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ACTION A.1: DESIGNING INTEGRATED BASELINE SCENARIOS

REVIEW OF CLIMATE CHANGE IMPACTS ON SEA-STORM OCCURRENCE

Andrea Valentini (Arpae-SIMC Emilia-Romagna)

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Contents

REVIEW OF CLIMATE CHANGE IMPACTS ON SEA-STORM OCCURRENCE 3

1. METEOROLOGICAL, WAVE AND TIDAL DATA-SETS 3
2. WAVE STORMINESS ANALYSIS 6
3. METEOROLOGICAL STORMINESS ANALYSIS 12
   - 3.1 Wind climatology 12
   - 3.2 Long term wind storminess 13
   - 3.3 Meteorological storminess associated with Emilia-Romagna severe sea storms 15
     - 3.3.1 Meteorological storminess associated with all severe wave storms 16
     - 3.3.2 Meteorological storminess associated with severe Bora wave storms 19
     - 3.3.3 Meteorological storminess associated with severe Sirocco wave storms 22
4. CONCLUSIONS 25
5. REFERENCES 27

Review of climate change impacts on sea-storm occurrence

This study presents an analysis of the meteorological and marine storminess climatology over the last 50 years in Emilia-Romagna and, more in general, over the Northern Adriatic Sea. It is based on the available meteorological and marine measurements. Unfortunately, numerical model outputs that extend so far in the past are generally available with a resolution that is too coarse. Long term numerical models extending in the past also have difficulties to simulate extreme Bora events, that are an important characteristic of the Northern Adriatic meteorology, due to their too coarse horizontal resolution. These limitations would affect wave hindcasting which uses wind as a wave forcing factor. Regarding the use of wind and wave data coming from offshore stations (i.e. platforms and buoys), they do not cover such a long period as well, and therefore the only solution is to rely on coastal meteo-marine stations. This study carries on and updates previous analyses mainly performed during two EU Projects: CADSEALAND (2004-2006), an INTERREG IIIB CADSES, and MICORE (2008-2011), an EU-FP7 research project.

1. Meteorological, wave and tidal data-sets

The meteorological data-set used in this section belongs to the Italian Adriatic-coastal stations of the SYNOP (surface synoptic observations) network. Data consist of time series of 3-hourly measurements of standard meteorological surface parameters, such as wind at 10 m above ground and mean sea level pressure. These time-series are available for many coastal stations along the Adriatic coastlines; in particular, data from Trieste, Venezia, Punta Marina (Ravenna), Rimini, Falconara (Ancona), Termoli, Brindisi were collected and used for storminess identification. Specifications about these stations are listed in table 1.1, while geographical locations are shown in figure 1.1. Yearly percentage of missing data is shown in figures 1.2 and 1.3. Considering that since 1960 data recovery improves, time series were studied only from this date onwards.

Measurements are the average over a 10 minute sampling period, both for wind direction and speed. The meteo dataset has been carefully checked and quality controlled. It has been shown by previous authors (Pirazzoli and Tomasin, 1999) that winds below 4 knots present a clear bias due to the improvement/changes in instrumentation occurred with time. For this reason, all the measurements below this threshold were considered as calm in the current analysis.

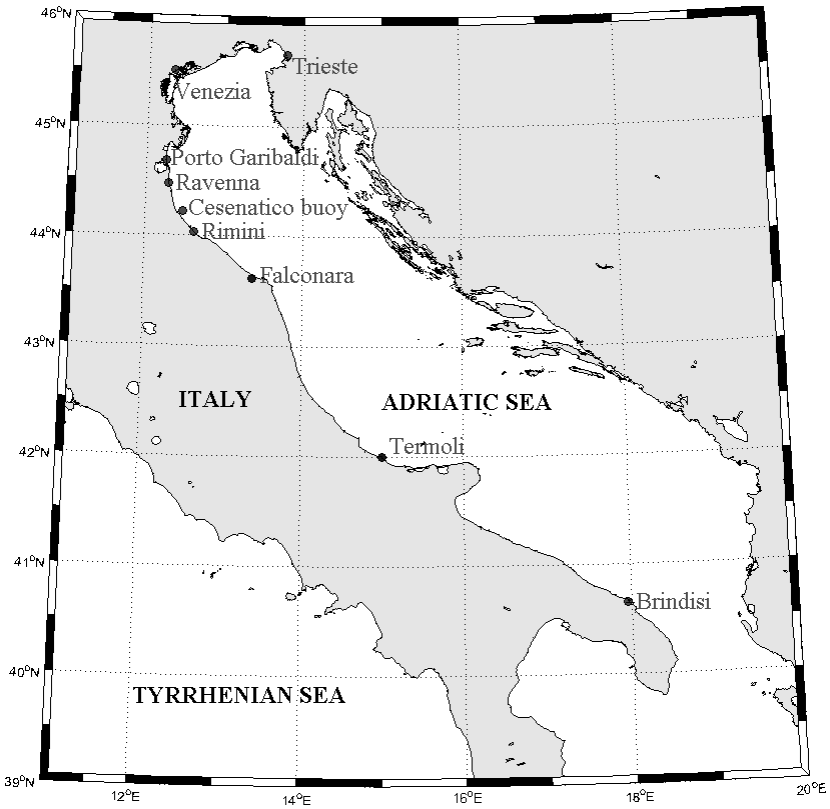


Figure 1.1. Meteorological stations and localities with tide and wave measurements used in the analysis

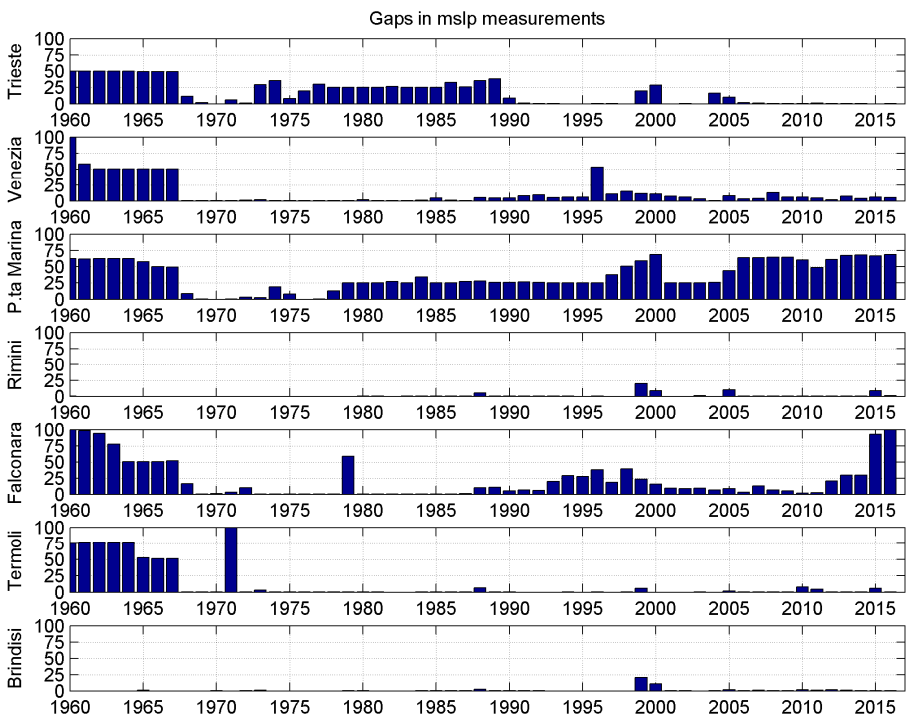


Figure 1.2. Percentage of mean sea level pressure missing data in the meteo time series.

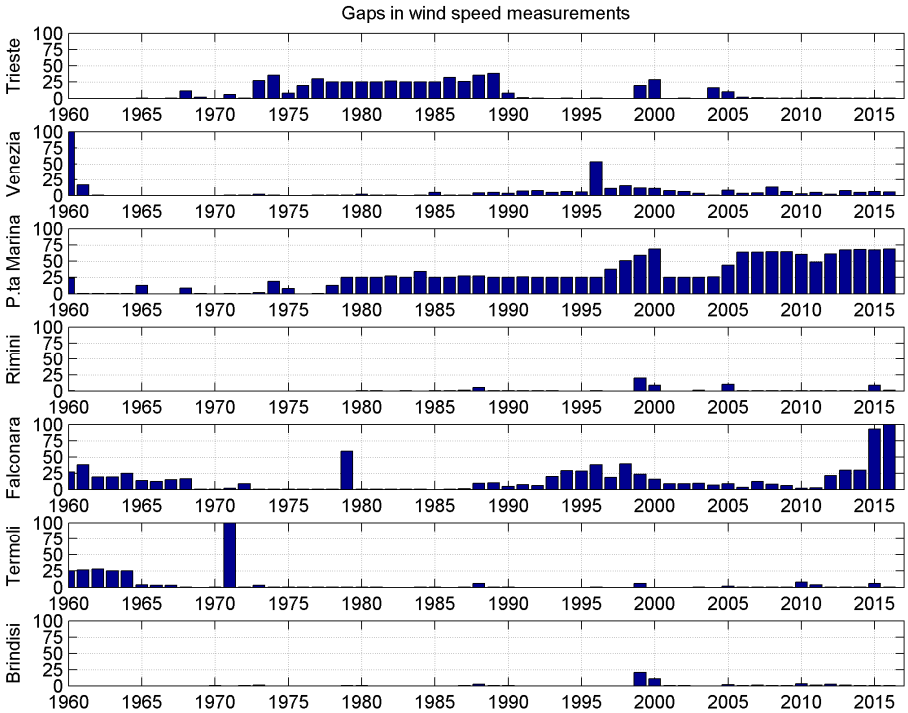


Figure 1.3. Percentage of wind speed missing data in the meteo time series.

Directional wave measurements have been provided by the wave buoy of the Emilia-Romagna region, managed by Arpae and located offshore of the town of Cesenatico http://www.arpa.emr.it/sim/?mare/boa. These wave data are available every 30 minutes and are collected in the Arpae-SIMC database since June 2007 up to now (in this study only data since June 2016 have been considered). As shown in figure 1.3, in which the yearly and seasonal percentage of missing data is plotted, the directional wave dataset is not characterized by a 100% data recovery rate. Some years (e.g. 2014, 2009, 2012) have a high percentage of missing data. For this reason, the main and longest gaps have been filled using archived SWAN forecasts by the Arpae-SIMC sea-state forecast system.

Finally, tidal measurements were obtained from two different sources: the tide gauge of Porto Garibaldi (FE), now part of the Arpae Emilia-Romagna measuring network and previously managed by the Province of Ferrara, and the tide gauge of Porto Corsini (RA) that is part of the RMN-ISPRA network. The periods of observation availability are listed in table 1.1.

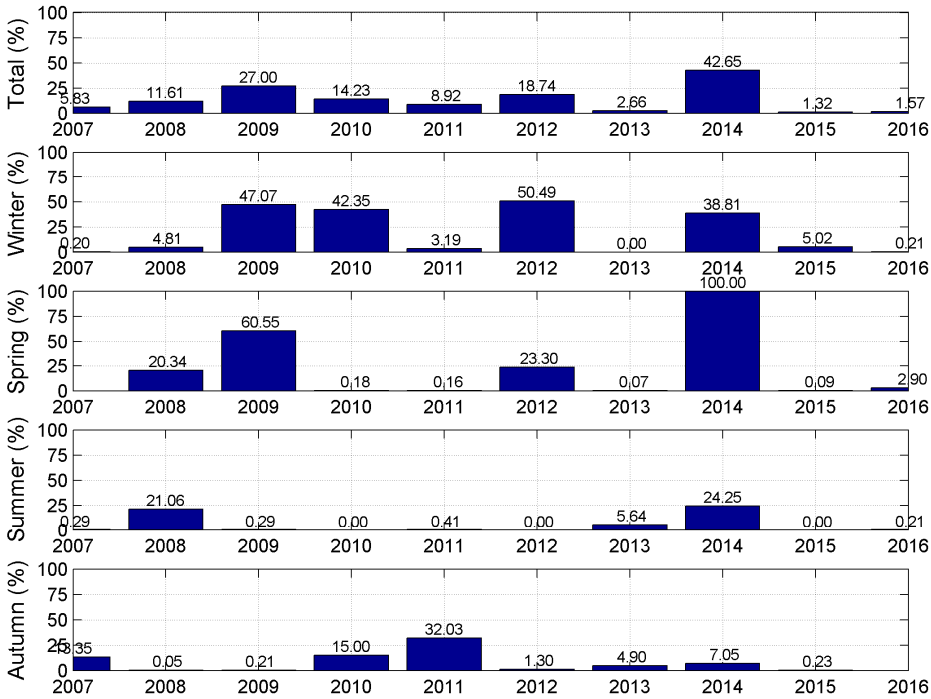


Figure 1.3. Percentage of missing data in the wave dataset of the Cesenatico buoy

Station	Latitude N	Longitude E	Water depth (m)	Period of observation
METEO SYNOP				
Trieste	45° 39'	13° 47'	-	1960-2016
Venezia	45° 30'	12° 20'	-	1961-2016
Punta Marina (RA)	44° 28'	12° 17'	-	1960-2016
Rimini	44° 02'	12° 37'	-	1960-2016
Falconara (AN)	43° 37'	13° 22'	-	1960-2016
Termoli	42° 00'	15° 00'	-	1960-2016
Brindisi	40° 39'	17° 57'	-	1960-2016
TIDE GAUGE				
Porto Garibaldi (FE)	44° 40.6'	12° 15'	-	2009-2016
Porto Corsini (RA)	44° 29.5'	12° 17'	-	1998-2015
WAVE BUOY				
Cesenatico	44° 12.9'	12° 28.5'	10	2007-2016
SWAN virtual buoy	44° 19.9'	12° 24'	10	2006-2016

Table 1.1: characteristics of data measurements used in this analysis.

