SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Evaluation of coastal climate trends in the Mediterranean area by means of high-resolution and multi-model downscaling of ERA5 reanalysis
Computer Project Account:	SPITBRAN
Start Year - End Year:	2018 - 2020
Principal Investigator(s)	Carlo Brandini
Affiliation/Address:	LaMMA Consortium - Environmental Modelling and Monitoring Laboratory for Sustainable Development
Other Researchers (Name/Affiliation):	Valerio Capecchi (LaMMA Consortium) Francesco Pasi (LaMMA Consortium – CNR IBE) Stefano Taddei (LaMMA Consortium) Valentina Vannucchi (LaMMA Consortium)

The following should cover the entire project duration.

Summary of project objectives (10 lines max)

The main aim of the SPITBRAN Special Project (hereafter SP) is to build a new climatic database of wind/wave regimes over the last 40 years (i.e. an hindcast), at high-resolution along the coasts of the Mediterranean Sea. This goal is achieved by using a cascade of state-of-the-art atmospheric and wave numerical models (BOLAM->MOLOCH->WW3), forced by the best (in terms of model cycle, output temporal frequency and horizontal resolution) reanalysis data currently available (ERA5). This new climatic database can provide many important inputs for the Integrated Coastal Zone Management (ICZM), with a particular focus on the North-Western Mediterranean Sea. This work will be partially connected with ongoing initiatives, such as the MAREGOT (www.lamma.rete.toscana.it/en/maregot) project, funded by the EU in the framework of the Italian-France Cross-border program, to which the LaMMA Consortium is involved as a partner.

Summary of problems encountered

The ECFS space requested in the SPITBRAN proposal was under-estimated, mainly because of the need to temporary store the ERA5 data for initialising the BOLAM model (currently ecfs_status returns about 12 TB). This is the main reason why we had to require additional SBUs for the second year of the SP. Because of this SBUs over-consumption, the WW3 simulations were run on the Principal Investigator’s computer facilities.

Experience with the Special Project framework

No problems encountered and we got all information and help needed.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

Atmospheric Forcing

To provide atmospheric forcing data to the wave model, a dynamical downscaling of the ERA5 reanalysis data was implemented through a nested domain configuration based on the BOLAM and MOLOCH models, which are limited-area numerical weather models, developed at the Institute of Atmospheric Sciences and Climate of the Italian National Research Council (CNR). Davolio et al. 2020 provides a list of the several applications over which the BOLAM and MOLOCH models are implemented. BOLAM is a primitive equations hydrostatic model with parameterized convec-tion. In our work, it was employed with a grid spacing of approximately 7 km to provide lateral boundary conditions to MOLOCH every hour. MOLOCH is a nonhydrostatic, fully compressible model that uses a hybrid terrain-following coordinate, relaxing smoothly to horizontal surfaces. The microphysical scheme is an upgrade of the parameterization proposed by Drofa and Malguzzi 2004, which describes the interactions of cloud water, cloud ice, rain, snow and graupel. In this study, the grid spacing of the MOLOCH model is about 2.5 km and the model was set to allow the explicit treatment of convective processes. We used the model version released in late 2017.

The domain of integration is shown in Figure 1 (outer rectangle) and it approximately covers the Med-CORDEX domain. Hourly outputs from the BOLAM simulation provide the initial and boundary conditions to the MOLOCH simulation, which starts each day at 21 UTC and has a forecast length equal to 27 h. The MOLOCH model produces outputs every hour over the domain of integration shown in Figure 1 (inner rectangle). The daily data of the BOLAM/MOLOCH hindcast were built using the last 24 h of the two model simulations, while the first six and three hours of integration of the BOLAM and MOLOCH models, respectively, were considered as spin-up times and thus discarded.

The wind hourly results of the atmospheric downscaling were used to force the WW3 model. To obtain a single gridded forcing field for the unstructured wave model on the whole Mediterranean Sea, at the best possible resolution, the data from BOLAM and MOLOCH were merged together.

More precisely, a 2.5 km grid was built over the entire Mediterranean domain, then it was filled with MOLOCH data in the inner domain and with interpolated BOLAM data outside. Furthermore, to achieve a smooth transition between the high- and low-resolution winds, the two datasets were averaged using linear weights, within an appropriate buffer zone about 150 km wide, around the boundary between internal (high resolution) and external (low resolution) domains.

