Nettuno: Analysis of a Wind and Wave Forecast System for the Mediterranean Sea

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ABSTRACT

Nettuno is a wind and wave forecast system for the Mediterranean Sea. It has been operational since 2009 producing twice-daily high-resolution forecasts for the next 72 h. The authors have carried out a detailed analysis of the results, both in space and time, using scatterometer and altimeter data from four different satellites. The findings suggest that there are appreciable differences in the measurements from the different instruments. Within the overall positive results, there is also evidence of differences in Nettuno performance for the various subbasins. The related geographical distributions in Nettuno performance are consistent with the various satellite instruments used in the comparisons. The extensive system of buoys around Italy is used to highlight the difficulties involved in a correct modeling of wave heights in Italy's coastal areas.

1. Purpose of the work

Nettuno is a high-resolution local-scale wind and wave forecast system operational in the Mediterranean Sea. Several parallel systems are available in this area, although often not on the whole basin. Some of these results are public domain (within limits), but a thorough analysis of the related performance is not a frequent product. A notable exception is the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) intercomparison exercise focused on wave model products managed by the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, United Kingdom; http://www.ecmwf.int/products/forecasts/d/charts/medium/verification/wave/intercomparison/). This comparison uses buoy data, and consequently for the most part it focuses its attention on the very coastal areas of the Mediterranean Sea. We have a different perspective. Our purpose is to analyze how a high-resolution forecast system can perform in the different geographical situations of a complicated basin as the Mediterranean. While our results are formally specific of the Nettuno system, we think they will be useful to provide an idea of the achievable accuracy and to show how a summary analysis can hide a much more detailed and variegated reality.

Our approach is straightforward. We use 18 months of daily operational products and compare them with all the measured data commonly and openly available. We proceed from a general view to a subbasin by subbasin analysis and from summary results to a more detailed check of Nettuno performance. While we did not study the details of the models to try to explain the physical and numerical reasons for the discrepancies—this would be at least an order of magnitude larger effort that is beyond the scope of our research—the final results provide a clear idea of the performance of the system and possibly a reasoned stimulus for further advances. After characterizing the Mediterranean area in section 2, section 3 provides a compact description of the Nettuno system. The available data are listed in section 4. Section 5, the bulk of the paper, analyzes the

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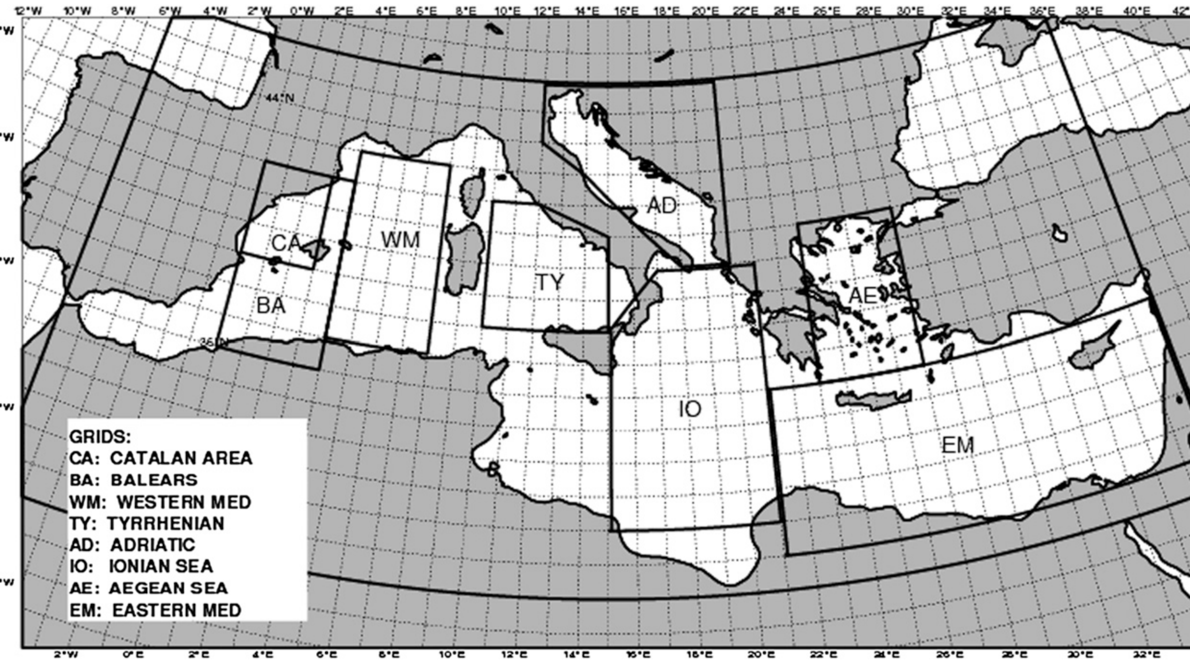

FIG. 1. Mediterranean Sea and subareas 1° resolution grid used in the study.

performance of the Nettuno system. Section 6 summarizes the main findings.

2. The Mediterranean area

Figure 1 provides a general view of the geometry of the basin. It spans more than 3500 km in longitudinal direction (6°W–36.5°E) and more than 1600 km in latitude (30°–46°N). The coasts on the northern side are very articulated, with protruding peninsulas and large islands. Besides, another obstacle to an accurate and reliable modeling of the area is the orography that characterizes its northern side (Pyrenees, Massif Central, Alps, Apennines, the Balkan Mountains, and the Turkish central region to mention the main systems). On its southern, African, side the only relevant ridge is the Atlas range toward its western end.

The sea is deep on most of the basin. The only shallow areas are the northern part of the Adriatic Sea (to the east of Italy), the Sirte gulf (Tunisia and Libya), and the Ebro (Spain) and Nile (Egypt) River exits to the sea. Also, here in most cases the waves are in deep-water conditions, except when closely approaching the coast.