2. Wave storminess analysis

Wave data from Cesenatico wave buoy have been quality checked and homogenised. Annual and seasonal distribution of data gaps are plotted in figure 1.3.

The wave climate during the 2007/06-2016/06 period (figure 2.1) shows that the most prevailing waves come from the eastern directions (ENE-E-ESE) whereas the highest waves come from North-East and East-North-East, associated with strong Bora winds that are the ones to which the Emilia-Romagna coast is mostly exposed and vulnerable.

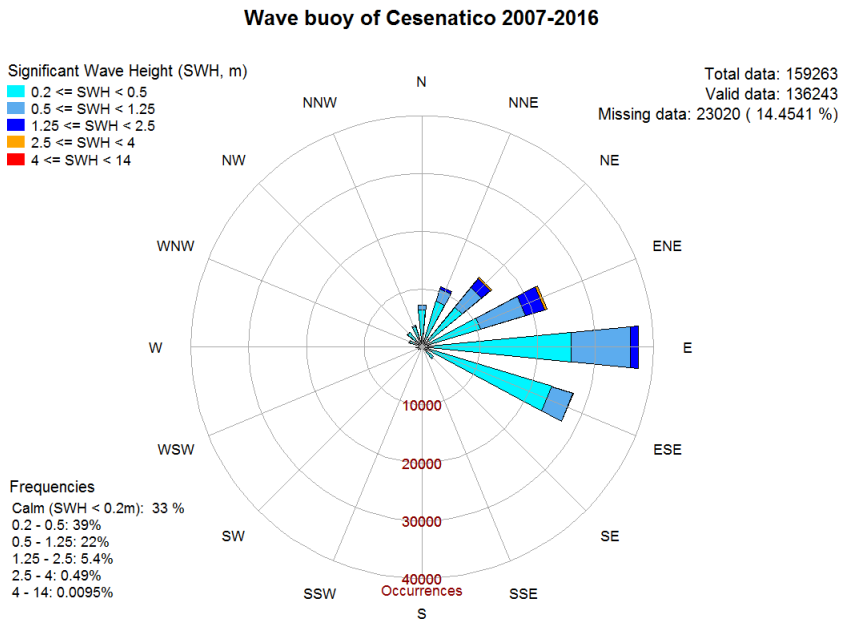


Figure 2.1. Wave rose for the period 2007-2016 of waves recorded by the Cesenatico buoy.

Considering the polar plot of every single year of the period (not shown) it is possible to assess that there are not variations in the wave climate direction during the last ten years.

Storms have been identified and isolated considering a wave height threshold of 1.5 m and a minimum gap of 12 hours (under the threshold) between two consecutive events (Boccotti, 1997). No constrains on storm duration have been considered in order to identify also very short storms that could be, in some way, very energetic. In this gap evaluation method also missing data are considered. It must be pointed out that there is no standard on storm thresholds in Italian seas in the literature. According to the Italian Wave Atlas (Corsini and Inghilesi, 2004), the threshold for H_s is fixed at 1.0 m for at least 12 consecutive hours and events are separated by 6 hours of wave height decay. In a specific study for the northern Adriatic Sea, Cavaleri et al. (1996) choose, on the other hand, 2.0 m as threshold for the wave height. In the current study the threshold and the separation interval were chosen examining the wave height time series for a number of storms.

Following the approach adopted by Mendoza and Jimenez (2004) and by Armaroli et al. (2006), the total energy (E) of each event was computed using the Significant Wave Height (H_s) integrated over the storm duration (t_1,t_2):

$$E = \int_{t_1}^{t_2} H_s^{\,2}\, dt \qquad \left[m^2 \cdot hr\right]$$

Yearly storminess was quantified in two ways. First, to understand if one particular year was more energetic than another one, the cumulative yearly wave energy was computed adding all events. To understand if the energy of events had changed through time, the specific event storm energy was computed, normalizing the total energy of a given year for the number of storms measured in that year.

Due to the lack of measurements in Winter (e.g. years 2009, 2010, 2012, 2014), Autumn (e.g. year 2011) and Spring (e.g. years 2008, 2009, 2012 and 2014), that are the seasons with the highest number of sea storms, stormy information obtained by observations has been integrated with stormy information provided by the outputs of the sea-state forecast model SWAN-MEDITARE (Valentini, 2007) that is operational at Arpae-SIMC since 2006. The two datasets (measurements and simulations) have been statistically compared: model simulation values have a good correlation with the measured waves (figure 2.2 and table 2.1) but tend to underestimate the Significant Wave Height; this underestimation is higher if considering only observed waves higher than 1.5 meters (figure 2.2 right and table 2.1 right).

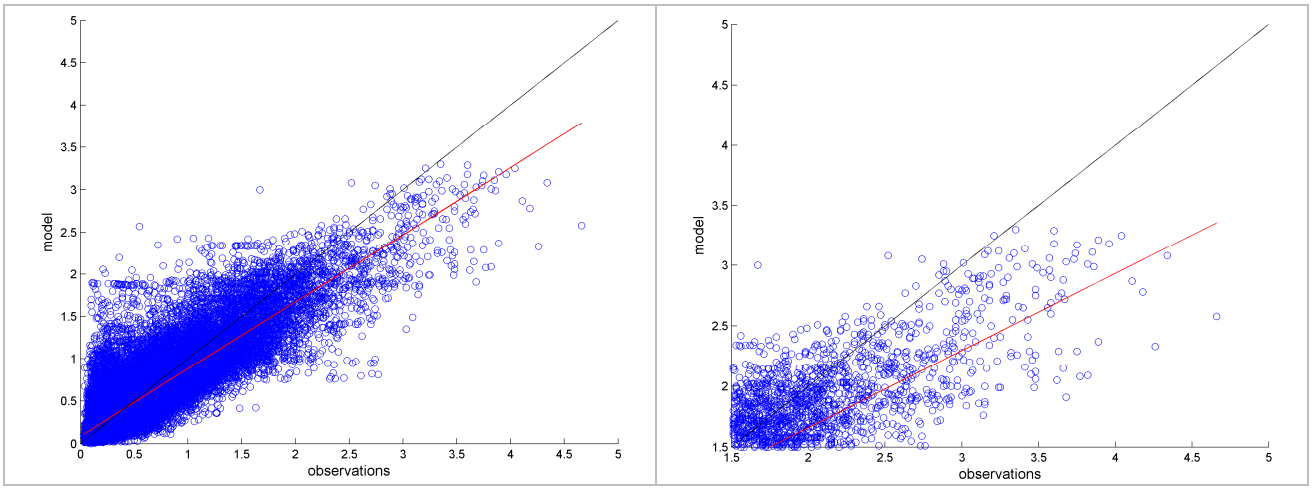


Figure 2.2. Scatter plots of the Significant Wave Height (SWH) measured by the wave buoy of Cesenatico against the simulated one by the SWAN wave model of Arpae-SIMC. On the left side all data have been considered whereas on the right side only observed SWH≥1.5m have been taken into account.

	SWH all	SWH≥1.5m
BIAS	-0.0054	-0.3337
MAE	0.1398	0.4144
MSE	0.046	0.2687
RMSE	0.2145	0.5184
R	0.8708	0.6457

Table 2.1. Statistical scores of the verification of wave measurements against the simulated waves.

Wave storms have been picked out (on the basis of the thresholds described above) using the observed and the simulated datasets separately.

Finally, sea level measurements provided by the two tide gauges installed in Emilia-Romagna have been used to complete the characteristics of storms: for each event, the mean and maximum sea level have been added.

For the period June 2007 - June 2016 189 storms have been pointed out, with an average duration of 18 hours and a maximum of 99 hours. On average the storms were coming from the direction 58°N (ENE), with an average storm maximum SWH of 2.24 m. The absolute maximum wave height measured in front of Cesenatico was 4.66 m on 02 February 2015. A detailed summary of the analysis is synthesized in table 2.2 in which are reported the main characteristics for each year.

	Number of storms	Total hours	Total energy (m^2 hr)	Normalized Storm Energy (m^2 hr)	Max SWH (m)	Mean SWH (m)	Max sea level (m)	Mean sea level (m)	% Dati modello
2007	13	324	1268.67	97.59	3.04	2.46	0.66	0.18	7.69
2008	17	363.5	1255.84	73.87	3.19	2.10	0.87	0.09	0.00
2009	22	228.5	813.69	36.99	2.96	2.04	0.92	0.19	9.09
2010	20	296	1139.77	56.99	3.91	2.21	0.87	0.28	20.00
2011	17	377	1465.96	86.23	3.92	2.29	0.66	0.15	17.65
2012	22	477	2133.56	96.98	3.27	2.36	1.24	0.17	36.36
2013	24	381.5	1632.94	68.04	3.79	2.21	1.02	0.35	0.00
2014	15	225.5	914.26	60.95	3.52	2.28	0.98	0.33	26.67
2015	26	508	2207.82	84.92	4.66	2.33	1.31	0.28	3.85
2016	13	192.5	657.34	50.56	3.11	2.09	0.93	0.39	0.00

Table 2.2. Summary of the wave storm analysis with the main characteristics for each year.

The number of storms varies from 15 to 26 (figures 2.3 and 2.4), not considering years 2007 and 2016 because only 6 months of each was taken into account, and there is not a trend for this variable but a high variability between the years. Also the total hours of storminess presents the same characteristics.

The years 2007, 2011, 2012 and 2015 result to be extremely energetic (see the normalized storm energy plotted in figure 2.4 right), due to wave storms lasting more than two days with associated maximum significant wave heights higher than 3 meters. To note that the 2012 results to be very energetic despite the fact that more than the 36% of data are provided by the numerical model that in general underestimate wave heights.

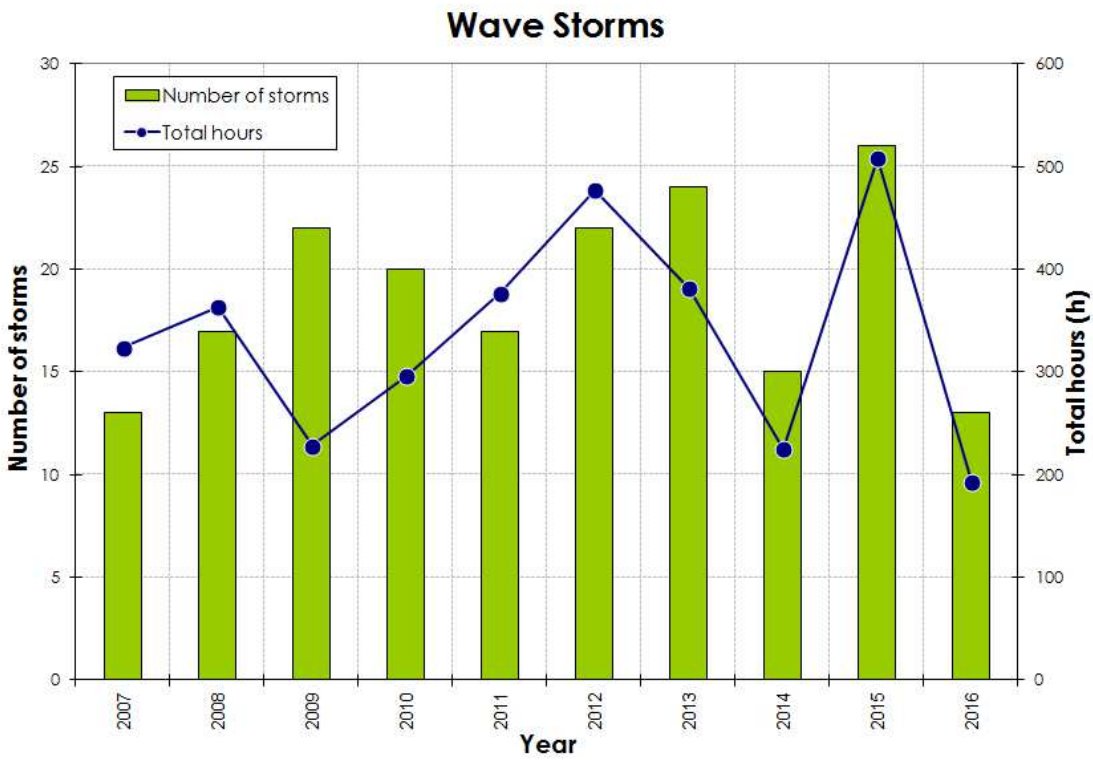


Figure 2.3. Distribution of the number of wave storm events and the total hours of storminess. Period 2007-2016.

