting the deepest point (5020 m) of the Mediterranean Basin located SW of Pylos (Southwest Peloponnese) (SoHelME, 2005; Bagiorgas *et al.,* 2012). The weather conditions of the Greek Seas are mostly linked with pressure systems developed in the Atlantic, Europe, Asia and North Africa as mentioned in (SoHelME, 2005). The physical and geographical characteristics and the complex topography often lead to the development of smaller scale weather conditions (Flocas & Karacostas, 1994; Trigo *et al.,* 1999, 2002; Lionello *et al.,* 2006a, b, 2006c).

During summer, persistent northerlies, known as Etesian winds, govern the atmospheric circulation of the eastern Mediterranean (Metaxas, 1977; Maheras, 1980; Nastos *et al.,* 1997). The Etesian winds are formed due to high barometric pressures over the Balkans and low pressures over Cyprus (Saaroni *et al.*1998; Tyrlis *et al.*2013). These winds have northeast to north directions in the North Aegean, turn northern in the Central Aegean and then northwest in the South Aegean (Poulos *et al.,* 1997; Bagiorgas *et al.,* 2012). The complex coastal topography, the orography of the Balkan Peninsula and the presence of islands in the Aegean affect their flow characteristics (e.g. channelling - funnelling) (Koletsis *et al.,* 2009, 2010). Over the Ionian Sea, they are mostly weakened, with NW directions at its southern areas (Klaic *et al.,* 2009). Transient periods are considered the changes from / to winter and summer climate patterns (Poulos *et al.,* 1997; SoHelME, 2005; Flocas *et al.,* 2010; Kouroutzoglou *et al.,* 2011;).

The wind and wave state of the Greek Seas has been described in detail in previous studies by using a variety of data:

- *in-situ measurements:* wave buoys of the POSEIDON project of the Hellenic Centre for Marine Research (HCMR) (Soukissian & Chronis, 2000). These data have been used for a variety of analyses (Ruti *et al.,* 2008; Kassis & Nittis, 2009; Bagiorgas *et al.,* 2012; Sifnioti *et al.,* 2014).
- *visual observations:* obtained by trained personnel on board of Voluntary Observing Ships (V.O.S.). A Wind - Wave Atlas, with observations from V.O.S. from the mid-1850s has been published and is considered of good quality with spatial resolution of 1°x1° (elementary regions) and from those 33 larger regions were created with homogeneous wave characteristics (Athanasoulis & Skarsoulis, 1992).
- *a third generation wave model (WAM):* The HCMR uses for wave forecasting a WAM-Cycle 4 model and SWAN for wave simulation at the coastal zone (Booij *et al.,* 1999). A full description of spatio-temporal behaviour of wind and wave propagation in the Greek Seas from the results of the aforementioned models can be found in (Soukissian, 2008; Soukissian *et al.,* 2007, 2009) on monthly, seasonal, annual and interannual temporal scales.
- *reanalysis datasets:* Lionello & Sanna (2005) used wave models with initial inputs from the ERA-40 and NCEP datasets and presented modelled wave characteristics of the Mediterranean Basin and their variability. In addition, Poupkou *et al.*(2011) and Tyrlis & Lelieveld (2013) identify negative trends regarding the frequency of appearance and the wind speed of the Etesians, from the analysis of ERA-40. ARPERA wind dataset has been used as input for wave hindcasting in the Greek Seas (Zacharioudaki & Reeve, 2011) while NOAA's CFRS wind data for wave energy estimates (Lavidas & Venugopal, 2017). Many researchers have used reanalysis wind data (ERA40, NCEP, CFRS, BOLAM, ARPERA - QuikSCAT) as inputs in hydrodynamic models (WAM, WaveWatch III, SWAN, MIKE21 SW) to represent the wave state of the Greek

Seas (Kechris & Soukissian, 2004; Soukissian, 2008; Soukissian *et al.,* 2009; Korres *et al.,* 2011; Mazarakis *et al.,* 2012; Zacharioudaki *et al.,* 2015; Emmanouil *et al.,* 2016; Jadidoleslam *et al.,* 2016; Lavidas & Venugopal, 2017;). To discuss the performance of reanalysis gridded dataset, the closest grid intersect to the *in-situ* data is considered as representative of the under examination area (Ruti *et al.,* 2008; Mazarakis *et al.,* 2012; Stopa *et al.,* 2013; Sanil Kumar & Muhammed Naseef, 2015; Zacharioudaki *et al.,* 2015; Lavidas & Venugopal, 2017).

In-situ data - POSEIDON Buoys

The POSEIDON project is run by HCMR and focuses on monitoring and assessing oceanographic data of the Greek Seas (Soukissian & Chronis, 2000; Nittis *et al.,* 2002; Soukissian, 2008; Soukissian *et al.,* 1999).The data used for this research are from 8 buoys located in the Greek Seas (Fig. 1) designed to measure oceanic and atmospheric variables.

Wind speed is recorded by a Lambrecht 145352 sensor (speed accuracy ± 1.05 m/s, direction accuracy ±1°) for a recording period of 10 minutes with a sampling frequency of 1 Hz and recording interval 3 hours. Wave characteristics are results of spectral analysis of sea surface elevation (SSE) data as obtained by a wave recorder (accelerometer), with a sampling frequency of 1 Hz for 1024 sec and recording interval 3 hours (Soukissian, 2008; Sifnioti *et al.,* 2014).

The raw buoy wind and wave data were filtered in order to exclude erroneous values (i.e. values coded as -9999.99 and -0.00001), mostly due to instrument false recordings. The datasets of atmospheric and sea-state parameters were given separately and therefore merged according to time to be used as one dataset for the comparison with ERA-Interim. As wind speed at the buoys is measured at 3m above sea level it has to be converted to 10m altitude in order to be compared with the data of wind speed from ERA-Interim. To do this the method of the logarithmic wind profile expression is applied.

The estimated winds would occur at the selected level if the atmosphere would be neutrally stable:

$$U_z\,(U_{z_m}) * \frac{\ln \frac{z}{z_0}}{\ln \frac{z_m}{z_0}} \qquad (1)$$

with U_z the wind speed at a height z (10m), U_{zm} wind velocity at the height of measurement, z_m (3m) and z_0 the roughness length of ocean surface equal to 1.52×10^{-4}m (Ruti *et al.,* 2008).

Reanalysis data set (ERA-Interim ECMWF)

The ERA-Interim dataset starts from the 1st of January 1979, is continued in real-time and updated every 2 months. Altimeter wave height data have been compared

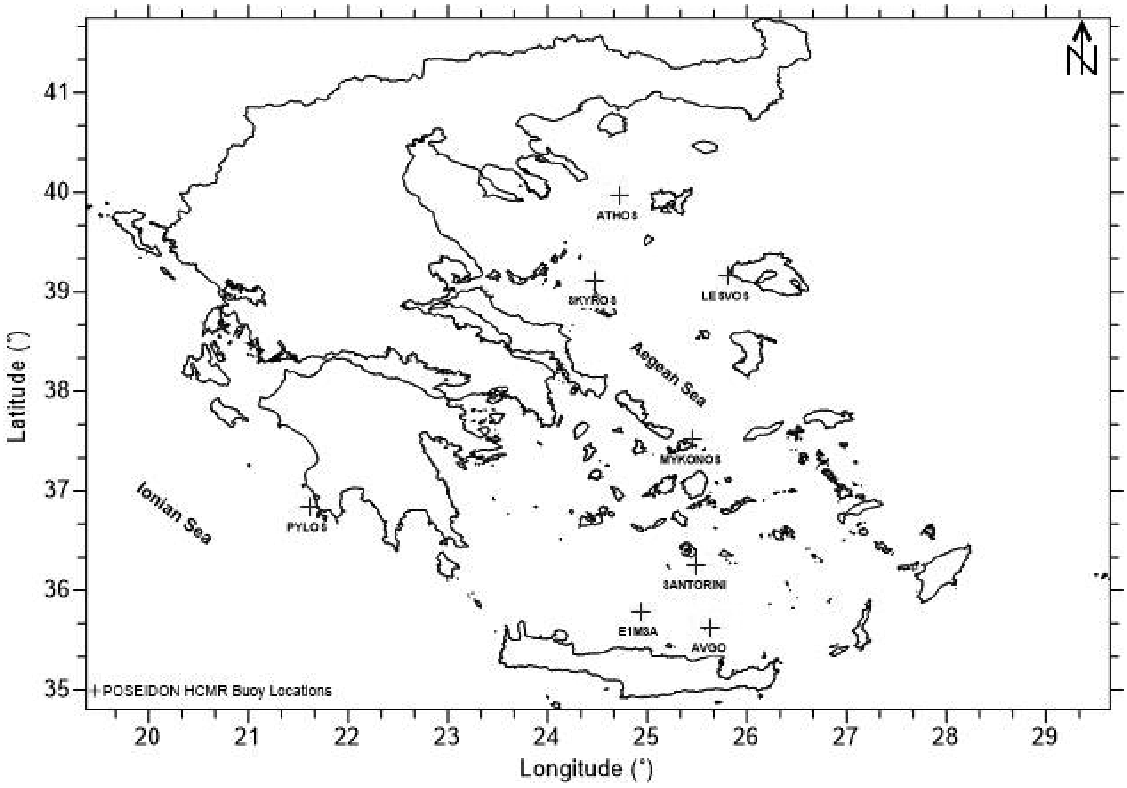

Fig. 1: HCMR Buoy Locations.

