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The predictability of meteo-oceanographic events

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Abstract We have explored the predictability of storms in a small enclosed basin with a complicated surrounding orography. We have considered two exceptional storms in the far past and three mild events happened in recent years. A posteriori forecasts have been done up to 6 days before the events. The results have been compared versus measured data and the related analysis. Good predictability (10–15% error in surface wind speed and wave height) have been found up to day 4, mildly larger (<30%) up to day 6 before the event. In no case was a storm missed. This suggests that the effective predictability in more open basins may extend to even larger ranges.

Keywords Wind · Wind waves · Storms · Predictability · Enclosed basins

1 Introduction

We analyse the predictability of meteo-oceanographic events. In particular, we focus on sea storms and want to see how far in advance we can expect to have a useful forecast and how much this depends on the intensity of the storm and on the location of interest. Global operational models, meteorological almost always with coupled wave models, have been running for years, producing both analysis and forecast fields, typically till 10 days in advance. Hence in principle, extensive datasets are available and a related statistics should be a straightforward matter. In practice, things are not so simple. First of all, the resolution of these models has changed in time, typically every 3 or 4 years, following the improvements of the available computer power. This has implied that also the quality of the analysis and forecast fields have been changing, generally improving, in time, and we want to assess the present state of the art. Then, and in some conditions more importantly, the level of predictability varies considerably from place-to-place, being strongly dependent on the size of the basin and on its geometry and surrounding orography. For these reasons, in this paper we focus on the expected worst conditions, i.e. a small enclosed basin surrounded by relevant mountain ridges. It is reasonable to assume, and statistics show this clearly, that this is indeed the case. Evidence is provided, among others, by the geographical distribution of the calibration factors required by the analysis wind and wave values of the European Centre for Medium-Range Weather Forecasts (Reading, UK, henceforth ECMWF) in the Mediterranean Sea (Cavaleri and Sclavo 2006).

We have pointed out above that statistics are available, at least for the years the latest model resolutions have been used. However, practical experience (see, e.g. Cavaleri and Bertotti 2006) shows that also with the latest resolution the modelled surface wind speeds, the dominant factor for the related oceanographic events, are often underestimated. Indeed we have been running for many years a wave forecast model in the Adriatic Sea (see, e.g. Bertotti et al. 2010). The input winds were and are the ones produced by ECMWF, suitably corrected, as wind speeds, according to resolution on the base of cross-comparisons between different resolutions and with extensive, wind and wave, and in situ measured data. This too could be a useful dataset

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(although using corrected wind speeds); however, our forecast range was 3 days, only recently updated to 5 days, while the range we want to explore is longer. Last, but not least, we want to explore also the realm of the ensemble approach to see if, albeit with a lower resolution, this may further extend the useful predictability range, at least in a probabilistic sense.

In recent years, the improved modelling capability and the steadily increasing computer power have led to substantially modelling efforts, especially for the past. A number of papers have been produced discussing different methodologies and the related results in various aspects of the problem. See, among others, Bertotti et al. (2011), Cavaleri et al. (2010), Bertotti and Cavaleri (2009), De Zolt et al. (2008), Horsburgh et al. (2008), and Bajo and Umgiesser (2010). Our present purpose is to summarise the situation providing, in a concise but clear way, a picture of the present situation.

All the above led to the following approach. We have chosen a number of storms (five), including both extreme and mild events, in past and recent times. Each one of these storms has been modelled with a coupled meteorological wave model system. The a posteriori forecasts have been issued starting from the data available in the days previous to the storms, in some cases newly analysed at a resolution higher than available at the time and comparable with the one recently used. We have explored both analysis and forecast fields, till a 6-day forecast range. Both deterministic and ensemble forecasts have been used. The modelled data have been validated versus measured wind and wave values. When, for the past storms, these are not available, also a storm surge model has been used (tidal data have been available for a long while).

After providing in Section 2 a very compact description of the area of interest; in Section 3, we briefly describe the selected storms. The models used for the numerical simulations are indicated in Section 4. In Sections 5 and 6 we provide respectively the deterministic and ensemble results. The paper is concluded (Section 7) with a discussion on the conclusions derived from this study.

2 The Adriatic Sea

The enclosed basin (see Fig. 1) between the Italian peninsula to the West and the Balcan countries to the East is about 750 km long (northwest to southeast direction) and 200 km wide. Deep in its central and southern part, it is shallow in its northern section, the bottom sloping up with about 0.1% inclination.

Two winds, bora from northeast, sirocco from south-east, dominate the situation. The classical storms leading to the flooding of Venice and its lagoon, on the northern side, are characterised by sirocco on most of the basin, often turning to bora on its more northerly part. The wind distribution is strongly forced by the bordering orography with the Apennins ridge on the Italian side, the Alps to the north, and the Balcan mountains to the east. Cross-sea conditions are often present in the gulf of Venice. These are associated to sirocco storms, the wind then veering to bora ("bora scura") in the most northerly part of the basin. Then in this area, we find long, well-developed waves from south-east superimposed to the locally generated wind waves from east or northeast. This leads to quite challenging conditions for an extended forecast range, as minor variations of the wind fields may lead to substantially different marine conditions. A full description of the basin and its related meteorology/oceanography can be found in Cushman-Roisin et al. (2001) and Cavaleri et al. (2010).

3 The selected storms

Following what was said in Section 1, five storms have been considered. The first two ones are the 1966 and 1979 historical events (particularly the former one) that led to the two highest recorded floods in Venice. Both, and more so for 1966, were characterised by extreme conditions, a relative lack of input information when compared to present, and a poor forecast. The question we want to answer is if the latter was the case because of the lack of data or of suitable, high resolution, numerical models.

On the other hand, and to cover the range of the possibilities, we have considered three mild sirocco storms in recent times, respectively in 2002, 2006, and 2008 (see Table 1). The last one was remarkable in that, notwithstanding far from being an extreme event, it led to the fourth-ranked flood of the town. In any case, these events were not only mild but also, from a meteorological point of view, the dimension of the areas involved was quite limited, which could cast doubt on their long-term predictability. A full description of the five storms can be found in Bertotti et al. (2010) and a deeper one of the two historical, 1966 and 1979, events in Cavaleri et al. (2010). The basic meteorological pattern of each storm is reported in Fig. 2. Figure 1 provides a view of the meteorological situation at the peak of the 1966 storm.