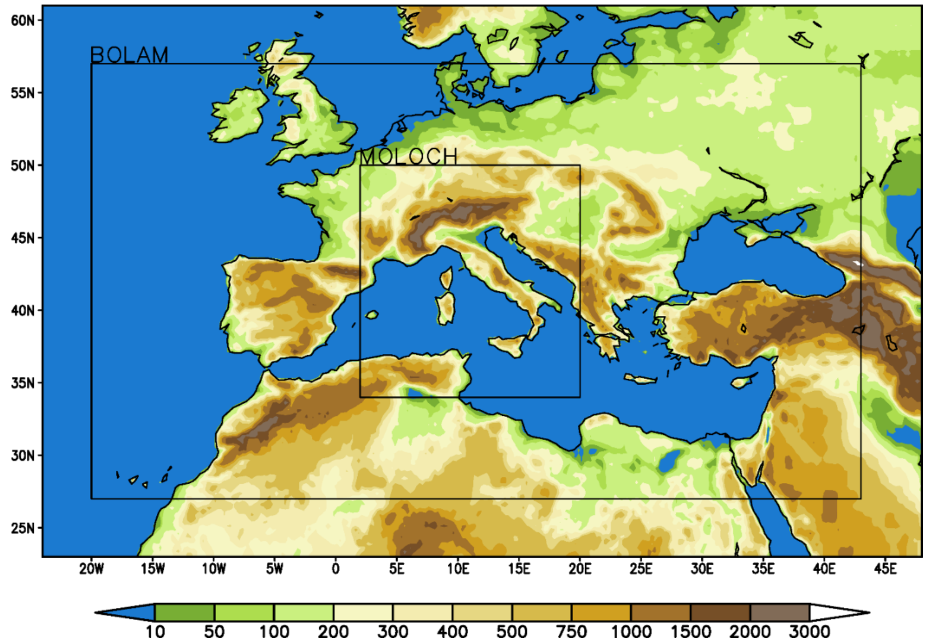


Figure 1. Extent of the BOLAM and MOLOCH domains with superimposed topography. The BOLAM domain approximately corresponds to the Med-CORDEX domain

Wave Model

The state-of-the-art third-generation WW3 unstructured grid model, version 5.16. The extent of the computational domain of the wave model includes the entire Mediterranean Basin and an area 150 km West of the Strait of Gibraltar (Figure 2). This domain has been discretized by an unstructured mesh with a variable resolution up to 500 m along the coasts on the North-Western Mediterranean Sea. The highest coastal resolution is dedicated to the coasts of Tuscany and the Tuscan Archipelago, Eastern Liguria (La Spezia- Levanto area) and the Straits of Bonifacio and Messina. Along the coasts of Sardinia and Corsica, the resolution is about 1 km; along the other Tyrrhenian coasts and on the Straits of Gibraltar, it is about 3 km; while for the remaining Mediterranean coasts, it is roughly 6 km. The minimum resolution in deep offshore areas reaches 30 km.