Details of the data used in the analysis, time-period of recording, number of data samples, depth of buoy installation, distance from the closest shoreline, location of closest grid intersect and distance of the intersect to the buoy are presented in Table 1.

with quality - checked in situ data such as buoys, platforms, weather ships (Bidlot *et al.,* 2002). Several geostationary satellites of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) provide Atmospheric Motion Vector (AMV) wind data. Data from ships, buoys and land stations are also collected (Berrisford *et al.,* 2011a). The wave-model component of ERA-Interim is based on the WAM model (Dee *et al.,* 2011) and has a horizontal resolution of 110km, with wave spectra discretization of 24 directions and 30 frequencies. More information can be found in the ERA-Interim archive in (Berrisford *et al.,* 2011a) and in http://www.ecmwf.int/research/era.

ERA-Interim can be downloaded from ECMWF's data archives and have a 6 hour temporal and 0.75° spatial resolution. However, for this research, the smallest grid resolution provided by ECMWF, of 0.125° x 0.125° (~14 x 14 km) is used, as a 0.75° x 0.75° grid would not adequately describe the Greek Seas, either for in-situ data comparison or for regional state comparison (Jadidoleslam *et al.,* 2016). To compare the time-series of the buoys and ERA-Interim, the data are compared according to the time-series of the buoy's wind-wave dataset (date and time in UTC) and only the data pairs that resulted from the temporal collocation are used for this analysis. Furthermore, as the buoys time - periods differ the number of pairs will also differ per location and parameter. The significant wave height is estimated in the case of the buoys as in ERA-Interim as follows:

$$H_{m_0} \approx 4\sqrt{m_0} \tag{2}$$

with the spectral moments estimated as: $m_n = f^n E(f)df$ for n = K, –3, –2, –1, 0, 1, 2, 3, K as described in Holthuijsen (2007).

To validate the performance of ERA-Interim in relation to in-situ (buoy) measurements, the following statistical measures are used (Table 2).

In the above relations, n is the number of the data pairs, x, y denote the buoy observations and the reanalysis data and $\overline{x}, \overline{y}$ denote the mean values of, x, y respectively. The Taylor diagrams Figure 2a and 2b present graphically the statistical measures per location and parameter. These results are discussed in detail in the Results section.

Results and Discussion

Wind Characteristics

Sub-daily analysis

The statistical measures of the estimated wind speed at 10 m from the buoys and from ERA-Interim, present a correlation coefficient of 0.71 - 0.84, absolute bias from 0.01 to 1.21 m/s and RMSE from 2 to 2.64 m/s (Table 3). Maximum average values of wind speed are in Mykonos (buoy, 7.88 m/s) and in Avgo (ERA-Interim, 6.81 m/s). The statistics per region present positive bias in the North, Central Aegean and the South Ionian and almost zero - negative in the South Aegean. In addition, in the North Aegean, the further the location is from land (Table 1), the larger the correlation coefficient and the smaller the RMSE become; however, this applies only for the RMSE in South Aegean. A relation between the number of data pairs with the correlation coefficient and the RMSE is not evident as mentioned in the data analysed from Stopa and Cheung (2014).

In Ruti *et al.*(2008), the authors discuss the performance of ERA-40 and NCEP (and other datasets) for various locations in the Mediterranean and especially for Santorini and Mykonos (Table 4). The results of the present analysis show that ERA-Interim provide better correlation in comparison to the results of Ruti *et al.*(2008). In (Korres *et al.,* 2011), a correlation analysis of wind speed from 4 buoys and ERA-40 data is presented. For Athos, Santorini and Mykonos the correlation coefficient is lower than the present analysis. Caution should be given to the number of pairs in comparing these analyses as in (Ruti *et al.,* 2008) the number of pairs is less than the present analysis (810 ERA-40 and NCEP for Mykonos and 1454 ERA 40 and NCEP in Santorini) and in (Korres *et al.,* 2011) a period of 2 years.

The correlation coefficients are lower than those described in Carvalho *et al.*(2012) for the Iberian Peninsula

Table 1. Time-period: time period of buoys records, Depth: Depth of installation, DNS: Distance from Nearby Shore, LCI: Location of Closest Intersect, DIB: Distance of Intersect to the Buoy, Region: Buoy's Location.

Buoy	Region	Time-period	Depth (m)	DNS (km)	LCI	DIB (km)
Athos	North Aegean	2000-2011	220	27.60	40° ,24.75°	4.7
Avgo	South Aegean	2000-2006	360	29.6	35.625° ,25.625°	1.6
E1M3A	South Aegean	2007-2011	1,440	43.90	35.75° ,25.00°	8
Lesvos	North Aegean	2000-2011	131	5.14	39.125° ,25.75°	5.8
Mykonos	Central Aegean	2000-2011	140	5.25	37.5° ,25.5°	4
Pylos	South Ionian	2007-2011	1,681	5.68	36.875° ,21.5°	11.4
Santorini	South Aegean	2000-2011	320	8.60	36.25° ,25.5°	0.6
Skyros	North Aegean	2007-2011	117	15.70	39.125° ,24.5°	3.4

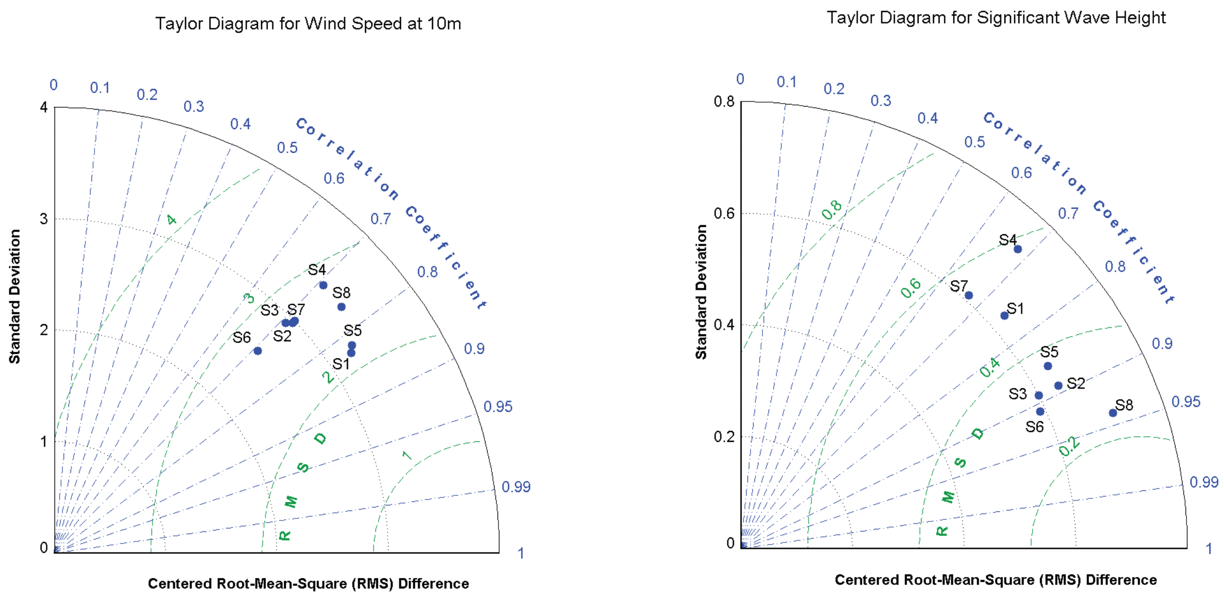

Fig. 2: Taylor Diagrams for the comparison of POSEIDON Buoys and ERA-Interim reanalysis for wind speed (a) and wave height (b). S1: Athos, S2: Avgo, S3: E1M3A, S4: Lesvos, S5: Mykonos, S6: Pylos, S7: Santorini and S8: Skyros.

Table 2. Statistical parameters for the comparison of the datasets.

