The WaveGlider Mission in Portugal

Assessment of the WaveGlider technology for sea conditions long term monitoring applied to energy resource evaluation.

Report for the Turnkey Project (Atlantic area Interreg project Contract Number: 2013-1/279)

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Introduction

During the months of April and June 2015, a Wave Glider SV2, an autonomous vehicle equipped with several sensors, was launched in the vicinity of Nazaré, a coastal town in centre of Portugal. The mission included the measurements of currents, waves and atmospheric parameters in several areas interesting for the exploration of marine renewable energies. As part of this mission, the vehicle performed twice the path described by the satellite Saral/AltiKa near the coast of Nazaré in order to evaluate the accuracy of the altimetry observations compared with the *in situ* collected data. The data observed by the satellite and the autonomous vehicle were also compared with waves simulated with operational models. Other parameters observed by the autonomous vehicle as meteorology, ocean currents and water temperature were also compared with operational models already implemented for the area.

In this report, the use of remotely operated vehicles equipped with instruments to observe the sea conditions would be described and evaluated for their adequateness to aid in the evaluation of the marine renewables resources.

Study area

The area covered by the mission corresponds to the central coast of the Portuguese Coast and was selected due to its suitability for the implementation of Marine Renewable Energies. The area covered by the WaveGlider was limited in the North by the Pilot Zone for the development of Marine Energies and in the South by the Peniche Peninsula and the channel that links to the Berlengas Islands and in the West by the longitude 9.50W in order to avoid interferences with the marine traffic. In the centre of the study area is located the Nazaré canyon, with is an undersea canyon with maximum depths of 4500 m and about 230 km long. The canyon reaches the coastal town of Nazaré crossing the continental platform in east-west direction playing a major role in the hydrodynamics of this coastal area.

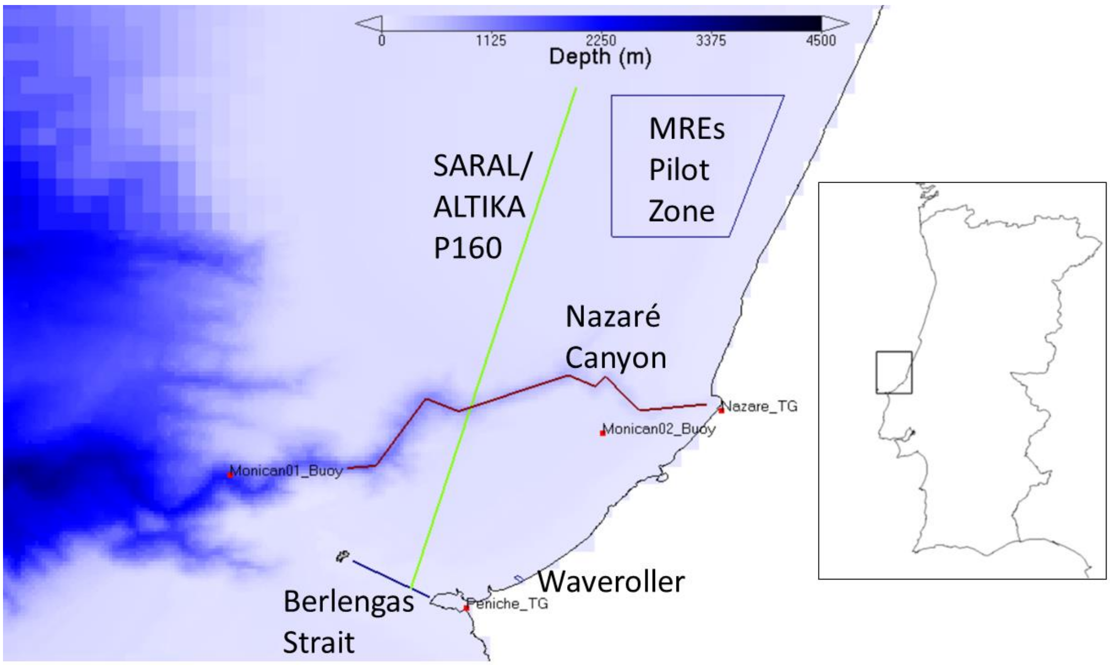


Figure 1 Bathymetry and location of the main objectives covered by the WaveGlider mission in Portugal and the current observing buoys (Monican01 and Monican02) and tidal gauges (Nazare_TG and Peniche_TG).

The WaveGlider would monitor the area comprised the municipalities of Peniche (Latitude 39.21N) and Marinha Grande (39.55N). Within this area, 5 are the objectives to be covered (Figure 1):

- The wave energy production area near Peniche (Waveroller);
- The Pilot Zone for the development of Marine Renewable Energy (MREs Pilot Zone);
- The Nazaré Canyon;
- The Strait between the Peniche Peninsula and the Berlengas Archipelago (Berlengas Strait);
- The observations performed by the SARAL/ AltiKa satellite along the pass 160.

Material and methods

In order to evaluate the quality of the data collected by the WaveGlider, the obtained data will be compared with operational observed data as the data collected by the Monican02 Buoy and the Saral/AltiKa satellite and the operational numerical models implemented in the study area.

Wave Glider SV2 "Hermes" and its Portuguese Mission

A WaveGlider SV2 named "Hermes" was deployed in the Portuguese coast for the period between the 28th of March and the 7th of June 2015. The wave glider is an unmanned autonomous marine robot that is propelled by the waves and can be used as a platform for several instruments. The "Hermes" WaveGlider was equipped during its mission in Portugal with the following instruments:

- Atmospheric station: Airmar 200WX;
- ADCP sensor (hydroacustic current meter): WorkHorse Monitor 300 kHz from Teledyne RD Instruments;
- Wave sensor (wave motion): MOSE-G Datawell;
- CTD (Temperature and conductivity): GPCTD from Sea-Bird Electronics;
- Telemetry: Iridium SBD for navigation and compressed data and Iridium RUDICS for the ADCP only;
- Photo camera to record bird populations;
- Passive Acoustic Monitoring (PAM) from St Andrews Instrumentation Limited.

Some instruments did not work as expected, the photo camera did not record any pictures for electronic reasons and the PAM system had to be removed due to technical problems that were unsolved. Due to the later, the Hermes had to be recovered the 5th of April, one week after the initial deployment in Nazaré the 28th of March (Picture 1 and Picture 2). After removing the PAM system, the WaveGlider was re-launched the 23rd of April 2015.

As the economist named Liquid Robotics, the WaveGlider developer, as Top Innovator for the Ocean Innovation Challenge (http://liquidr.com/company/news/pr/2015/05june2015.html) during the World Ocean Summit 2015 (http://www.economistinsights.com/sustainability-resources/event/world-ocean-summit-2015), the TURNKEY project benefited of an extended free period through negotiations with Liquid Robotics, the device owner, being finally recovered the 7th of June 2015 (Picture 3).

During that period, the WaveGlider was able to observe twice the SARAL/ AltiKa path and to visit the areas defined as priority in the monitoring plan (Figure 2).

The deployment required many meetings with the local and national authorities and to find local companies to support the deployments, monitoring, surveillance and recoveries of the equipment.

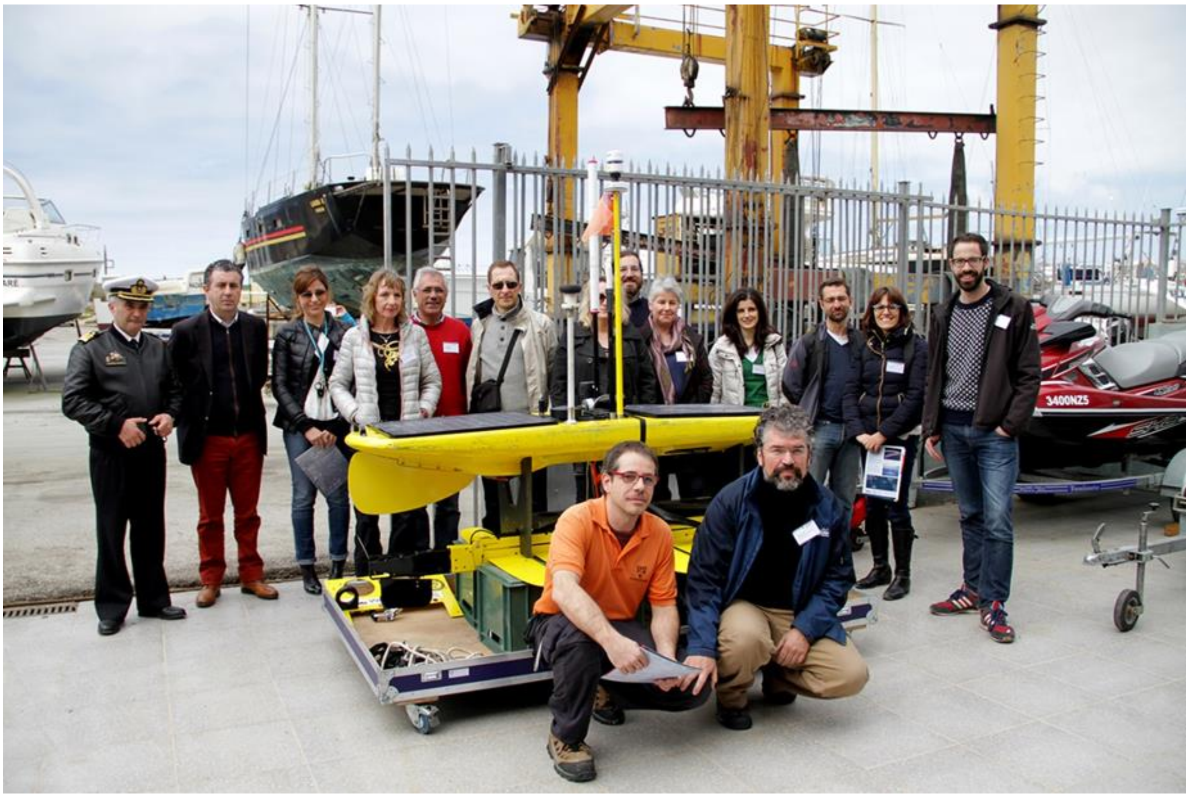
Prior to the launch of the WaveGlider it was necessary the authorisation of the Captain of the Port of Nazaré, positon held by Commander Lourenço Gorricha during the WaveGlider Mission. The WaveGlider was the first device authorised to enter the MREs Pilot Zone. That part of the mission required of the authorisation from ENONDAS (http://oceanplug.pt/), the legal stakeholder of the administrative concession, in addition to other national bodies as: the Portuguese Environmental Agency (APA by its Portuguese acronym), the General Direction of Energy and Geology (DGEG by its Portuguese acronym) and the General Direction of Natural Resources, Security and Maritime Services (DGRM by its Portuguese acronym).