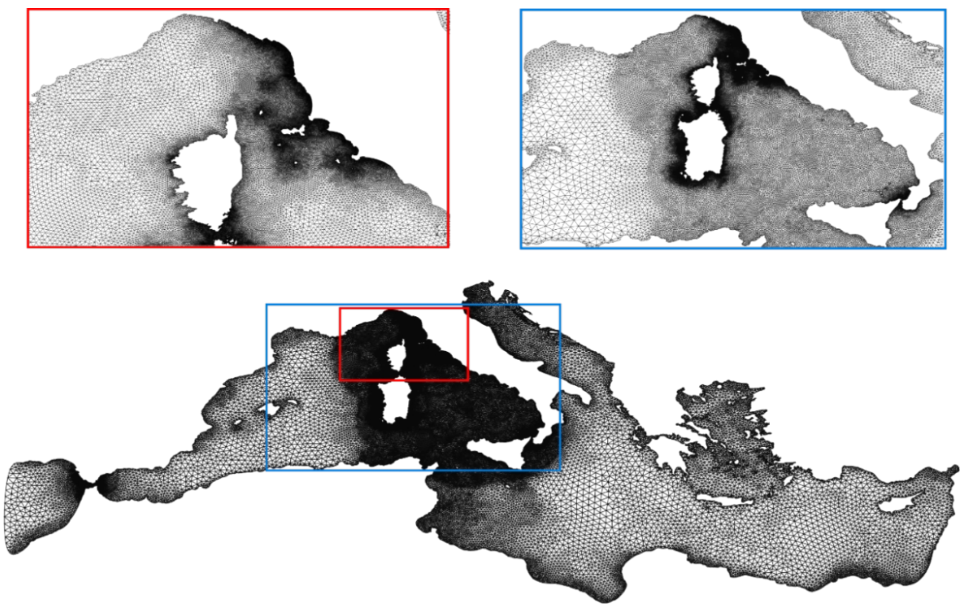


Figure 2. Extent of the WaveWatch III (WW3) domain with enlarged views of North-Western Mediterranean Sea (light blue box) and Tuscany Archipelago and Eastern Ligurian Coast (red box).

Observed Data

To validate wind/wave model outputs, observations were collected from different in-situ measurement stations located in the North-Western Mediterranean Sea (Figure 3). Eleven wind stations were selected among those available along the Ligurian and Tuscany coasts. Such wind stations were evaluated to be representative of the wind climate over the sea, because of their proximity to the coast and relatively long historical time series (at least 3 years).

Figure 3. Location of wind stations (orange points) and wave buoys (light green points) used to calibrate and validate the wind/wave hindcast. The length of the time series period is shown after the underscore ("_") symbol following the name of the wind station or wave buoy.

Wave Model Calibration Procedure

The calibration was carried out in three subsequent phases by comparison of statistics from simulated and observed wave climates for twelve case studies, including both calm and severe weather conditions. Each phase corresponds to the calibration of a specific parameter/setup, namely: (i) time step duration, (ii) numerical scheme and (iii) physical parameterization.

In addition, several statistical parameters were determined for each calibration phase for Hs and Tm (Wilks, 2001): Mean Bias Error (MBE), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The correlation between two directional variables (i.e., mean wind direction and mean wave direction) was assessed by computing the circular version of the Pearson's product moment correlation coefficient (circ-r, Jammalamadaka and SenGupta, 2001).

Wind Validation Results

Based on the outcome of the wave calibration procedure we produced a 29-year (1990–2018) wind/wave hindcast.

The BOLAM and MOLOCH wind hindcasts were validated using the entire set of records from the 11 wind stations listed in Figure 3, located along the Liguria and Tuscany coasts. To highlight the possible improvements obtained with the high-resolution simulation, a comparison was made with the mean wind speed (V) and wind direction (Dir), extracted from the ERA5 wind dataset (CDS), with a horizontal resolution of 0.25°x0.25° and 1 h in time. The gridded mean wind parameters were interpolated at the wind station positions by means of bilinear interpolation. For the wind speed validation, we used values above the 33rd percentile of the cumulative distribution of measurements (Turchi et al., 2017), computed for each wind station. The statistical indicators for mean wind speed and direction are reported in Table 1. The wind speed correlations are similar among the three atmospheric models, with the exception of Capalbio station, where the MOLOCH values show a 20–24% improvement over those of the other models. The higher wind speed correlations (greater than 0.7) were obtained for Capo Mele, Livorno Offshore and Vada wind stations. The wind direction correlations (circ-r) are quite similar among the three models, with some exception: the BOLAM model at the Bocca d'Arno station has a circ-r value of 0.19 compared to the 0.64 and 0.67 of the others; the ERA5 dataset at the San Vincenzo and Vada stations has a circ-r values of 0.59 and 0.46, respectively, compared to values higher than 0.68 for the BOLAM and MOLOCH models. The highest values (all the models above 0.70) were obtained for Genova P. Vagno, Livorno Offshore and Pianosa wind stations.

Figure 4 shows the normalized Taylor diagrams for the data from the BOLAM, MOLOCH and ERA5 datasets, which are compared with measurements recorded at the Bocca d'Arno, Capalbio, Livorno Offshore and Vada wind stations. By looking at the position of each symbol and its relative distance to the point lying on the X-axis, we note that the MOLOCH data provide the best overall performance as regards the Bocca d'Arno and Capalbio stations (Figures 4 a,b). For the Livorno Offshore station, the ERA5 data instead show a standard deviation close to that of observed data (in the normalised Taylor diagram equal to 1), the highest correlation coefficient (approximately 3–7% higher) and the lowest cRMSE (see Table 1). Regarding the Vada station the high-resolution models provide standard deviations closer to the observed data than ERA5 data, but also higher errors and slightly lower correlation coefficients (around 3–5%).

