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Multiple year characterization of the wave field in the Gulf of Naples by multi-platform measurements

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***Abstract* – Surface gravity waves retrieved by a network of HF radars and an *in situ* wave measurement were used to carry out a multiple year characterization of the wave field of the Gulf of Naples. The patterns of the wave fields were in agreement with the wave climatology of the Tyrrhenian Sea.**
The results highlighted seasonal and interannual consistency in the wave characteristics for a given site, and support the potential of these systems as long-term observatories.

I. INTRODUCTION

The monitoring of the wave field over several years is a fundamental prerequisite for the knowledge and definition of the wave climate of a given basin. Wave climatology has direct consequences on the design of offshore and coastal structures and their management, as well as renewable energy assessment [1]. Wave climate is defined as the distribution of wave height, period and direction averaged over a period of time for a given site [2, 3]. While for the open sea the wave climate can be assumed as invariant, it might be profoundly modified in coastal areas [3].

The correct assessment of wave climatology is strongly dependent on the number of years included in the analysis [3]. A data set spanning a period of almost 10 years obtained from a combination of in situ measurements and remote acquisition through HF radars is here used to construct a climatology of wave conditions in the coastal area of the Gulf of Naples (GoN, Tyrrhenian Sea, Western Mediterranean Sea). Wave historical data in the GoN [4, 5, 6, 7] and a recent study [8] showed a marked seasonality of the wave climate related to the meteorological features of the study area.

In winter and autumn, numerous low-pressure systems pass over the basin, with frequent stormy and windy events, often resulting in severe sea state. By contrast, in spring and summer the set up and reinforcement of the Azore anticyclone determines the onset of moderate breeze systems [9, 10, 11, 12, 13]. These determined a stable and persistent high-pressure field, with lower wave heights. The data presented in this contribution highlight recurrent patterns, depicting seasonal-specific dynamics in different sub-areas of the GoN. In addition, they emphasize the possibility of resorting to an integrated, multi-platform approach to build a robust observation system, retrieving real-time data for the proper management and monitoring of coastal areas.

II. MATERIAL AND METHODS

The HF radar network installed in the GoN, operated by the Department of Science and Technology at the 'Parthenope' University of Naples, is a system composed of three SeaSonde 25 MHz transreceiving stations (CODAR Ocean Sensors, Mountain View, California, USA) located in Portici (PORT), Castellammare di Stabia (CAST) and Massa Lubrense (SORR) (Fig.1). In SeaSonde systems, information on wave parameters (significant wave height Hs_{HF}, centroid period T_{HF} and direction θ_{HF}) are extracted from the second-order spectrum by applying a Pierson–Moskowitz model [13]. The wave characteristics are measured along equally spaced (1 km), circular annuli (range cells, RCs) centred on the antenna. For each RC, a single spatially averaged value for each wave parameter is then provided. In the GoN system, single spectra were recorded and averaged every 10 min over 12 RCs for PORT and SORR sites, and over 15 RCs for CAST with CODAR proprietary software (Seasonde Radial Suite R7u2). Based on previous analysis [8] we focused on data retrieved from a range cell representative of the annulus located between 5 and 6 km from the coast (RC5) (red semi-circles, Fig. 1).

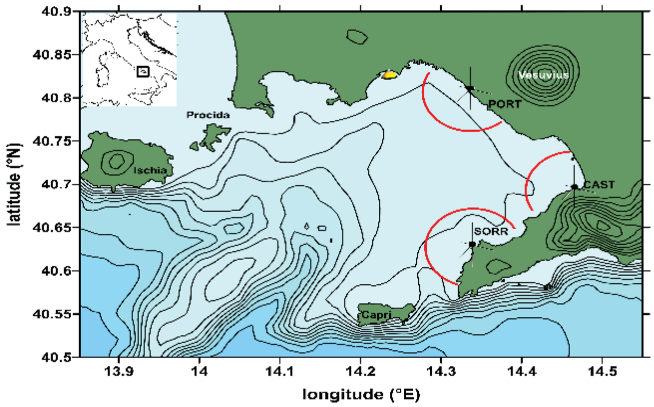

Fig. 1 - HF network in the Gulf of Naples (red semi-circles indicates RC5) and MEDA B buoy position (yellow point).

In the present work, wave data collected from all three sites over the period between May 2008 and December 2012 have been used.