Two open sessions were organised in the area of the deployment to inform the local communities in 27-28 March 2015 at Nazaré and 29 May 2015 at Peniche that generated a considerable impact of the project in the local, national and international media (Annex I).

The deployment required many meetings with the local and national authorities and to find local companies to support the deployments, monitoring, surveillance and recoveries of the equipment. In addition, two open sessions were organised in the area of the deployment to inform the local communities:

- 27-28 March 2015, Nazaré:
    - 27 March 2015: presentation of the WaveGlider Mission
    - 28 March 2015: presentation of the device in the port and launching
- 29 May 2015, Peniche
    - Presentations related to the activities performed during the Wave Glider mission and presentations with a Wave Glider replica and representatives from marine renewable devices and the developers of the Wave Glider, the US company Liquid Robotics.

The technical work for the installation and configuration of the WaveGlider was carried out by the company EMS - Sistemas de Monitorización Medio Ambiental S.L.U. (http://www.ems-sistemas.com/). The local company Atlantic Safaris (http://www.atlanticsafaris.com/) provided their facilities and their team and equipment for the deployment, recovering and monitoring the status of de vehicle in a weekly-fortnightly basis, from the sea and also from land.



Picture 1 The WaveGlider SV2 Hermes presentation in the port of Nazaré the day prior to its deployment. Along with the Turnkey project members are the Nazaré port (first on the left) and municipality authorities (second in the left) and the technicians from EMS-Sistemas (front) (Credits: Vítor Estrelinha/Câmara Municipal de Nazaré).

Picture 2 The WaveGlider SV2 Hermes during its deployment in the coast of Nazaré the 28th of March 2015. (Credits: Vítor Estrelinha/Câmara Municipal de Nazaré).

Picture 3 The WaveGlider SV2 Hermes after its final recovery with covered with fouling organism. (Credits: Atlantic Safaris).

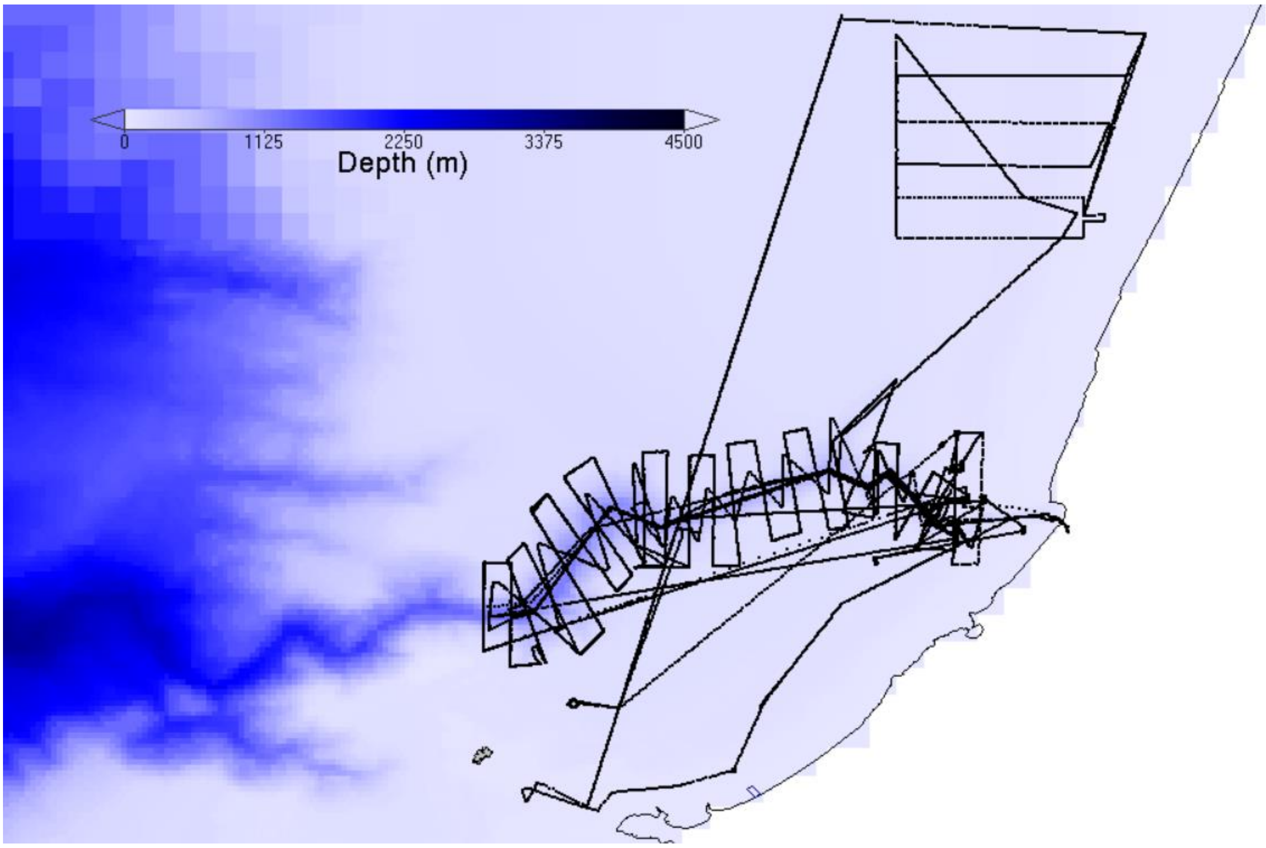


Figure 2 Monitored paths during the WaveGlider mission in Portugal.

Monican02 Buoy

The Monican02 Buoy is Wavescan buoy located at coordinates (9.21E, 39.56N) and part of the MONICAN observing system operated by the Instituto Hidrográfico (IH). This system is composed by two Wavescan buoys, wave directional buoys, measuring meteorology, wave and environmental parameters.

Those buoys are coupled with a set of thermistors for collecting temperature data at different layers and one has an Acoustic Doppler current profiler. The land part of the station consists of a telemetric system and a computer for data reception.

These buoys are equipped with the following sensors:

- Wavesense 3 (Fugro Oceanor, integrated wave sensor and data logger);
- Wind speed and direction (Young);
- Air pressure (Vaisala);
- Air temperature (Vaisala);
- Relative humidity ((Vaisala);
- Oil spil (Nereides Oil Spy);
- Oxygen (Royce);
- Chlorophyll-a (Chelsea MiniTracka II).

The mooring includes also other sensors:

- Temperature (Sea Bird, SBE 39-IM);
- Current profiler (RDI WorkHorse Sentinel, 300 KHz).

This monitoring system is complemented with 2 Valeport stations from the National Tide Gauge network responsibility of Instituto Hidrográfico, located at Peniche and Nazaré.

The Monican02 Buoy data is obtained from the CMEMS (Copernicus Marine environment monitoring service) Global Ocean- In-Situ Near-Real-Time Observations product. This product includes the only following properties:

- Significant wave height;
- Average zero crossing wave period;
- Wave direction relative to the true north;
- Atmospheric pressure at sea level;
- Air temperature in dry bulb;
- Horizontal wind speed;
- Wind from direction relative true north;
- Sea temperature.

Those properties will be used to validate the observations collected by the WaveGlider, especially during the period were the device was positioned in the close vicinity to the buoy.

SARAL/ALTIKA satellite passes

SARAL or Satellite with ARgos and ALtiKa is a cooperative altimetry technology mission of Indian Space Research Organisation (ISRO) and CNES (Space Agency of France). The SARAL/AltiKa satellite performs altimetry measurements designed to study ocean circulation and sea surface elevation. The satellite executes a complete cycle every 35 days. During the "Hermes" mission, the satellite completed twice the Pass 160, which crosses the study area, on the 28/04/2015 and 02/06/2015 by different trajectories due to an orbital drift (Figure 3).

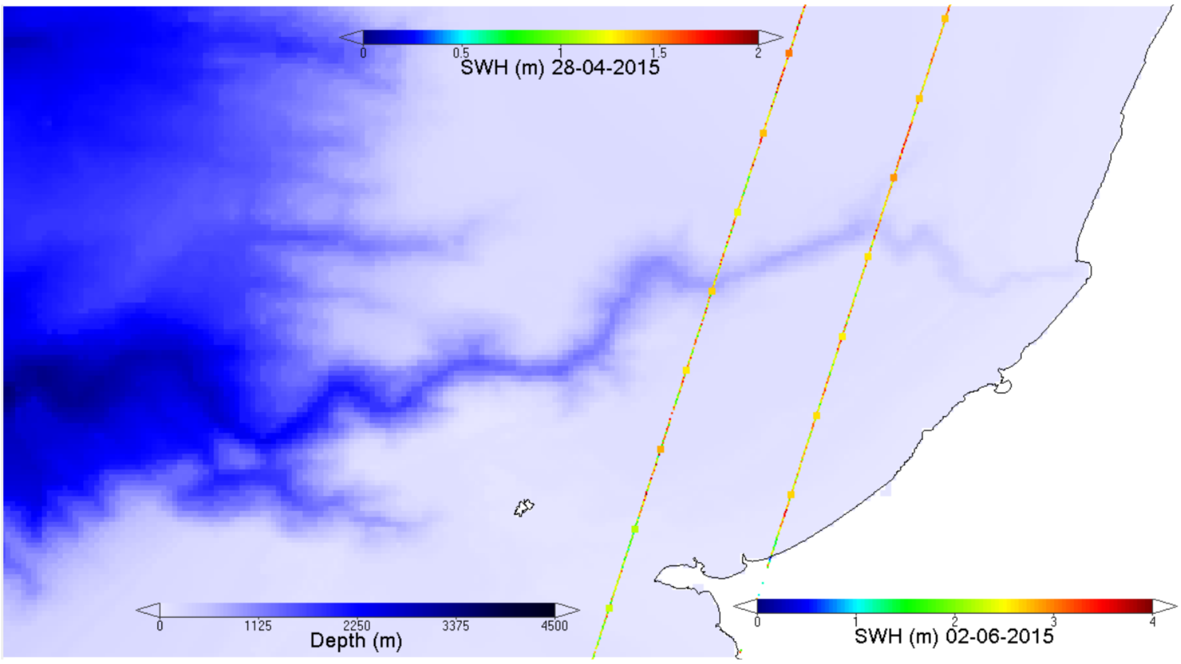


Figure 3 Significant Wave Height (SWH) performed by the SARAL/ALtiKa during the WaveGlider mission in the study area. Due to an orbital drift the path described by the satellite on the 2nd of June 2015 (right path) was different than the one performed by the same satellite on the 28th of April 2015 (left path). The latter correspond to the Pass 160 that should be performed twice.