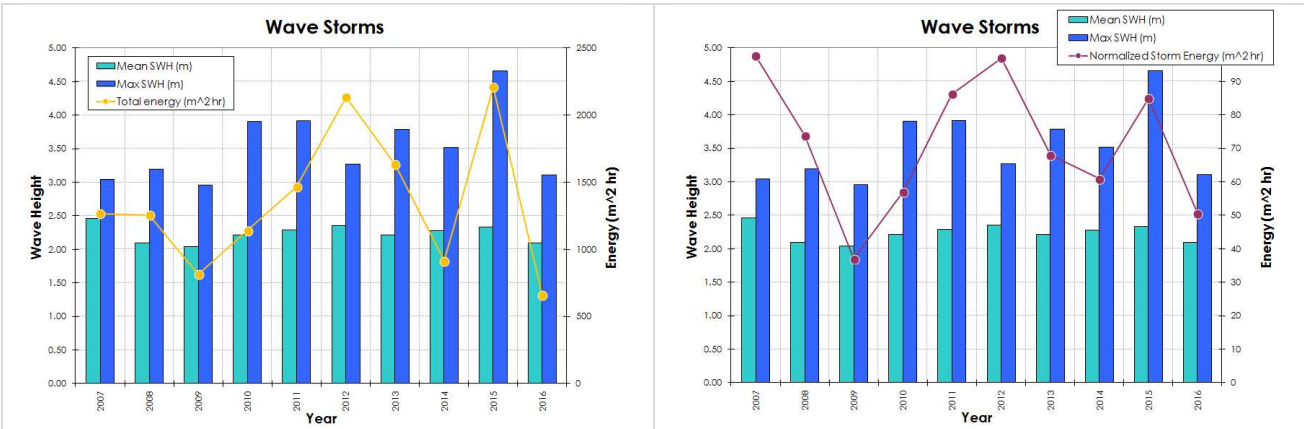


Figure 2.4. Distribution of the wave height (mean and maximum), of the annual total storm energy (left) and of the normalized storm energy (right). Period 2007-2016.

In figures 2.4 and 2.5 it is possible to note that the mean significant wave height during all storms of the period has a steady trend, while the maximum significant wave height, that presents extreme values in 2015 and 2004, seems to have a small positive trend in the period. The same trends characterize the mean and the maximum sea level recorded during the isolated storms (figure 2.5).

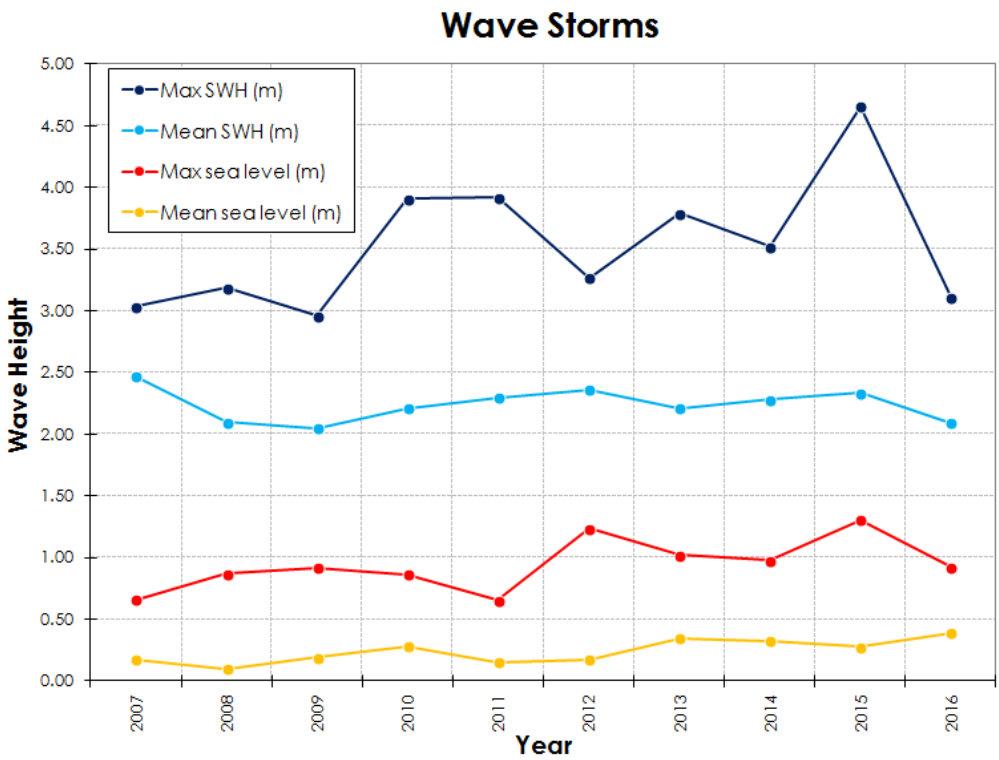


Figure 2.5. Trend of wave height and sea level (both mean and maximum) during the sea storm events isolated in the period 2007-2016.

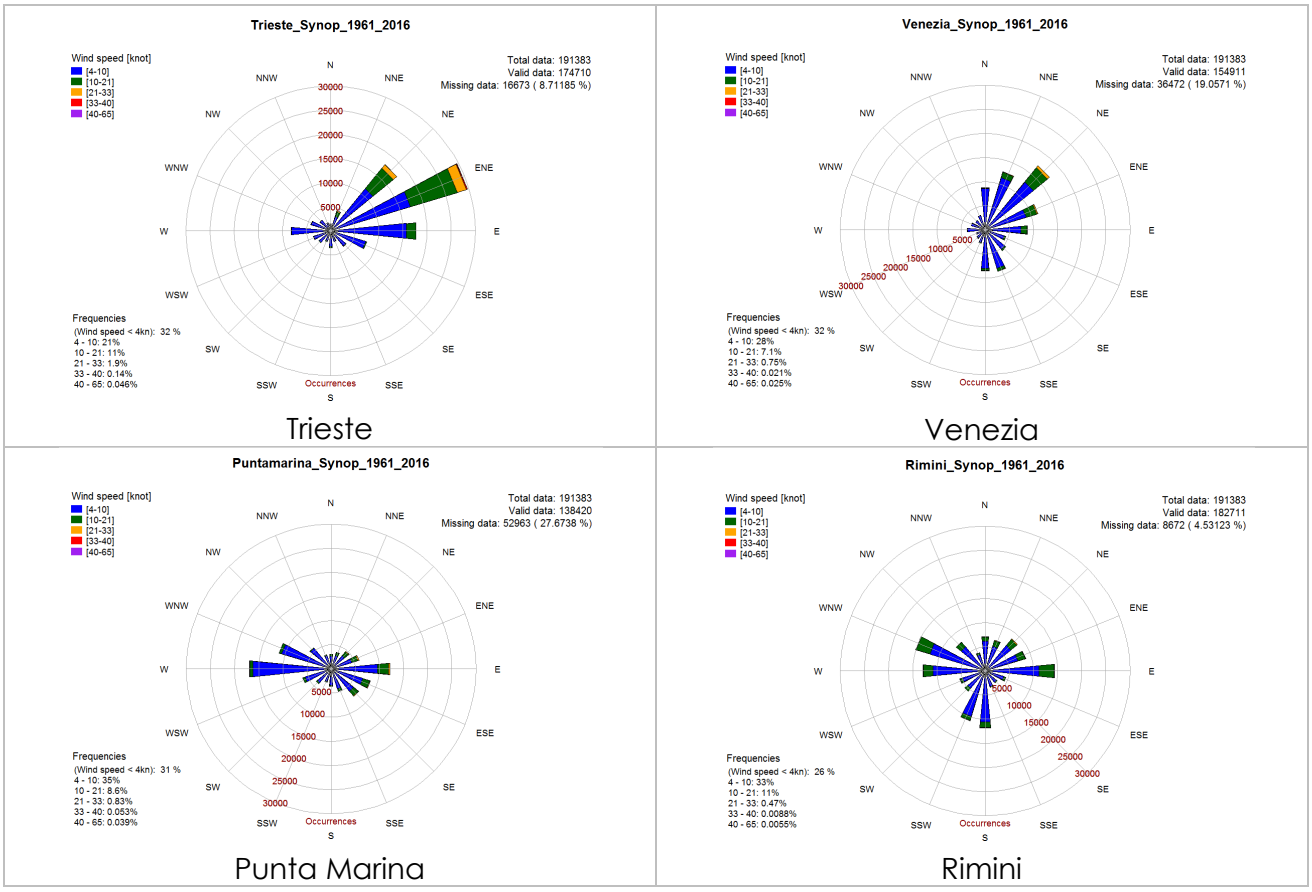
Summarizing the results discussed above, regarding yearly storminess it is not possible to highlight a defined positive or negative trend since 2007 to nowadays; mild positive trends could be dared for the maximum wave height and the maximum sea level during the events, but it must be pointed out that a period of almost only 10 years of data is too short to deduce long-term trends, moreover, in this specific case, the interannual variability is much higher than the trend itself as confirmed also by Lionello et al. (2012).

3. Meteorological storminess analysis

In order to analyze the meteorological storminess characterizing the Adriatic Basin during the considered period, the methodology used by Trigo and Davies (2002) was chosen. The method was originally developed to study a 40 year climatology of meteorological conditions in the Adriatic Sea associated with storm surges in Venezia.

3.1 Wind climatology

The climate of the datasets is synthesised by means of wind roses (figure 3.1), depicting most prevailing directions. It can be noted that the Adriatic coastline can be divided into three different surface wind regimes. In the very northern area (Trieste ad Venice), most prevailing wind are easterlies, in particular E-NE. In the central sector (Punta Marina, Rimini, Falconara), there is not a clear signal of prevailing wind directions, while to the south, at Termoli and Brindisi, the strongest signal is from north-west, even if Brindisi also has a clear signal of southerly winds.