From the meteorological point of view the Mediterranean is situated at the junction between the African tropical zone and the storm belt that characterizes central and northern Europe. Consequently, periods of calm and stormy ones alternate in the area. Most of the violent storms are associated with depressions moving from west to east; hence, the repetitive strong winds are mainly from the northern and westerly sectors. Southerly winds are often associated either with frontal conditions or to localized lows developing via cyclogenesis over the local relatively warm waters. On the whole, during most of the summer the Mediterranean does exhibit rather balmy conditions; however, winter and intermediate seasons can be remarkably stormy. While the local wave heights do not compare with heights in major Atlantic storms, they can be, and often are, much higher than expected. As a single example, during the Klaus storm (January 2009; see Bertotti et al. 2012) the maximum significant wave height H_s was with good reasoning, estimated to be more than 11 m.

3. The Nettuno modeling system

Nettuno is a state-of-the-art meteorological and wave forecast system based on the Consortium for Small-Scale Modeling (COSMO-ME) and WAM models (see appendix A for acronym definitions). COSMO-ME (http://www.cosmo-model.org/content/tasks/operational/usam/default.htm) is the 7-km CNMCA operational version of the nonhydrostatic regional model developed by COSMO (Steppeler et al. 2003) integrated over the European–Mediterranean area. COSMO-ME is initialized by the CNMCA analysis system and driven by the IFS forecast fields. The operational CNMCA data assimilation system was based on the three-dimensional variational data assimilation (3D-VAR) scheme (Bonavita and Torrisi 2005) and it has been replaced since 1 June 2011 by an

TABLE 1. Geographical boundaries of the areas in Fig. 1. Note also the inclined border for the Tyrrhenian, Ionian, and Adriatic Seas. The enclosed sections of the Bay of Biscay and Black Sea have not been considered in this study.

Location	Lat °N	Lon °E
Mediterranean	30°–46°	−6°–36°
Catalan	39°–42°	0°–3°
Balears	36°–42°	0°–4°
Western Mediterranean	37°–43°	4°–8°
Tyrrhenian	38°–42°	10°–15°
Adriatic	40°–46°	12°–20°
Ionian	32°–40°	15°–21°
Aegean	36°–41°	23°–27°
Eastern Mediterranean	31°–36°	21°–36°

TABLE 2. Meaning of the symbols for statistical analysis used in Tables 3 and 5. Their definition is given in appendix B. The *X* is the measured and *Y* is the model value.

NUM	No. of samples
YM	Mean model value
STDY	Std dev of *Y*
XM	Mean measured value
STDX	Std dev of *X*
SSLO	Symmetric best-fit slope of *Y* vs *X*
RMSE	Root-mean-square error
BIAS	Bias
CORR	Correlation coefficient
SI	Scatter index

ensemble data assimilation technique based on the LETKF algorithm (Bonavita et al. 2008, 2010).

WAM (Komen et al. 1994) was the first so-called third-generation wave model, where each physical process is fully and singularly described with a minimum of parameterization. It is a spectral model, amply described in the literature [see, among others, The WAMDI Group (1988) and Janssen (2008)]. In Nettuno WAM is run with 36 directions and 30 frequencies starting from ≈0.05 Hz then increasing with a 1.1 geometrical progression. It is forced with 3-hourly COSMO-ME winds. The regular geographical grid covers the area between 30° and 46°N and −6° and 36.5°E. The 3′ resolution corresponds respectively to 5.5 and 4 km. Nettuno is integrated twice a day (starting at 0000 and 1200 UTC) for a 72-h forecast. [Three-hourly forecast plots of wind and wave fields (significant wave height, mean period, and direction) are available online at http://www.meteoam.it and http://ricerca.ismar.cnr.it/MODELLI/ONDE_MED_ITALIA/ONDE_MED_ITALIA.php.]

4. Data used for the analysis

As mentioned in section 1, the JCOMM intercomparison exercise provides overall statistics of the performance of several operational systems by comparison with a number of buoys. Our approach is different. We use scatterometer and altimeter data to assess, within the limits later discussed, the quality of the Nettuno wind and wave fields in the various areas of the Mediterranean Sea. The data are from ASCAT and the *Jason-1*, *Jason-2*, and *Envisat* altimeters. The scatterometer data have been retrieved from the ECMWF archive, the altimeter data via the service provided by the Delft University (http://rads.tudelft.nl/rads/rads.shtml). In addition, we use the extensive Italian wave buoy system (15 of them) to explore how model results vary close to the coast.

We focus on the 18-month period between September 2010 and February 2012. Each datum is identified by date–time and geographical coordinates (for the scatterometer the center of the $25 \times 25\,\mathrm{km}^2$ area of each measurement). The model data, available at 3-h intervals, have been linearly interpolated in space and time to match the datum ones. These collocated data have been the reference for our analysis.

Our reference period, September 2010–February 2012, practically includes two winters and one summer. The implications on the overall statistics are briefly discussed in section 6. We have evaluated both overall and seasonal performance.

5. Analysis of results

First we focus our discussion on the 0–12-h forecast range. More specifically, the results for +3, +6, +9, and +12 h forecasts. Then we will discuss how the performance varies with the full forecast range.

For our analysis we have identified eight subareas in the Mediterranean. They are shown in Fig. 1 and listed, with their limits, in Table 1. Besides giving a flavor of the performance in different part of the basin, some of these have been selected for their peculiar situation, as the Adriatic Sea (enclosed sea with bordering orography), the Aegean Sea (bordering orography and many islands of different size), and the Catalan coast (difficulties for a detailed modeling of the area).

Table 2 lists the statistical parameters used for the comparison, which are fully defined in appendix B.

a. ASCAT observations

Table 3 summarizes the overall results from the comparison with the scatterometer measured wind speed U10. There is a slight underestimate by the model, −4% on the average, with the symmetric best-fit slope (SSLO) showing some evident variability from area to area (±2%). Notable for later discussion are the

TABLE 3. Statistics of the comparison between model results (Y) and corresponding ASCAT measured wind speeds (X). Units are in m s^{-1}. See Table 2 for the meaning of the various parameters. The locations in the first column are shown in Fig. 1.