Numerical Modelling

The meteorological, waves and circulation operational models implemented in the monitored area by the Maretec group of the Instituto Superior Técnico (http://forecast.maretec.org/) would be used to complete the information obtained by the Monican02 buoy, the WaveGlider and the SARAL/ALtiKa and also to validate the consistency of the obtained data during long periods.

Meteorological Model

In order to evaluate atmospheric properties: atmospheric pressure, air temperature and wind intensities and directions were obtained from a meteorological numerical model. Hourly model results were obtained by a MM5 model (Meteorological Model 5; Grell *et al.*, 1994) application based in two nested grids with a horizontal resolution of 27 km and 9 km respectively (Figure 4Figure 1) implemented by the IST meteorological group (http://meteo.ist.utl.pt; Trancoso, 2012).

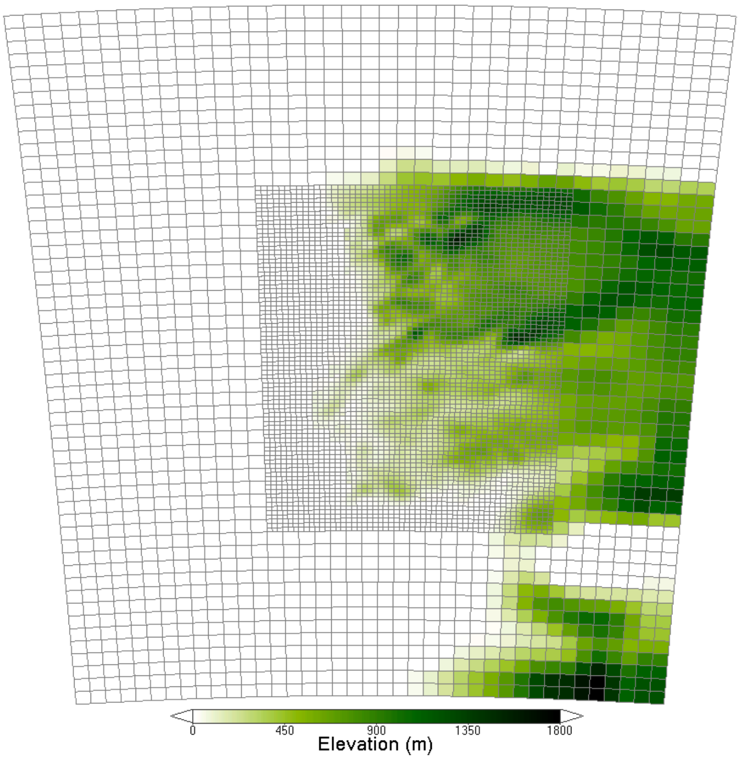


Figure 4 Domains grids for the meteorological model MM5 for the Portuguese mainland application.

Waves Model

In order to model the generation, propagation and dynamics of the waves reaching the Portuguese continental coast it was used the NOAA WAVEWATCH III (R) Model V4.18. This modelling system is an upgrade of the scheme used to create the Wave Energy Atlas for Portugal (Campuzano *et al*, 2015) as part of the EnergyMare project, another Interreg Atlantic project.

In the case of the Portuguese coast, swell waves are generated in the western side of the Atlantic Ocean. To simulate the waves arriving to the Portuguese coast, three nested levels with increasing horizontal resolution -0.5, 0.25 and 0.05 degrees- (Figure 5) covering the North Atlantic Ocean (NAt), the southwest part of Europe (SWE) and the Portuguese Continental Coast (PCC) respectively, were defined. The latter domain results are compared with the significant wave heights measured by the SARAL/AltiKa satellite, Monican02 buoy and the wave glider.

Two bathymetric sources were combined to populate all levels grids: the European Marine Observation and Data Network (EMODnet) Hydrography portal (http://www.emodnet-hydrography.eu) completed by the 30” resolution global bathymetry data SRTM30_PLUS (Becker *et al.*, 2009) for regions where EMODnet data were absent.

The NCEP operational Global Forecast System (GFS) 0.25 Degree Global Forecast (NCEP/NWS/NOAA/U.S. Department of Commerce, 2015) was used to feed the wave model with winds intensities and direction.

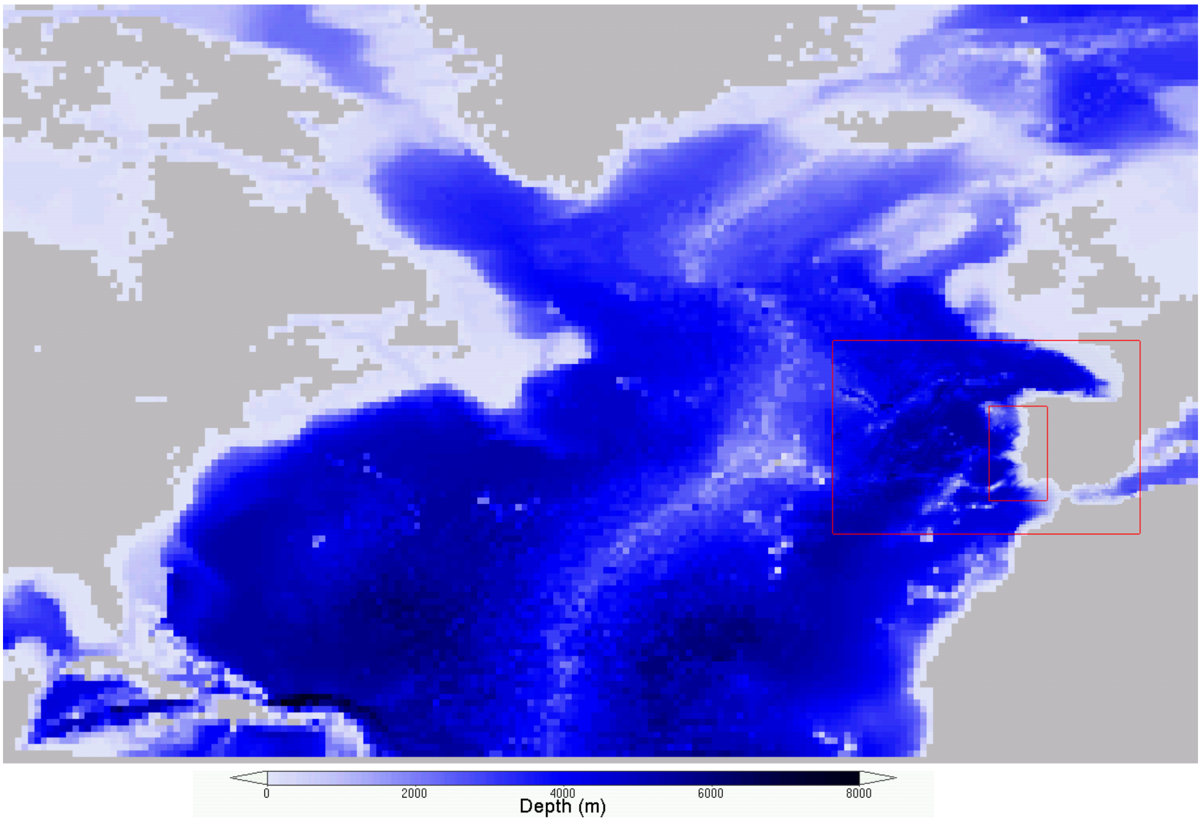


Figure 5 Domains for the waves model WaveWatch III for the Portuguese continental coast application. Nested domains are enclosed by red lines.

MOHID Water Modelling System

The tides, circulation and water properties as temperature for the Nazaré region has been obtained by an operational model application using the MOHID Water which is part of the MOHID Modelling System (http://www.mohid.com; Neves, 2013). The MOHID is an open source numerical model programmed in ANSI FORTRAN 95 using an object orientated philosophy. This system is being developed since 1985 mainly by the MARETEC group at the Instituto Superior Técnico (IST) which is part of the Universidade de Lisboa. The model adopted an object oriented philosophy integrating different scales and processes. The core of the model is a fully 3D hydrodynamic model which is coupled to different modules comprising water quality, atmosphere processes, discharges, oil dispersion, jet mixing zone model for point source discharges.

The Nazaré Canyon operational model is based in the work described in Pando *et al.* (2013) and Ballent *et al.* (2013) and consists of two nested domains, Nazare L1 and Nazare L2, that receive offline boundary conditions from the Portuguese Coast Operational Modelling System (PCOMS; Mateus *et al.*, 2012) (Figure 6) following the methodology described in . The Nazaré L1 covers the central region of Portugal comprised by the range of latitudes (39.02N, 40.08N) and longitudes (8.86W, 10.38W) with a horizontal resolution of 0.02 degrees. Meanwhile, the Nazaré L2 focuses in the Nazaré Canyon with a higher horizontal resolution of 0.004 degrees covering the following range of latitudes (39.30N, 39.80N) and longitudes (9.00W, 10.22W).