MEDA B buoy managed by Stazione Zoolgica Anton Dohrn is located near the coast of Naples (latitude: 40°49.669'N, longitude:014°13.984' E) over a depth of 17.5 m (Fig.1). MEDA B has been operating since November 2015, the buoy is equipped with a directional wave data sensor and collects information on: wave height (HsB); period (TB) and direction (ϴB). Data are outputted at 1 hour intervals.

The climatology study was primarily performed through the joint frequency distribution. The number of occurrences (frequency) can be easily calculated for each class by dividing the number of events falling within the considered class and the total number of data. Wave height measurements have been divided into eight classes, while each direction sector covers an angle of 15 deg.The statistics taken into account is the joint frequency distribution of significant Hs with respect to direction.

III. RESULT AND DISCUSSION

In Fig.2 the time series of significant wave height of HF stations and MEDA B is shown.

As expected, PORT and CAST recorded HsHF values lower than the concomitant ones by SORR site, which is closer to the open Tyrrhenian waters. SORR presented the most complete radar-derived dataset (with minimal gaps).

Although the datasets covered different years of acquisition, an agreement among the observations can be noticed in term of Hs pattern between PORT and MEDA B, both representative of the internal part of the basin. In table1 the min, max and mean value of the datasets are reported.

The difference in the mean value is due to HF radar low sea-state limitations [8]. It is evident from Fig. 2 that, as soon as HsB went below the 0.5 m threshold, the HF radars could not detect waves efficiently.

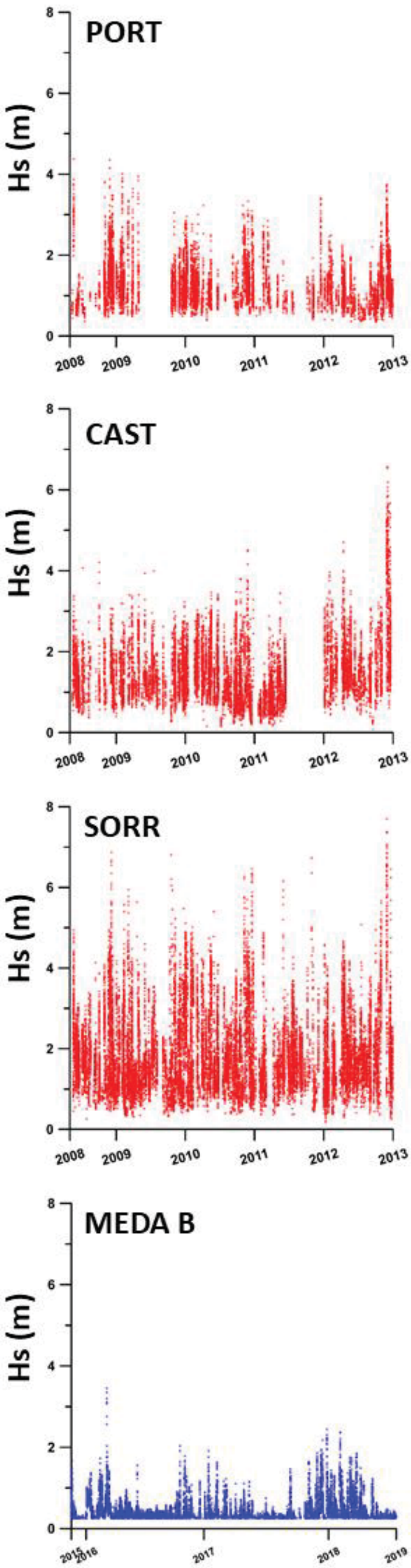

Fig. 2 – HF time series (red) and MEDA B time series (blue)

Table 1. Hs metrics

Hs (m)	PORT (2008-2012)	CAST (2008-2012)	SORR (2008-2012)	MEDA B (2015-2018)
min	0.35	0.35	0.38	0.25
max	4.37	6.56	7.6	3.45
mean	1.30	1.49	1.89	0.52

The information shown in the polar diagrams (Fig.3) enables immediate visual identification of the most frequent wave direction and the directional distribution of the sea state with the most frequent wave heights. The site-specific feature of wave direction depends upon the local bathymetry and orography, and indicates that the wave field presents spatially variable characteristics. The sector of wave provenance was constant over the year for each individual HF station due to the geomorphological configuration of GoN.