Locations	NUM	YM	STDY	XM	STDX	SSLO	RMSE	BIAS	CORR	SI
Mediterranean	1 141 482	6.75	3.44	7.09	3.15	0.96	1.53	−0.34	0.90	0.22
Catalan	14 158	6.27	3.33	6.39	2.85	0.98	1.88	−0.12	0.83	0.29
Balears	65 469	6.63	3.34	6.84	2.94	0.97	1.69	−0.21	0.86	0.25
Western Mediterranean	49 591	7.65	4.10	7.90	3.76	0.98	1.62	−0.24	0.92	0.21
Tyrrhenian	95 278	6.47	3.44	6.68	3.09	0.97	1.60	−0.20	0.89	0.24
Adriatic	25 797	6.36	3.41	6.65	2.91	0.96	1.80	−0.29	0.85	0.27
Ionian	266 047	6.58	3.34	7.02	3.11	0.94	1.54	−0.44	0.90	0.22
Aegean	17 783	7.79	3.66	8.05	3.23	0.97	1.64	−0.26	0.90	0.20
Eastern Mediterranean	329 667	6.39	3.05	6.75	2.82	0.95	1.40	−0.36	0.90	0.21

relatively low values of the Ionian and eastern Mediterranean, with low scatter index (SI) values. Note the low SI (0.20) in the Aegean Sea, and the relatively large values in the Adriatic and on Catalan areas. Model wind directions (not shown) are generally consistent with the measured ones, the larger errors are found in the enclosed basins and in coastal areas. When looking at seasons (not shown) SSLO are about 2% higher in winter and correspondingly lower in summer. The SI with an opposite trend (lower in winter, higher in summer), follow accordingly. Also the wind direction statistics are better in winter.

The 0.98 SSLO value for Catalonia in Table 3 can be misleading. We realized the local difficulties by repeating the local analysis according to wind (flow) direction. Considering four 90° sectors, the SSLO calculated for north, east, south, and west are 1.07, 1.01, 0.87, and 0.96, respectively (with similar number of cases). We hypothesize that the Pyrenees to the north are substantially affecting the winds from that direction.

CONCLUSIONS

- The model performs better in stormy conditions, with well-defined patterns and stronger winds.
- Coastal areas, particularly those with a pronounced orography and under certain conditions, show poorer results than the open seas.

b. *Altimeters (*Jason-1*,* Jason-2*, and* Envisat*)*

For each satellite a similar analysis as for ASCAT has been done, extended to wind speed and significant wave height. Table 4 reports the summary best-fit slope results for the whole Mediterranean (buoy results will be discussed later). Clearly there are inconsistencies. However, each figure is derived from a large number of data (18 months) and it is, therefore, pretty robust. At the same time, the differences we find among the various altimeters as well as, the wind speed scatterometer results being much larger than expected cannot be justified on the basis of the expected statistical accuracy of the best-fit slopes. This suggests that the accuracy of the measured wind data we can rely upon is of the order of at least several percent. This may overshadow the errors found in the model estimates. The differences for the wave SSLO are more limited, but they are not always consistent with the corresponding wind values.

It is valuable to look at the full table for wave results, shown in Table 5 for *Jason-1*. We see that the best-fit slopes vary substantially from area to area, with the largest overestimate in the Aegean and Catalonia. This overestimate of the significant wave height H_s in the Aegean is consistent for all the altimeters. Because this is not the case for wind, we hypothesize that the large errors in the model results for the Aegean Sea are a result of the large number of islands there present. The model grid does not adequately resolve these features (designated by land) or consistently replicate the shadowing effect. Depending on the elevation of the islands, there could also be local orographic effects on the wind. However, given the orography of most of the islands, we consider this a less important effect. For Catalonia the problem is related to the wind, with SSLO 1.08 and 1.10 for wind and waves, respectively. We also point out the relatively low values (1.00) of the Ionian and eastern Mediterranean and recall our previous similar comment for ASCAT wind. Indeed a similar result is found for every satellite and for both wind and waves.

Looking again at Table 5, we note that the lowest correlation factors and largest scatter indices are found

TABLE 4. Symmetric best-fit slopes from the comparison between model results and measured data. U10 wind speeds and significant wave heights are used for wind and waves, respectively.

	ASCAT	*Jason-1*	*Jason-2*	*Envisat*	Buoys
Wind	0.96	1.03	0.91	0.98	—
Waves	—	1.02	1.02	1.05	1.01

TABLE 5. As in Table 3, but for model results (Y) and corresponding *Jason-1* altimeter measured significant wave heights (X). Units are in meters.

	NUM	YM	STDY	XM	STDX	SSLO	RMSE	BIAS	CORR	SI
Mediterranean	118 491	1.53	0.96	1.51	0.82	1.03	0.38	0.02	0.92	0.25
Balears	8448	1.46	0.86	1.39	0.72	1.06	0.38	0.07	0.90	0.27
Western Mediterranean	13 839	1.99	1.28	1.90	1.09	1.06	0.44	0.08	0.94	0.23
Tyrrhenian	7925	1.56	0.90	1.51	0.72	1.05	0.41	0.05	0.90	0.27
Adriatic	5129	1.35	0.76	1.31	0.58	1.05	0.41	0.04	0.85	0.31
Ionian	22 664	1.56	0.95	1.58	0.85	1.00	0.36	−0.02	0.92	0.23
Aegean	5818	1.52	0.92	1.41	0.68	1.10	0.46	0.11	0.89	0.32
Eastern Mediterranean	30 218	1.38	0.84	1.40	0.72	1.00	0.34	−0.02	0.92	0.24
Catalan	2343	1.34	0.68	1.22	0.53	1.10	0.37	0.12	0.86	0.30

in the Adriatic, Aegean, and Catalonia. Although for different reasons, this points to the modeling difficulty in these areas.

We want to explore further if the differences we find from area to area are indeed a characteristic of the various subbasins or if they are chance results. At this aim we plot in Fig. 2 all the best-fit slopes and scatter indices, for both wind and waves, as a function of the area. It is clear that, independent of the specific satellite, hence instrument, there is a well-defined pattern that is area dependent. Beside the expected similarity between the wind and wave patterns, there is an obvious tendency to have larger SI values when the best-fit slopes show the largest variations from unity. This suggests that the two results are related and are indeed area dependent, pointing to higher difficulties in modeling certain parts of the Mediterranean.