4 The numerical models

Three different models, meteorological, wave and tide ones, have been used for the present study. The meteorological model is the one developed and used at ECMWF. It is a spectral model, i.e. the fields are represented as 2D

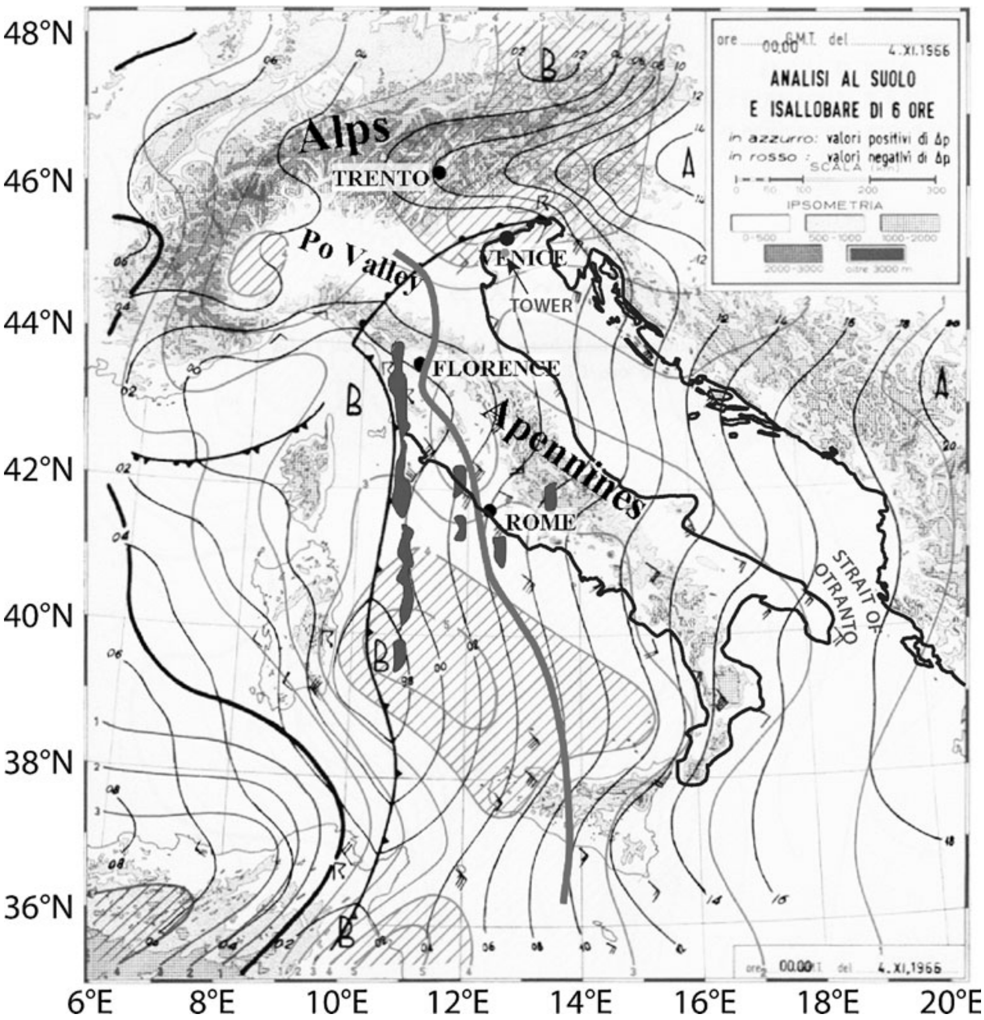

Fig. 1 Meteorological situation at the peak of the storm of 04 November 1966. We focus our attention on the Adriatic Sea, the elongated basin to the East of the Italian peninsula. Its dimensions are about 750×200 km (after Malguzzi et al. 2006)

spherical Fourier series. Each resolution of the model is indicated as Txxx, e.g. T511, where ‘xxx’ is the highest cut-off of the Fourier series. The present operational resolution is T1279 (corresponding to about 16 km resolution). A full description of the model can be found in Beljaars et al. (2004) and Hortal (2004). For the purpose of this study, operational data has been used for 2002 (T511, 40 km resolution), and for 2006 and 2008 (T799, ~25 km resolution).

The WAM spectral wave model has been used (Komen et al. 1994; Janssen 2008). This first third-generation model is based on the energy balance equation. With the partial exception of white capping, all the relevant physical processes are modelled in pure physical terms. The meteorological and wave models are coupled at the sea surface with the surface wind speed depending on the surface drag, in turn related to the wave conditions and the wave evolution.

Table 1 Date of the five considered storms

Storm	Date
1	04 November 1966
2	22 December 1979
3	16 November 2002
4	09 December 2006
5	01 December 2008

The SHYFEM model (Umgiesser et al. 2004) has been used for the evaluation of the meteorological tide throughout the Adriatic Sea for three of the five considered storms (1966, 1979, and 2008). For our present purposes, only the 1966 results are discussed in this paper. The model uses an unstructured grid and incorporates all the physical processes that dominate the circulation in the basin, in particular its shallow northern part. The meteorological tide is superimposed to the astronomical one. This makes the timing of the forecast quite critical, as minor time shifts can change completely the overall results. Being the conditions in the Adriatic Sea depending on the sea level at the Otranto strait (the narrow connection with the Mediterranean Sea, see Fig. 1), a 1-