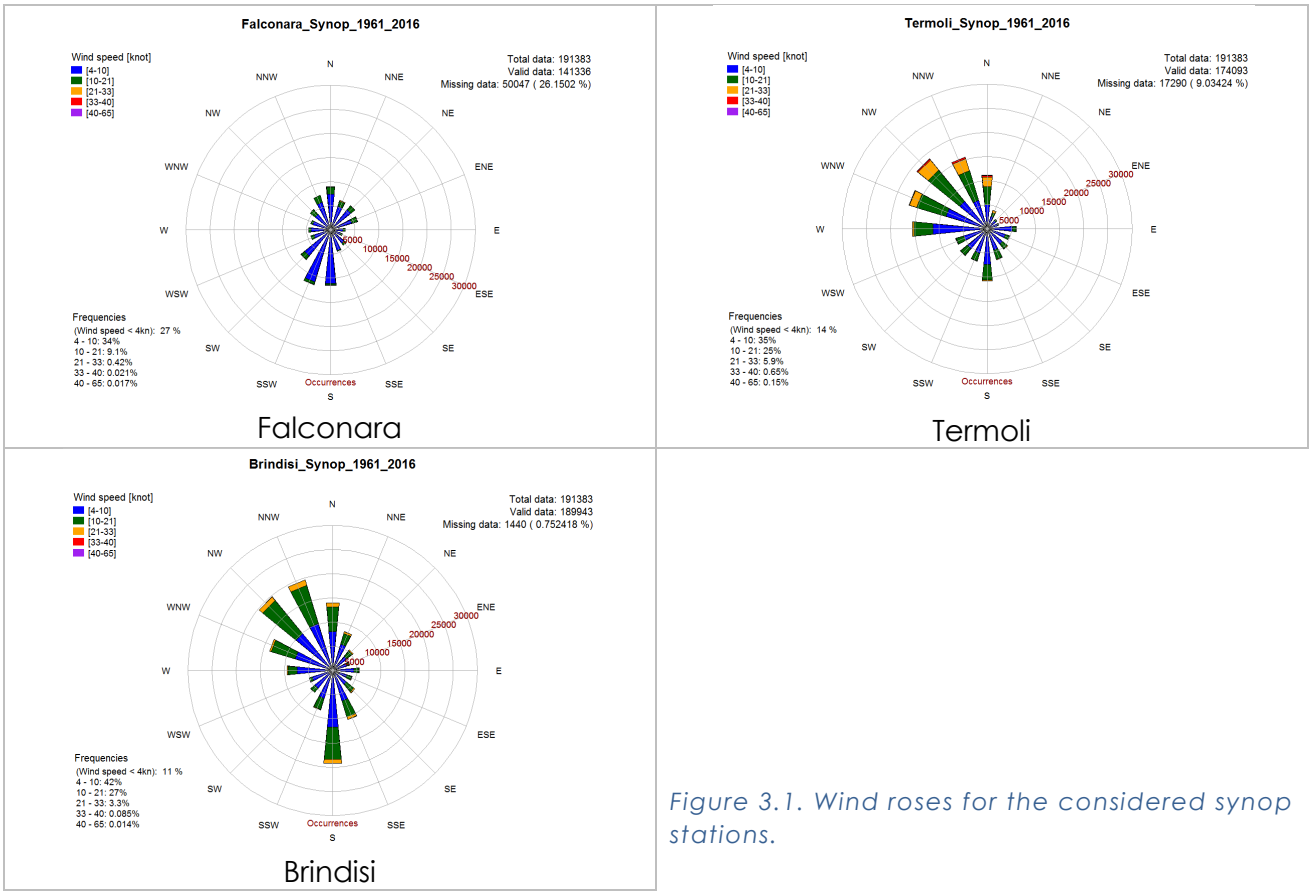


Figure 3.1. Wind roses for the considered synop stations.

3.2 Long term wind storminess

Following the method of Smits et al. (2005), the three-hourly wind speeds and directions have been processed. For each station, independent events have been selected flagging a measurement as an event if it equals the maximum speed of a 99 hours time windows centred on the measurement itself (considering three-hourly measurements, a range of 16 data before and 16 data after the selected measurements has been checked). This time window is often used in extreme values analysis of wind speed since it guarantees that independent subsequent extremes are separated by a minimum separation time of 48 hours (Palutikof *et al.*, 1999). Winds below 4 knots have been considered as a calm, since it has been shown (Pirazzoli and Tomasin, 1999) that winds below that threshold present a clear drift due to the improvement/changes in instrumentations. Once the time series of selected events was created, the 90th percentile of the wind speed distribution was used to determine the most intense events and their distribution over the years 1960-2016. This methodology provides a "climatology" that is considered representative for the whole period of wind measurements. Results are plotted in figure 3.2.

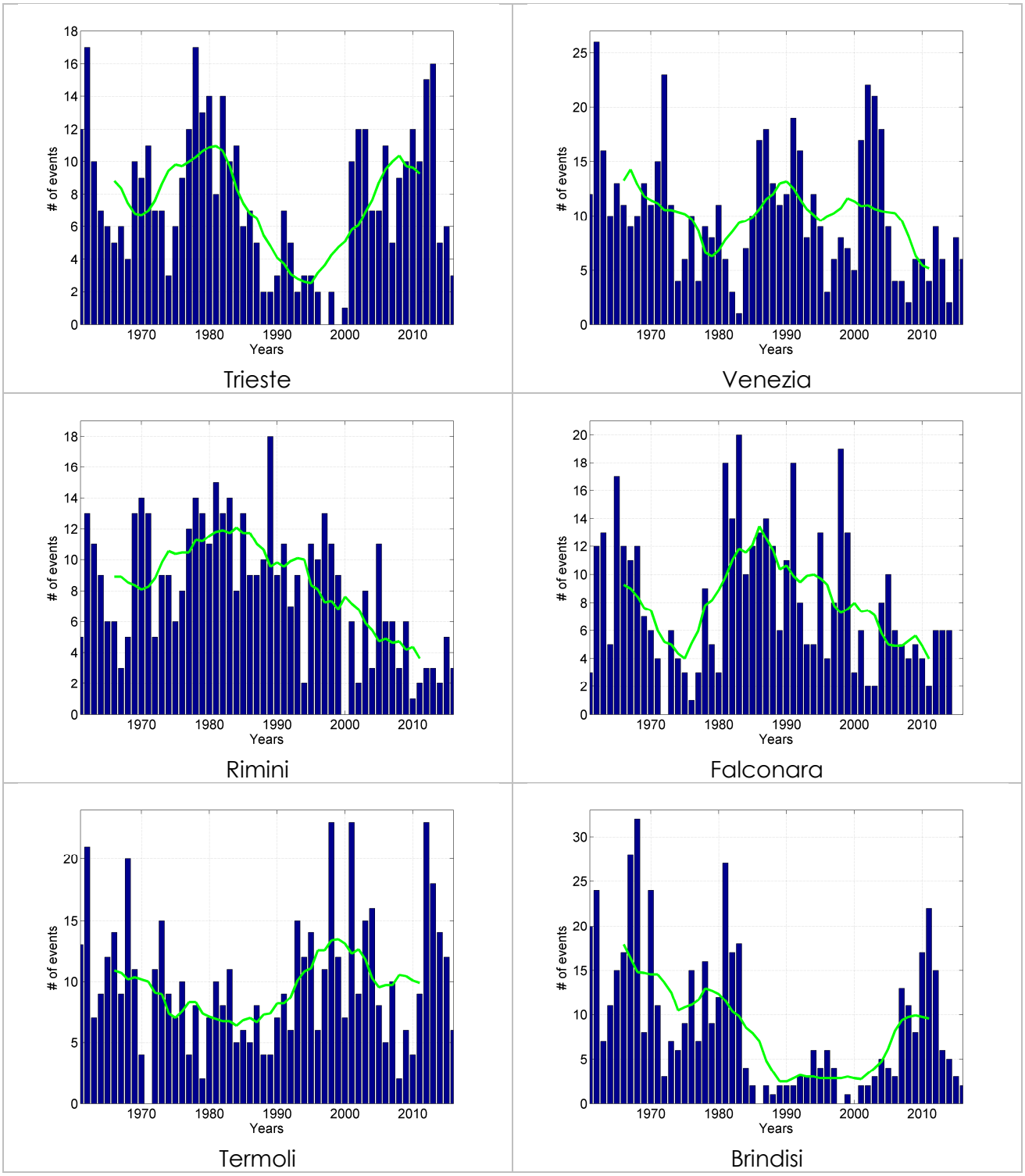


Figure 3.2. Events distribution over years considering all wind speeds > 4 knots and all directions. Blue bars represent the number of events selected year by year with the 90th percentile, whereas the green line is the 10-years moving average.

Taking into consideration the percentage of wind speed measurement gaps shown in figure 1.3 the station of Punta Marina (RA) has not been included in this analysis since it presents a total gap of data higher than the 27% over the whole considered period.

Wind speed trends are very different for each station and it is not possible to highlight an univocal information for all datasets. Trieste and Brindisi show a negative trend till the middle 1990s when they show a break point changing sign from significantly negative to positive. Venezia and Rimini seem to have a general negative trend in the period but with relevant interannual variability. Falconara is characterized by three well defined trends, the first, till the middle 1970s, is negative, the second is a positive trend till the middle 1980s when the sign inverted to negative till nowadays. Termoli, compared to the other ones, has smoother and more regular variations that do not show a clear positive or negative trend.

3.3 Meteorological storminess associated with Emilia-Romagna severe sea storms

For this analysis the dataset (described in paragraph 2) of wave measurements from Cesenatico wave buoy has been considered. In particular, following the same methodology used for the meteo storminess climatology described in the previous paragraph, the full time series of wave data has been processed in order to isolate sea storm events, with a running time-window of 48 hours, selecting as an event the measurement that equals the maximum of the time-window from 24 hours before the considered observation, till 24 hours later. The 85th percentile of all the events isolated has been considered, in order to select all the strongest events, in terms of wave height. The 85th percentile has been chosen because it returns a yearly distribution of wave storm events (figure 3.3) that is very similar to the distribution (figure 2.3) found in chapter 2, applying another method of identification and isolation.

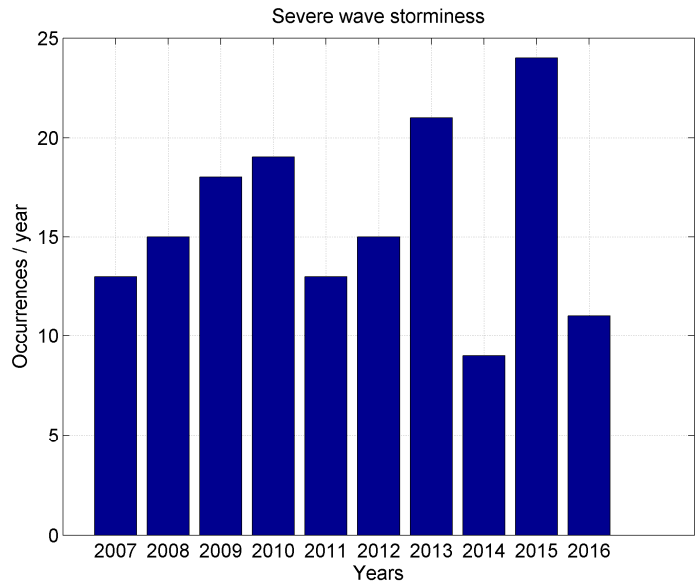


Figure 3.3. Yearly distribution of the number of wave storms in the period June 2007 - June 2016, considering the 85th percentile of a group of maxima isolated by means of a moving window of 48 hours along the whole dataset.

Once that the wave events were selected with the procure described above, SYNOP data have been used to look for typical meteorological "stormy" conditions, i.e. mean meteorological conditions before and during the wave events. For this purpose, mean sea level pressure (mslp), wind speed and wind direction from Venezia, Rimini and Brindisi coastal stations were rearranged to provide an overview during the event and respectively 3, 6, 12, 18, 24 hours. Moreover a climatology of the considered variable has been reconstructed for the period of wave measurements available (June 2007 - June 2016).

The meteorological "stormy" conditions observed during the wave storms, have then been applied to the whole SYNOP datasets (1960-2016) in order to identify possible long-term trends.

This procedure has been applied to three different configurations:

- all the wave dataset has been considered;

- only waves produced by Bora winds have been considered, i.e. coming from the north-eastern sector;

- only waves produced by Sirocco winds have been considered, i.e. coming from the south-eastern sector.

Related results are discussed in the following paragraphs.

3.3.1 Meteorological storminess associated with all severe wave storms

In this paragraph the whole dataset of wave measurements at Cesenatico has been considered.

Pictures 3.4, 3.5 and 3.6 represent meteo storminess in terms of mean sea level pressure, wind speed and wind direction associated with all severe wave storms isolated at Cesenatico. It is hard to deduce any assumption on wind speed and mean sea level pressure since there are not clear indications. For this reason the difference of mean sea level pressure between the station of Venice-Brindisi and Rimini-Brindisi has been computed (figure 3.7).