Table 1. Statistical indicators for wind speed and direction obtained for the wind speed values above the thresholds of the 33rd percentile.

Wind Station No.	**Atmospheric Model**	**Wind Speed (m/s)**					**Dir (°N)**
		MBE	***MAE***	***RMSE***	***cRMSE***	***r***	***circ-r***
BOCCA D'ARNO	BOLAM	−0.09	1.41	1.90	1.90	0.56	0.19
	MOLOCH	−0.11	1.29	1.78	1.78	0.62	0.67
	ERA5	−0.47	1.35	1.80	1.74	0.62	0.64
CAPALBIO	BOLAM	1.34	1.96	2.59	2.21	0.50	0.75
	MOLOCH	1.23	1.72	2.26	1.89	0.62	0.73
	ERA5	1.33	1.94	2.56	2.19	0.52	0.68
CAPO MELE	BOLAM	−0.36	1.78	2.31	2.28	0.70	0.55
	MOLOCH	0.38	1.83	2.44	2.41	0.70	0.54
	ERA5	−1.10	1.69	2.13	1.83	0.73	0.62
GENOVA-PUNTA_VAGNO	BOLAM	−0.83	1.57	2.00	1.82	0.50	0.75
	MOLOCH	0.47	1.87	2.38	2.34	0.45	0.72
	ERA5	−0.80	1.62	2.04	1.88	0.51	0.75
LA SPEZIA RMN	BOLAM	−0.18	1.56	1.99	1.98	0.45	0.67
	MOLOCH	−0.82	1.44	1.90	1.71	0.54	0.64
	ERA5	−0.53	1.46	1.88	1.80	0.52	0.70
LIVORNO OFFSHORE	BOLAM	−0.21	1.63	2.20	2.19	0.74	0.72
	MOLOCH	0.11	1.66	2.24	2.24	0.71	0.77
	ERA5	−1.30	1.79	2.29	1.89	0.76	0.80
MARINA DI CAMPO RMN	BOLAM	0.24	1.68	2.16	2.14	0.60	0.65
	MOLOCH	0.61	1.98	2.53	2.46	0.55	0.72
	ERA5	1.74	2.47	3.18	2.66	0.58	0.68
PIANOSA	BOLAM	2.08	2.51	3.22	2.46	0.62	0.76
	MOLOCH	2.38	2.75	3.50	2.57	0.60	0.74
	ERA5	2.15	2.56	3.10	2.23	0.65	0.76
SAN VINCENZO	BOLAM	0.63	1.76	2.32	2.23	0.58	0.74
	MOLOCH	1.25	2.11	2.70	2.40	0.56	0.73
	ERA5	−0.85	2.00	2.57	2.43	0.53	0.59
SAVONA ISTITUTO NAUTICO	BOLAM	0.40	1.46	1.82	1.77	0.60	0.53
	MOLOCH	1.62	2.32	2.90	2.41	0.60	0.50
	ERA5	−0.12	1.25	1.57	1.57	0.62	0.46
VADA	BOLAM	−1.11	1.92	2.55	2.30	0.70	0.68
	MOLOCH	−0.43	1.82	2.44	2.41	0.68	0.69
	ERA5	−2.21	2.41	3.12	2.20	0.72	0.46