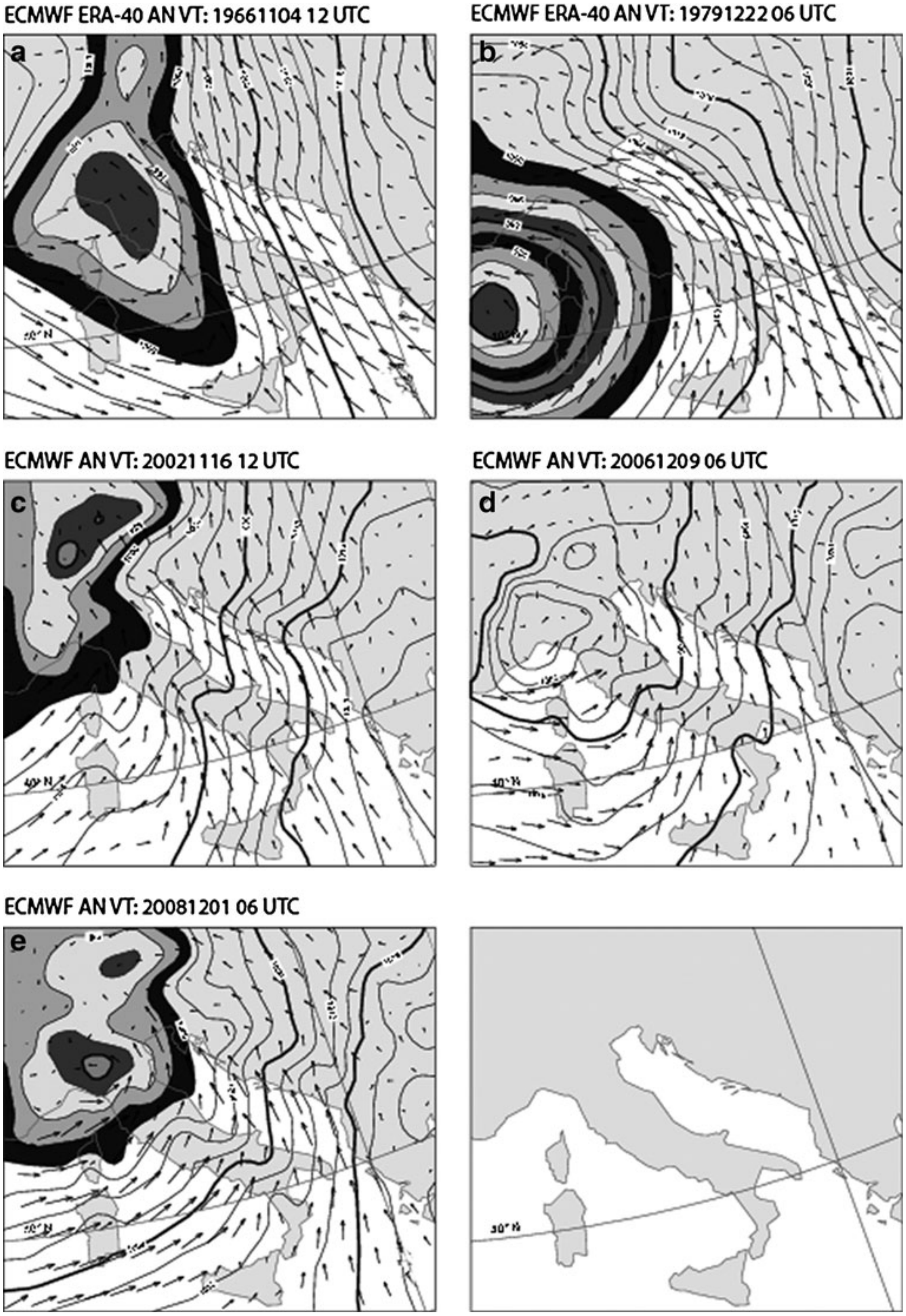

Fig. 2 Meteorological situation at the peak of the storm of **a** 04 November 1966, **b** 22 December 1979, **c** 16 November 2002, **d** 09 December 2006, **e** 01 December 2008

month spin-off of this larger basin has been used before modelling the actual storms.

5 The deterministic forecast

In this section, we consider the usual deterministic forecast. In particular, we consider the five events mentioned in Section 3 (see Table 1) and shown in Fig. 2. As expected from the previous discussion, all of them are sirocco storms. Note the isobars cutting diagonally across the Adriatic Sea, typically with a low pressure centre to the west. Also note how the bordering mountain ridges (see Section 2) force the surface wind to align along the axis of the basin at a large angle with respect to the isobars. In this situation, a small shift of the low pressure centre, while maintaining the general meteorological situation, can change appreciably the intensity of the wind in part of or the whole Adriatic Sea (Signell et al. 2005). As both wave heights and meteorological surge depend on wind speed with a power close to (lower than) two (see, e.g. Cavaleri and Bertotti (2006) and Komen et al. (1994)), the wave heights, and in their absence the tidal, results turn out to be highly sensitive indicators of the quality of the meteorological ones, both as analysis and forecast.

In our analysis of the present forecast capability, we compare analysis and forecast results. For this, first we need to acknowledge the quality of the analysis data. This is achieved by comparing the model results versus both in situ and satellite data. Of most importance are the results at the ISMAR oceanographic tower at 15 km off the coast of Venice, on 16 m of depth, at the upper end of the basin. Its position is indicated by the small arrow ('tower') close to the VENICE position in Fig. 1. The tower is operational since the early 1+70s, fully equipped with meteo- and oceanographic instruments. A full description of this facility is provided by Cavaleri (2000).

Figure 3 reports the comparison of the used wind speeds and modelled wave heights during storm 5 (see Table 1). This result is typical of the long-term performance of the model in the area. Through extensive comparisons, Bertotti and Cavaleri (2009) report a unitary best-fit slope for the significant wave height H_s at the tower. However, this result may vary considerably from case-to-case. Table 2 shows the statistics for the considered storms. Note that the tower was built in 1970; hence, no data exists for 1966. As for 1979, the tower suffered heavy damage during the storm. Measured data (wind and tide) exists only from two mechanical instruments that survived the storm.

The results for the whole basin are in general of the same quality or better than at the tower, located in a geographically very difficult position, surrounded by land and mountains, open only to southeast. From the previous example of the locally frequent cross-sea conditions, it is straightforward to derive that a minor change of the meteorological pattern may lead to different wind and wave conditions in this area. The different difficulty of modelling the wind in the various areas of the basin (north, centre and south) is shown by the different calibration factors required by the ECMWF wind in the different areas of the basin (see Cavaleri and Sclavo 2006 and Cavaleri and Bertotti 2006). As derived from these studies, on average, there is a slight overestimate of the wind speeds moving toward the southeast part of the basin, but with a substantial decrease of the scatter of the data. As expected, this is larger for wind than for waves. The latter ones, being an integrated effect, in space and time, of the driving wind fields, tend to smooth the spatial wind variability, both natural and due to orographic features.

Summarising the situation of the analysed data in the Adriatic Sea and in particular in its northern part (the most difficult one), we consider the results not at the level of the ones available in the open ocean (see, e.g. Janssen 2008), but still of a quality sufficient for all the practical purposes.

Having assessed the quality of the analysis fields, we consider now the related forecasts. For each storm, we consider different forecast ranges, at 12 h steps, up to 6 days (114 h). For each storm and forecast range, we evaluate the ratios between the forecast and analysis values at the oceanographic tower. This is done both for wind speeds and significant wave heights. The results are reported in Fig. 4. Here, the horizontal scales represent the forecast range, in days, the vertical ones the ratio forecast/analysis. Obviously, a unitary value represents a perfect forecast (within the accuracy of the analysis and as far the considered parameter is concerned). We can summarise the results as follows.