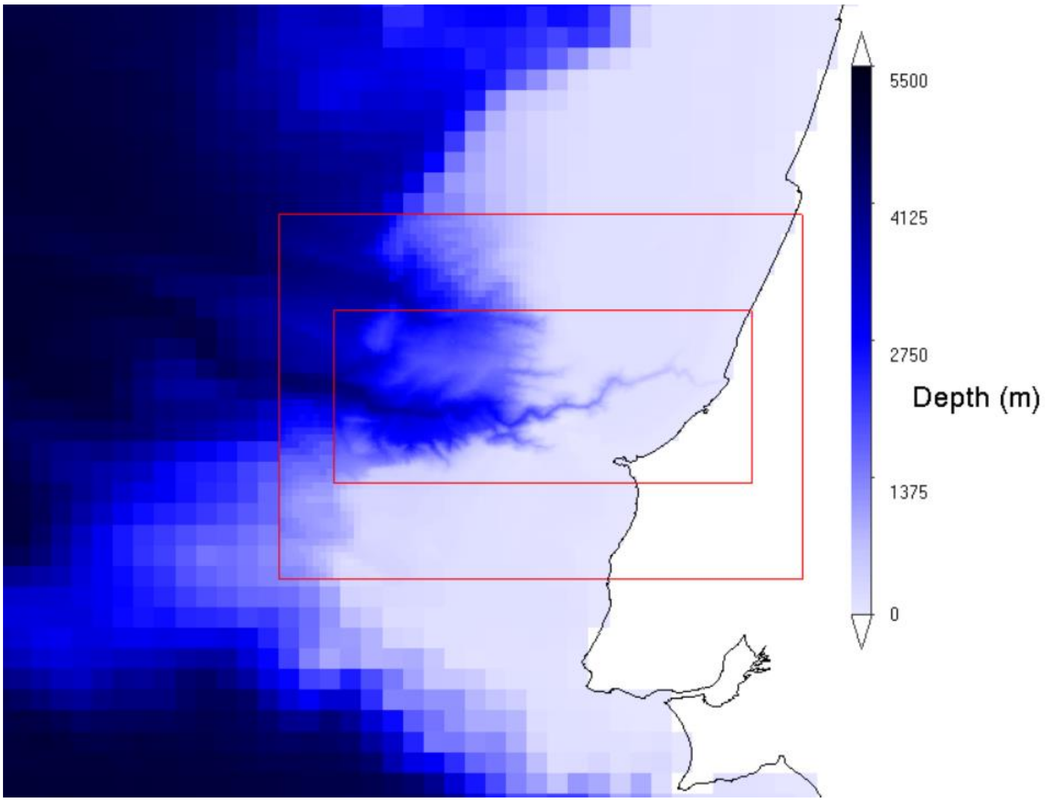


Figure 6 Domains for the circulation application for the Nazaré coast consisting in two nested domains to the PCOMS regional ocean model. Nested domains are enclosed by red lines.

Validation

In this section, the values observed with different technologies: WaveGlider, buoy and satellite will be compared between them and with the numerical models for each variable and grouped in atmospheric, waves and circulation variables.

Atmospheric Parameters

The air temperature, atmospheric pressure and wind intensity and direction would be compared between the WaveGlider Hermes, the Monican02 buoy and the meteorological model MM5 operated by Maretec

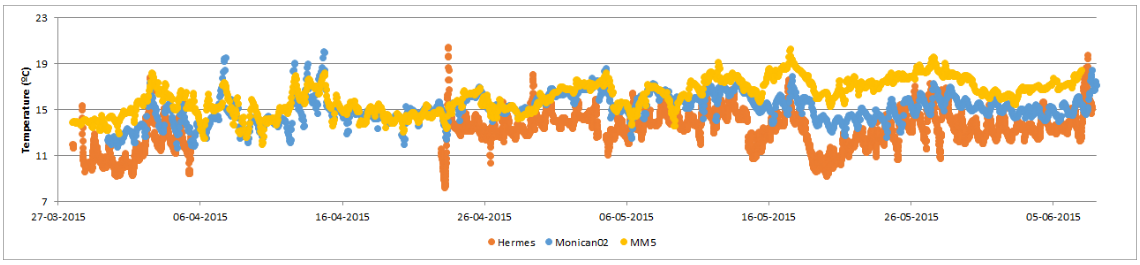


Figure 7 Air temperature for the complete period of the mission observed by the WaveGlider Hermes, the Monican02 buoy and the MM5 model.

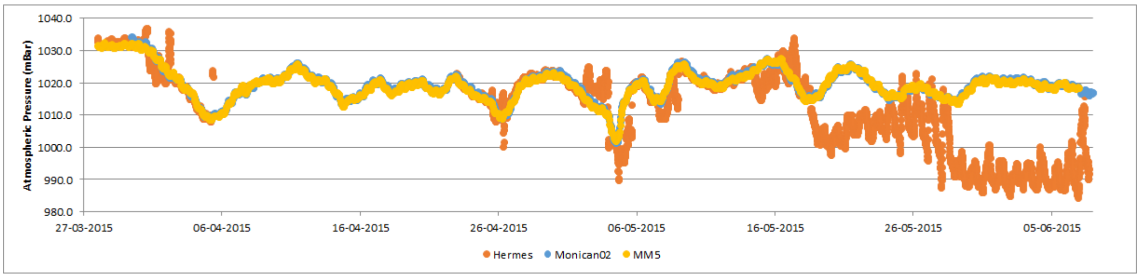


Figure 8 Atmospheric pressure for the complete period of the mission observed by the WaveGlider Hermes, the Monican02 buoy and the MM5 model.

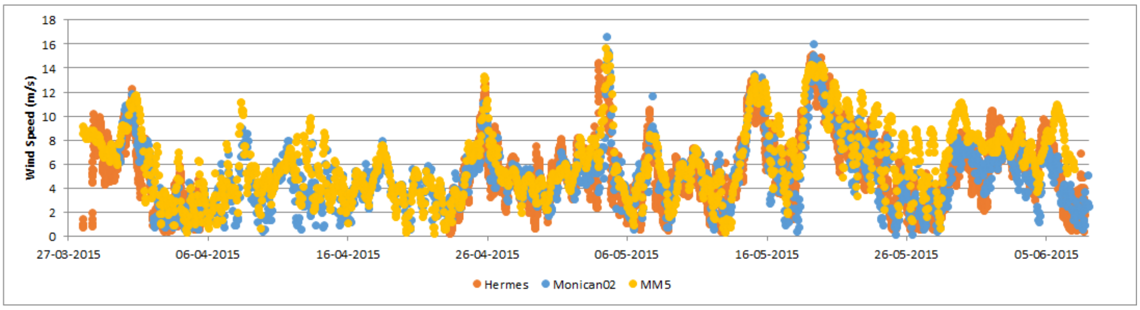


Figure 9 Wind speed for the complete period of the mission observed by the WaveGlider Hermes, the Monican02 buoy and the MM5 model.

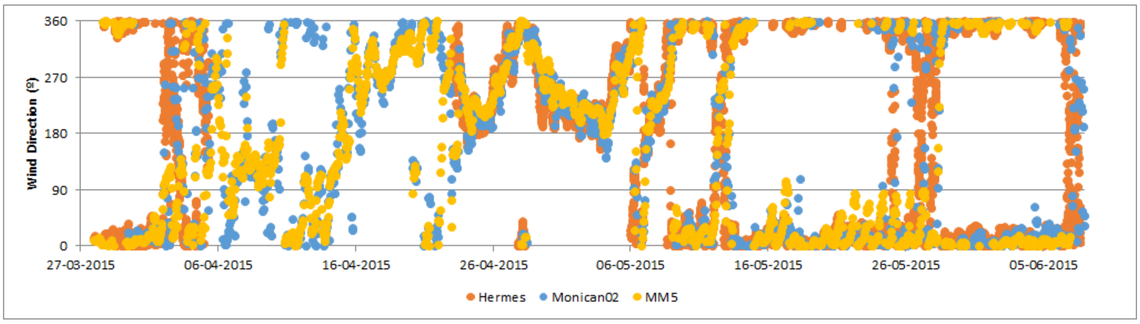


Figure 10 Wind direction for the complete period of the mission observed by the WaveGlider Hermes, the Monican02 buoy and the MM5 model.

Table I Average Atmospheric properties for the period 24-04-2015 0h to 06-06-2015 23h

Average	Air Temperature	Atm Pressure	Wind Modulus	Wind U	Wind V
Monican02	15.47	1019.09	5.64	0.45	-2.92
Hermes WG	13.54	1017.93*	5.76	0.13	-3.11
MM5	16.89	1018.81	6.92	0.71	-3.88

Table II Standard deviation of the atmospheric properties for the period 24-04-2015 0h to 06-06-2015 23h

St Dev	Air Temperature	Atm Pressure	Wind Modulus	Wind U	Wind V
Monican02	0.97	4.00	2.89	2.44	4.95
Hermes WG	1.29	5.85*	2.90	2.46	5.09
MM5	1.12	4.01	2.98	3.08	5.46

Table III Statistic parameters for the different sources of air temperature for the period 24-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Hermes WG vs Monican02	-1.92	5.24	0.28	
Monican02 vs MM5	-1.43	3.67	0.07	
Hermes WG vs MM5	-3.33	13.49	0.04	

Table IV Statistic parameters for the different sources of atmospheric pressure for the period 24-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Hermes WG vs Monican02	-1.13	20.049	0.47	
Monican02 vs MM5	0.28	0.47	0.98	
Hermes WG vs MM5	-0.63	19.8941	0.45	

Table V Statistic parameters for the different sources of wind intensity for the period 24-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Hermes WG vs Monican02	0.15	4.03	0.58	
Monican02 vs MM5	-1.30	5.21	0.64	
Hermes WG vs MM5	-1.11	7.11	0.44	

Table VI Statistic parameters for the different sources of wind component U for the period 24-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Hermes WG vs Monican02	-0.34	3.48	0.52	
Monican02 vs MM5	-0.23	2.82	0.70	
Hermes WG vs MM5	-4.74	41.06	0.53	

Table VII Statistic parameters for the different sources of wind component V for the period 24-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Hermes WG vs Monican02	-0.08	5.16	0.90	
Monican02 vs MM5	0.97	5.17	0.59	
Hermes WG vs MM5	-3.25	27.29	0.61	

Waves

Significant wave height obtained from the “Hermes” WaveGlider was compared with the fixed buoy “Monican02” and a timeseries from the WaveWatch III model extracted for that same location.

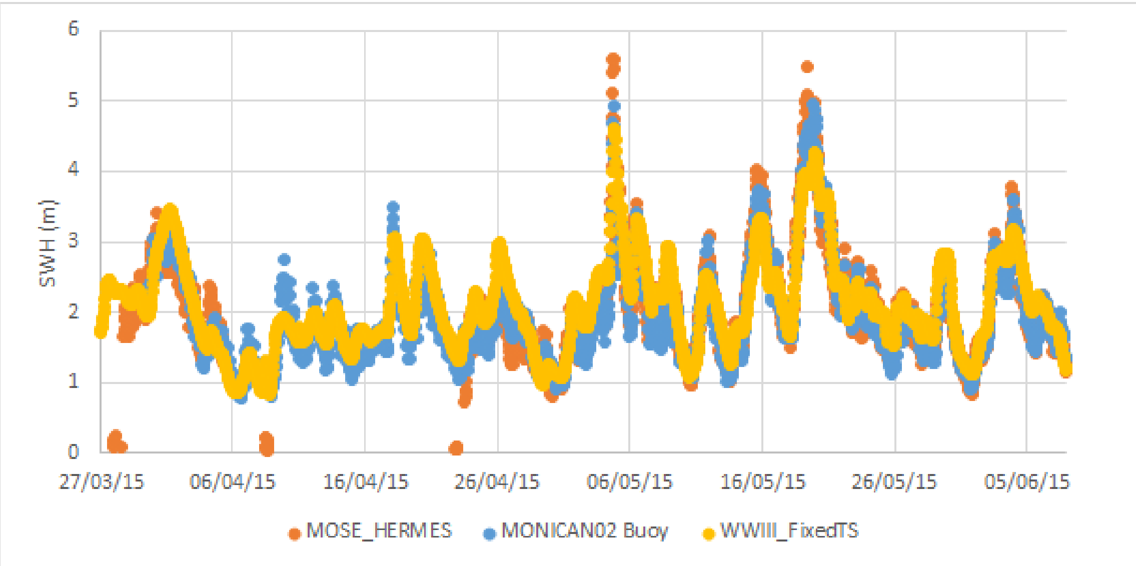


Figure 11 Significant wave height (m) for the complete period of the mission observed by the WaveGlider Hermes, the Monican02 buoy and the WaveWatch III model.