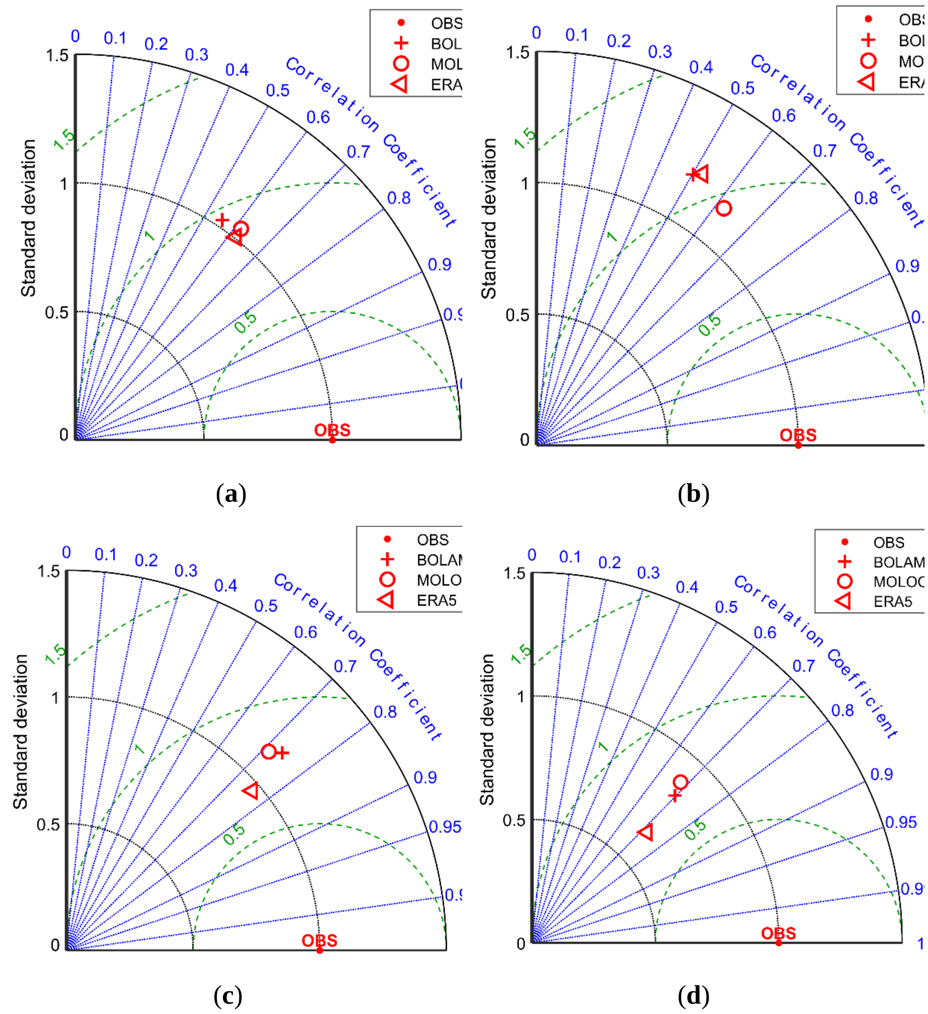


Figure 4. Normalized Taylor diagrams for the: (**a**) Bocca d'Arno, (**b**) Capalbio, (**c**) Livorno offshore and (**d**) Vada wind stations. The plus (+), circle (◯) and triangle (△) symbols refer to the BOLAM, MOLOCH and ERA5 data, respectively.

<u>Wave Validation Results</u>

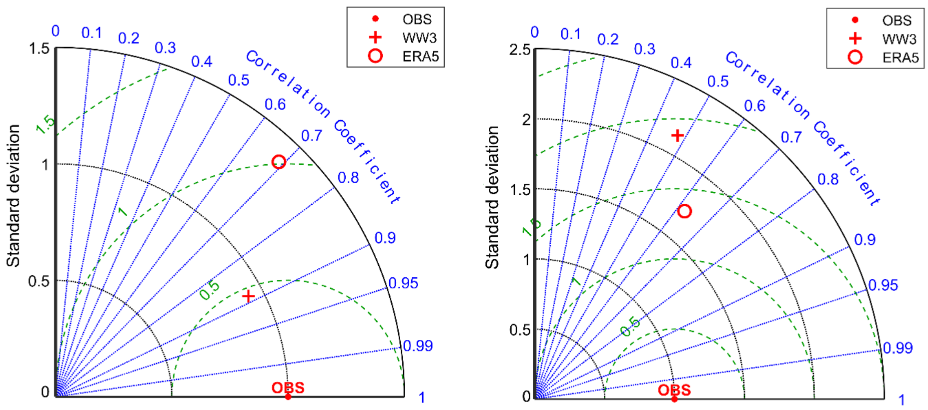
The wave hindcast was validated using data from 14 buoys located in the North-Western Mediterranean Sea. The synthetic wave parameters were computed directly by the WW3 point output at the buoy locations. To highlight the possible improvements obtained with the high-resolution simulation, a further comparison was performed with the Hs of combined wind waves and swell, and Tm and Dirm, from the ERA5 wave dataset (CDS), which have horizontal resolutions of 0.5°x0.5° and temporal resolutions of 1 h. In this case, the gridded wave parameters were interpolated at the buoy positions by bilinear interpolation. For coastal buoys where the bilinear interpolation reported a missing value, a distance-weighted average remapping interpolation was used.