The short-term predictability, i.e. up to 3–4 days, is better for waves than for wind. Forecast H_s are very similar to the analysis values till day 4 included. On the contrary,

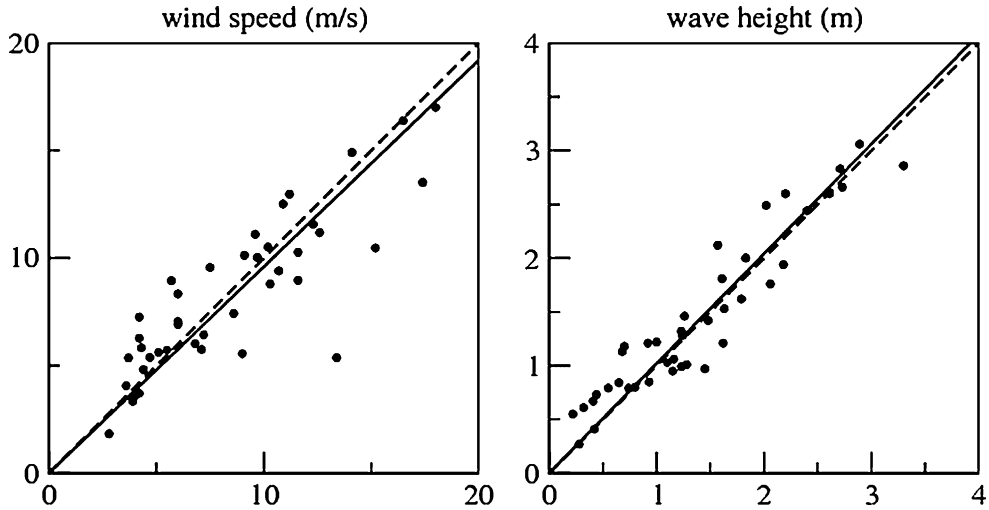

Fig. 3 Scatter plots of model (analysis) vs. measured values during the event of December 2008. Wind speeds (*left*) and significant wave heights (*right*) at the ISMAR oceanographic tower. See Fig.1 for its position (after Bertotti et al. 2010)

Table 2 Statistics of comparison at the ISMAR oceanographic tower (see Fig. 1 for its position) between the hindcast (analysis) and the corresponding measured data

	1966		1979		2002		2006		2008	
	Wind	Waves	Wind	Waves	Wind	Waves	Wind	Waves	Wind	Waves
Best-fit slope	–	–	1.14	–	0.72	0.88	0.92	0.89	0.95	1.03
Mean X	–	–	7.06	–	8.46	1.49	5.94	0.86	8.54	1.40
Mean Y	–	–	8.01	–	5.86	1.43	5.26	0.72	8.33	1.43
Bias	–	–	0.95	–	−2.60	−0.06	−0.68	−0.14	−0.21	0.03
Correlation	–	–	0.91	–	0.66	0.91	0.77	0.83	0.84	0.94
SI	–	–	0.29	–	0.32	0.31	0.35	0.37	0.26	0.20

The period is the 5-day slot preceding and across the peak period of each storm. See Table 1 for their dates. Comparisons are analysis vs. measured data

SI scatter index, the rms error divided the mean measured value; *X* measurement; *Y* analysis

the wind speeds show, for two of the storms, some appreciable differences already at short-term forecasts. Note the very good long-range forecast for 1966, possibly connected to the very large dimension and intensity of the storm. In any case, the quality of the forecast winds does not seem to vary with the forecast range. However, while this is true at the tower position, something different seems to happen at the level of the basin, as shown by a tendency of the wave heights to decrease, in four out of the five cases, with the extent of the forecast.

It is worthwhile to explore further the case of 1966. Although with a substantial lack of data (all the offshore protruding jetties at the three entrances to the lagoon were destroyed, including of course the located tide gauges), any derived indication may be quite valuable as it concerns extreme conditions. The only available data is wind speed measured on land stations and the tide history in Venice. Hence in this case, the predictability has been explored using the tidal data and the corresponding results of the storm surge model (see Section 4). The results are in Fig. 5 showing the time series of the meteorological tide in Venice according to measurements, analysis, the forecast issued the day of the storm, and the ones issued 1, 2, …, 6 days before. It is clear that up to day 5, there is an extremely good agreement of the peak values, the only problem being a shift of the few hours of the peak time. In the specific case of 1966, this is not significant. On the base of previous experience, the instruments used at the time were built with the upper end of the scale at 1.80 m. For the period (several hours), the water was above this level, the record showed a horizontal line at this height. The diagram was completed by hand a posteriori on the base of proxy data. However, for practical applications involving tidal levels, this may be important. A time error of a few hours at 5- or 6-day forecast is likely to be the case, but this may have drastic consequences for what the actual tide, a superposition of the astronomical and meteorological ones, is concerned.

While the model performance at the tower position is significant because in the most difficult area of the Adriatic Sea, we need to have a more collective view of the general performance in the basin. For this, we compare the forecast and analysis fields, for both wind and waves. This is achieved using the vector analysis explained in details in Appendix A. Basically, the analysis provides an ‘average’

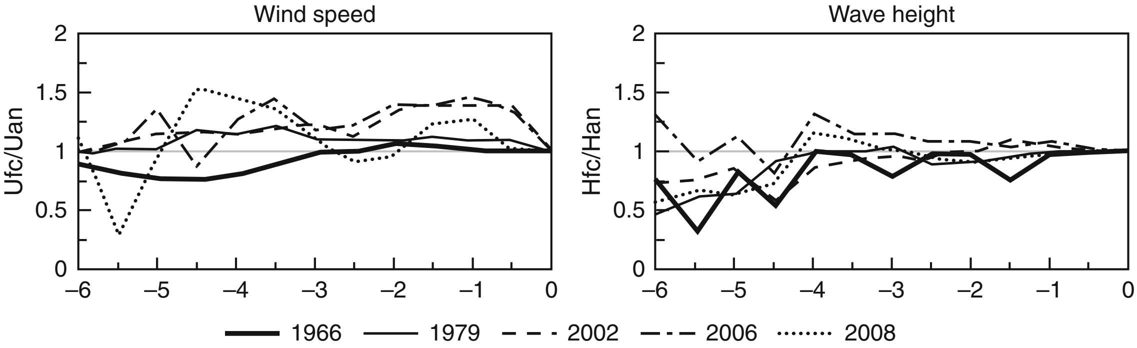

Fig. 4 Each panel shows the ratios between the (wind speed and significant wave height) forecasts issued at different forecast range (days) and the corresponding final analysis at storm peak time. Five different storms are considered (see Table 1). The reference positions are the oceanographic tower (wind speeds, see Fig. 1 for its position) and a slightly more offshore position for significant wave height