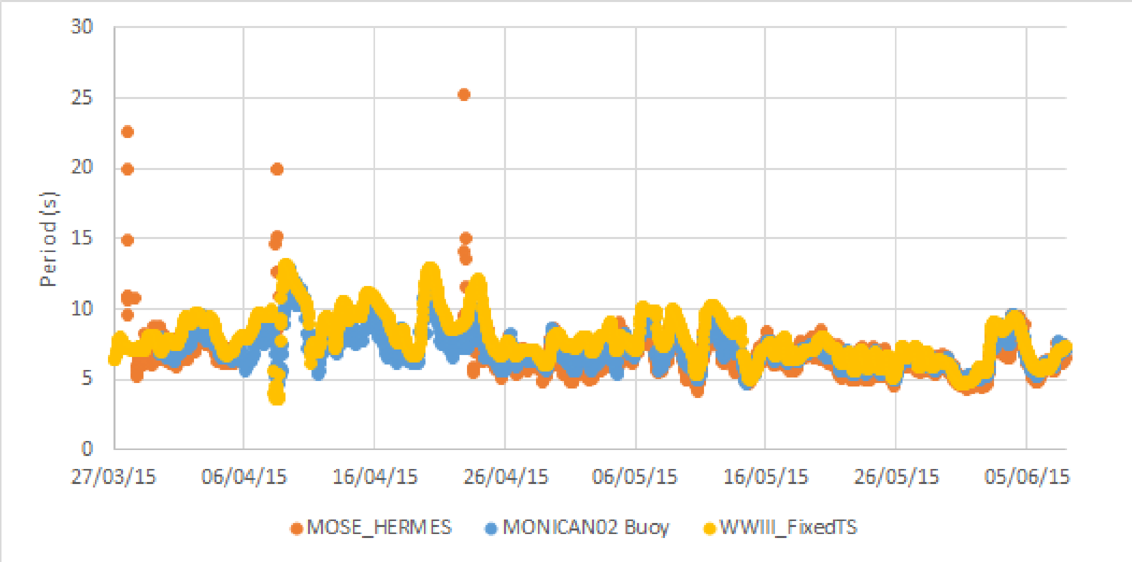


Figure 12 Average wave period (s) for the complete period of the mission observed by the WaveGlider Hermes, the Monican02 buoy and the WaveWatch III model.

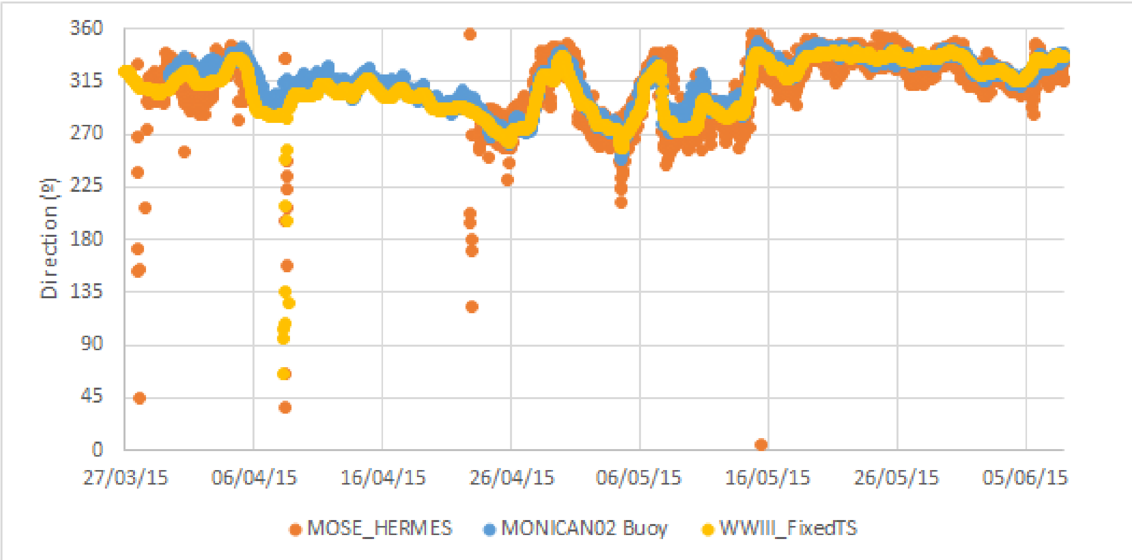


Figure 13 Average wave direction (s) for the complete period of the mission observed by the WaveGlider Hermes, the Monican02 buoy and the WaveWatch III model.

Table VIII Average wave properties for the period 26-04-2015 0h to 06-06-2015 23h

Data Source	SWH	Period	Direction
Monican02	2.063	6.721	316.941
Hermes WG	2.099	6.502	313.177
Portugal WWIII_FixedSt	2.023	7.227	314.331
Portugal WWIII_MovingTS	2.025	7.194	314.857

Table IX Statistic parameters for the different sources of significant wave height for the period 26-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Monican02 Buoy Vs Hermes WG	0.037	0.253	0.900	0.891
Monican02 Vs WWIII_FixedSt	0.168	0.341	0.850	0.802
Hermes WG Vs WWIII_MovingTS	0.162	0.375	0.817	0.773
Hermes WG Vs WWIII_FixedSt	0.132	0.354	0.827	0.799

Table X Statistic parameters for the different sources of wave period for the period 26-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Monican02 Buoy Vs Hermes WG	-0.219	0.574	0.758	0.695
Monican02 Vs WWIII_FixedSt	0.505	0.800	0.775	0.408
Hermes WG Vs WWIII_MovingTS	0.690	1.068	0.624	-0.020
Hermes WG Vs WWIII_FixedSt	0.719	1.061	0.637	-0.007

Table XI Statistic parameters for the different sources of wave direction for the period 26-04-2015 0h to 06-06-2015 23h

Data Source	Bias	RMSE	R^2	Efficiency
Monican02 Buoy Vs Hermes WG	-3.763	12.034	0.796	0.713
Monican02 Vs WWIII_FixedSt	-2.610	6.605	0.936	0.913
Hermes WG Vs WWIII_MovingTS	1.440	13.636	0.733	0.722
Hermes WG Vs WWIII_FixedSt	1.117	13.525	0.732	0.726

The comparison of the wave properties observed by the MOSE-G installed in the WaveGlider with the Monican02 Buoy and the WaveWatch III model for the period 28-30/05/2015 when the glider was parallel parked in the buoy vicinity show high similarity (Figure 14, Figure 15 and Figure 16).

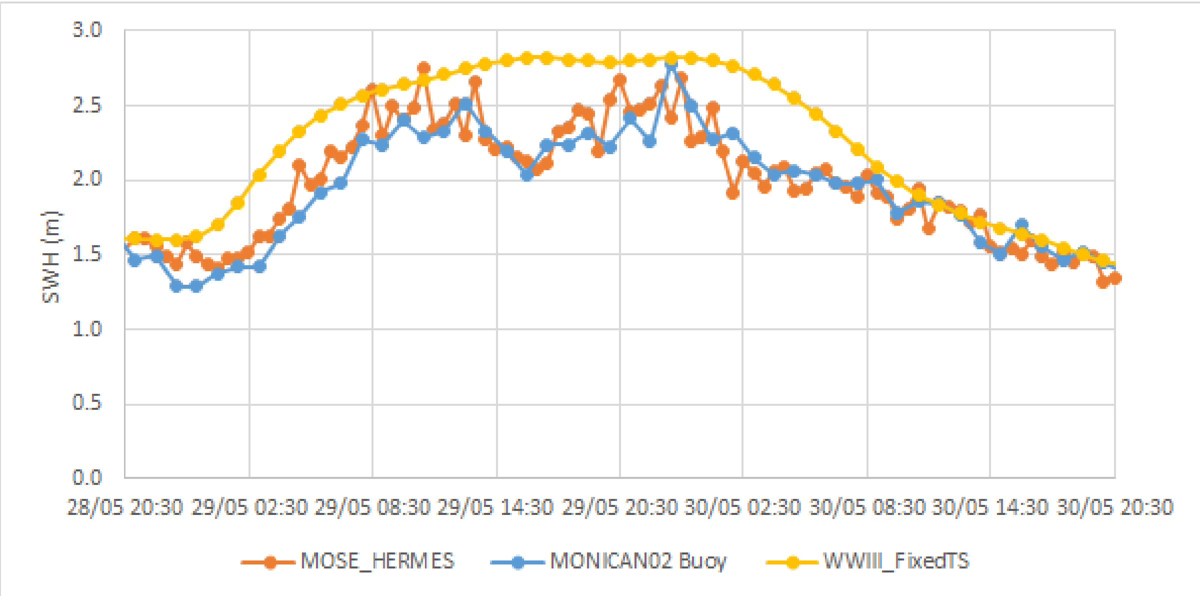


Figure 14 Significant wave height (m) for the period 28-30 May 2015 when the WaveGlider was positioned in the vicinity of the Monican02 buoy. The graph shows the values obtained by the WaveGlider, the Monican02 buoy and the WaveWatch III model.