Statistical Parameters	Equation	Definition
BIAS		Mean data tendency
STD		Standard deviation
COR		Correlation coefficient to quantify the linear relation between the observed and simulated data
RMSE		Standard deviation amongst the observed and simulated data

Table 3. Correlation statistics of Buoy and ERA-Interim for Wind Speed at 10m, N: data pair

	ATHOS	AVGO	E1M3A	LESVOS	MYKONOS	PYLOS	SANTORINI	SKYROS
N	11740	7969	4157	12453	13042	5523	14674	4890
CORR	0.83	0.72	0.71	0.71	0.82	0.71	0.72	0.76
BIAS (m/s)	0.32	-0.38	-0.28	0.21	1.18	0.89	0.01	0.03
RMSE (m/s)	2.14	2.57	2.35	2.8	2.37	2.3	2.45	2.45
$\overline{W}_{buoy}$ (m/s)	5.71	6.43	6.17	6.95	7.88	5.7	6.49	5.97
$\overline{W}_{ERA-I}$ (m/s)	5.4	6.81	6.45	6.75	6.69	4.81	6.48	5.94

Table 4. Correlation statistics of wind reanalysis datasets and buoys for the Greek Seas.

Author	Location	Datasets	Correlation	RMSE (m/s)	Bias (m/s)
(Ruti *et al.,* 2008)	Santorini	ERA-40	0.73	2.89	-1.33
		NCEP	0.63	3.13	-0.99
	Mykonos	ERA-40	0.79	3.78	-2.71
		NCEP	0.56	4.56	-2.68
(Korres *et al.,* 2011)	Athos	ERA-40	0.78	2.23	0.23
	Santorini		0.68	-0.74	-0.06
	Mykonos		0.79	2.56	-0.74
	Lesvos		0.77	2.33	-0.88

and in Stopa and Cheung, (2014) (0.8 to 0.93). The RMSE falls in the ranges provided by Carvalho *et al.*(2012) (i.e., 1.76 to 2.26 m/s) but is higher than those given by Stopa and Cheung (2014) (1.02 to 1.56 m/s). Main difference of these studies with the present is that the *in-situ* data are in less land-blocked waters and not enclosed areas such as the Greek Seas, i.e. it is possible that the physical models included for wave propagation with wind speed inputs in the assimilation of ERA-Interim dataset, not to adequately describe the nearshore coastal processes in cases as the Central Aegean Sea with wave blocking by the islands.

Variations in datasets might be due to larger wind variability at those locations, the number of observations under evaluation, the method of collocation as well as to the elevation of the observations at 10m through neutral stability of atmospheric conditions (Ardhuin *et al.,* 2007; Stopa *et al.,* 2013). Furthermore, as mentioned in (Cavaleri & Sclavo, 2006), and especially for the generation of ECMWF datasets for coastal areas, the model winds might not be reliable due to the important influence of orography, that is not properly represented in the meteorological model because of its limited resolution (80 km for T255 of ERA-Interim). The same authors note that the representation of the coastline as well as the modelling of marine boundary layer might also affect wind speed estimates.

From the density scatter plots in Figure 3, the density of points and the magnitude of wind speed the different states per location can be discussed. The North Aegean buoys (Athos, Lesvos and Skyros) show higher densities (frequencies) in values from 2 to 8 m/s, Mykonos (Central Aegean) from 2 to 10 m/s, South Aegean (E1M3A, Avgo and Santorini) ranges in 3 to 9m/s and finally Pylos (South Ionian) from 2 to 6 m/s. The intercept ranges from 1.4 to 3.05 m/s and the slope from 0.56 to 0.72. The maximum value is recorded in Lesvos buoy with wind speed of 30.24 m/s that is greatly underestimated by ERA-Interim (24.4 m/s). An average of 10-15% underestimate is evident by ERA-Interim for the upper quartiles in relation to the buoy. The prediction intervals represent where future observations are most likely to fall, according to the probability of 95%.

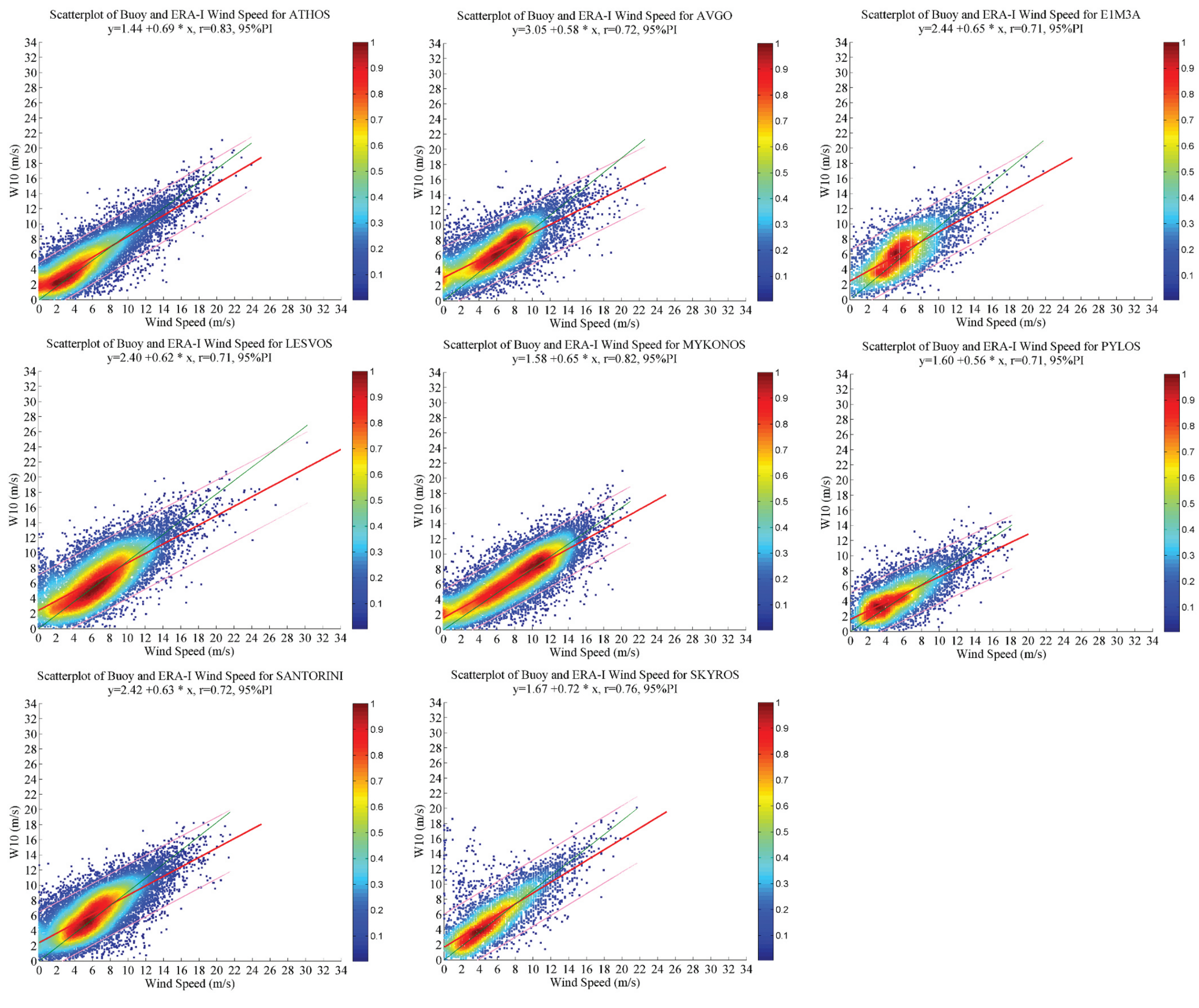

Fig. 3: Density scatterplots of Wind Speed at 10 m (Buoy) and W10 (ERA-Interim) with the linear fit (red) and 95% Prediction Intervals (pink) and the ideal Y=X (green line) for Athos, Avgo, E1M3A, Lesvos, Mykonos, Pylos, Santorini and Skyros. The colorbar depicts the density of points per location (red more frequent, blue less frequent values).