The statistical indicators for Hs, Tm and Dirm (or Dirp for the observed data that do not provide the Dirm) were reported in Table 2 for both offshore and coastal (i.e., located at water depths around 15 m) buoys. The correlation coefficients r between observed and simulated Hs values are around 0.9 or higher. Moreover, it can be observed that the performances of the wave hindcast and the ERA5 dataset in terms of statistical indicators for Hs are rather similar at the offshore points, but in the coastal areas the wave hindcast performs better than ERA5. In fact, on average, the correlations for Hs differ less than 2.5% for the offshore buoys, and stay between 8 and 29% for the coastal ones. This is also clear by observing the Hs normalized Taylor diagrams for both the offshore (Figure 5c,g) and coastal (Figure 5a,e) buoys.

Table 2. Statistical indicators for Hs, Tm and Dirm (or Dirp) evaluated for the offshore and coastal buoys in Table 3. In this table, the WW3 model represents the wave hindcast results and the relative ERA5 dataset.

Buoy No. [1]	Model	Hs (m)					Tm (s)					Dirm (°N)
		MBE	*MAE*	*RMSE*	*cRMSE*	*r*	*MBE*	*MAE*	*RMSE*	*cRMSE*	*r*	*circ-r*
OFFSHORE BUOY												
ALGHERO	WW3	−0.12	0.24	0.38	0.36	0.96	0.46	0.82	1.01	0.9	0.86	0.76 [1]
	ERA5	−0.25	0.28	0.43	0.35	0.98	0.36	0.71	0.87	0.79	0.88	-
ALISTRO	WW3	0.01	0.14	0.2	0.2	0.93	0.09	0.67	0.88	0.88	0.77	0.75
	ERA5	0.03	0.14	0.21	0.2	0.92	0.05	0.53	0.7	0.7	0.77	0.40
CAP CORSE	WW3	−0.19	0.31	0.47	0.44	0.92	0.32	0.73	0.93	0.87	0.85	-
	ERA5	−0.43	0.47	0.68	0.53	0.91	0.14	0.55	0.72	0.71	0.86	-
CAPO MELE	WW3	−0.07	0.2	0.28	0.27	0.86	−0.1	0.71	0.91	0.91	0.73	0.55
	ERA5	−0.15	0.21	0.29	0.25	0.88	−0.03	0.58	0.74	0.74	0.81	0.52
CIVITAVE CCHIA	WW3	−0.07	0.16	0.24	0.23	0.91	0.39	0.72	0.95	0.87	0.78	0.58 [1]
	ERA5	−0.03	0.18	0.26	0.26	0.89	0.52	0.71	0.9	0.73	0.77	-
GIANNUT RI	WW3	−0.04	0.17	0.24	0.24	0.92	0.16	0.53	0.73	0.71	0.85	0.62 [1]
	ERA5	−0.12	0.19	0.28	0.25	0.91	0.18	0.45	0.58	0.55	0.87	-
GORGON A	WW3	−0.1	0.2	0.29	0.28	0.92	0.2	0.64	0.85	0.83	0.84	0.59 [1]
	ERA5	−0.2	0.24	0.36	0.3	0.93	0.27	0.56	0.73	0.68	0.87	-
LA REVELLA TA	WW3	−0.08	0.2	0.3	0.29	0.95	0.42	0.73	0.93	0.83	0.89	0.81
	ERA5	−0.05	0.17	0.24	0.24	0.97	0.49	0.71	0.87	0.72	0.91	0.79
LA SPEZIA	WW3	−0.1	0.19	0.29	0.27	0.92	0.34	0.83	1.09	1.04	0.74	0.50 [1]
	ERA5	−0.19	0.23	0.33	0.27	0.93	0.37	0.75	0.96	0.88	0.77	-
LIVORNO OFFSHOR E	WW3	−0.1	0.19	0.29	0.27	0.93	0.52	0.79	1.03	0.89	0.85	0.59 [1]
	ERA5	−0.2	0.24	0.36	0.3	0.93	0.59	0.74	0.93	0.72	0.86	-
MONACO	WW3	−0.02	0.18	0.24	0.24	0.89	−0.02	0.7	0.91	0.91	0.69	0.70
	ERA5	−0.01	0.16	0.24	0.24	0.89	0.13	0.6	0.76	0.75	0.79	0.72
COASTAL BUOY												
BASTIA	WW3	−0.02	0.11	0.15	0.15	0.89	−0.52	0.91	1.25	1.14	0.48	0.65
	ERA5	0.24	0.27	0.4	0.32	0.69	0.3	0.67	0.87	0.81	0.62	−0.42
CASTIGLI ONE	WW3	−0.03	0.1	0.14	0.14	0.94	0.44	0.81	1.08	0.98	0.78	0.44 [1]
	ERA5	0.15	0.19	0.3	0.26	0.82	0.8	0.88	1.08	0.74	0.75	
GOMBO	WW3	−0.06	0.14	0.22	0.21	0.93	0.52	0.88	1.16	1.03	0.8	0.40 [1]
	ERA5	0.04	0.19	0.3	0.29	0.86	0.75	0.89	1.14	0.86	0.79	