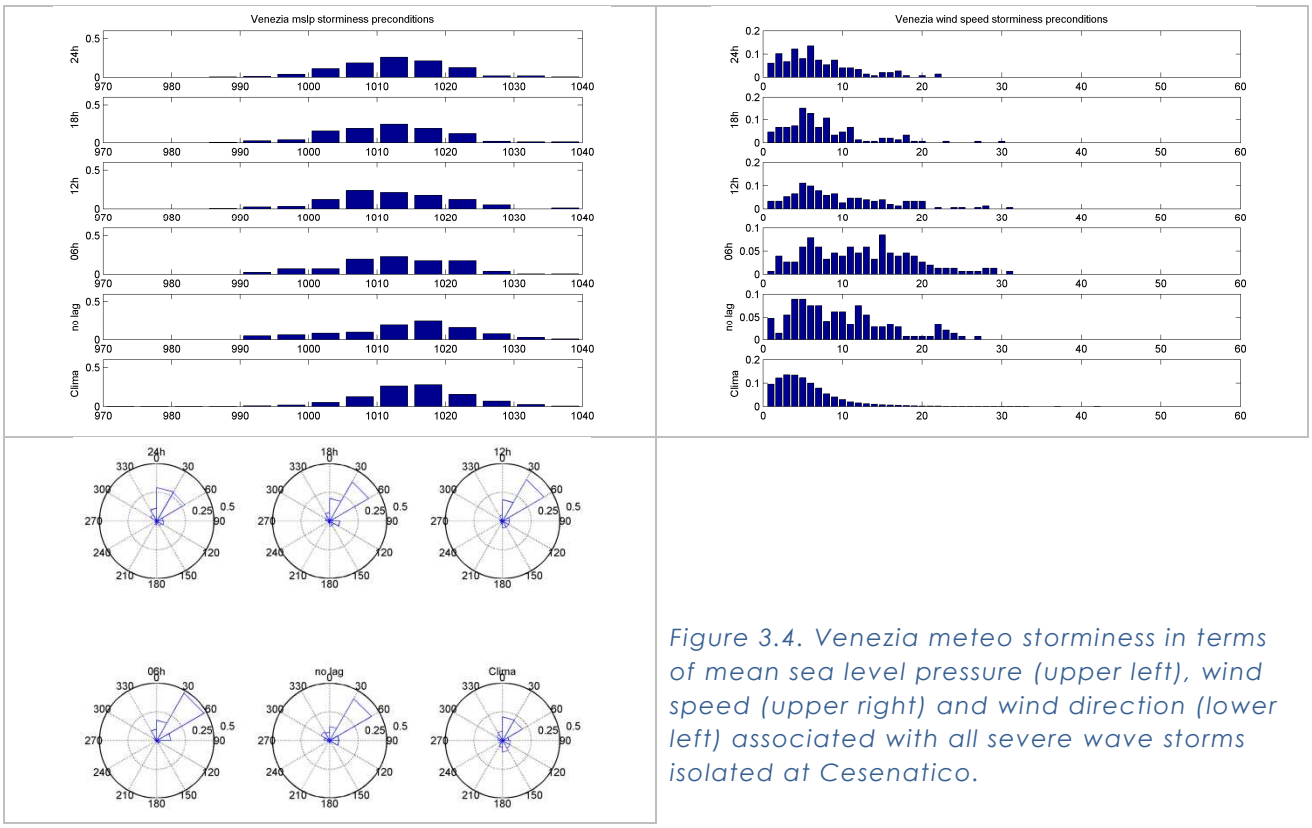


Figure 3.4. Venezia meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with all severe wave storms isolated at Cesenatico.

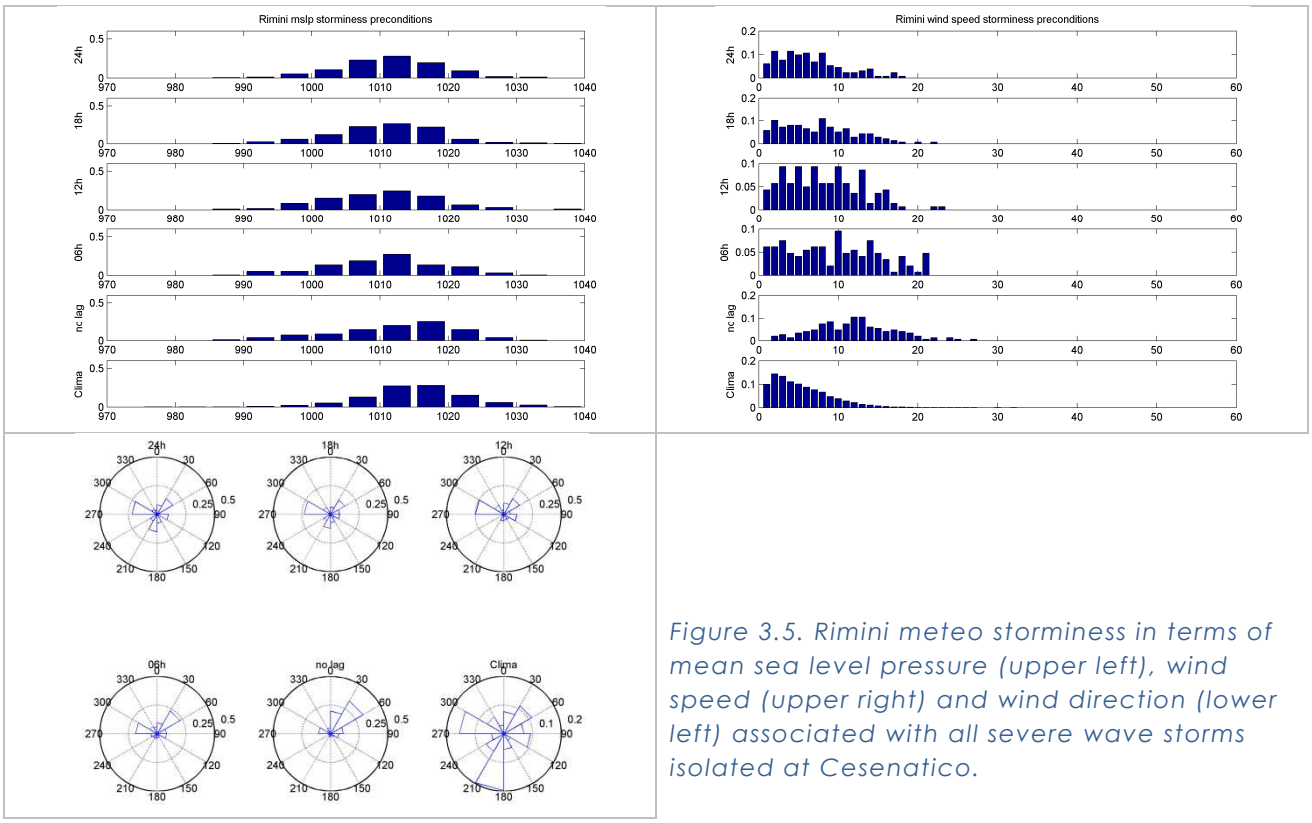


Figure 3.5. Rimini meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with all severe wave storms isolated at Cesenatico.

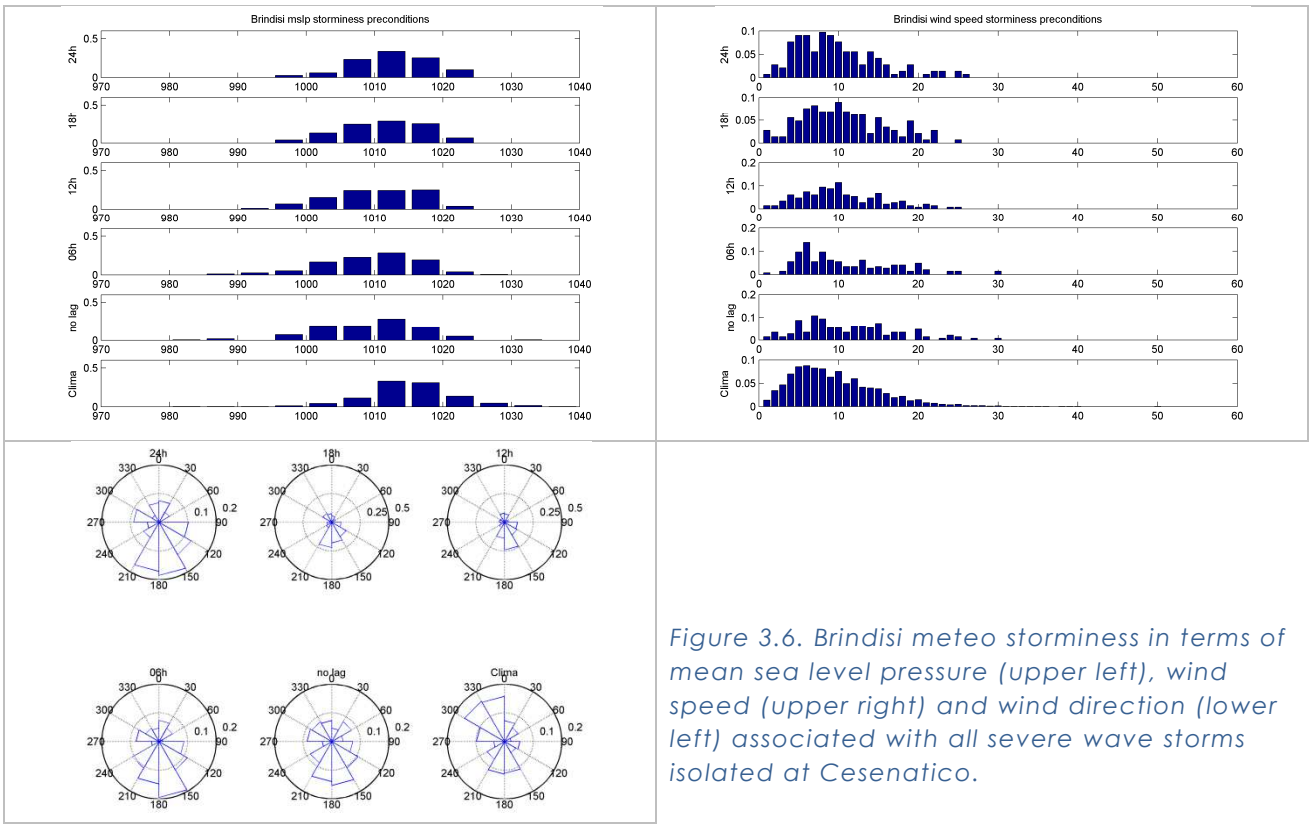


Figure 3.6. Brindisi meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with all severe wave storms isolated at Cesenatico.

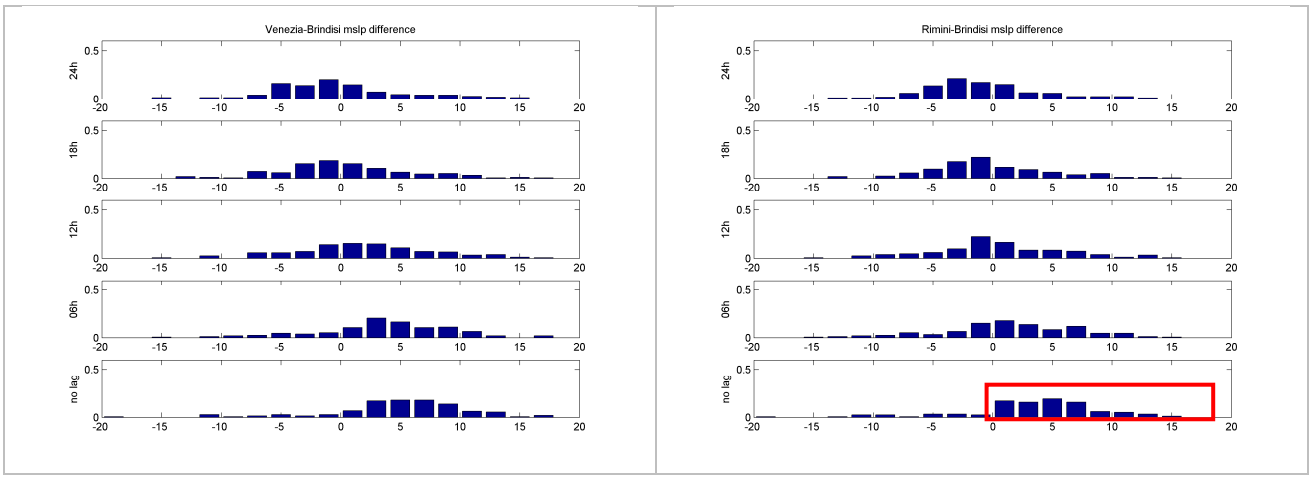


Figure 3.7. Difference of mean sea level pressure between Venezia and Brindisi (left) and between Rimini and Brindisi (right). Differences are plotted during the event (no lag) and respectively 3, 6, 12, 18, 24 hours before the event.

Considering the meteorological conditions during wave storms ("no lag" panel in figure 3.7), it is possible to assume that the difference of mean sea level pressure between the station of Rimini and the station of Brindisi must be positive. At the same time, the wind direction at Rimini must be included into the range 270°-120° (figure 3.5, lower left panel). No assumptions can be deduced about the wind direction at Brindisi (figure 3.6, lower left panel).

Applying these conditions to the long-term SYNOP datasets, it is possible to note (figure 3.8) that a positive trend has been recorded till the middle 2000s, when the trend inverted its sign to negative. It is possible to highlight that till the middle 1990s the trend mildly increases (sometime it seems to be steady or even negative), but during the period middle 1990s - middle 2000s the positive trend increased much faster than the years before.