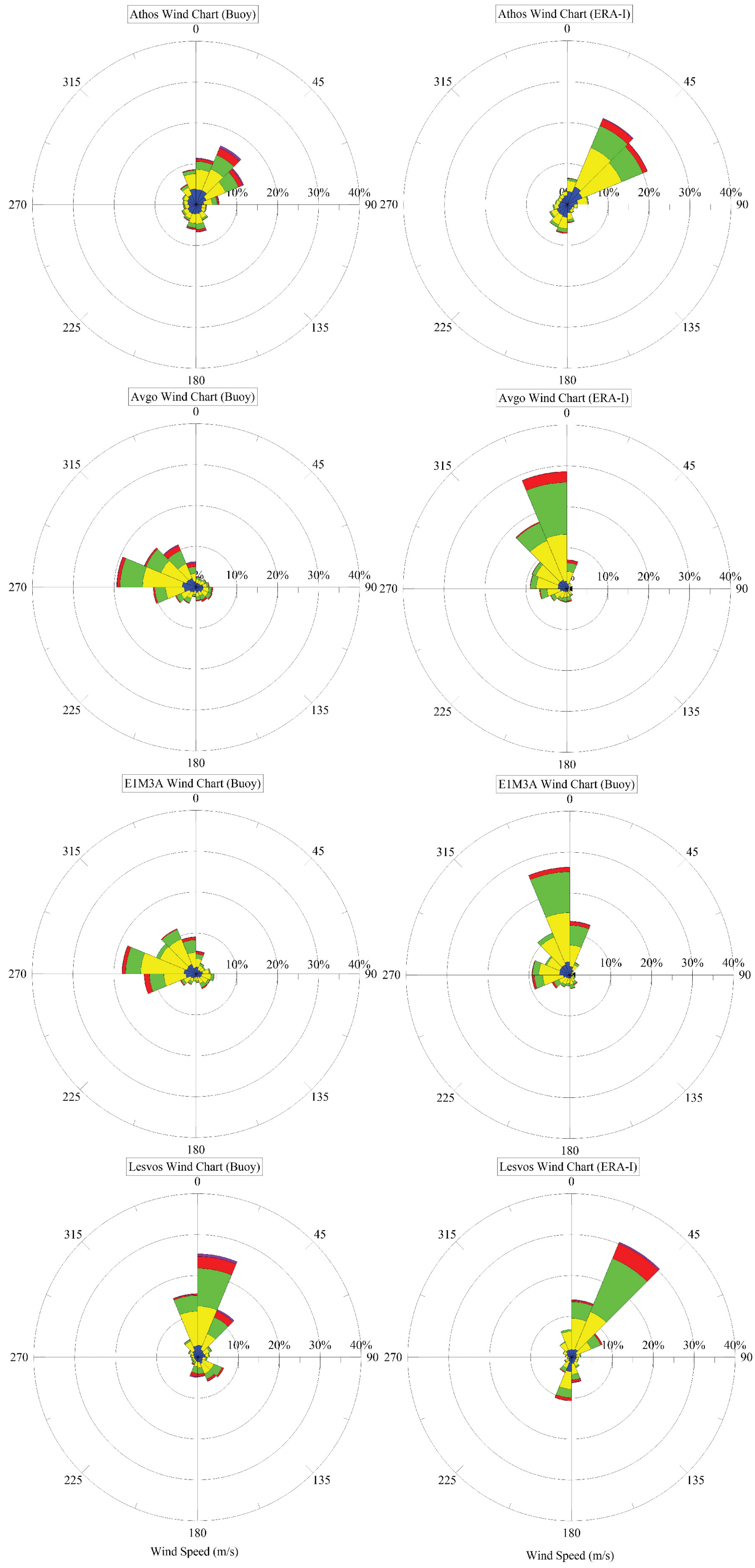

Fig. 4-part 1: Wind Charts for Buoys (left) and ERA-Interim (right).

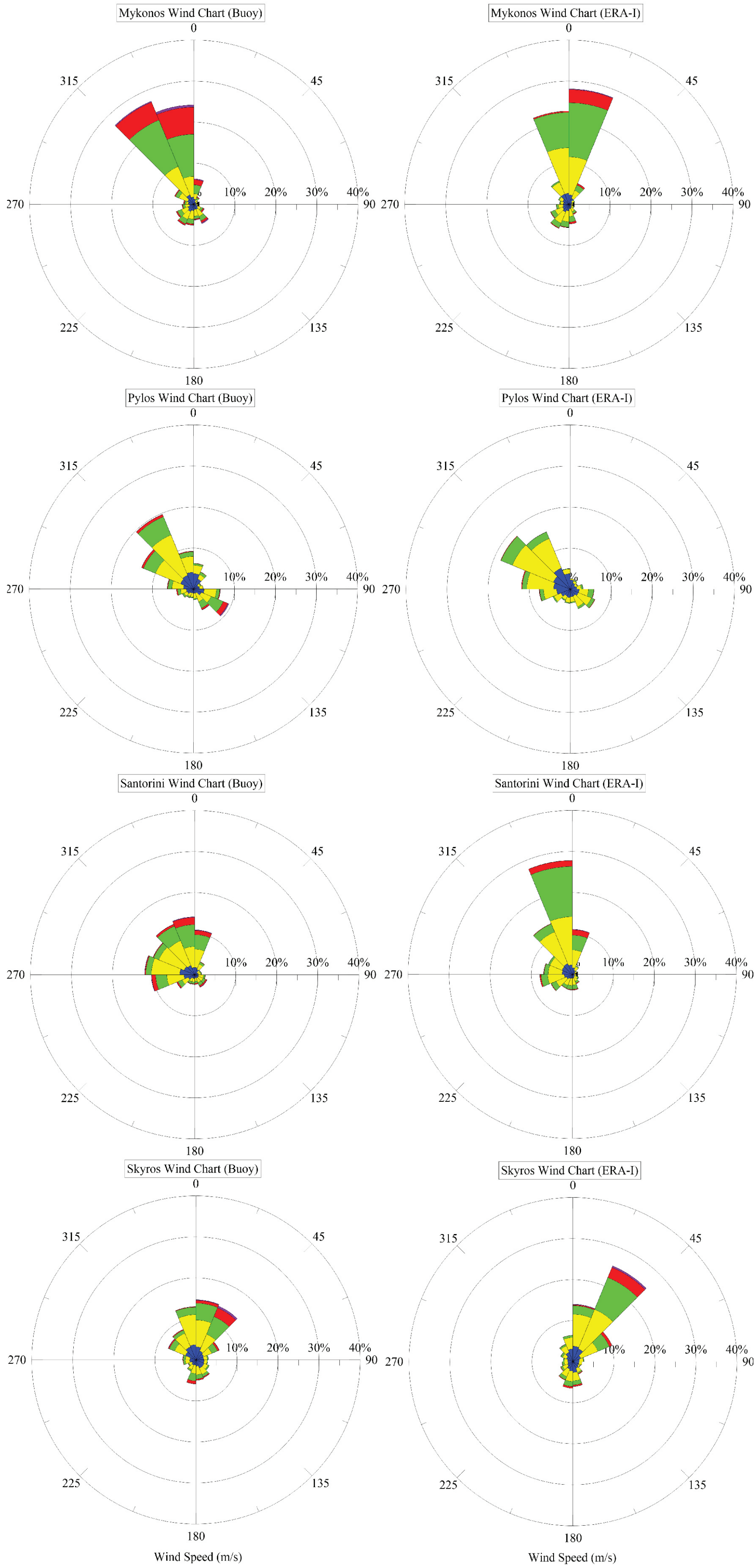

Fig. 4-part 2: Wind Charts for Buoys (left) and ERA-Interim (right).

The wind charts Figure 4, part 1 and Figure 4 part 2 show the differences in wind speed and direction per location and according to dataset. It is evident that asides the underestimate in most locations of the higher wind speeds, the direction wherefrom the wind is blowing also differs along with the frequency of the recorded winds. For example, in Avgo, the buoy shows that the most frequent winds (20%) are blowing from W-NW while ERA-Interim shows that the most frequent winds (30%) are NW-N. In addition, as Greece is described by its complex topography and coastline, in most of the locations the buoys and ERA-Interim agree in the direction of the less frequent - blocked winds such as the east directions in Athos and Lesvos. This issue is also related to the selection of the closest intersect of the grid to the buoy. Higher wind speeds are quite similar in terms of directionality, but this remark should be interpreted carefully taking into account to the particular location.

In order to show the comparison of the extreme values, the 90% upper quantile of wind speed as recorded by the buoy, has been selected as a threshold per location (Table 5). The correlation decreases in comparison to the 6hour full data sample (see Table 5) with the lowest value in Pylos (0.32) and the highest in Athos (0.65). The higher mean of the upper 10% is in Mykonos 15.93m/s (buoy) and 14.49m/s (ERA-Interim).

Furthermore, BIAS is positive for all locations, clearly showing the underestimate of ERA-Interim high wind speeds, a result that is in agreement with other studies as well (Ardhuin *et al.,* 2007; Shanas & Sanil Kumar, 2013; Stopa & Cheung, 2014; Carvalho *et al.,* 2014b; Aarnes *et al.,* 2015; Shanas & Kumar, 2015;).