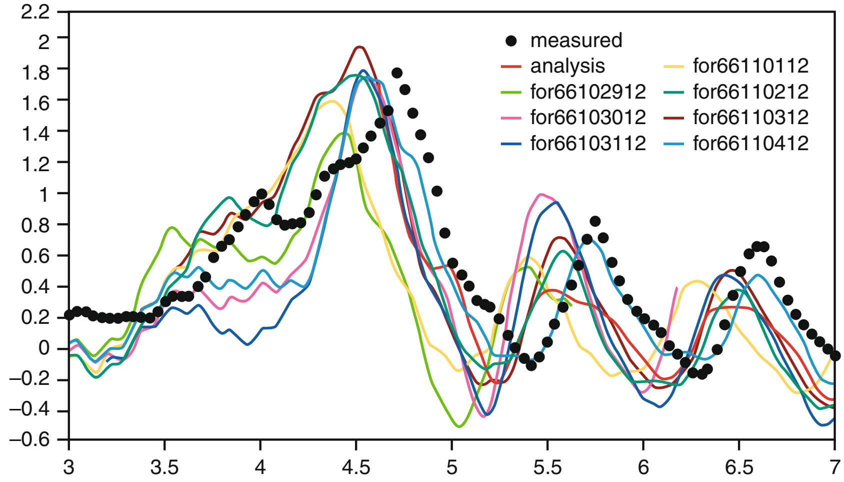

Fig. 5 Time history of the sea level in Venice according to recorded and model data, the latter both as analysis and forecasts initialised at the indicated times (all 1200 UTC). Input wind fields according to the T511 ECMWF analysis. Time scale: days of November 1966. Height scale, metres (after Bertotti et al. 2010)

difference between the two compared fields, expressed as a ratio between the corresponding moduli and an angular difference between the corresponding directions. These results are shown in panels c and d of Fig. 6 for the ratios, respectively of the surface wind speed U_{10} and H_s, and in panels e and f for the directions. For the time being, please focus the attention only on the thick black lines. We will discuss the other curves in the next session.

Figure 6c, d show very clearly how the forecast fields fit, on 'average', with the analysis ones till day 3 or 4, better for waves than for wind as we had already seen for the tower data. However, there is a difference. At the tower, the explanation we had given was that, although the local wind may be 'wrong', the local waves are related to the wind conditions in the whole basin. Figures 6a, b suggest a possible alternative explanation. If the forecast winds,

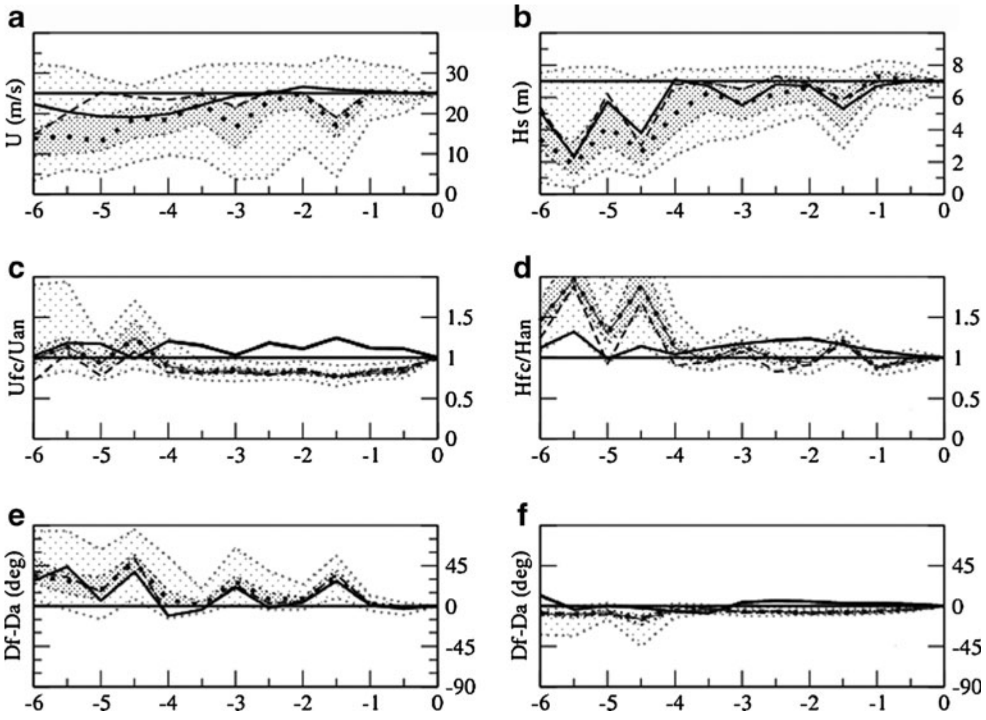

Fig. 6 Storm 04 November 1966. Each panel shows the results for the various forecasts issued at different time range (days) versus the corresponding final analysis at storm peak time. Deterministic forecast (*straight line*), control forecast (*dash line*), median of ensemble forecasts (*dotted*) are shown. Heavily and lightly dotted areas include the 25% and 75%, respectively, of the span of the overall ensemble forecasts. **a** Wind speed at the oceanographic tower (see Fig. 1 for its position), **b** significant wave height at a point slightly more offshore, **c** 'average' ratios of the wind speeds over the Adriatic Sea, **d** 'average' ratios of the significant wave heights over the Adriatic Sea, **e** 'average' differences in wind direction over the Adriatic Sea, **f** 'average' differences in mean wave direction over the Adriatic Sea. See Appendix A for the meaning of 'average' (after Bertotti et al. 2010)

meant on the whole basin, show an appreciable difference at day 4, so should do the waves. However, we are dealing with sirocco storms with winds (see Fig. 2) typically blowing along the whole basin. Hence the waves retain, partly at least, the memory of the previous day winds that had been, on 'average' (see Fig. 6c), of better quality. This suggests that, assuming a better wind quality for the shorter range forecasts, the waves may further extend the range of the good results. However, this is true only in the case of long fetches, hence with a memory of the previous day(s). Should the fetch be short, then the waves would be 'good' only as far as winds are so. In the Adriatic Sea, this is the case of bora. Blowing transversally to the main axis of the basin, the fetch is very short, 200 km at most, see Fig. 1. It is reasonable to think and confirmed by model results (see, e.g. Cavaleri and Bertotti 1996), that waves react quickly to any change from this direction. Concerning directions (Fig. 6e, f), we find more or less the same results as for moduli. The forecasts are good till day 4, and they show later on, at longer range, an appreciable deviation from the analysis directions.