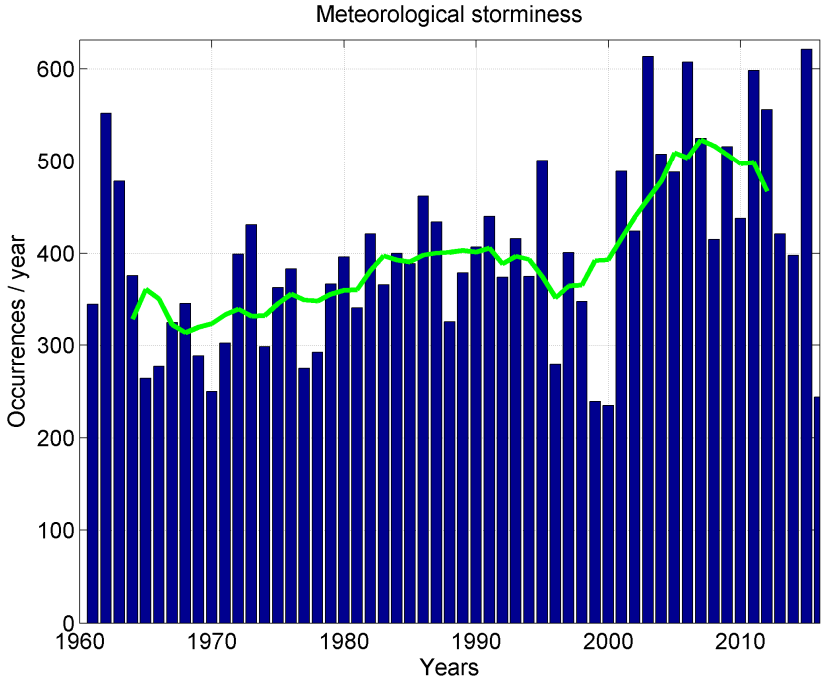


Figure 3.8. Hours per year of meteorological storminess (blu bars). The green line is the 10-years moving average. Period 1960-2016.

3.3.2 Meteorological storminess associated with severe Bora wave storms

The meteorological analysis described in this paragraph is based on the dataset of wave measurements at Cesenatico, taking into account only waves produced by Bora winds (North-East winds).

Pictures 3.9, 3.10 and 3.11 represent meteo storminess in terms of mean sea level pressure, wind speed and wind direction associated with severe wave storms isolated at Cesenatico and produced by Bora winds. It is hard to deduce any assumption on wind speed and mean sea level pressure since there are not clear signals. For this reason the difference of mean sea level pressure between the station of Venice-Brindisi and Rimini-Brindisi has been computed (figure 3.12).

It is interesting to note that graphs in pictures 3.9-3.12 are very similar to the ones in pictures 3.4-3.7, to denote that meteorological storminess in correspondence of wave storms in Emilia-Romagna is mostly caused by Bora winds.

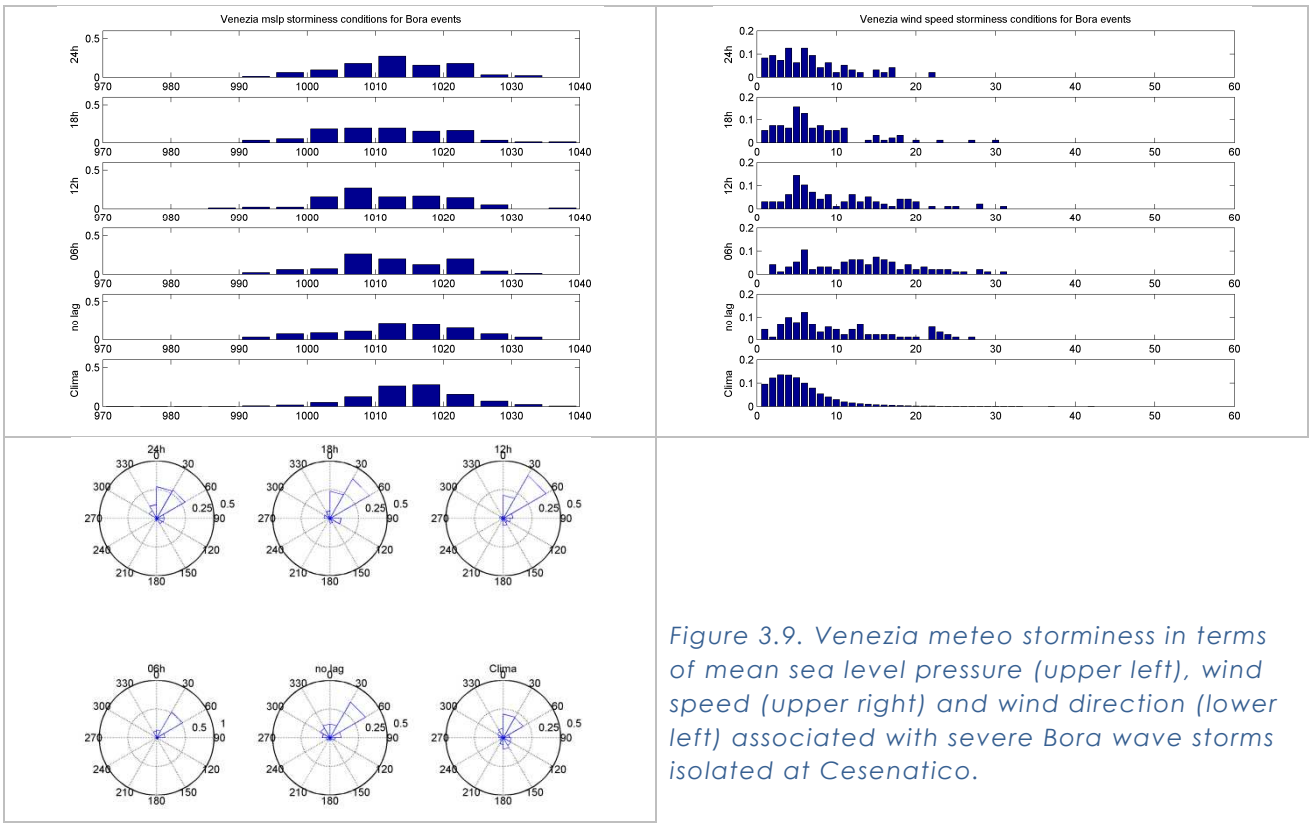


Figure 3.9. Venezia meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with severe Bora wave storms isolated at Cesenatico.

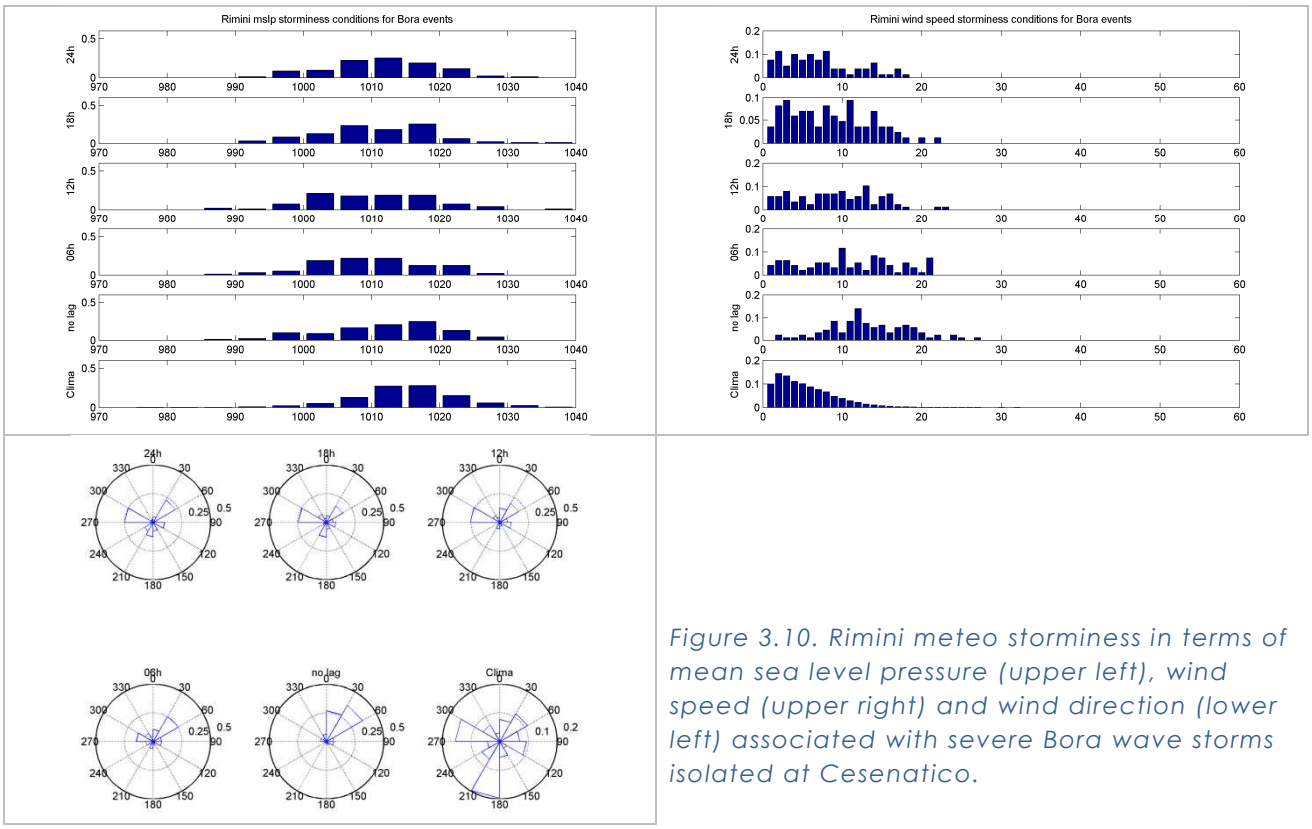


Figure 3.10. Rimini meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with severe Bora wave storms isolated at Cesenatico.

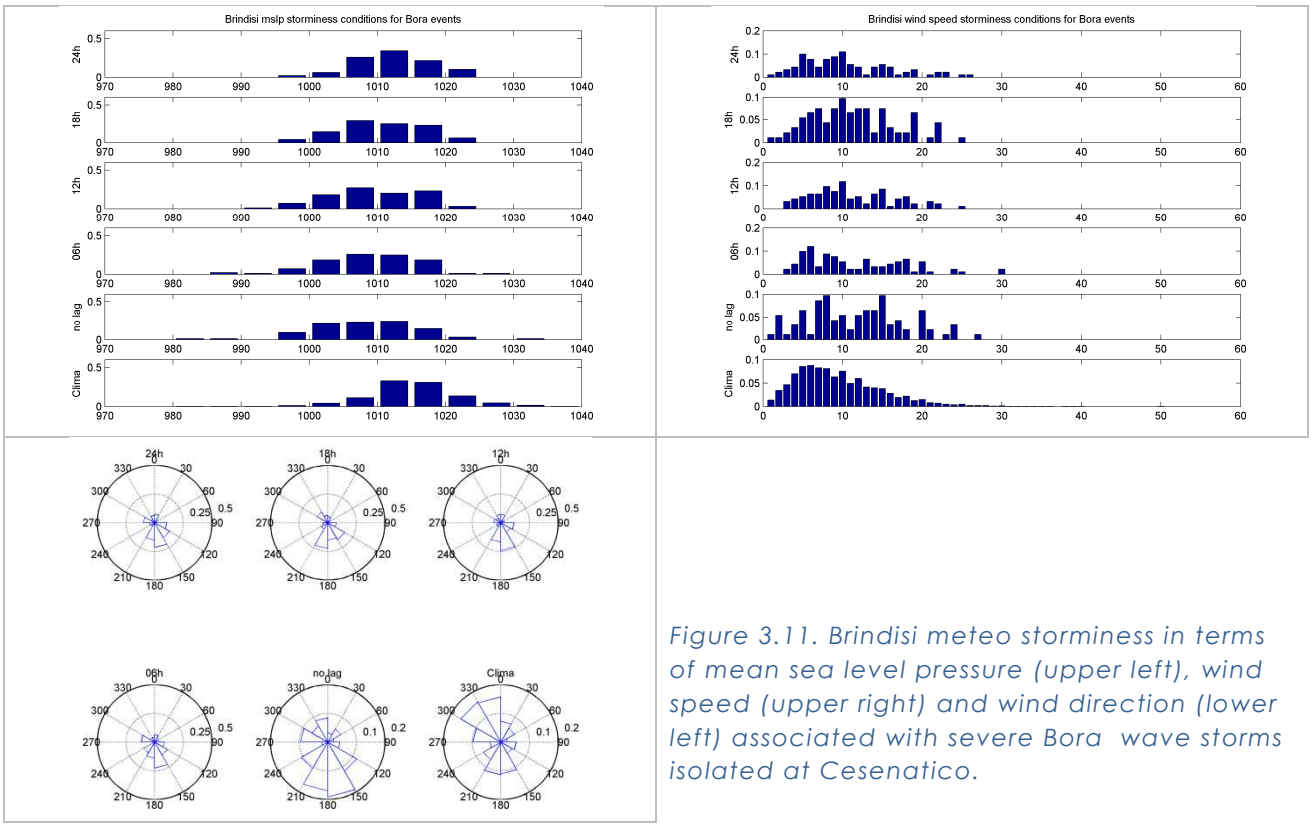


Figure 3.11. Brindisi meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with severe Bora wave storms isolated at Cesenatico.