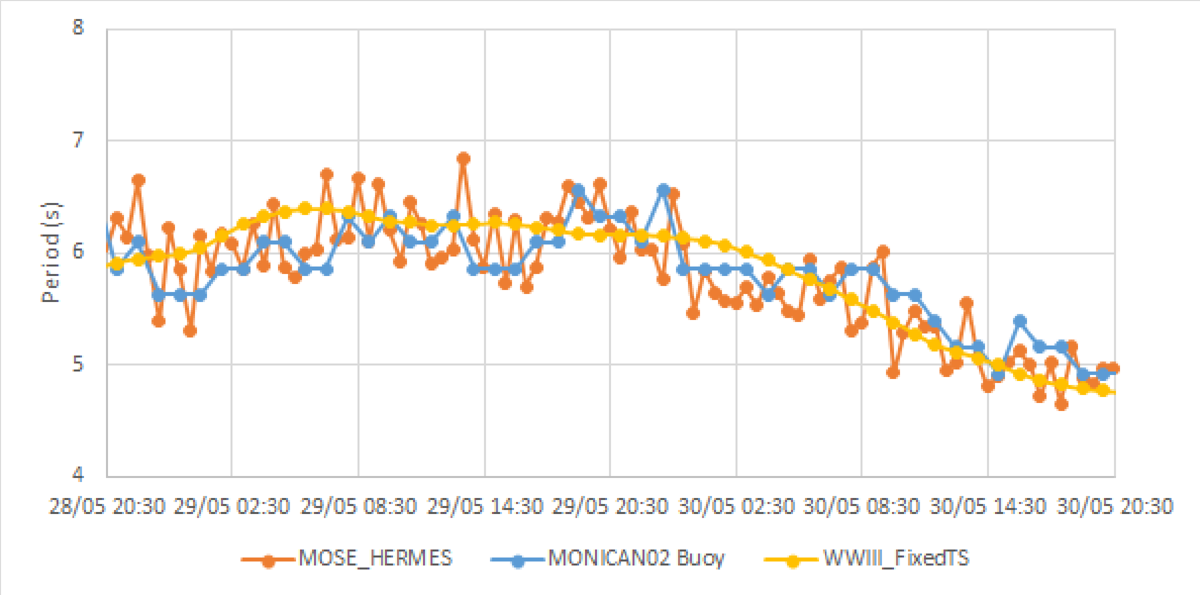


Figure 15 Average wave period (s) for the period 28-30 May 2015 when the WaveGlider was positioned in the vicinity of the Monican02 buoy. The graph shows the values obtained by the WaveGlider, the Monican02 buoy and the WaveWatch III model.

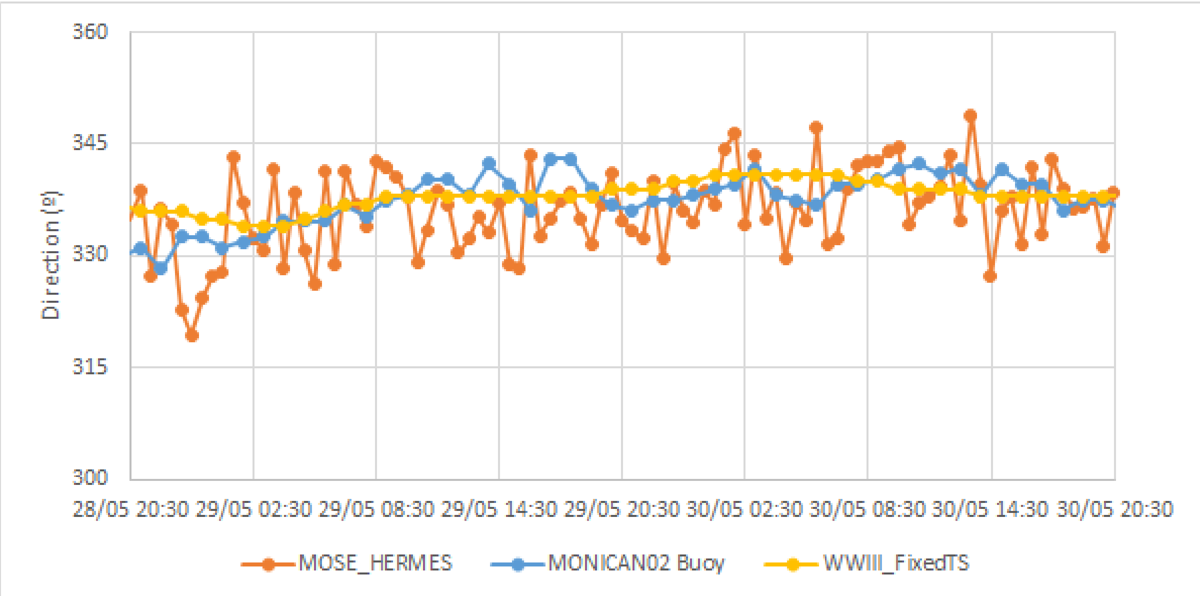


Figure 16 Average wave direction (s) for the period 28-30 May 2015 when the WaveGlider was positioned in the vicinity of the Monican02 buoy. The graph shows the values obtained by the WaveGlider, the Monican02 buoy and the WaveWatch III model.

Table XII Average hourly wave properties for the period 28-05-2015 21h00 to 30-05-2015 20h00

Average	SWH	Period	Direction
Monican02	1.95	5.81	337.71
Hermes WG	1.98	5.79	336.38
Portugal WWIII_FixedSt	2.28	5.86	338.10

Table XIII Standard deviation of the hourly wave properties for the period 28-05-2015 21h00 to 30-05-2015 20h00

Standard Deviation	SWH	Period	Direction
Monican02	0.38	0.41	3.43
Hermes WG	0.37	0.53	5.40
Portugal WWIII_FixedSt	0.49	0.51	1.95

Table XIV Statistic parameters for the different sources of significant wave height for the period 28-05-2015 21h to 30-05-2015 20h

Data Source	Bias	RMSE	R^2	Efficiency
Monican02 Buoy Vs Hermes WG	0.031	0.169	0.822	0.808
Monican02 Vs WWIII_FixedSt	0.328	0.397	0.831	-0.059
Hermes WG Vs WWIII_MovingTS	0.292	0.366	0.809	0.106
Hermes WG Vs WWIII_FixedSt	0.288	0.364	0.814	0.117

Table XV Statistic parameters for the different sources of wave period for the period 28-05-2015 21h to 30-05-2015 20h

Data Source	Bias	RMSE	R^2	Efficiency
Monican02 Buoy Vs Hermes WG	-0.022	0.332	0.625	0.392
Monican02 Vs WWIII_FixedSt	0.046	0.278	0.740	0.572
Hermes WG Vs WWIII_MovingTS	0.083	0.319	0.671	0.633
Hermes WG Vs WWIII_FixedSt	0.061	0.315	0.679	0.642

Table XVI Statistic parameters for the different sources of wave direction for the period 28-05-2015 21h to 30-05-2015 20h

Data Source	Bias	RMSE	R^2	Efficiency
Monican02 Buoy Vs Hermes WG	-1.26	5.616	0.08	-1.722
Monican02 Vs WWIII_FixedSt	0.430	2.679	0.401	0.380
Hermes WG Vs WWIII_MovingTS	2.025	5.632	0.119	-0.013
Hermes WG Vs WWIII_FixedSt	2.046	5.622	0.126	-0.009

In the graphs below can be observed the significant wave height (SWH) obtained by the WaveGlider "Hermes" following the path described by the pass 160. The Wave Glider covered the same area in around two days, the moment when the glider and the satellite coincided are marked with a vertical grey line. The WaveWatch III results for the glider transect was obtained with a moving time series for the same time and location of the satellite. The three time series show good agreement for both AltiKa passes with different wave conditions

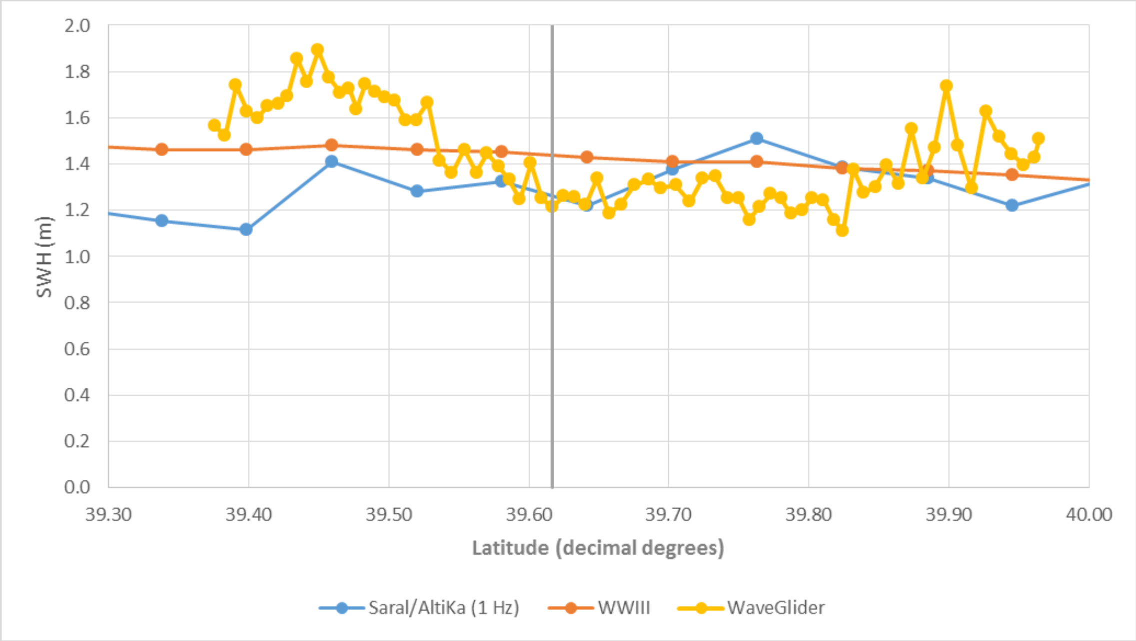


Figure 17 Significant wave height (m) observed by the Saral/AltiKa satellite along the pass 160 on the 28 of April 2015 with 1 Hz resolution (blue line), WaveWatch III modelling results for the same instant and location of the satellite and the observed values by the northward trajectory of the WaveGlider along the same pass starting at 03:00 28-04-2015 and ending at 16:00 29-04-2015. The vertical grey line indicates the instant when the WaveGlider coincided in time and location with the satellite pass.