Having characterized how Nettuno performs in the first 12 hours of the forecast, we now explore how its performance varies with longer forecast periods. In particular, we analyze the six 12-h intervals: 0–12, 12–24, 24–36, 36–48, 48–60, and 60–72h. For each interval, we investigate the +3-, +6-, +9-, and +12-h extent with respect to the initial forecast time (e.g., for the forecast interval 36–48 h we examine the +39-, +42-, +45-, +48-h forecasts).

Figure 3 shows the overall best-fit slopes and scatter indices for the ASCAT wind speeds and the *Jason-2* significant wave heights. It is clear that, while the SSLO values show some very limited variability, the SI values are steadily climbing with the extent of the forecast. The lack of any definite trend (and this is the case for all the satellites and for both wind and waves) suggests that the limited variability of SSLO can be attributed to statistical reasons. On the contrary, the obvious "growth with range" of the SI values shows the deterioration of the forecast, at least in term of "where and when." As an example, the meteorological model can correctly forecast the development of a low that can, however, be misplaced and "mistimed." In the "goodness of fit" analysis this will result in a best-fit slope similar to a "no space and time error" forecast, but with a larger scatter of the data. For Nettuno we have found that the SSLO values do not vary more than 2%, at most 3%,

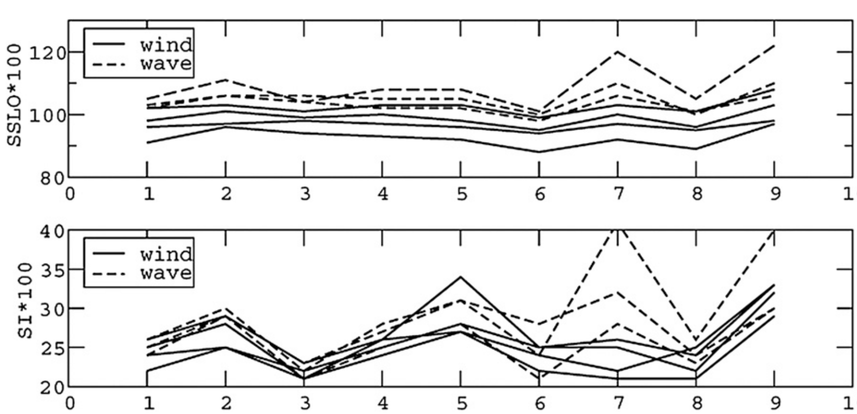

FIG. 2. Best-fit (top) slopes and (bottom) scatter indices (both × 100) between Nettuno wind and waves and the corresponding measured data from the various satellite instruments. Each line corresponds to a given instrument. The 1–9 numbers on the x axis are the location sequence used in Table 3. Figure 1 gives their geographical location.

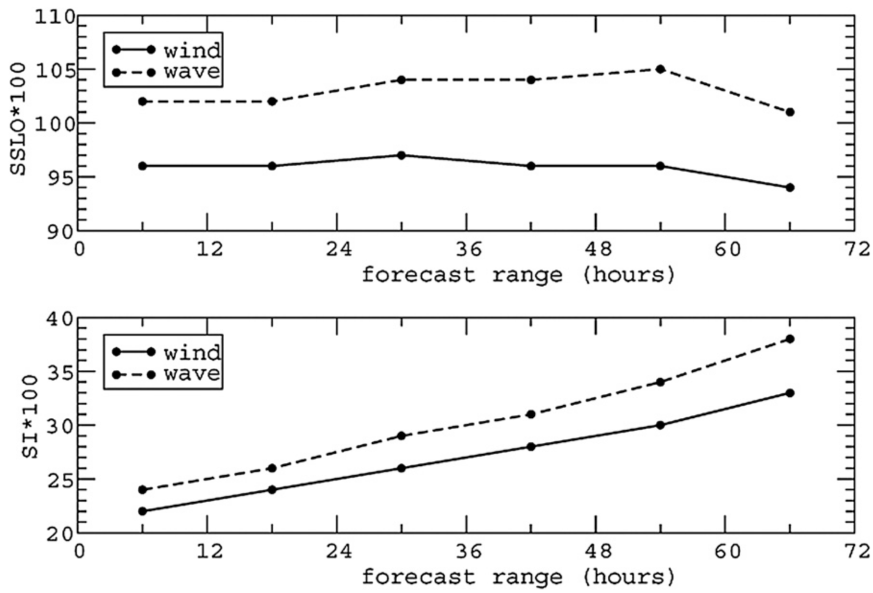

FIG. 3. (top) Best-fit slope and (bottom) scatter index of Nettuno wind and waves versus scatterometer and altimeter measured data, respectively, as a function of forecast time.

throughout the forecast range, without any indication of trend. This suggests that the meteorological model is a self-consistent machine, without any artificial progressive increase or loss of energy in time, at least in the surface layer. On the contrary the scatter index for wind speed increases 2–2.5 (SI $\times$ 100) with each 12-h increase of the forecast range. A slightly larger figure ($\sim$3) is found for the significant wave height, showing the sensitivity of the wave field to also limited variations of the input wind fields. This result is rather solid and consistent for all the satellites we have considered. A similar result (not shown) has been found for each of the considered subareas (see Fig. 1 and Table 3). However, we also found a larger variability (scatter) of the SSLO values in the areas where the slope differs more from unity.