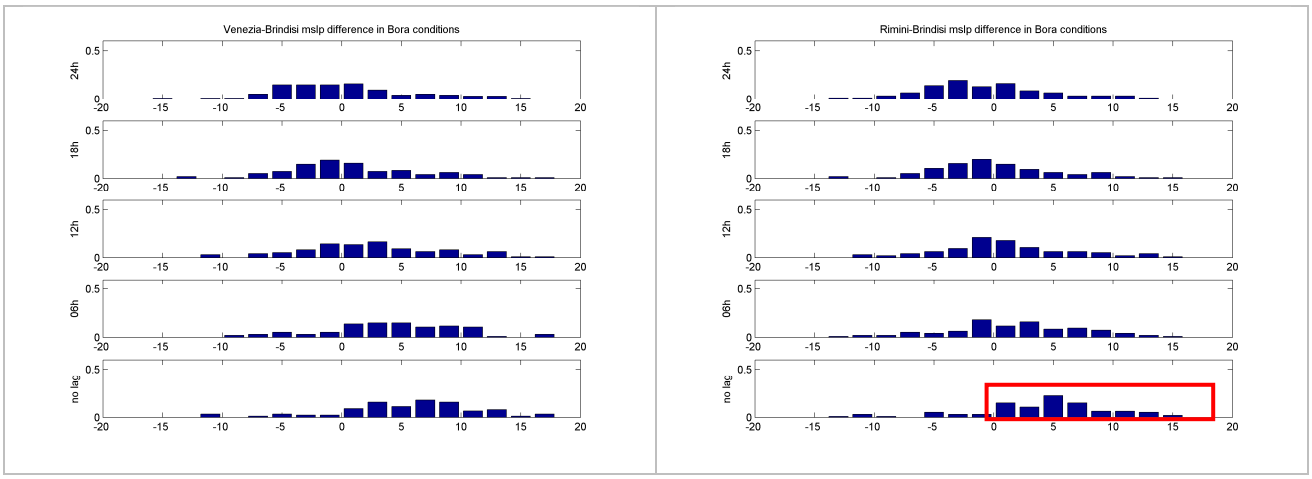


Figure 3.12. Difference of mean sea level pressure between Venezia and Brindisi (left) and between Rimini and Brindisi (right). Differences are plotted during the event (no lag) and respectively 3, 6, 12, 18, 24 hours before the event.

Considering the meteorological conditions during Bora wave storms ("no lag" panel in figure 3.7), it is possible to assume that the difference of mean sea level pressure between the station of Rimini and the station of Brindisi must be positive. At the same time the wind direction at Rimini must be included into the range 0°-90° (figure 3.10, lower left panel). No assumptions can be defined about the wind direction at Brindisi (figure 3.11, lower left panel).

Applying these conditions to the long-term SYNOP datasets, it is possible to highlight (figure 3.13) that a positive trend has been recorded till the middle 2000s, when the sign inverted to negative.

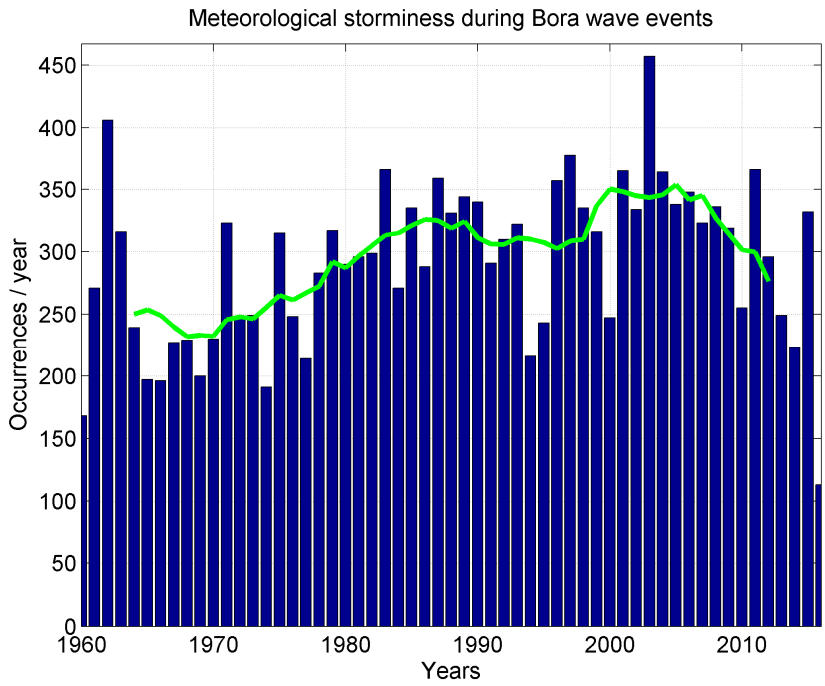


Figure 3.13. Hours per year of meteorological storminess during Bora wave events (blu bars). The green line is the 10-years moving average. Period 1960-2016.

3.3.3 Meteorological storminess associated with severe Sirocco wave storms

After the analyses of the previous paragraphs, here only waves produced by Sirocco winds (South-East winds) have been considered.

Pictures 3.14, 3.15 and 3.16 represent meteorological storminess in terms of mean sea level pressure, wind speed and wind direction associated with severe wave storms isolated at Cesenatico and produced by Sirocco winds. It is hard to deduce any assumption on wind speed and mean sea level pressure since there are not clear correlations. For this reason the difference of mean sea level pressure between the station of Venice-Brindisi and Rimini-Brindisi has been computed (figure 3.17).

In this case graphs in pictures 3.14-3.16 are different from the ones in pictures 3.4-3.7, to denote that meteorological storminess is less affected by Sirocco conditions, on the contrary of what it has been seen in the previous paragraph for Bora.

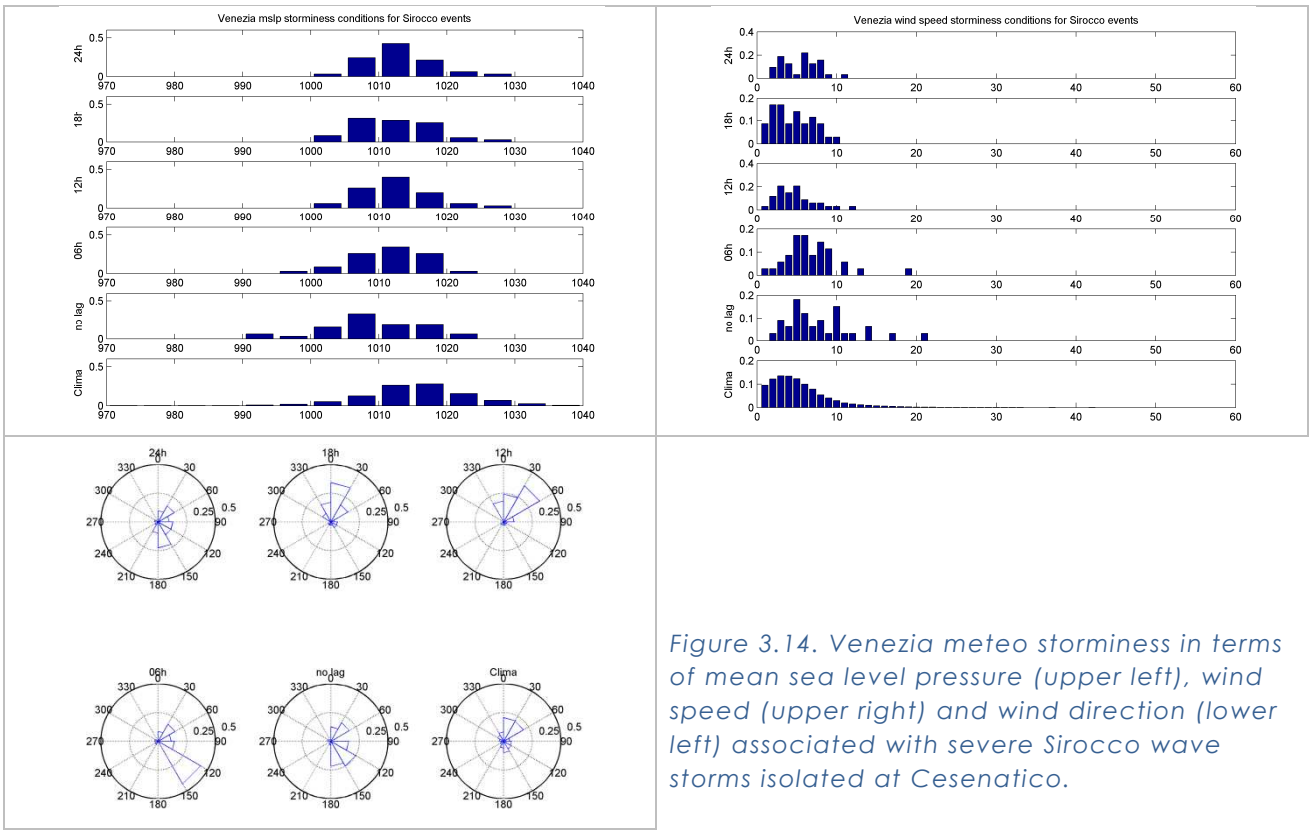


Figure 3.14. Venezia meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with severe Sirocco wave storms isolated at Cesenatico.

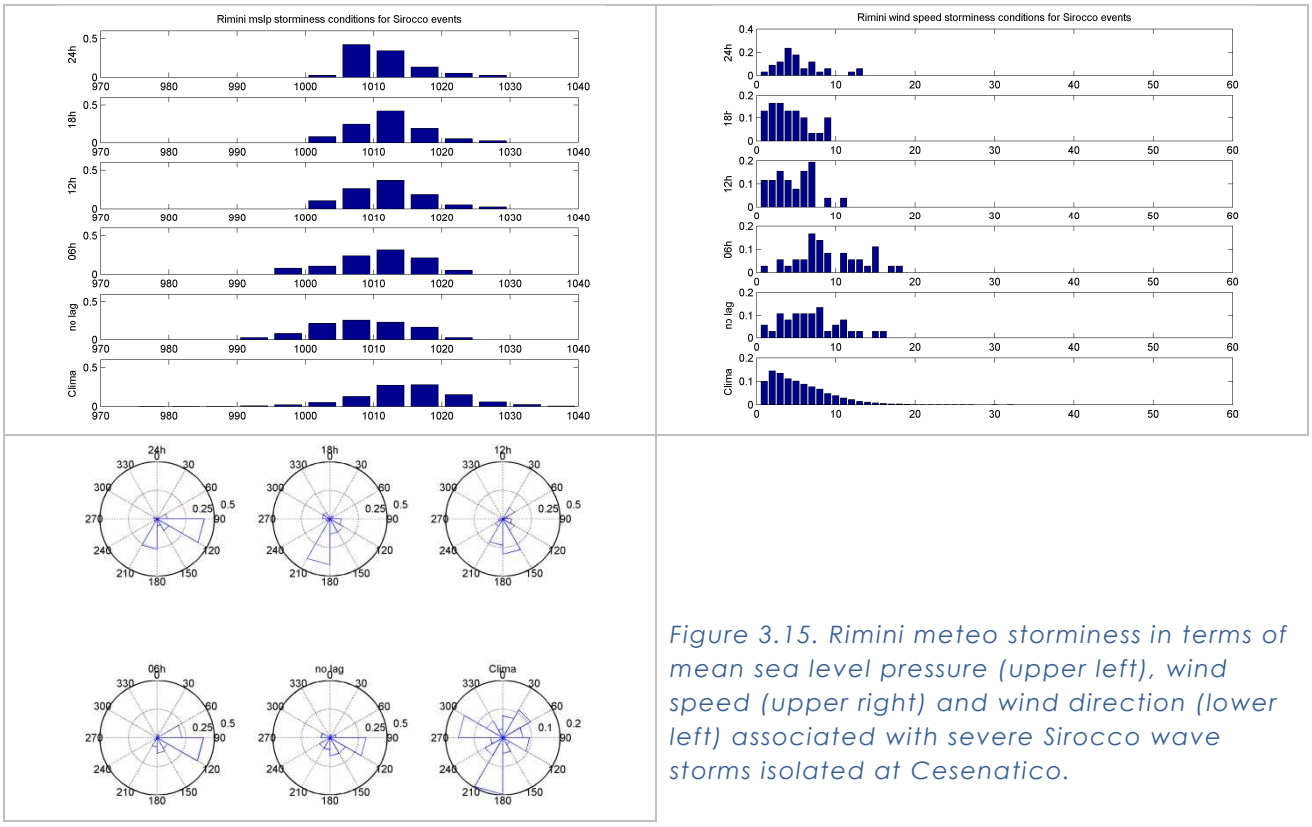


Figure 3.15. Rimini meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with severe Sirocco wave storms isolated at Cesenatico.