Intra-annual Analysis

The comparison of the monthly variations of wind speed per location is shown in Figure 5. In the cases of Athos and Mykonos, ERA-Interim underestimate wind speed, especially during the months with stronger winds; the difference increases after August and decreases after April. The underestimate is also evident in the case of Pylos with a slight pattern difference in the months of April to June. For the other locations, the variations differ per month, while in South Aegean ERA-Interim overestimates wind speed during the summer months. The Etesian winds that occur from May to September (with high peak in the end of July beginning of August) are evident in the Aegean locations in both datasets. The largest mean monthly value is exhibited by the buoy of Mykonos in February with a value of 8.66m/s and is underestimated by ERA-Interim (7.94 m/s). In Bagiorgas *et al.*(2012), the mean monthly wind speeds at 3 m and 10 m are presented for 10 locations at the Greek Seas, but a description of their variability per month is not discussed. The seasonal conditions as described by this study coincide with the results of (Bagiorgas *et al.,* 2012) for 10 m wind speed estimates. The predominant appearance of the Etesian winds in the Aegean Sea is evident in the monthly plots and their peak period (end of July - beginning of August) can be highlighted.

Significant Wave Height (SWH)

Sub-daily analysis

The correlation statistics for the buoy and ERA-Interim data for significant wave height per location are given in Table 6. The correlation coefficient varies from 0.67 to 0.94, the absolute bias from 0.002 to 0.17 m and the RMSE from 0.23 to 0.56 m, suggesting a rather good agreement amongst the two datasets for the Greek Seas. In Stopa and Cheung (2014), the regional error statistics in the North East Pacific and North West Atlantic present correlation coefficients amongst 0.89 and 0.96 and RMSE in ranges from 0.29 to 0.51 m, while Shanas and Sanil Kumar (2013) estimate the correlation coefficient equal to 0.96, RMSE of 0.26-0.29 m and absolute bias from 0.18 to 0.21 m for a location at the Arabian Sea. Similarly, in Shanas and Kumar (2015), data from nearshore waters around India are compared with ERA-Interim and their results are closer to those represented in this study with correlation coefficients ranging in 0.71-0.98, RMSE ranging in 0.18-0.4 m and absolute bias in 0.09-0.31 m.

Furthermore, in the North and South Aegean, where the larger fetch distances are present, the larger the sample size the smaller the correlation coefficient (also in the case of Stopa and Cheung (2014)) in contradiction to the

Table 5: Statistics for 90% quantiles of wind speed per location

	ATHOS	AVGO	E1M3A	LESVOS	MYKONOS	PYLOS	SANTORINI	SKYROS
N	580	405	219	589	286	135	734	303
90% (m/s)	11.19	11.04	10.60	12.01	13.12	10.26	11.15	10.91
COR	0.65	0.47	0.59	0.55	0.53	0.32	0.49	0.64
BIAS (m/s)	1.69	0.97	0.37	1.24	1.44	1.83	1.02	0.74
RMSE (m/s)	1.73	2.06	1.61	2.23	1.53	2.06	1.79	1.33
$\overline{W}_{>90\%buoy}$ (m/s)	14.92	14.08	12.93	15.47	15.93	13.58	13.93	13.76
$\overline{W}_{>90\%ERA-I}$ (m/s)	13.23	13.11	12.56	14.23	14.49	11.75	12.91	13.02

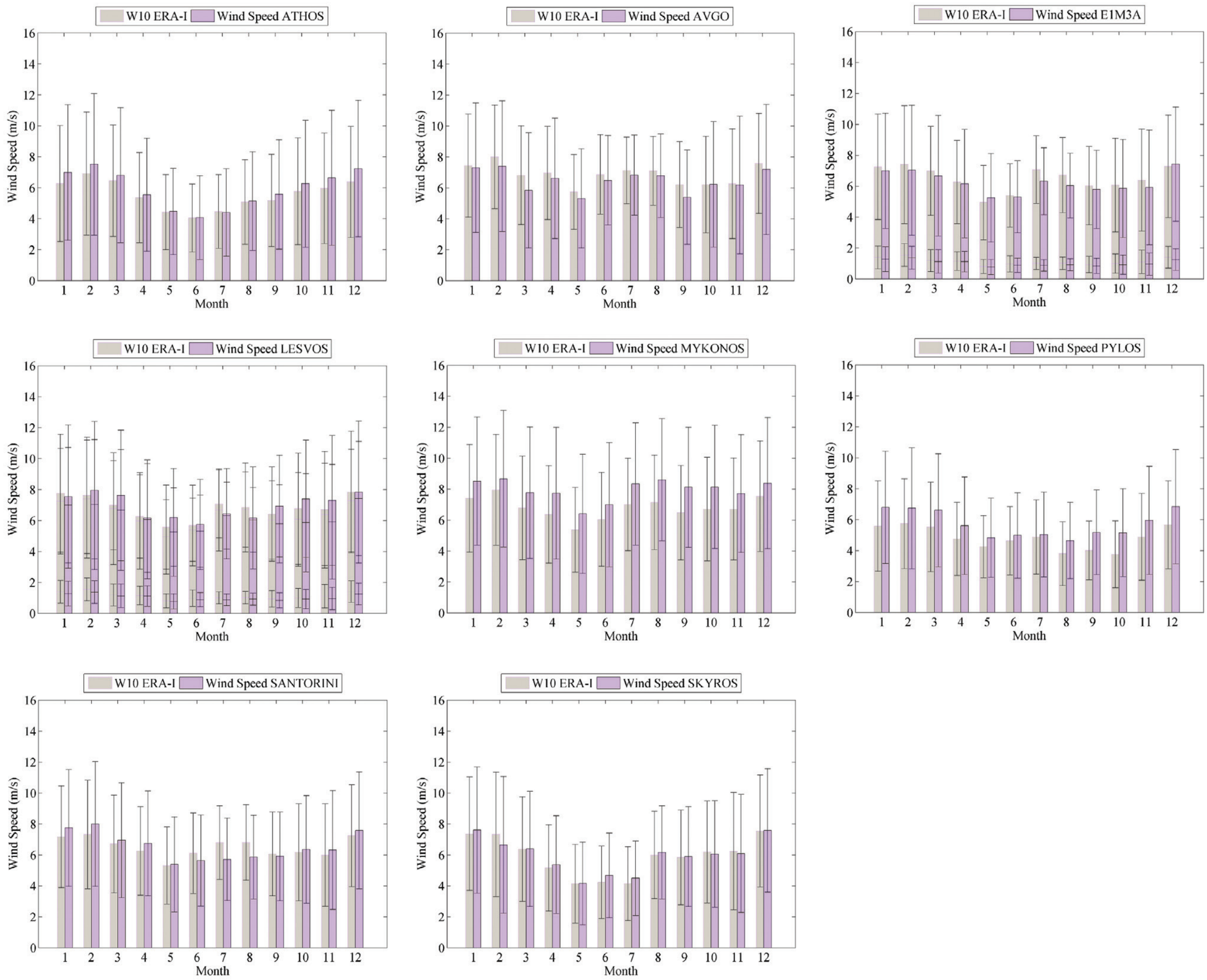

Fig. 5: Monthly means of wind speed at 10m for Buoy and ERA-Interim for the locations of Athos, Avgo, E1M3A, Lesvos, Mykonos, Pylos, Santorini and Skyros. Whiskers show the standard deviation per month and per dataset.

absolute values of RMSE and BIAS, that tend to increase with increasing fetch.

Previous studies that have used wind reanalysis datasets as inputs for hydrodynamic modelling have compared their results for several locations at the Greek Seas (Table 7). The results of Jadidoleslam *et al.*(2016) give the best error statistics for Athos, Lesvos, E1M3A, Mykonos, Santorini and Skyros when compared to the other studies. For Avgo, the results of this analysis are similar to the results of Zacharioudaki *et al.*(2015), while the results of Lavidas and Venugopal (2017) are better for Pylos. With the wind input data not describ-

Table 6: Correlation statistics of Buoy and ERA-Interim for Significant Wave Height, N: data pair

	ATHOS	AVGO	E1M3A	LESVOS	MYKONOS	PYLOS	SANTORINI	SKYROS
N	11740	7969	4157	12453	13042	5523	14674	4890
CORR	0.75	0.89	0.89	0.68	0.86	0.91	0.67	0.94
BIAS (m)	0.09	-0.09	-0.15	-0.16	0.05	0.12	-0.16	0.01
RMSE (m)	0.49	0.29	0.29	0.54	0.38	0.33	0.47	0.25
$\overline{H}_{m_0(buoy)}$ (m)	0.81	1.00	0.91	0.79	1.01	0.97	0.89	0.88
$\overline{H}_{m_0(\mathrm{ERA-I})}$ (m)	0.72	1.1	1.06	0.95	0.96	0.85	1.05	0.87

Table 7. Correlation statistics of hydrodynamic models and buoys for the Greek Seas.