CONCLUSIONS

- There is a different level of performance in different areas of the Mediterranean.
- This depends on the geometry and orography of the single subbasins (wind, hence wave, fields), for wave. It also depends on the lack of sufficient resolution in detailing the many smaller islands in the Aegean Sea.
- Within the limits of the statistics of the fit, the best-fit slopes do not change along the forecast, suggesting that COSMO is self-consistent in time, without any artificial increase or loss of energy.
- The scatter indices increase with the extent of the forecast, suggesting expected, but limited, growing errors in the where and when details of the forecast.

c. Buoys

Close to the coast the performance of Nettuno depends on the local geometry. As said in section 4, we explore this aspect in more detail analyzing the model comparison with the large set of buoys distributed all along the coasts of the Italian peninsula and main islands (Bencivenga et al. 2012). This distribution (see www.telemisura.it) is

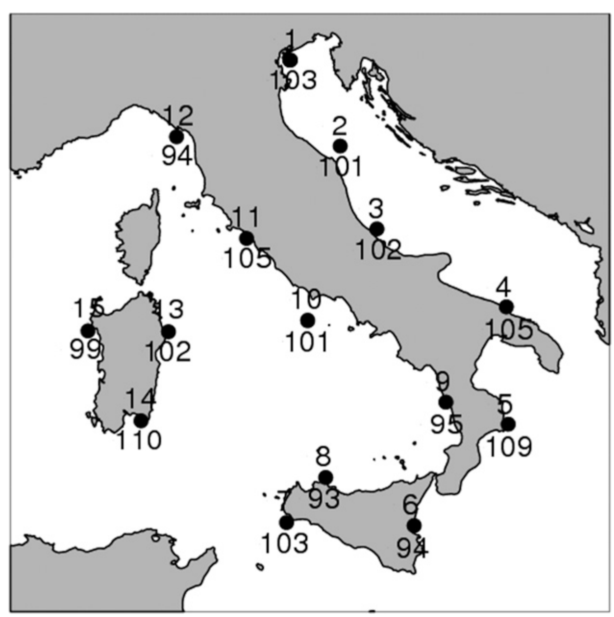

FIG. 4. Numbering (1–15) of the buoy network around the Italian peninsula with corresponding best-fit slopes ($\times$100) of the Nettuno wave heights vs the buoy measured data.

TABLE 6. Best-fit slope SSLO (×100) and scatter index SI for the comparison between model and buoy measured significant wave heights at the 15 buoys shown in Fig. 4. All is for the overall fit.

Buoy	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	All
SSLO	103	101	102	105	109	94	103	93	95	101	105	94	102	110	99	101
SI	27	28	30	30	36	28	27	25	25	26	31	26	27	35	21	29

shown in Fig. 4. All the buoys are moored in deep water, but at only a few kilometers off the coast. They are Triaxys buoys (see http://www.axystechnologies.com/BusinessUnit/AXYSMarineEnvironmentalMonitoring/WaveCurrentWaterLevelMonitoringSolutions/TRIAXYSDirectionalWaveBuoy.aspx). With some short period of interruption, the network has been in operation since 1989. The nominal heave accuracy is 2%.

Figure 4 shows the position of the buoys, numbered from 1 to 15, along the Italian coastline. For each buoy the best-fit slope (×100) of model versus buoy significant wave heights is shown. Table 6 reports the same information plus the scatter index and the overall average values. Although on the average correct (a 1.01 SSLO is a very good result), there is an evident large variability of performance. On one hand this reflects the different level of performance in the various areas we have derived from the comparison with satellite data. On the other hand it seems to depend on the specific position of the buoy within the local geometry and the resolution with which this is represented in the model grid. Two opposite examples are given by buoys 13 and 14. Buoy 13 is well exposed to the locally dominant easterly sector winds. Therefore, together with the positive performance of COSMO-ME in the Tyrrhenian Sea (see Fig. 2), this ensures the local good results (SSLO = 1.02, SI = 0.27). On the contrary the coastal geometry at buoy 14 is not well represented in the WAM grid (see Fig. 5). The seemingly minor difference between the true and model coastline is sufficient to expose in the model the (point close to the) buoy position to the easterly waves more than is actually the case. Hence, the evident overestimate (Fig. 4 and Table 6) of the model significant wave heights.

The lack of shadowing becomes manifest looking at the wave directional distributions at the buoy and at the close-by grid point (Figs. 6a and 6b, respectively). Note in Fig. 6b the large contribution directed to 300° almost absent in the buoy diagram.

As a positive counterexample we report the buoy and model distributions (Figs. 6c and 6d, respectively) where a good positioning off a straight coastline ensures a faithful representation of how the energy is spread among the various directions. Similar arguments hold for most of the buoys (see Fig. 4). Buoy 5 is very close to a promontory. Buoy 6 is enclosed within a small bay. Another common problem is the distance from the coastline, for logistical reasons often limited to a few kilometers. In these conditions the approximation of the grid is likely to lead to nonnegligible fetch differences when, following the main meteorological patterns, the wind is blowing from the coast.

More related to the meteorological model is the difficulty present in properly modeling the local meteorological events (e.g., the land–sea breezes). This would suggest an underestimate on the low value range, both for wind and waves. Indeed, as seen in some directional distributions (not shown) and soon further discussed in this section, this is what we found. Together with the nominal and actual accuracy of the buoys in this range, this can be a reason for the underestimate we see at some buoy positions.

In this respect it is worthwhile to look at the scatter indices in Table 6. Note first the large scatter index at buoy 14, the one with the missing peninsula in the grid we have just discussed. We interpret this as a clear sign of the local poor representation of the specific local conditions. This suggests another diagram, shown in Fig. 7, where we have plotted the scatter index at the various buoys as a function of the corresponding best-fit slope. The diagram is clearly suggestive of a correlation between a poor, high or low, best-fit slope result and an increase of the corresponding scatter of the data.

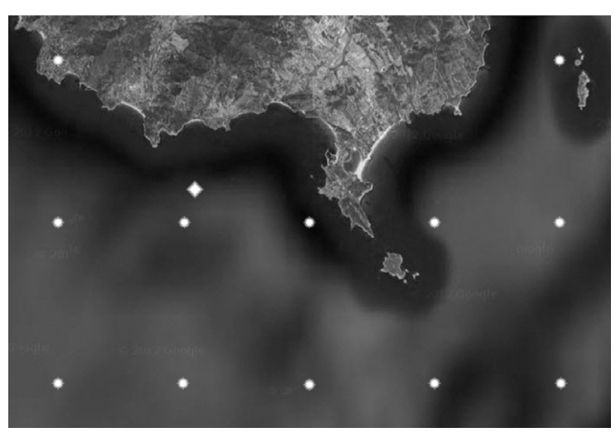

FIG. 5. Satellite view of area near buoy 14 (white diamond; see Fig. 4) and the nearby grid points in the Nettuno WAM wave model (circles) located at an interval of 1/20°.