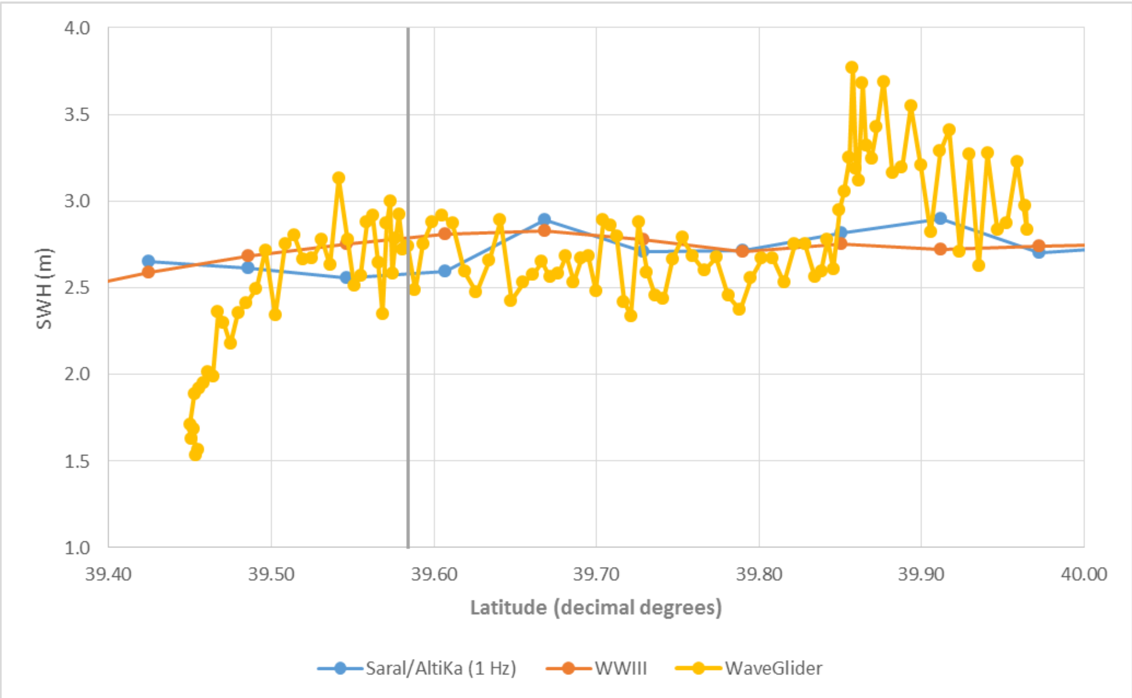


Figure 18 Significant wave height (m) observed by the Saral/AltiKa satellite along the pass 160 on the 02 of June 2015 with 1 Hz resolution (blue line), WaveWatch III modelling results for the same instant and location of the satellite and the observed values by the northward trajectory of the WaveGlider along the same pass starting at 00:00 02-06-2015 and ending at 07:30 04-06-2015. The vertical grey line indicates the instant when the WaveGlider coincided in time with the satellite pass.

Temperature

The Wave Glider was equipped also with a CTD that is attached to its propeller mechanism around 5 m depth and an ADCP incorporated in the floating part of the structure. The figures below illustrate the temperature obtained by the CTD at 5 m and the MONICAN02 buoy at the surface in comparison with the Mohid results for the 0.02 model resolution showing a similar evolution of the property with the observations at both depths. Temperatures values increase continuously, in a similar manner at the surface and at 5 meters depth, from the beginning of the mission until mid-may where upwelling events take place bringing colder water to the surface. At the end of the monitoring period, it can be observed several episodes of temperature inversion related to upwelling events. The coefficient of determination (R^2) between the hourly-averaged observations performed with the buoy and the WaveGlider is 0.60 when considering the whole observed period and decreases to 0.52 when considering form the 24 of April, indicating the different dynamics influencing the surface and the near subsurface. When comparing with the modelling results the Nazare L1 is able to obtain a coefficient of determination of 0.80 for both couple of timeseries, Monican02 buoy vs surface model timeseries and WaveGlider vs depth dependent moving time series.

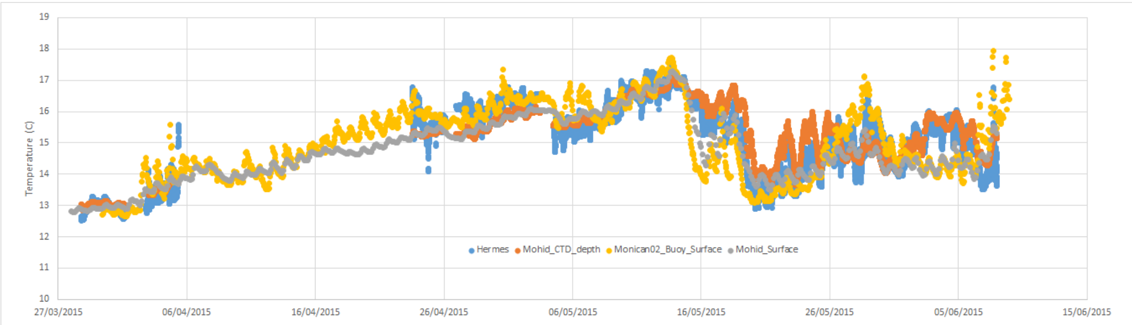


Figure 19 Temperature (ºC) for the complete mission period observed by the WaveGlider Hermes, the Monican02 buoy and the MOHID model.

The intensity of the upwelling event could also be observed by satellite images even though the sea surface temperature (SST) products are not as accurate on coastal waters than in the open sea. Figure 20 shows the low values of SST centred in the Nazaré coast obtained by the MUR (Multi-scale Ultra-high Resolution; JPL MUR MEaSUREs Project, 2010) satellite product and the Nazaré Level1 MOHID model. The model fit the satellite observations with a coefficient of determination (r^2) of 0.85.

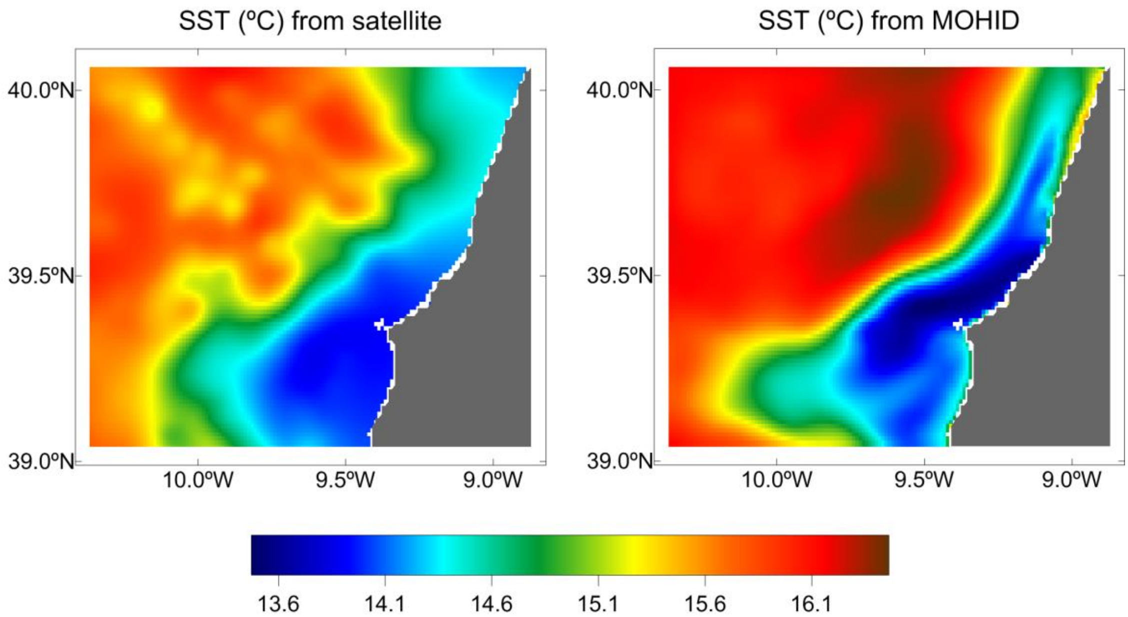


Figure 20 Sea surface temperature (SST) observed by the MUR satellite product (Multi-scale Ultra-high Resolution) (left) and the results by the Nazaré L1 MOHID model (right) for the 21st of May 2015.

Currents

Current intensities obtained by the "Hermes" ADCP and the model they are also in agreement as shown in the example below for the ADCP bin 4 (bin size 4 m).

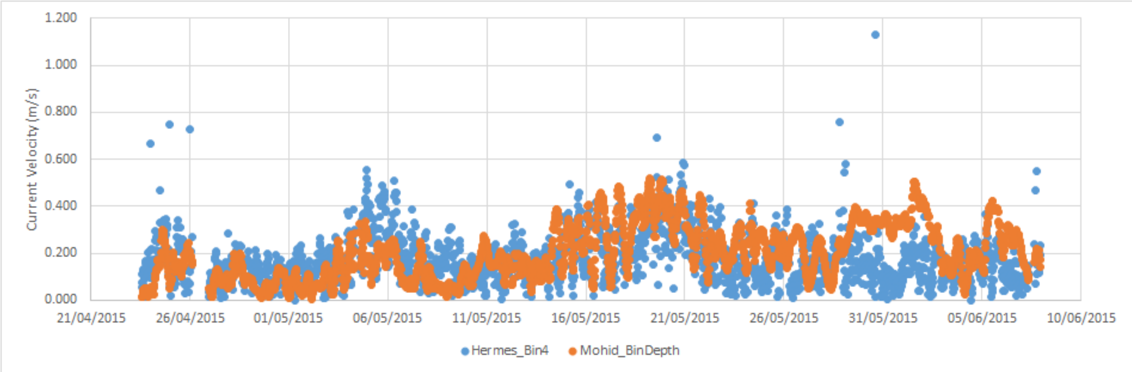


Figure 21 Current intensities obtained by the "Hermes" ADCP for bin 4 (bin size 4 m) and the MOHID model 18 m deep approx.

Tides

The MOHID model applications for the Nazaré Canyon area where also validated using the tidal gauges installed in the study area (Peniche and Nazaré; Figure 1). Hourly water levels for both stations were obtained from the CMEMS and compared with the modelled sea level. Model results show a very high level of agreement with coefficient of determination above 0.99 for both locations. Figure 22 shows the high level of correspondence between the observed and modelled water levels and highlight one of the main advantages of the modelling results compared to the *in situ* observations that is the ability to provide gapless series of data in periods when observed data is not available for any reason. The Nazaré MOHID model was implemented operationally allowing also to provide accurate forecasts for the studied region.