Author	Input	Time step Interval	Wave Model	Buoys	Time period/ Samples	Correlation	RMSE (m)	Bias (m)
(Zacharioudaki *et al.,* 2015)	ARPERA	6hr	WAM	Avgo	2294	0.9	0.34	0
(Jadidoleslam *et al.,* 2016)	ERA INTERIM	6hr	MIKE 21 SW	Athos	1yr	0.94	0.28	0
				E1M3A		0.89	0.37	-0.07
				Lesvos		0.91	0.27	-0.03
				Mykonos		0.91	0.35	-0.01
				Santorini		0.85	0.33	-0.06
				Skyros		0.95	0.31	-0.05
(Lavidas & Venugopal, 2017)	CFSR	1hr	SWAN	Pylos	2007 -2014	0.93	0.38	0.01

ing accurately high wind speeds, it might be possible that the wave model in ERA-Interim to not represent the associated wave heights and this uncertainty can be increased with the topographical lacks that the (meteorological or oceanographic) model might have as was the case of previous ECMWF reanalysis data (Cavaleri & Sclavo, 2006). Any discrepancies can be attributed to the different sample sizes, and grid/model set-up wave characteristics changes due to the complex topography and bathymetry.

The density scatterplots in Figure 6 depict the relation between the significant wave height obtained from the buoy and ERA-Interim for the examined locations. As in the case of wind speed, the different local wave climates are depicted in the density scatter plots. Areas that are characterized by long fetches and allow the waves to fully develop, do exhibit higher wave heights that those that are more secluded or blocked by the near land, agreeing with the results of Soukissian (2008) and Zacharioudaki *et al.*(2015). The intercept ranges from 0.04 to 0.36 m and the slope from 0.67 to 0.95. The maximum value from all locations is recorded in Pylos, with a height of 7.58 m that is underestimated by ERA-Interim (4.62 m). Similarly to the wind speed analysis, there is an underestimate of wave height for the upper quartiles of around 8-10% from the ERA-Interim dataset.

However, to accurately describe this, the location of the buoy and of the selected ERA-Interim point should be kept in mind; for example in Pylos, Mykonos and Lesvos the data are from close to the shore points and, thus, might not show higher heights (less than 6km from nearby shore). Moreover, Athos, Lesvos and Santorini show a large scattering of the data points, and consequently exhibit lower correlation coefficient and higher RMSE in comparison to other positions (Table 6).

The wave charts (Figure 7) exhibit differences in directionality, frequencies of occurrence and wave heights as in the case of wind speed. For example, in Athos, a 30% of the waves are propagating from the NE as shown in ERA-Interim while for the same direction the buoy is characterized by a 25% frequency. ERA-Interim show as secondary direction waves propagating from S whilst the buoy from S to SSE. However, areas where wave directionality is affected by land blocking are depicted in both datasets, i.e. Athos (E, S to NW), Avgo, E1M3A and Santorini (southern waves not apparent due to blockage from Crete), Mykonos (southern waves not apparent due to Cyclades complex), Lesvos (no incoming waves from E due to the island of Lesvos), Skyros (no west incoming waves due to blockage from Sporades Isl. complex) and Pylos (no incoming waves from North to East due to the Peloponnese) (Figure 1). In Emmanouil *et al.*(2016), differences are evident for the directionality and frequency of wave occurrence for Lesvos amongst buoy and model results. Their model presents more than 50% incoming waves from NNW in contrast to the buoy that presents 33% for the same direction and N waves with almost 40% whilst the model shows less than 10%.

This study for Lesvos, presents frequencies around 25% for N and around 28% for NW waves from the buoy data and 25% for N and around 26% for NE waves. Differences in directionality (travelling to) and frequencies of occurrence are also shown in Zacharioudaki *et al.*(2015), where the authors also note that the complex topography and obstacles might affect fetch and direction.

To discuss the 90% upper quantile data differences amongst the datasets for significant wave height, the correlation statistics have been estimated and are presented in Table 8. The lower coefficients are exhibited in Lesvos and Santorini (as was in the 6-hourly data), while the RMSEs are higher in Lesvos, Santorini and Pylos. These locations are the closest to the nearby shore (Table 1).

The means of the more than 90% quantile records are also shown, with the higher values in Pylos for the buoy (3.11 m) and Mykonos for ERA-Interim (2.65 m). Bias is negative in Avgo, E1M3A, Lesvos, Santorini and Skyros with the mean values higher in ERA-Interim from the buoys. These results agree overall with the analysis of Zacharioudaki *et al.*(2015).

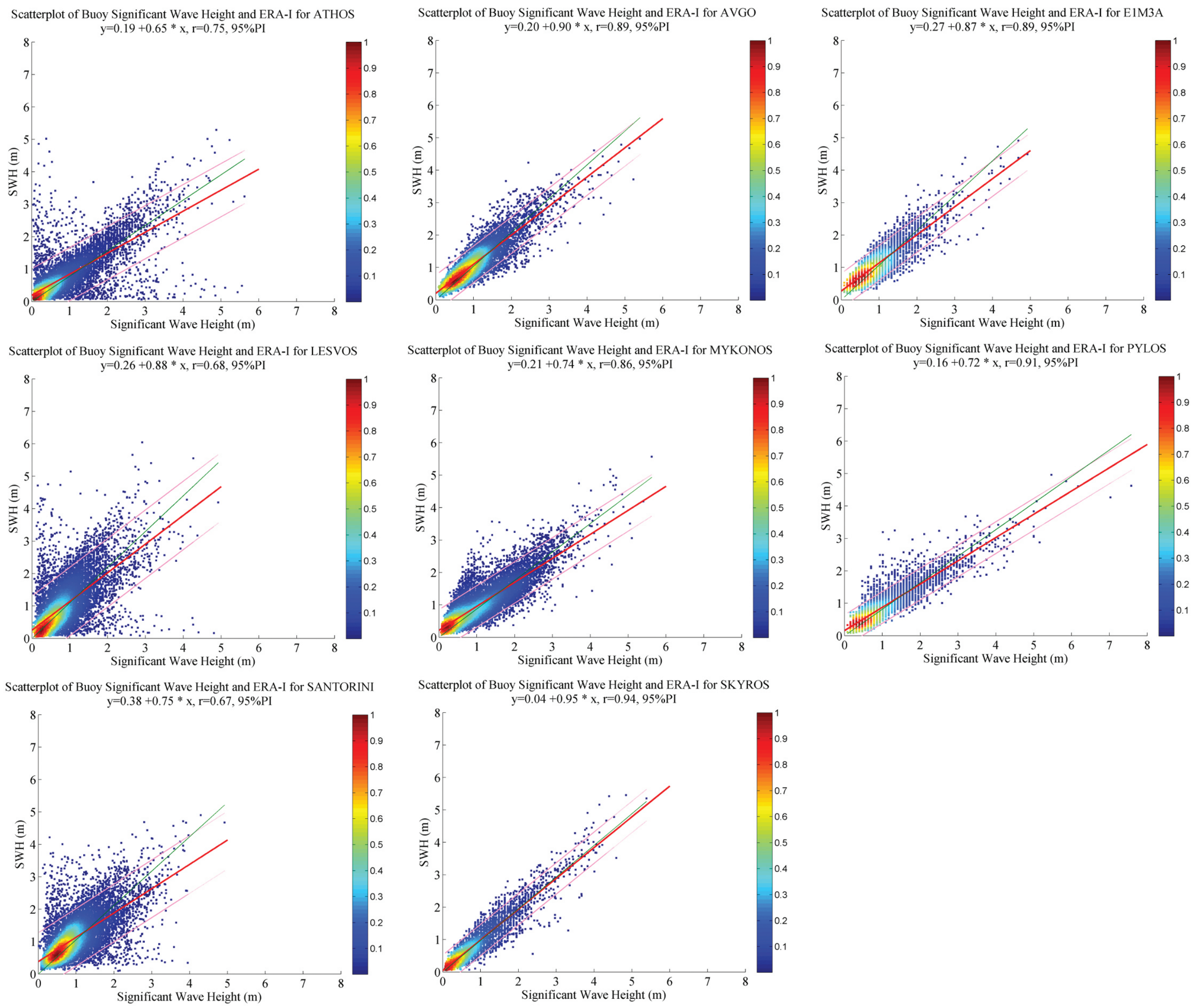

Fig. 6: Density scatterplots of Hm_0 (Buoy) and SWH (ERA-Interim) with the linear fit (red) and 95% Prediction Intervals (pink) and the ideal Y=X (green line) for Athos, Avgo, E1M3A, Lesvos, Mykonos, Pylos, Santorini and Skyros. The colorbar depicts the density of points per location (red more frequent, blue less frequent values).