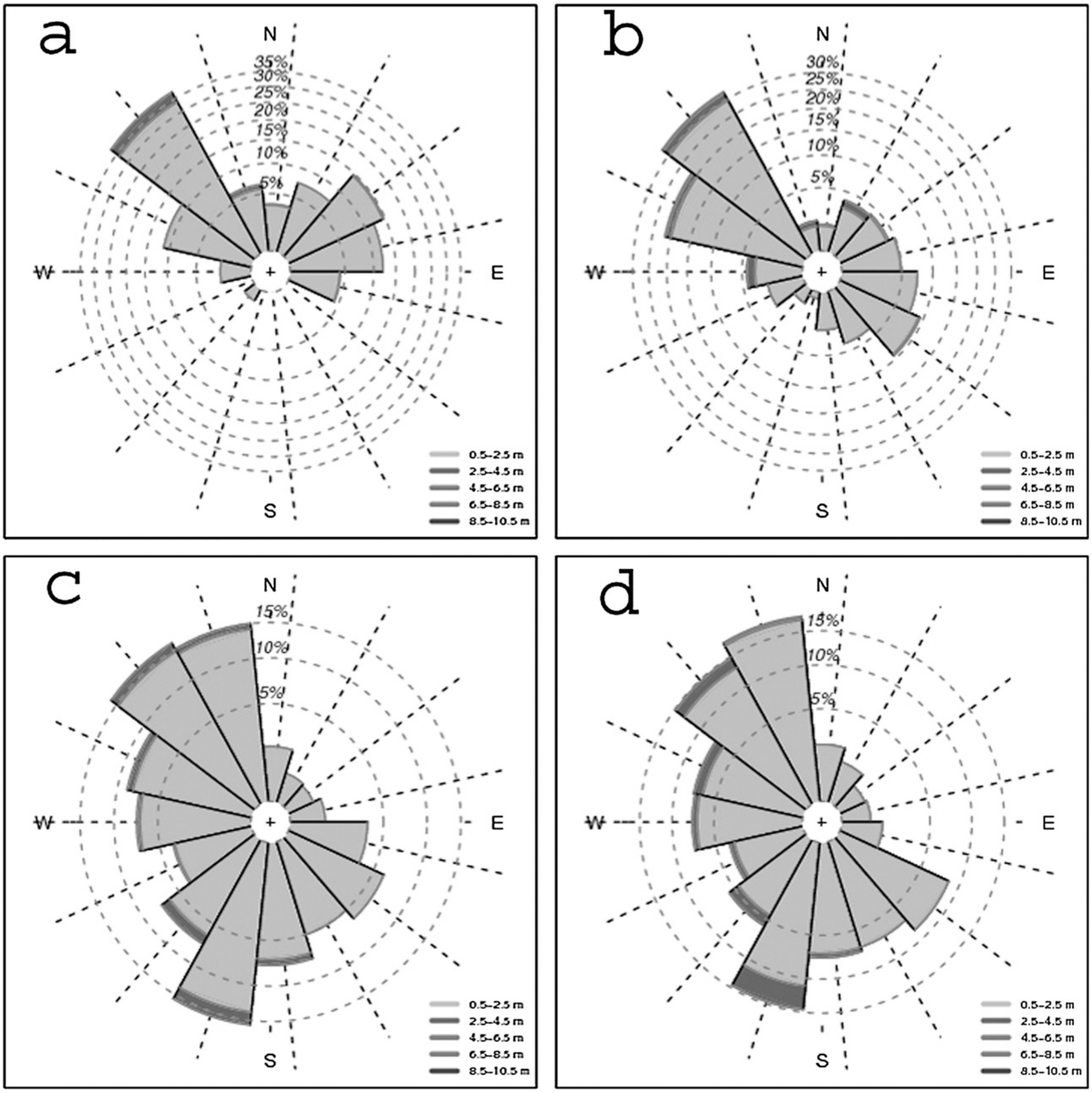

FIG. 6. (a) Buoy-14 measured and (b) Nettuno wave model directional wave distributions at and close by to buoy 14 in Fig. 5. (c),(d) As in (a),(b), but for buoy 13 (see Fig. 4 for its position).

Looking at how the coastal performance of the model depends on the season, we have found on average a 3% lower best-fit slope in summer. We interpret this as further confirmation of the lack of sufficient representation of the local meteorological events in summer.

CONCLUSIONS

- The coastal performance of Nettuno depends on the local geometry and the corresponding representation in the wave model grid; that is, small differences, still justified by the grid resolution, may be sufficient to significantly alter the local results.
- Well-exposed buoys, facing dominant incoming winds, perform well pointing to a good wind and wave representation in the Nettuno system.
- This holds for both wave height and direction.
- Slightly lower model wave heights in summer hint to a partial lack of coastal breezes in COSMO.
- A good performance in best-fit slope is preferentially associated with a similar result for scatter index.

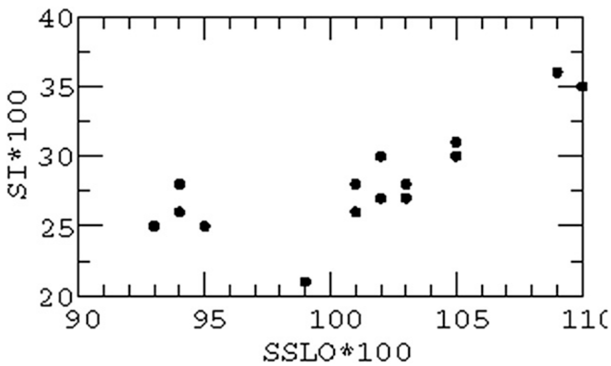

FIG. 7. Relationship between the scatter index SI and the best-fit slope SSLO (both ×100) for the various buoy positions shown in Fig. 4.

d. Performance according to wave severity

Until now we have analyzed the overall performance of the models, independent of the severity of the conditions. Now, as a final step, we explore how the COSMO and WAM models perform for low and high wind speeds and wave heights, respectively. Fig. 8 shows the scatter diagrams for wind (ASCAT, Mediterranean) and waves (buoy 15 in Fig. 4). Both diagrams represent the whole year. Note that in the two fits we have neglected U10 and H_s values lower than $2\,\mathrm{m\,s^{-1}}$ and 0.5 m, respectively.