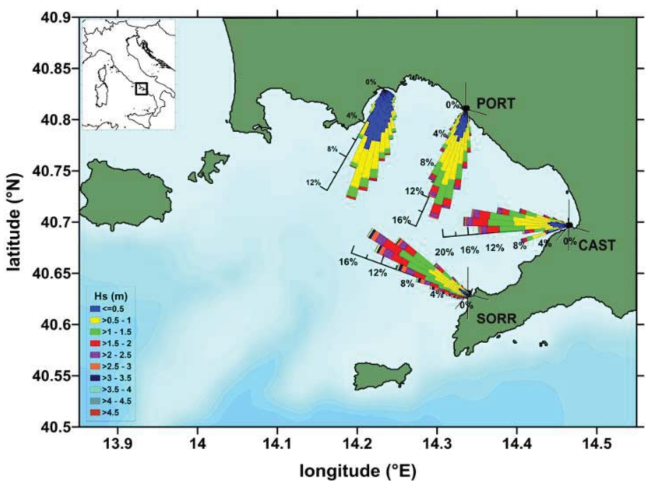

Fig. 3. Wave rose diagramm.

All the HF radars acquisitions had typically unimodal annual directional climates. As expected, wave height at PORT and CAST were less than those recorded at SORR station, due to the modification occurring during the propagation in the area.

The SORR station showed a marked directionality from north –west and an absence of wave from south- west. This is due to the presence of Capri island which creates a shadow zone shielding the sector.

In autumn and winter stronger winds resulted in higher wave events with dominant wave direction between 180° and 210° for PORT, 265° and 275° for CAST and 270° and 300° for SORR.

The acquisition patterns characterized by high waves mainly originating from the west are in agreement with those described in [15] for the Tyrrhenian Sea, owing to its particular geomorphological and meteorological characteristics.

The same analysis was conducted on the MEDA B dataset. The MEDA B data showed a marked directionality from South – West and an absence of wave from North as expected, due to morphology of the GoN.

The joint frequency distributions for MEDA buoy (Fig.4) and HF sites (Fig.5, Fig.6, Fig.7) confirm that Hs value are strongly dependent on the site of acquisition. It is worth underlining that PORT and MEDA joint distributions show coherent patterns, evidencing convergence of the results. The percentage of captured data below 1 m of Hs is low for all HF sites, due to instrumental intrinsic limitations. Such issue does not have effect on supporting the use of HF radars in coastal engineering and renewable energy studies from waves, where Wave Energy Converters have usually maximum efficiency in the ranges of significant wave heights greater than 2 m [16].

Wave Direction deg N \ Significant Wave Height (m)	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	
	18210	2613	587	129	22	2	6	0	0	0	0	0	0	0	0	0	21569
360	218	11	1	-	-	-	-	-	-	-	-	-	-	-	-	-	230
345	238	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	253
330	225	13	1	-	-	-	-	-	-	-	-	-	-	-	-	-	239
315	193	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	196
300	203	2	-	1	-	-	-	-	-	-	-	-	-	-	-	-	206
285	214	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	218
270	289	11	1	-	-	-	-	-	-	-	-	-	-	-	-	-	301
255	623	20	8	1	-	-	-	-	-	-	-	-	-	-	-	-	652
240	954	41	9	1	1	1	-	-	-	-	-	-	-	-	-	-	1007
225	1200	53	13	-	-	-	3	-	-	-	-	-	-	-	-	-	1269
210	1740	139	40	3	-	1	-	-	-	-	-	-	-	-	-	-	1923
195	2420	395	94	27	3	-	3	-	-	-	-	-	-	-	-	-	2942
180	3040	794	209	60	13	-	-	-	-	-	-	-	-	-	-	-	4116
165	2878	843	172	33	4	-	-	-	-	-	-	-	-	-	-	-	3930
150	1282	157	22	1	1	-	-	-	-	-	-	-	-	-	-	-	1463
135	550	31	2	-	-	-	-	-	-	-	-	-	-	-	-	-	583
120	387	21	1	-	-	-	-	-	-	-	-	-	-	-	-	-	409
105	289	9	2	-	-	-	-	-	-	-	-	-	-	-	-	-	300
90	252	4	2	-	-	-	-	-	-	-	-	-	-	-	-	-	258
75	157	12	3	2	-	-	-	-	-	-	-	-	-	-	-	-	174
60	189	10	1	-	-	-	-	-	-	-	-	-	-	-	-	-	200
45	269	10	2	-	-	-	-	-	-	-	-	-	-	-	-	-	281
30	196	8	1	-	-	-	-	-	-	-	-	-	-	-	-	-	205
15	204	7	3	-	-	-	-	-	-	-	-	-	-	-	-	-	214

Fig. 4 - Joint frequency distribution MEDA B

IV. CONCLUSIONS

Surface gravity wave data retrieved by HF radar measurements covering a 4-year period, from May 2008 to March 2012, and *in situ* measurements of MEDA B buoy from November 2015 until August 2018 have been employed to describe and analyze the wave field of the GoN.