We summarise the overall results for the five storms in Table 3 where we report the average ratios between forecast and analysis for wind speed and significant wave height and the corresponding differences in direction. Note that, while averaging the results, we have given a lower weight to the ones of storm 1. While interesting for the good forecast at 6-day range notwithstanding the scarceness of the data at the time, the data availability in 1966 is obviously not comparable with, hence representative of, present times.

The results in Table 3 convey a very clear message. The forecasts are, on average, pretty good till day 4 or 5, and quite acceptable till day 6. Obviously, this judgement depends on the purpose and the use of the forecast, but, if a storm, mild or severe, is coming, the above results suggest we should be able to know about it till at least 6 days in advance. Note how the results for direction are, especially for waves, somehow better than for the moduli. This suggests that the forecasts do anticipate well the meteorological pattern, a possible error being more likely to affect the moduli, rather than direction, of the wind and wave fields.

6 The ensemble approach

Summarised in its essential approach, the ensemble technique aims at determining the reliability of the deterministic forecast, providing at the same time a range of alternative possibilities, each one with its own probability. The approach is based on the intrinsic approximations present both in the analysis fields the forecasts must start from, and in the way the physical processes are represented in the model. These unavoidable errors imply a 'path' of the forecast different from the actual one, the difference increasing in time (see the classical Lorenz's model, 1963), the more so the more 'unstable' is the situation we start from.

In the ensemble approach, the initial situation and the model are 'perturbed' according to a previous sophisticated analysis to detect which perturbations the following evolution is more sensitive to. Typically, a few tens of alternative forecasts are produced, necessarily at a lower resolution with respect to the deterministic approach. At ECMWF 50 ensemble forecasts are regularly produced plus a non-perturbed control forecast with the same reduced resolution. The wealth of data so obtained obviously requires a statistical approach. Figure 7 shows a possible way to represent the overall results. The two panels show the forecasts issued at 00 UTC 26 November 2008 (storm 5). The location is the ISMAR oceanographic tower (see Section 5 and Fig. 1). For each panel, wind speed and wave height respectively, we see the time evolution of, the analysis AN, the deterministic DF and the control CF forecasts. The 50 ensemble forecasts are somehow distributed around the control one. Their distribution is conveniently summarised with the shadowed area that include, respectively, 25% and 75% of the overall 50 members. PF refers to the range covered by the ensemble members.

A reliable forecast is characterised by a narrow ensemble distribution, typically following the deterministic or control

Table 3 Average performance of the forecasts at different forecast ranges (hours)

	12	24	36	48	60	72	84	96	108	120	132	144
U_{fc}/U_{an}	1.00	1.05	1.02	1.06	1.05	1.00	1.02	1.15	1.12	1.00	0.98	1.11
H_{fc}/H_{an}	1.11	1.12	1.06	1.01	1.04	0.99	1.12	1.06	0.88	0.85	0.74	0.75
DU_{fc}-DU_{an}	0	0	0	4	5	1	8	2	0	18	15	16
DH_{fc}-DH_{an}	0	1	1	1	2	4	0	0	2	−7	−10	−9

Differences are positive clockwise. Averages are considered over the whole Adriatic Sea

U wind speed; *H* significant wave height; *DU* wind direction; *DH* mean wave direction; *fc* forecast, an analysis forecasts. The wider the distribution, the stronger its uncertainty. Clearly (see, e.g. Fig. 7), the width of the distribution increases with the extent of the forecast.

The flood of 2008 (see Fig. 7) was rather unusual in the sense that the specific storm in the day of the flood, December 1, was not particularly intense. However, as already mentioned, this flood ranked fourth in historical records. The reason for this was that, as it is evident in Fig. 7, there were three storms in a row, all not very intense, but at 24-h interval that superimposed their effects leading to the oceanographic heavy conditions. For the tide, it is tempting to associate the storm interval with the natural oscillation periods of the basin (the Adriatic has two basic seiches, with about 11- and 22-h periods, see Robinson et al. 1973). Also, the wave conditions were enhanced, the second and third storms acting on the still existing wave background of the respective previous storm.

To report in a compact way the ensemble results, we resort again to Fig. 6. Beside the already discussed deterministic results, each panel shows also the related ensemble results with the same graphical convention used in Fig. 7. For a collective view of the performance in the five storms, we report in Fig. 8 for each storm the corresponding a and b panels of Fig. 6.

First, we focus on the width of the ensemble distributions. As expected, this increases with the extent of the forecast range. For our present purposes of assessing the present forecast capabilities, the remarkable point is the clear tendency of the ensemble width, seen exploring in sequence the five storms, to decrease while approaching present times. This is obviously related to the accuracy of the analysis, in turn related to the amount of data available for their estimate. This suggests that, while we were able to show a good potential predictability of the 1966 and 1979 storms up to day 6, this was possible because of the exceptional character of the storms, both in terms of intensity and spatial impact in the atmosphere.

For the immediate interest of present predictability, it is certainly reassuring that (1) the ensemble distributions are relatively narrow also at day 6; (2) also at day 6, the 75% range always includes the day 0 values. This means that, also in the case, the deterministic forecast does not suggest, as for instance in panel b of storm 5, wave conditions as heavy as the ones to come, the ensemble points out a substantial probability that such an event is indeed to come. As a matter of fact, Buizza et al. (2008) point out that the use of the ensemble may extend the range of the useful forecasts of about 1 day with respect to the deterministic approach. While this may be fully true in more open space as the oceans or at least in large basins without a strong orographic influence, still the above results suggest that a 6-day useful forecast range, at least in a probabilistic sense, is within the present possibilities also for the smaller enclosed seas. The parallel results for panels c–f, as seen in Fig. 6, fully confirm this conclusion.