Looking at the ASCAT diagram we note a marked tendency for underestimating the low wind speeds and overestimating the high ones. As a matter of fact our best fits have been done forcing the line through the origin. An $a + bx$ fit would have likely led to a steeper slope and to a negative y intercept. We preferred the simpler $y = bx$ expression as more physically consistent. On the whole, Fig. 8 suggests that a nonlinear fit as $y = ax^b$, with $b > 1$, would better represent the actual trend of the COSMO model.

As expected, this is reflected into the WAM performance, shown for buoy 15 and the whole period. Again, although less marked, there is an underestimate of the low wave heights (between 2- and 3-m H_s). The model excess in the large value range is much more evident. This tendency is pretty robust, basically found for the large majority of the buoy stations and for all the subbasins and considered satellites. Note that, because of the few data in the upper range, we have limited our analysis to the $H_s \leq 6$-m range. However, data points at the top of the graph are evident (two model H_s values >8 m).

CONCLUSION

- Nettuno has a limited, but marked, tendency to underestimate low wind and wave values and to overestimate the high ones.

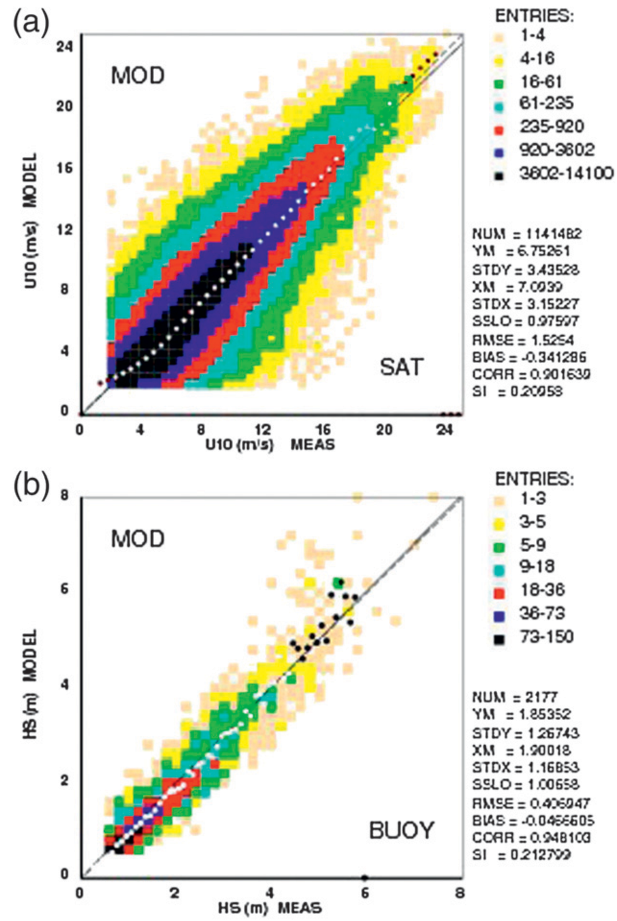

FIG. 8. Scatter diagrams of Nettuno (a) wind vs ASCAT measurements and (b) wave height vs buoy 15 in Fig. 4 measurements. The dots, white or black depending on the underlying background, show the mean model value in each measured bin.

6. Summary

The extensive comparison between measured and Nettuno wind and wave data has led to a number of conclusions. In general these are rather solid. However, because of errors in the measurements and sample variability, the reported figures should only be considered as good approximations of the truth.

We have considered 18 months of wind and wave model data at 3-h intervals. This has been done at different forecast ranges, from 12 to 72 h at 12-h intervals. The measured data have been derived from ASCAT (wind), *Jason-1*, *Jason-2*, and *Envisat* altimeters (wind and waves), and from 15 buoys (wave) distributed along, and close to, the Italian coastline. Satellite data have been used for deriving conclusions about the various subbasins of the Mediterranean Sea. The comparison with buoy data has provided useful examples of how models perform close to the coasts.

The use of different satellite data has also implied a comparison of their accuracy (differences) that, by and large, is (are) of the order of a few percent. A notable exception is the winds from *Jason-2* that, with reference to both the other satellites and the model results, seem to be substantially overestimated (confirmed by S. Abdalla, ECMWF, 2013, personal communication). While used to derive the relative consistency, these data have not been used to quantify the performance of Nettuno.

In general Nettuno performs well, with differences from measurements, both satellites and buoys, of the order of a few percent. However, things change when we look at the single subareas of the Mediterranean. The comparison with ASCAT winds, especially considering the best-fit slopes and the scatter indices, indicates that some areas are easier than other ones. As expected, we find problems (slight underestimates) in the enclosed areas where prominent orographic features affect the wind passing above or around them before reaching the sea. A surprising result is the limited, but marked (4%–5%), underestimate in the Ionian Sea and the eastern Mediterranean (see Fig. 1 for area definition). This result is robust as confirmed by the altimeter wave data at least in relative terms.

Another robust result, derived from both wind and wave comparison with measured data, is the tendency of Nettuno to slightly underestimate the low values and to overestimate the large ones. On the whole these two characteristics compensate for each other, but, if limited to one of the extreme (low or high) ranges, the differences from the measurements would be larger than reported above.