The multi-platform acquisition has typically unimodal annual directional climates, characterized by high waves mainly originating from the west in line with the climatology of Tyrrhenian Sea.

Wave Direction deg N	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	
	78	2907	3739	1538	617	275	90	29	4	0	0	0	0	0	0	0	9277
360	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
345	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
330	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
315	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
285	-	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	2
270	1	27	31	5	6	1	2	-	-	-	-	-	-	-	-	-	73
255	1	126	94	25	16	9	14	1	-	-	-	-	-	-	-	-	286
240	6	258	187	40	22	13	5	1	-	-	-	-	-	-	-	-	532
225	22	522	538	134	45	35	9	8	1	-	-	-	-	-	-	-	1314
210	26	992	1347	604	236	108	37	10	2	-	-	-	-	-	-	-	3362
195	16	746	1164	536	221	84	13	5	-	-	-	-	-	-	-	-	2785
180	6	225	368	188	69	24	10	4	1	-	-	-	-	-	-	-	895
165	-	10	9	6	2	1	-	-	-	-	-	-	-	-	-	-	28
150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
135	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
105	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

Significant Wave Height (m)

Fig. 5 - Joint frequency distribution PORT site

Wave Direction deg N	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	
	365	2878	3880	2623	1405	639	174	75	62	42	32	12	2	2	0	0	12191
360	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
345	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
330	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
315	17	135	98	54	89	23	9	3	-	-	-	-	-	-	-	-	428
300	71	526	650	368	213	93	19	18	2	-	-	-	-	-	-	-	1960
285	66	1120	1882	1281	657	290	79	16	16	13	8	7	-	2	-	-	5437
270	52	615	979	804	387	195	63	29	38	28	22	4	2	-	-	-	3218
255	159	482	271	116	59	38	4	9	6	1	2	1	-	-	-	-	1148
240	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
225	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
210	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
195	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
165	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
135	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
105	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

Significant Wave Height (m)

Fig. 6 - Joint frequency distribution CAST site

Wave Direction deg N	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	
	158	2531	5488	4568	2795	1795	1364	755	437	167	56	31	28	16	4	0	20193
360	5	34	49	38	13	3	6	1	1	1	-	-	-	-	-	-	151
345	6	121	167	84	45	15	12	2	-	-	-	1	1	-	-	-	454
330	15	329	449	247	141	71	46	29	10	5	1	0	0	-	-	-	1343
315	55	921	2224	1867	952	509	260	109	67	18	4	6	6	2	-	-	7000
300	45	609	1729	1699	1038	617	376	206	104	35	6	7	3	6	-	-	6480
285	7	239	476	421	374	330	331	178	105	50	20	9	7	5	2	-	2554
270	4	89	161	123	162	177	227	159	92	29	19	3	9	3	2	-	1259
255	3	66	94	63	46	59	92	58	46	25	5	5	2	-	-	-	564
240	3	62	93	19	14	13	13	11	11	3	1	-	-	-	-	-	243
225	7	22	22	4	3	-	1	-	1	1	-	-	-	-	-	-	61
210	6	32	19	1	4	1	-	2	-	-	-	-	-	-	-	-	65
195	2	6	5	2	2	-	-	-	-	-	-	-	-	-	-	-	17
180	-	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-	2
165	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
135	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
105	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

Significant Wave Height (m)

Fig. 7 - Joint frequency distribution SORR site

The approach used in the present paper represents, to the best of present knowledge, the first use of HF radars combined with buoy measurements to reconstruct the wave climatology (at least partially, owing to the limitation in the number of years of recording) of a coastal basin. The results demonstrate the ability of an integrated system to provide a detailed view of surface wave dynamics over a decade, and spur to further integrations and implementations of current ocean observatories.

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