[1] Dirp



(a) **(b)**

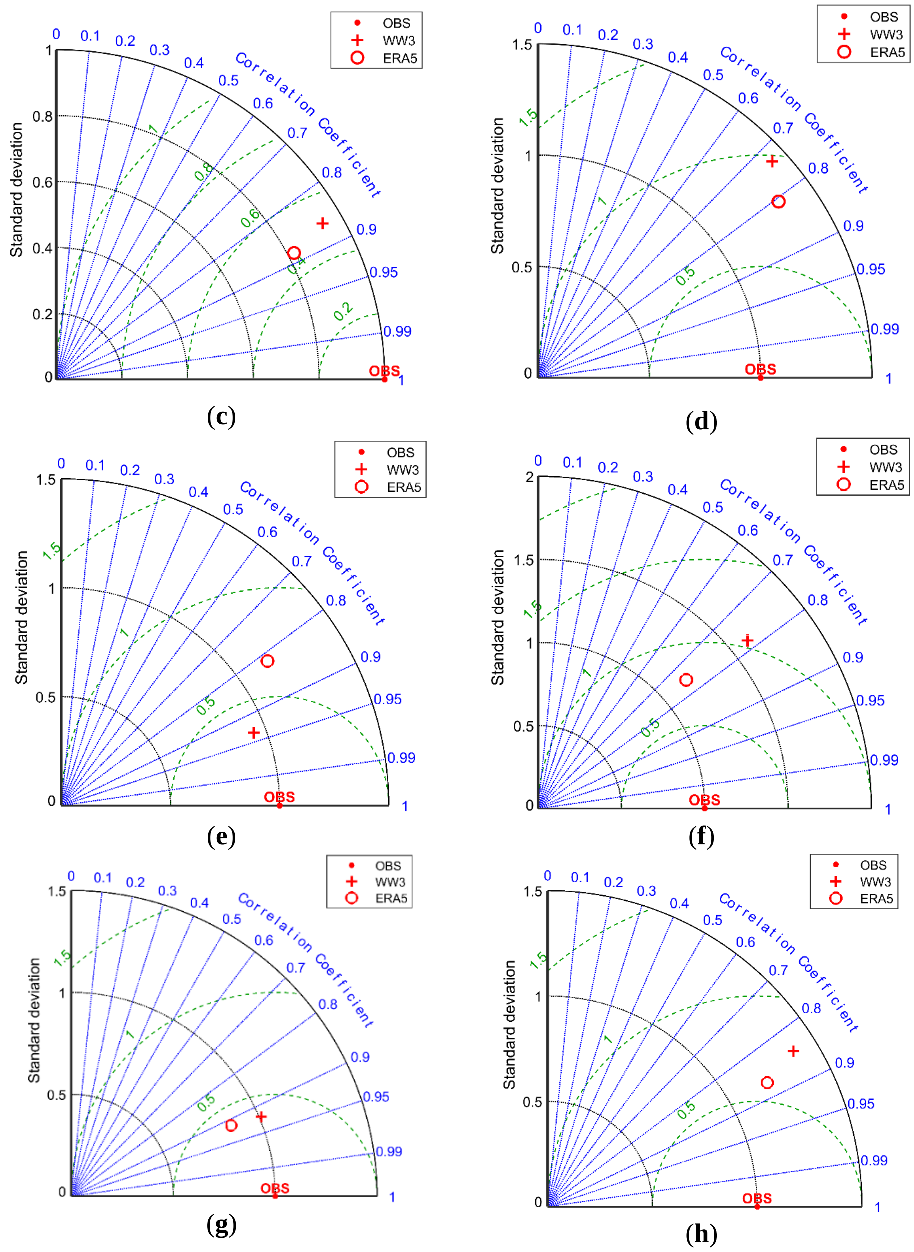


Figure 5. Normalized Taylor diagrams for: (**a**,**b**) the Bastia, (**c**,**d**) Capo Mele, (**e**,**f**) Castiglione, (**g**,**h**) Giannutri buoys. The results are relative to Hs (**a**,**c**,**e**,**g**) and Tm (**b**,**d**,**f**,**h**). The plus (+) and circle (◯) symbols refer to the wave hindcast (here WW3) and ERA5 data (here ERA5), respectively.

The correlations for Tm are around 0.7 or higher with the exception of the Bastia coastal buoy, for both models. The statistical indicators of Tm for the wave hindcast and ERA5 are very similar for all buoys. The Tm correlations differ, in general, less than 4%, with the exception of Capo (about 10%), Monaco (about 14%) and Bastia (about 29%). The circular correlations between observed and simulated Dirm values (or Dirp) are higher than 0.5, with the exceptions of two coastal buoys: Castiglione and Gombo. This reduced value of circ-r for the coastal area is probably due to the intrinsic difficulty of modelling complex wave patterns at variable depths and with jagged coastlines even in the presence of reliable bathymetric data.

As regards the comparison with the ERA5 data, the wave hindcast circular correlation coefficients of the wave directions are always higher (differences greater than 2.5%), with the sole exception of the Monaco buoy. We underline the fact that the comparison with ERA5 data was only possible for the five buoys (Alistro, Capo Mele, La Revellata, Monaco, Bastia) that were able to record the mean wave direction; the other buoys measured only the peak wave direction, excluding the Cap Corse buoy, which did not record any wave direction. A noteworthy result was obtained for the Bastia coastal buoy: the circ-r is equal to 0.65 for the wave hindcast and negative for ERA5.