The wave model results follow accordingly, but according to altimeter comparisons with only a slight (2%–3%) excess in wave height. However, the corresponding figures vary substantially (several percent) from basin to basin, and, as expected, more than for wind. Consistently with the wind, the lowest figures (best-fit slopes model vs altimeter) are on the Ionian and eastern Mediterranean. In a way these figures are puzzling. They are perfect unitary values, and this is what one would expect given that these are the most open areas, where the meteorological model, not affected by coasts and orography, is expected to perform better. On the other hand, if so, we cannot justify the overestimate in all the other basins. However, there is one exception, the Aegean Sea. The lack of representation in the wave model of many of the small islands scattered throughout the sea implies a lack of shadowing, hence, an excess of wave heights.

Another interesting example is the Catalan coast where the performance (best-fit slope) varies substantially (from 0.87 to 1.07 for wind) according to direction. From a more general point of view, the intercomparison with the Italian wave buoys has shown how critical the correct representation of the coastline is to derive meaningful results in coastal areas. This enhanced local variability suggests an obvious conclusion: that, to be really representative of the general situation in the area, the waves at the buoy position should never be affected by the close-by coastline features.

For our comparison in the low value range a limiting factor has been the frequent proximity (a few kilometers) of the buoys to the coast. Especially in areas where the wind blows frequently from the coast, the model grid resolution is an obvious limitation leading to some local apparent under or overestimates. In the longer term an unstructured grid would be the natural solution. In this respect and for what concerns the low wave height range, also the possible lack of a proper representation of the local meteorological events in the COSMO model is a reason for wave underestimates in this range.

The results vary appreciably from satellite to satellite. However, the relative performance in the various subbasins seems to be a rather robust feature as we found it consistently and coherently in the comparison with the various sources.

Considering the variability of the performance with the forecast range, the results suggest that COSMO is a consistent model, without any evident artificial increase or decrease of energy in the system. As expected, the scatter index increases with the forecast range, typically of 2%–2.5% for wind and 3% for waves, for each 12-h increase in the forecast. We suggest this to be mainly due to increasing errors in ''where and when'' a specific event takes place (i.e., in time and space), rather than missing or producing a nonexistent event.

We have wondered if having two winters and one summer could affect the overall statistics. We consider this not to be the case, at least at an appreciable level, for two reasons. In the first stage of this analysis, before having the second winter at disposal, we had analyzed only the first 12 sequential months. Although not done to the same extent as for the full period, the results did not show appreciable differences with respect to the ones here reported. Then, on a more climatological basis, the extended Mediterranean summer makes the considered temporal extent of mild weather not so different from the addition of two winters.

Our main conclusions are as follows:

- Satellite data (wind and wave) varies appreciably according to the specific instrument.

- In general Nettuno performs well, both for wind and waves, with a limited tendency to overestimate wave heights.
- There are differences from basin to basin, the lowest wind speeds, and wave heights (from the model) found in the Ionian Sea and the eastern Mediterranean.
- Still within the variability among the satellite instruments, the relative performance in the different basins is a rather well-assessed fact.
- Nettuno, for both wind and waves, has a limited, but evident, tendency to underestimate the low, and to overestimate the large, values.
- The comparison with the buoy data has highlighted the difficulties of coastal modeling in geometrically complicated areas; and also, especially in these cases, the convenience of mooring the buoys further off the coast to obtain data well representative of the overall area.
- Nettuno performs consistently within the forecast range, with only a limited increase in time of the scatter index with respect to the measured data.

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APPENDIX A

Definitions of Acronyms

ASCAT — The Advanced Scatterometer is a satellite-borne real aperture radar, operating at 5.255 GHz (C band) and using vertically polarized antennas. Operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), it measures wind speeds in two 500-km-wide swaths, on each side of the satellite ground track.

CNMCA — Centro Nazionale di Meteorologia e Climatologia Aeronautica (National Centre for Air Forces Meteorology and Climatology). It is the operational section of the Meteorological Service of the Italian Air Forces. It also acts as the National Meteorological Service.

Envisat — The *Environmental Satellite* is the largest satellite launched by the European Space Agency (ESA). With 10 instruments on board and an 8-ton weight, it is the largest civilian Earth observation mission. Launched in 2002, it stopped transmitting data on 8 April 2012.

IFS — The Integrated Forecast System of the ECMWF. This comprehensive earth-system model developed at ECMWF forms the basis for all the local data assimilation and forecasting activities.

LETKF — The local ensemble transform Kalman filter is an advanced data assimilation method for many possible applications. It has been tested with numerical weather prediction models at global scales.

WAM — It was the first Wave Model (spectral) of the so-called third generation. The aim was, and still is, to describe the physical processes (generation, dissipation, nonlinear interactions, and advection) on the base of only physical principles, reducing as much as possible the related parameterizations.

The WAMDI Group — The informal group of wave modelers who collectively developed the first version of the WAM model.

APPENDIX B

Definitions of Acronyms Listed in Table 2

Definition of the parameters listed in Table 2: X is the measured and Y is the model value. Summations refer to all the NUM data:

$$\mathrm{NUM} = \text{number of samples}$$

$$\mathrm{YM} = \frac{\sum Y}{\mathrm{NUM}}$$

$$\mathrm{STDY} = \sqrt{\frac{\sum (Y - \mathrm{YM})^2}{\mathrm{NUM}}}$$

$$\mathrm{XM} = \frac{\sum X}{\mathrm{NUM}}$$

$$\mathrm{STDX} = \sqrt{\frac{\sum (X - \mathrm{XM})^2}{\mathrm{NUM}}}$$

$$\mathrm{SSLO} = \sqrt{\frac{\sum Y \times Y}{\sum X \times X}}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum (Y - X)^2}{\mathrm{NUM}}}$$

$$\mathrm{BIAS} = \mathrm{YM} - \mathrm{XM}$$

$$\mathrm{CORR} = \frac{\frac{(X - \mathrm{XM})(Y - \mathrm{YM})}{\mathrm{NUM}}}{\mathrm{STDX} \times \mathrm{STDY}}$$

$$\mathrm{SI} = \frac{\mathrm{RMSE}}{\mathrm{XM}}.$$

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