7 Discussion and conclusions

The aim of our analysis was to determine how far ahead the present forecast systems can usefully predict a storm in an enclosed sea with accuracy sufficient for practical applications. For more open spaces, in principle, this can be derived from the extensive archives present in the large operational meteo-oceanographic centres. However, the spatial resolution of both meteorological and oceanographic, typically wave, models change rather frequently, usually every 3 or 4 years. As the results are resolution dependent,

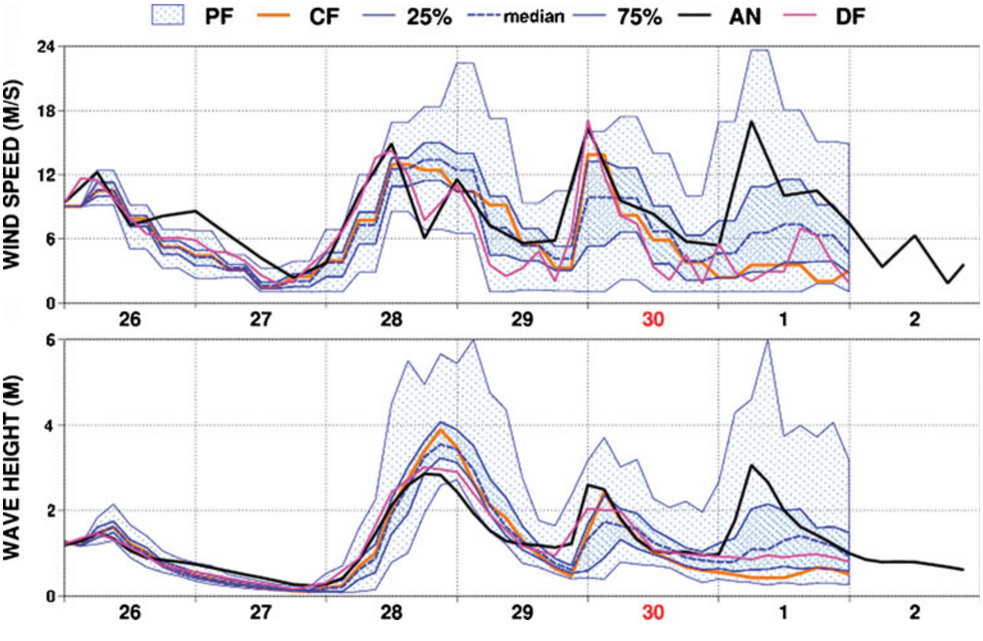

Fig. 7 Ensemble forecasts of wind speed and wave height issued at 00 UTC 26 November 2008 vs. the corresponding analysis data. The target point is the ISMAR oceanographic tower (see Fig.1 for its position). *AN* analysis, *DF* deterministic forecast and *CF* control forecasts. The ensemble distribution is represented by the median and by the shadowed areas including 25% and 75%, respectively, of its 50 members. PF indicates the range of the ensemble members

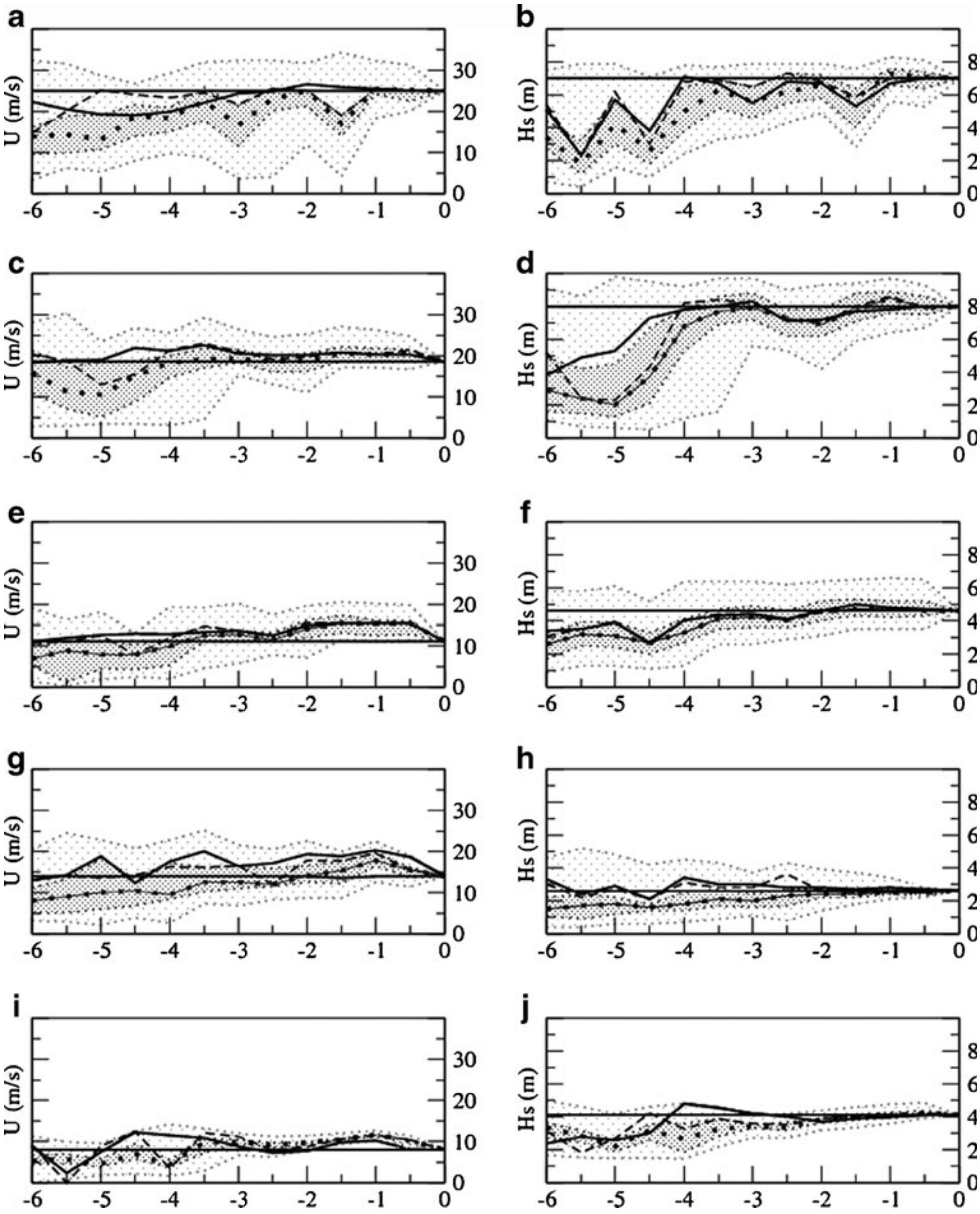

Fig. 8 Each line (two panels) corresponds to **a** and **b** in Fig. 6, but for the five considered storms. In the order from top to bottom 1966, 1979, 2002, 2006, 2008

the statistics is relatively limited. More important, frequently the accuracy of these models decreases when focusing the attention on the inner seas, the more so the smaller their dimensions, and when the situation is affected by a relevant orography. We have chosen to focus our attention on one of such basins, the idea being that this would have provided a minimum result, the results for other areas, especially in more open spaces, being likely better. For this, we have focused our attention on the Adriatic Sea, a small (750× 200 km) elongated basin to the East of Italy, surrounded on three of its four sides by a relevant orography.