Intra-annual Analysis

The monthly variations of significant wave height per buoy are presented in Fig. 8. Overall, the patterns are similar per location but differ in overestimating or underestimating the monthly means of the buoys by ERA-Interim. Specifically, in Athos and Pylos, ERA-Interim present lower means than that of the buoys in contradiction to the buoys of Lesvos, Avgo, E1M3A and Santorini (for all months). In Skyros, ERA-Interim overestimate the wave height for January, August, September, October, November and December, and in Mykonos in January, February, March, November and December. The winter months in all locations and both datasets present the largest means of significant wave height. The peaks in July and August in the Aegean buoys can be attributed to the Etesians that blow with highest intensities during those months. This pattern is not evident for the South Ionian location of Pylos (Poulos *et al.,* 1997; Soukissian *et al.,* 2007; Soukissian, 2008). Avgo location presents the highest mean monthly variations (either from ERA-Interim or buoy records) in relation to the other locations. This can be due to its location as it is affected by waves propagating from the west with long fetches, from the North (with most of the wind patterns in the Aegean having northerly directions) and from the East with waves propagating from the straits of Karpathos - Rhodes - Crete. Maximum monthly deviations appear for the winter months (DJF) for both datasets and in all locations in agreement to the research of Zacharioudaki *et al.*(2015).

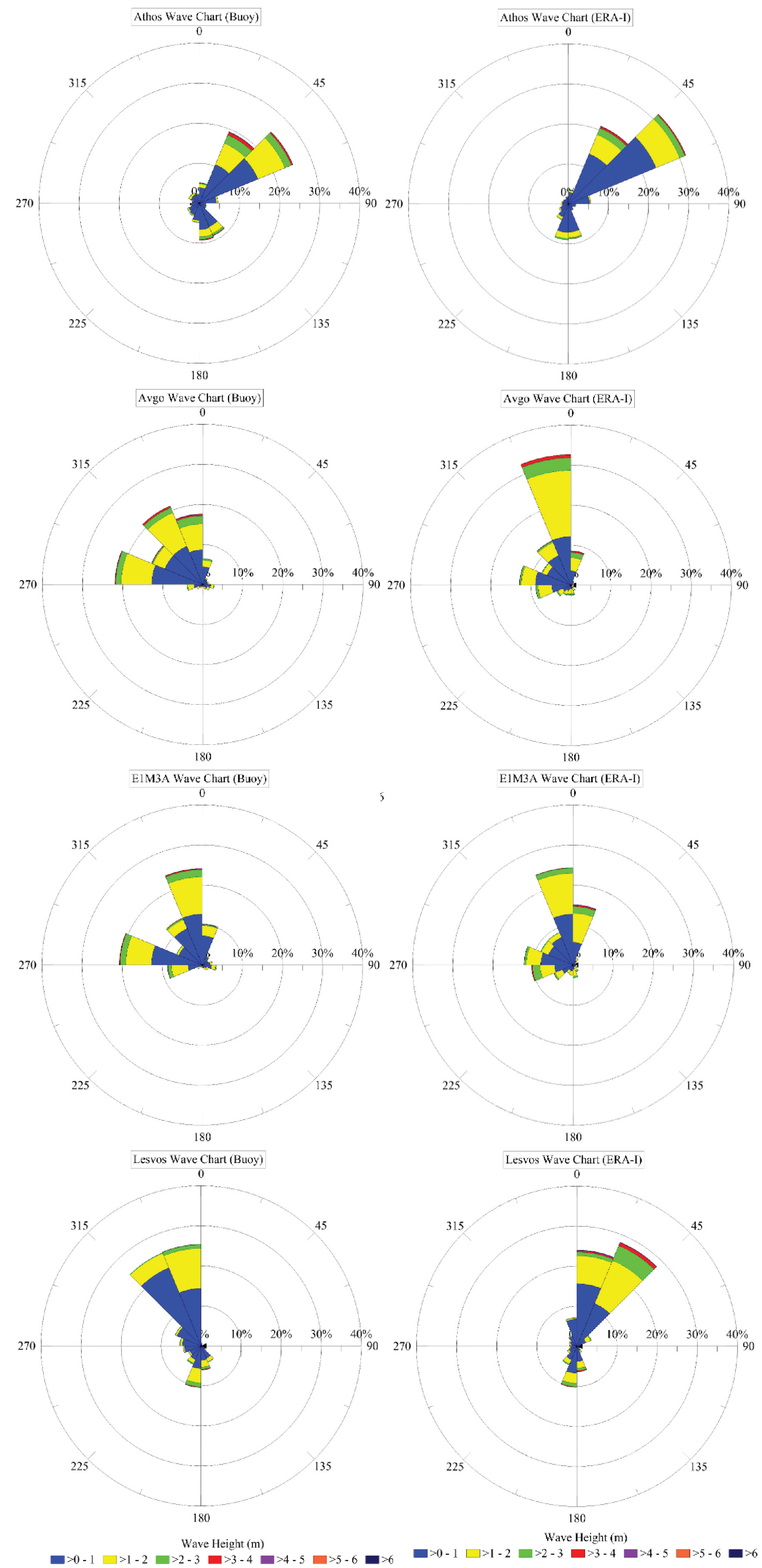

Fig. 7-part 1: Wave charts for Buoys (left) and ERA-Interim (right).

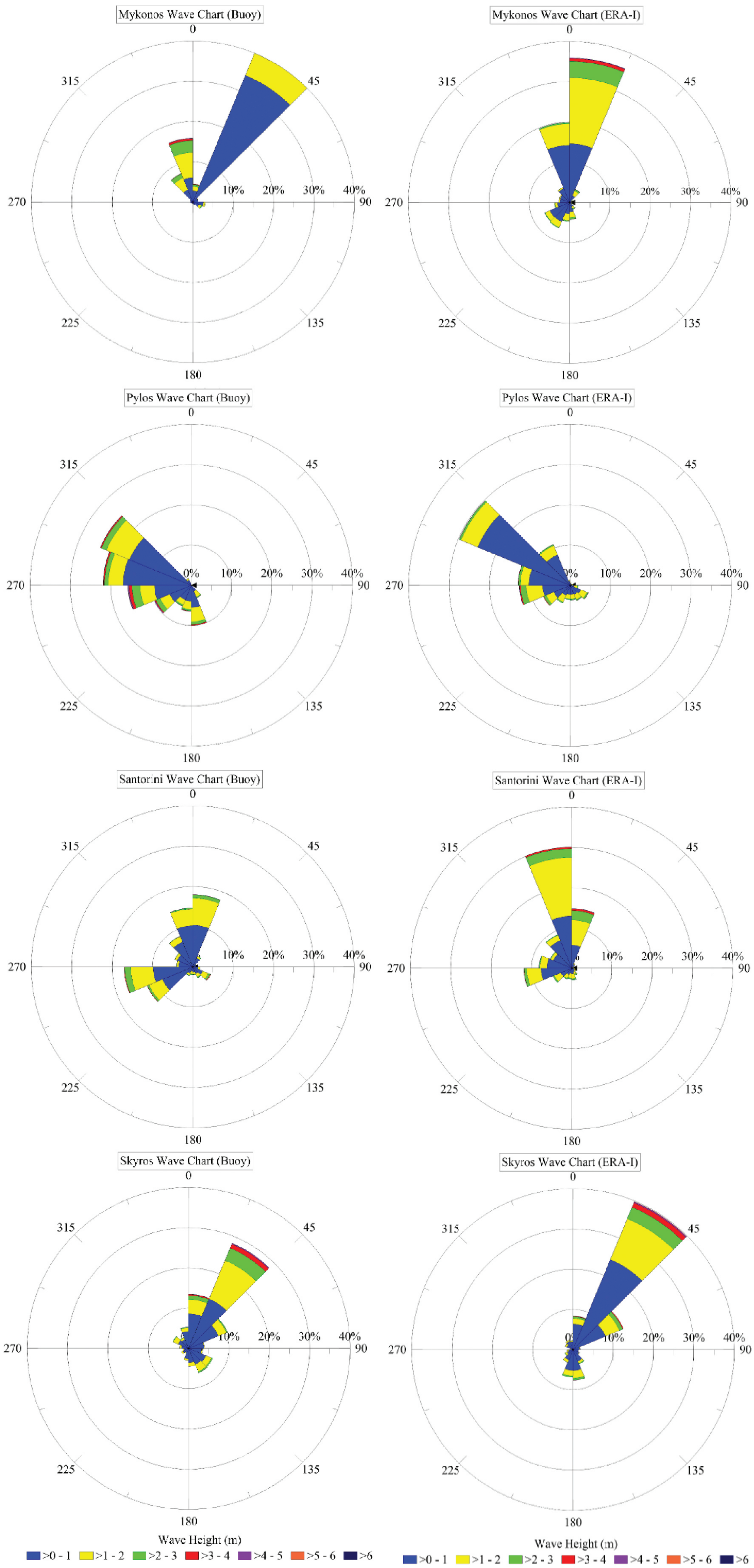

Fig. 7-part 2: Wave charts for Buoys (left) and ERA-Interim (right).