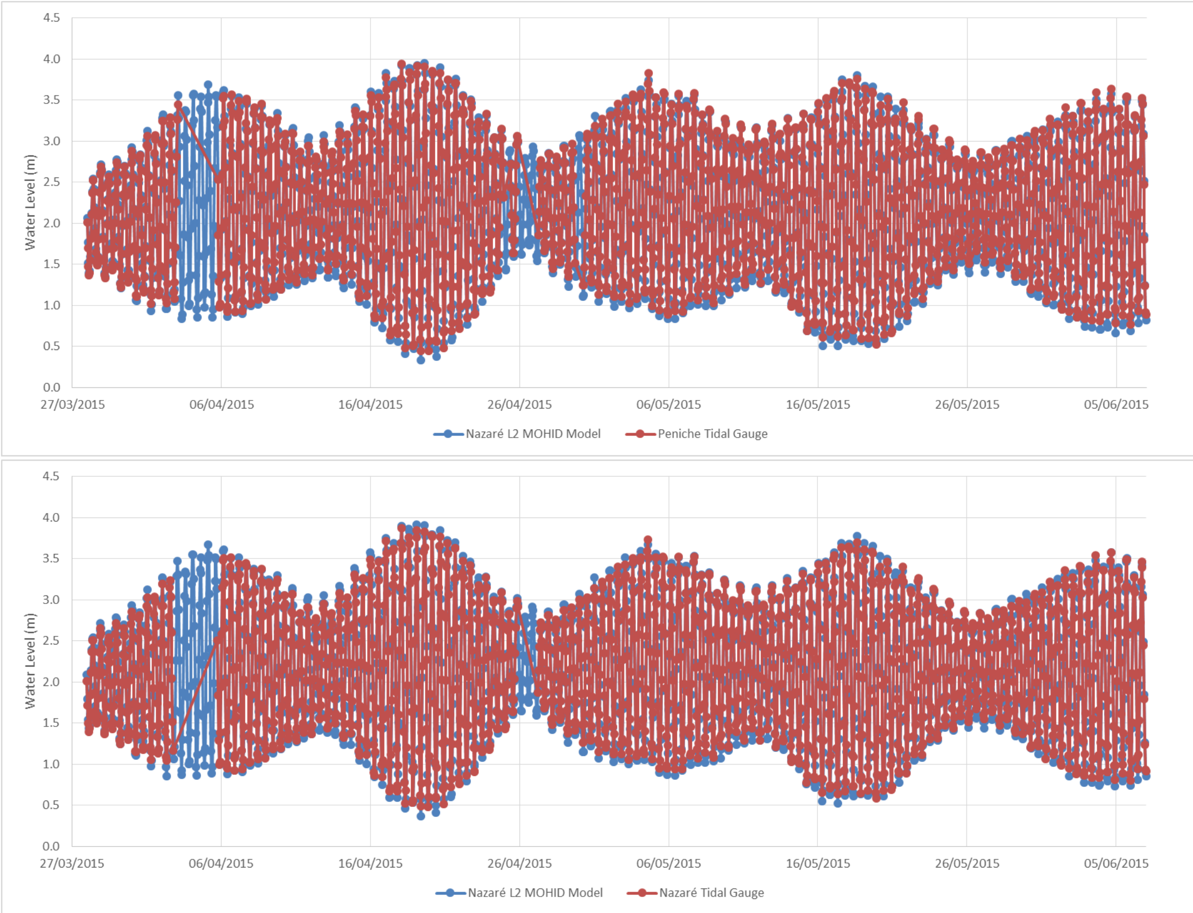


Figure 22 Hourly water levels observed (red dots) and modelled (blue dots) during the WaveGlider mission in Portugal for the Peniche tidal gauge (above) and Nazaré tidal gauge (below).

Conclusions

The combination of this novel monitoring methodoly along with the classic observing stations as tidal gauges and coastal buoys allows to monitor and collect metocean information in larger areas and longer periods and during coastal conditions that would not be possible by a classic monitoring campaing. The combination of those monitoring methodologies with numerical models allow to complete spatially and temporally the information. The observations and the models allow to validate each other values as have been seen some of the sensors went out of callibration during the mission and by adding with other source of information the wrong information can be easily discarded. During this mission, all the possivel observation sources for the Nazaré area has been taken into consideration including the remote satellite sources for wave height and sea surface temperature allowing to generate a greater picture of the oceanic conditions during the WaveGlider mission in Portugal.

Acknowledgements

This work was funded by the Turnkey Project (Transforming Underutilised Renewable Natural Resource into Key Energy Yields - Project number: 2013-1/279) which has been funded through the Atlantic Area Transnational Cooperation Programme, financed by the European Regional Development Fund (ERDF). The project is very grateful for the support of the Nazaré and Peniche local and coastal authorities and the assistance of the company Atlantic Safaris and ENONDAS for

help with the authorizations for the MREs Pilot Zone. The project would like to thank also to the Liquid robotics operations centre for the successful piloting of the WaveGlider in the Portuguese coast. Special thanks to François Leroy from Liquid Robotics for participating in the open session in Peniche and allowing us to observe the Portuguese waters with the WaveGlider for a longer period.

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Annex I The WaveGlider Mission in the media

Announcements through specialised information channels:

http://www.wavec.org/content/files/Turnkey_Peniche_29_Maio_2015.pdf

http://www.wavec.org/content/files/Press_Release_Turnkey.pdf

http://www.cm-peniche.pt/_uploads/PDF_Noticias/Poster_Turnkey.pdf

http://www.apren.pt/pt/calendario/index.php?day=29&month=5&year=2015&tipo=d

http://www.oceanplug.pt/pt-PT/arquivo_noticioso/waveglider_apresenta_resultados_da_campanha_maritima/

http://atlanticarea.ccdr-n.pt/news/turnkey-wave-glider-public-presentation https://twitter.com/atlanticarea/status/580450374605279232

Local, regional and National News:

http://www.cm-peniche.pt/News/newsdetail.aspx?news=2640d245-0873-4b49-b486-841cad410318

http://www.cm-peniche.pt/News/newsdetail.aspx?news=50dc96f0-a40e-472e-8fd8-43bd5b723852

http://www.oestedigital.pt/RSS/GetFeed.aspx?feed=6A96567D-F4DD-4cb7-ADC2-F036EA8FB72D

http://oesteglobal.com/Equipamento_movido_a_energia_das_ondas_monitoriza_mar_da_Nazare_

http://regiaodanazare.com/Wave_Glider_vai_recolher_dados_sobre_as_ondas_ao_largo_da_Nazare_

http://www.prensalibre.com/economia/meca-lusa-del-surf-investiga-como-explotar-energia-renovable-de-sus-olas

http://www.regiaodeleiria.pt/wp-content/uploads/2015/04/REGIAOdeLEIRIA_ed4072_02abr2015_9hg43.pdf (Printed page 16)

http://www.tintafresca.net/News/newsdetail.aspx?news=e26515c4-6ab2-4612-a0d5-de72081e2a91&edition=173

http://cister.fm/cister/noticias/sociedade-e-ambiente/nazare-acolhe-apresentacao-publica-e-lancamento-do-wave-glider/

http://cister.fm/cister/noticias/sociedade-e-ambiente/wave-glider-vai-recolher-dados-sobre-as-ondas-ja-navega-no-mar-ao-largo-da-nazare/

News in Portuguese media:

http://issuu.com/jem6/docs/jem_10/28 (printed, journal of economy of the sea)

http://www.ionline.pt/artigos/portugal/inovacao-no-mar-da-nazare

http://www.noticiasaominuto.com/tech/367484/nazare-equipamento-movido-a-energia-das-ondas-monitoriza-mar

http://www.publico.pt/tecnologia/noticia/equipamento-movido-a-energia-das-ondas-monitoriza-mar-da-nazare-1690548

http://www.sol.pt/noticia/127966/inova%C3%A7%C3%A3o-nas-ondas-da-nazar%C3%A9

http://diariodigital.sapo.pt/news.asp?id_news=766065

http://observador.pt/2015/06/05/vencedor-do-concurso-inovacao-da-the-economist-silicon-valley-navega-mar-portugues/

International News (out of the Atlantic Region):

Argentina:
http://epre.gov.ar/web/la-meca-lusa-del-surf-investiga-como-explotar-la-energia-renovable-de-sus-olas/

http://www.lacapitalmdp.com/noticias/El-Mundo/2015/03/28/278650.htm

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Colombia:
http://www.wradio.com.co/noticias/economia/la-meca-lusa-del-surf-investiga-como-explotar-energia-renovable-de-sus-olas/20150328/nota/2695060.aspx

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France:
http://radioalfa986.net/parution.php?larticle=969a086e0717a9b496dd0e9a50ec8010

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Spain:
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http://www.invertia.com/noticias/articulo-final.asp?idNoticia=3020449

http://www.lavanguardia.com/economia/20150328/54429311133/la-meca-lusa-del-surf-investiga-como-explotar-energia-renovable-de-sus-olas.html

http://www.radiointereconomia.com/2015/03/28/la-meca-lusa-del-surf-investiga-como-explotar-energia-renovable-de-sus-olas/

http://www.eldiario.es/economia/investiga-explotar-energia-renovable-olas_0_371313185.html

http://www.eleconomista.es/energia/noticias/6592200/03/15/La-meca-lusa-del-surf-investiga-como-explotar-la-energia-renovable-de-sus-olas.html

http://www.negocios.com/noticias/meca-lusa-surf-investiga-explotar-energia-renovable-olas-28032015-1648

http://elperiodicodelaenergia.com/nazare-la-meca-portuguesa-del-surf-investiga-como-explotar-la-energia-de-sus-olas/

http://www.oepm.es/export/sites/oepm/comun/documentos_relacionados/Boletines/energias_marinas/2015_1_Trimestre_Energias_Marinas.pdf (National institution bulletin)

International Press Agencies:

http://www.efeverde.com/noticias/portugal-nazare-olas-energia-surf-meca/ (With Video)

Electronic blogs:

http://www.surf30.net/2015/03/nazare-investiga-como-explotar-la.html

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http://redesmundoelectrico.blogspot.pt/2015/04/nazare-aprovechara-sus-olas-gigantes.html

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http://www.nauticapress.com/apresentacao-publica-e-lancamento-do-wave-glider-em-portugal/

Conferences:

GODAE Oceanview COSS-TT conference 31 August-4 September 2015 Lisbon, Portugal

http://www.godae.org/~godae-data/OceanView/Events/COSS-TT-WS-2015/PA.2-Poster_COSS-TT_2015_corr.pdf

TURNKEY project_ Novel Marine Monitoring Methodologies 23 September, 2015 Weigh Inn, Thurso, UK

http://www.eri.ac.uk/remote_turnkey/dissem/final_poster3.pdf