Our results can be summarised in the following. Also in the Adriatic Sea a storm is forecast with good accuracy (10–15% for H_s) till 4 days in advance, up to 6 days (the maximum we have explored) with the accuracy deteriorating to 20–30%. The percentages refer to the wind speed and significant wave height and concern the northern part of the basin, the most difficult one for predictability. We have considered both extreme, in the far past and mild storms in recent times. In no case, a storm was missed and a substantial warning was available till at least 6 days before the event. This result is consistent with the present statistics of ECMWF, see, e.g. Buizza et al. (2008). The predictability of waves is slightly better than for wind. This is due to the memory of waves of the previous situations. However, this holds when the fetch is not too short. In the case of the Adriatic Sea, this cannot be the case for bora storms. Blowing across the main axis of the basin, the fetch is very short, 200 km at most, and local waves are strongly related to the present driving winds.

We have explored the extra information brought by the ensemble approach. We have stressed that a small shift of the overall meteorological pattern may have drastic consequences in a small enclosed basin, especially on its wave conditions. This is particularly the case for the ensemble members that, for obvious reasons and as specified above, have a lower resolution with respect to the global deterministic model. It is clear that the use of the ensemble fits very well the situation, as it allows to explore, especially in the 3- to 6-day range, the implications of, e.g. a spatial or temporal shift of a storm. Besides providing possible alternative solutions, it allows also to characterise them with a probability, allowing possible preliminary mitigation actions to be taken whose intensity will increase if, with time passing, a serious event is progressively confirmed with higher and higher probability.

In the three cases we have explored, the predictability of recent storms, the range of solutions indicated by the ensemble was quite limited. It also always included the analysis values, also at 6-day range. Having obtained this result for mild storms is particularly encouraging. The fact that, albeit for very severe storms, this was the case also when the number of available data was quite limited, suggests that for such storms the present predictability may be larger. The exception is when the evolution of the meteorological situation and the details of the fields depend on processes and/or details whose relevant spatial scale is below the resolution of the ensemble. In these cases, a possible solution is the use of ensemble limited area models (LAM; see Frogner et al. 2006 and Montani et al. 2011, for two examples of such approach). The alternative use of LAMs deserves some further discussion. Focusing on the Adriatic Sea as a suitable example, in the case of sirocco, with the wind field well distributed along the whole length of the basin, we can expect that also a global model with the present resolution of ECMWF, about 16 km, should be able to provide a fair picture of the situation. On the contrary, in the cases of bora, the wind blows across the Dinaric Alps and crosses the Adriatic Sea along its minimal dimension (<200 km). As repetitive measurements and high resolution modelling have shown (see, e.g. Signell et al. 2005), bora flows at high wind speed along some preferential valleys in the Dinaric Alps, then impinging as narrow jets on the Adriatic Sea. In these conditions, a LAM is obviously the solution. So the convenience of using a LAM depends on the situation we are interested in.

This is not the only problem. As in most of the cases, a LAM derives its initial and boundary conditions from the parent, typically global, model, one of the key assumptions is that the pattern to start from for enhanced resolution, and more so the boundary conditions along the forecast, are correct. If this is not the case, drastic errors can be the consequence, at least at local level. Two examples, respectively for wind and wave and for tide are discussed in the two papers by Cavaleri and Bertotti (2006) and Cavaleri et al. (2010).

Having considered only three, or five, storms, clearly our statistics does not have an historical perspective. Nevertheless, the results appear robust and self-consistent. Besides, although only for the deterministic approach, the long-term wave forecast system operational at ISMAR for the Adriatic Sea (see Bertotti et al. 2010) strongly suggests that this is indeed the case.

A possible objection to our conclusions is that, having considered only storm events, we could not exclude the possibility of false alarms. That this is not the case is shown (a) by Bertotti et al. (2010) who have shown the capability of the ensemble forecast to discriminate between occurrence and non-occurrence using three skill scores (ROCA, spread skill and CRPSS) for long-term statistics both in the North Atlantic and the Mediterranean, (b) the cited statistics for the ISMAR Adriatic forecast system.

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Appendix A

Intercomparison of two vector fields

We want to intercompare two vector fields on the same grid, say **b** with respect to **a** (see Marsden 1987). We consider each vector as a complex number, i.e. **a**=[ax,ay]→(ax+*i* ay)=a exp(iΦ), with a the modulus and Φ the phase. If we have only one vector (i.e. one-grid point)

$$\mathbf{b}/\mathbf{a} = \mathrm{b}/\mathrm{a}\,\exp[\mathrm{i}(\Phi_\mathrm{b} - \Phi_\mathrm{a})]$$

provides the ratio of the moduli and the phase difference. The result of a point-by-point comparison of the two fields is another vector field. To summarise this result in a more compact way, we can proceed as follows. Obviously

$$\mathbf{b}/\mathbf{a} = (\mathbf{ba^*})/(\mathbf{aa^*})$$

with **a*** the complex conjugate of **a**. We consider the quantity

$$\Psi = \left(\sum \mathrm{i}\, \mathrm{a_i}^* \, \mathrm{b_i}\right) / \left(\sum \mathrm{i}\, \mathrm{a_i}^* \, \mathrm{a_i}\right)$$

Ψ can be considered as the regression coefficient of the **b** field with respect to **a**. If we consider also the expression

$$\sum_\mathrm{i} ||\mathrm{b_i} - \Psi \mathrm{a_i}||2$$

this can be interpreted as a sort of minimum square quantity. Alternatively, Ψ is the quantity that minimises the distance between the two points $[b_i]$ and $[\Psi a_i]$ in an n dimensional space (i=1–n).

The complex number

$$\Psi = \alpha + i\beta$$

provides the ‘average’ ratio and the ‘average’ phase difference between the two fields.

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