References

- Davolio, S.; Malguzzi, P.; Drofa, O.; Mastrangelo, D.; Buzzi, A. The Piedmont flood of November 1994: A testbed of forecasting capabilities of the CNR-ISAC meteorological model suite. Bull. Atmos. Sci. Technol. 2020.
- Drofa, O.V.; Malguzzi, P. Parameterization of microphysical processes in a non hydrostatic prediction model. In Proceedings of the 14th International Conference on Clouds and Precipitation, Bologna, Italy, 18–23 July 2004.
- User Manual and System Documentation of WAVEWATCH III; Version 5.16; Environmental Modeling Center: College Park, MD, USA, 2016.
- Turchi, A.; Masciadri, E.; Fini, L. Forecasting surface-layer atmospheric parameters at the Large Binocular Telescope site. Mon.Not. R. Astron. Soc. 2017.
- Wilks, D.S. Statistical Methods in the Atmospheric Sciences, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2011; Volume 100.
- Jammalamadaka, S.R.; SenGupta, A. Topics in Circular Statistics;World Scientific: Singapore, 2001; Volume 5, ISBN 978-981-02-3778-3.
- Climate Data Store. Available online: https://cds.climate.copernicus.eu/cdsapp#!/home.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The 40-year wave and wind hindcast will be used for different scopes such as climatological studies and extreme value analysis. The atmospheric data will be also compared against independent weather observations.

The data produced within the framework of the SPITBRAN Special Project, will be part of the request for the continuation of the research activity.