Table 8. Statistics for 90% quantiles of significant wave height per location.

Parameter	ATHOS	AVGO	E1M3A	LESVOS	MYKONOS	PYLOS	SANTORINI	SKYROS
N	622	613	359	885	666	283	951	396
90%	1.79	1.82	1.72	1.49	2.06	1.96	1.64	1.79
CORR	0.71	0.72	0.73	0.41	0.69	0.76	0.48	0.86
BIAS (m)	0.2	-0.09	-0.12	-0.37	0.17	0.62	-0.15	-0.06
RMSE (m)	0.47	0.44	0.43	0.69	0.43	0.56	0.54	0.34
$\overline{H}_{m_0>90\%(buoy)}$ (m)	2.66	2.49	2.3	2.09	2.83	3.11	2.2	2.55
$\overline{H}_{m_0>90\%(ERAI)}$ (m)	2.46	2.58	2.42	2.47	2.65	2.5	2.35	2.61

Intra-annual Analysis

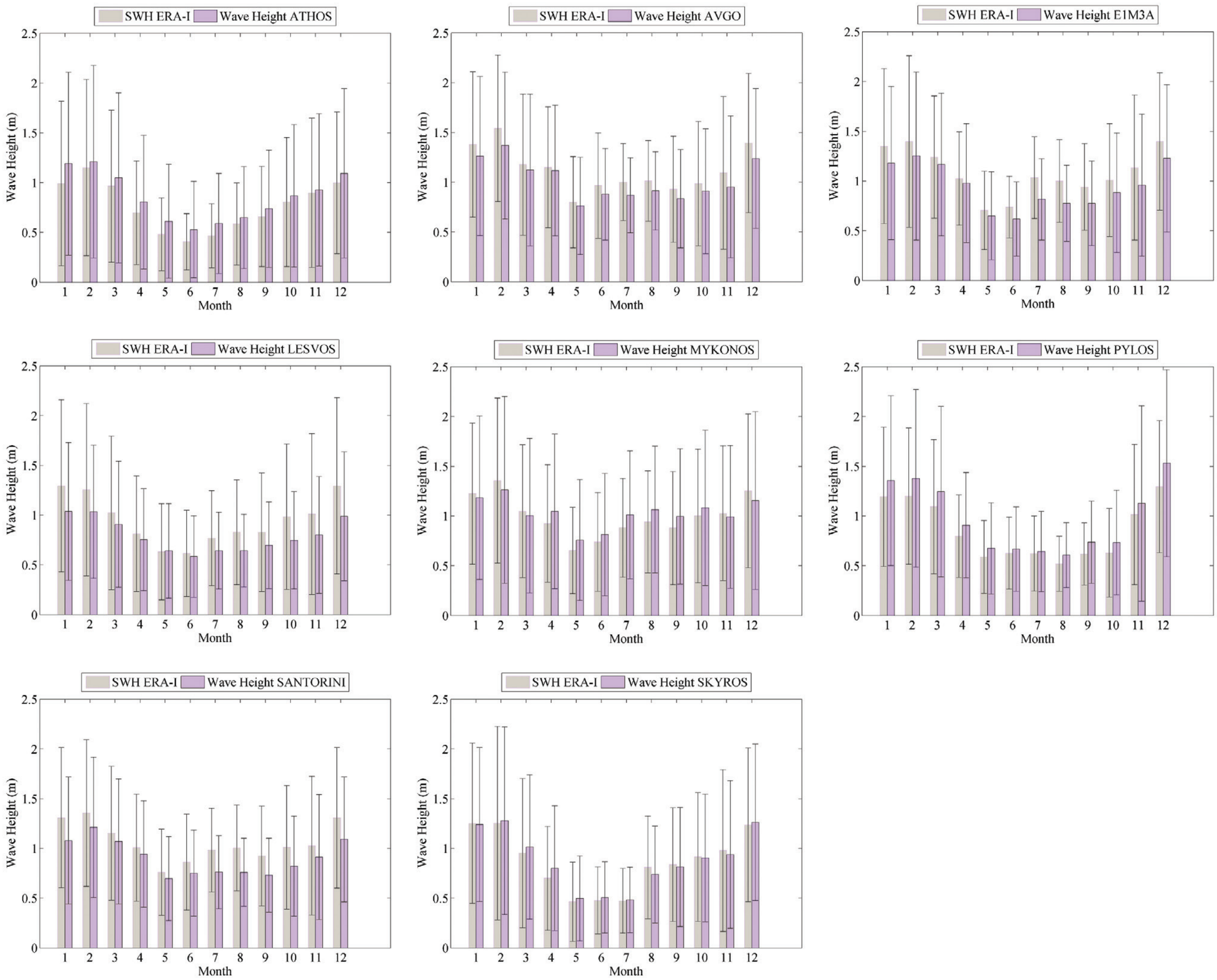

Fig. 8: Monthly means of Significant Wave Height for Buoy and ERA-Interim for Athos, Avgo, E1M3A, Lesvos, Mykonos, Pylos, Santorini and Skyros. The whiskers represent the standard deviation per month and per dataset.

Conclusions

The present analysis has discussed the performance of ERA-Interim wind and wave dataset in 8 locations of the Greek Seas. The evaluation of their performance has been based on correlation statistics and a comparison with results of similar analyses for the Mediterranean and global locations for the 6-hourly data, the 90% values, wind direction/speed, wave direction/ height and monthly data.

For the 6-hourly data, the correlation coefficient is fair to good ranging from 0.67 to 0.94 for wave height and 0.71 to 0.84 for wind speed, BIAS from 0.17 to 0.12 m and -0.38 to 1.21 m/s, RMSE from 0.23 to 0.57 m and 2 to 2.8 m/s, respectively. For the North Aegean, the correlation coefficient decreases, the BIAS and the RMSE increase with increasing sample size for wave height. For wind speed, with increasing distance from the closest shore the correlation coefficient and the RMSE are increasing. For the South Aegean, wave height shows that with increasing sample size and distance from nearby shore, the correlation coefficient decreases and RMSE increases. In the SE Ionian, the correlation coefficient for wave height is 0.91 and for wind speed 0.72 giving a good relation between the datasets. For the 90% upper percentile significant wave height analysis, the correlation coefficient decreases; the lower correlation coefficients and the higher RMSEs are exhibited in locations closer to land (Lesvos, Santorini and Pylos). Moreover, ERA-Interim overestimates wave height in the South Aegean, Lesvos and Skyros. ERA-Interim underestimates the 90% wind speed values for all locations. The lowest correlation coefficient (0.32) is exhibited in Pylos. Generally, the ERA-Interim underestimate by 8-15% (depending on location and parameter) the upper quartiles compared to the buoys' measurements.

Differences are evident in wave and wind directionality amongst the two datasets, especially in terms of the most frequent directions and high values, but overall agree in land blocking for specific directions. The monthly variations in the case of the North Aegean show that the buoy values are higher than those of ERA-Interim for both wave height and wind speed, especially when the distance from shore increases. For the South Aegean, ERA-Interim data are higher than the buoy data with no relevance to the proximity to the shore and especially during the summer months.

The previous studies that have evaluated ERA-40 and NCEP datasets show lower correlation coefficients and higher RMSEs for 4 locations of the Greek Seas for wind speed, thus, suggesting that ERA-Interim are better. However, as similar studies for the description amongst datasets for significant wave height are based on hydrodynamic models with inputs of wind reanalysis data, a similar conclusion cannot be drawn for the Greek Seas. The variety of the locations and the differences of the global studies can be attributed to different characteristics (weather patterns, such as Monsoons for the Indian Ocean, high frequency of hurricanes at the Atlantic, offshore circulation, proximity to the shore) and model - reanalysis setups.

Overall, the observational and the reanalysis data for wind and wave present fair to good correlations for the Greek Seas. However, it has to be mentioned that although ERA-Interim reanalysis dataset includes real time data, their assimilation process is based on numerical and physical modelling schemes that can raise uncertainties on their outputs. Moreover, attention should be paid for more localised analyses due to the complexity of the Greek coastline and the presence of the islands.

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