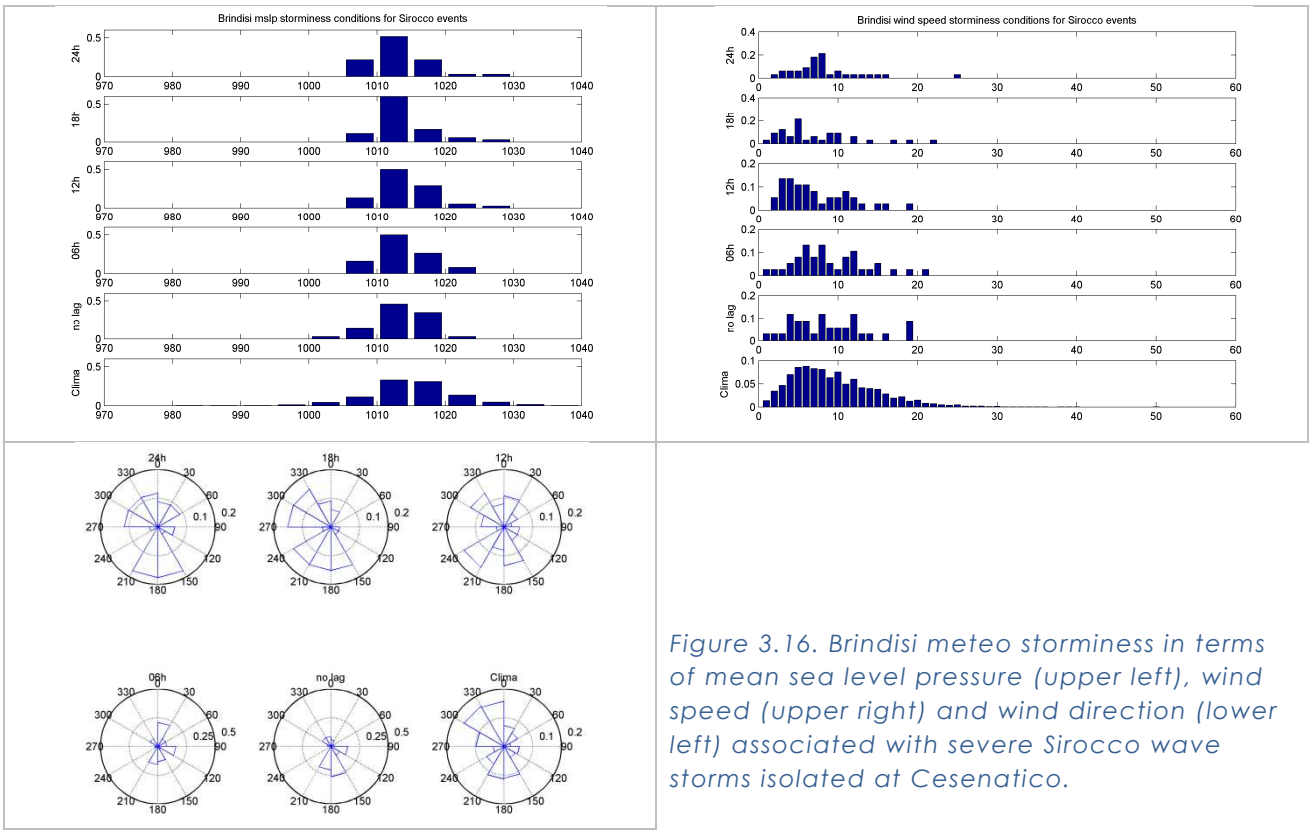


Figure 3.16. Brindisi meteo storminess in terms of mean sea level pressure (upper left), wind speed (upper right) and wind direction (lower left) associated with severe Sirocco wave storms isolated at Cesenatico.

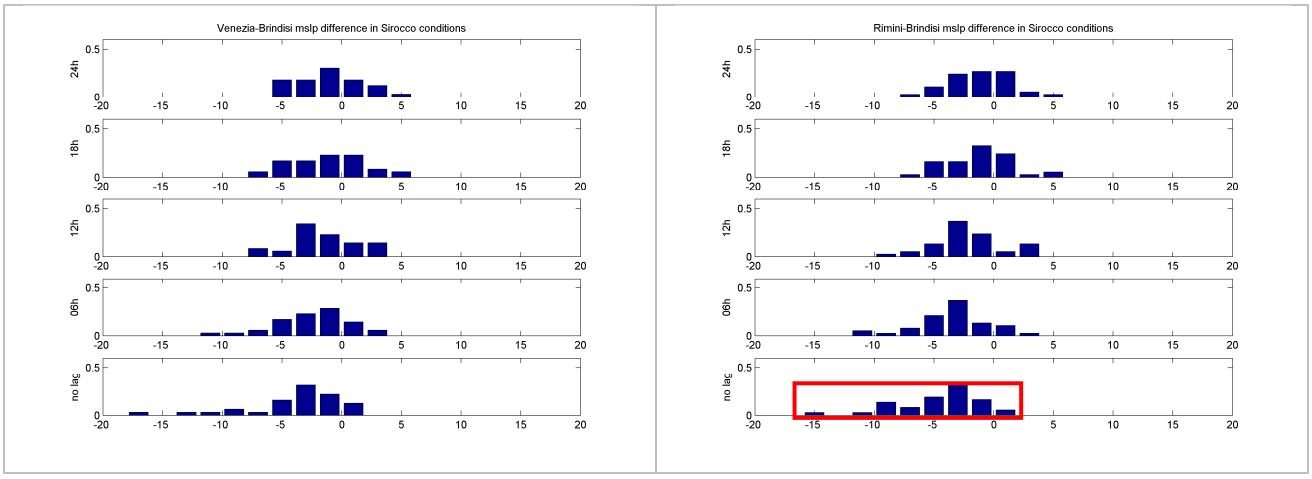


Figure 3.16. Difference of mean sea level pressure between Venezia and Brindisi (left) and between Rimini and Brindisi (right). Differences are plotted during the event (no lag) and respectively 3, 6, 12, 18, 24 hours before the event.

Considering the meteorological conditions during Sirocco wave storms ("no lag" panel in figure 3.7), it is possible to assume that the difference of mean sea level pressure between the station of Rimini and the station of Brindisi must be less than 2 mbar. At the same time, the wind direction at Rimini has been considered in the range 90°-180° (figure 3.15, lower left panel). No assumptions can be highlighted about the wind direction at Brindisi (figure 3.16, lower left panel).

Applying these conditions to the long-term SYNOP datasets, it is possible to highlight (figure 3.17) a small and mild positive trend during the period of 50 years considered, with interannual variations that are comparable to results obtained in the previous paragraphs but with a ten-years moving average less variable.

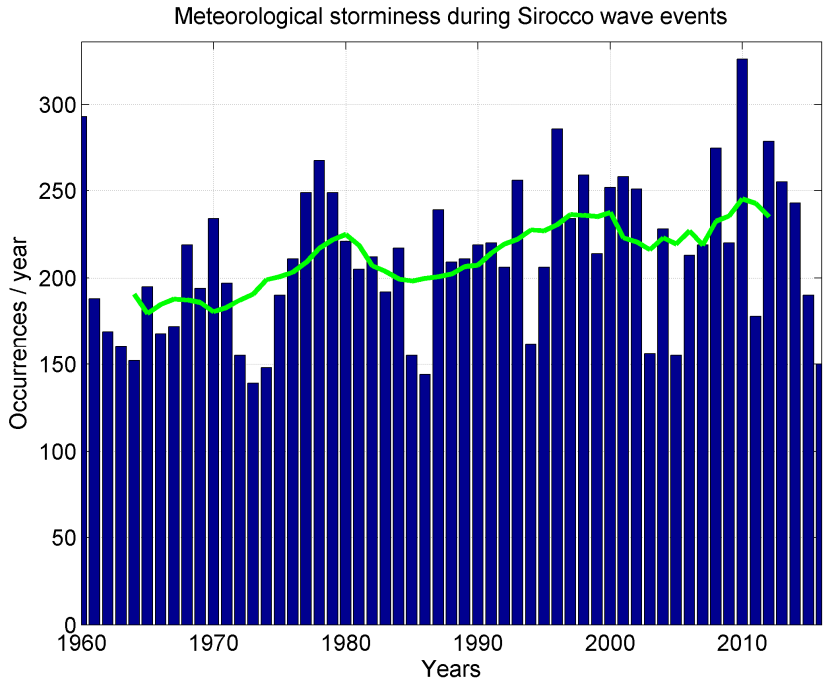


Figure 3.17. Hours per year of meteorological storminess during Sirocco wave events (blu bars). The green line is the 10-years moving average. Period 1960-2016.

4. Conclusions

This study presents different analyses of the meteorological and marine climatology for the Emilia-Romagna coast; and it is based on the meteorological and marine measurements available at the Hydro-Meteo-Climate Service of Arpae Emilia-Romagna. As mentioned in the introduction, this study carries on and updates previous similar analyses performed during two main EU Projects: CADSEALAND (2004-2006) and MICORE (2008-2011).

Directional wave measurements, that have been used for the wave storminess analysis, have been provided by the wave buoy of Cesenatico. This dataset covers only the last 10 years and it hasn't been possible to extend longer in the past due to non homogeneous sources of data available.

Results discussed in paragraph 2 show that there is not a defined trend for the number of wave storms in the last 10 year. Mild positive trends could be dared for the maximum wave height and the maximum sea level during the events, but a period of 10 years of data is too short and it is difficult to generalize the obtained information for long-term

considerations; moreover, in this specific case, the interannual variability is large compared with the little overall tendency on the decal time scale.

In the period June 2007 - June 2016 189 wave storms have been pointed out, with a mean duration of 18 hours. A detailed summary of the analysis is synthesized in table 2.2 in which are reported the main characteristics for each year. The number of storms has not a clear trend along the years but presents a large interannual variability, so as the total hours of storminess. The most energetic years result to be 2007, 2011, 2012 and 2015.

A previous analysis of the trends of the severe significant wave height events based on instrumental observations has been done by Lionello et al. (2012), using the 30-years-long Acqua Alta dataset of CNR-ISMAR. They detected steady storminess conditions, or a small trend toward a milder regime, that substantially agrees with results obtained with the wave storminess analysis of this study.

For the analysis of the meteorological storminess climatology the datasets of to the Italian Adriatic-coastal stations of the SYNOP (surface synoptic observations) network have been used. Data consist of time series of 3-hourly measurements of standard meteorological surface parameters, such as 10-meters wind and mean sea level pressure. Stations of Trieste, Venezia, Punta Marina (Ravenna), Rimini, Falconara (Ancona), Termoli and Brindisi have been considered. The same datasets were previously investigated by Pirazzoli and Tomasin (1999, 2003), and this study is somehow an update of their analyses since it takes into account more than 50 years, starting from 1960 to nowadays.

The wind speed climatology analysis returns different trends along the stations. Trieste and Brindisi show a negative trend till the middle 1990s when they show a break point changing, sign from significantly negative to positive. Venezia and Rimini seem to have a general negative trend in the period but with relevant interannual variability. Falconara is characterized by three well defined trends, the first, till the middle 1970s, is negative, the second is a positive trend till the middle 1980s when the sign inverted to negative till nowadays. Termoli, compared to the other ones, has smoother and more regular variations that do not show a clear positive or negative trend.

In order to have specific indication of the meteorological storminess associated with Emilia-Romagna severe sea storms, the dataset of wave measurements from Cesenatico wave buoy has been considered. In particular the full time series of wave data has been processed in order to isolate sea storm events (in terms of significant wave height), then SYNOP data have been used to look for typical meteorological “stormy” conditions, i.e. mean meteorological conditions before and during the wave events. For this purpose, mean sea level pressure (mslp), wind speed and wind direction from Venezia, Rimini and Brindisi have been considered, since they are the station with the lowest number of measurement gaps during the period. The meteorological "stormy" conditions observed during the wave storms, have then been applied to the whole SYNOP datasets (1960-2016) in order to identify possible long-term trends.

This procedure has been applied to three different configurations: all the wave dataset has been considered, only waves produced by Bora winds have been considered and finally only waves produced by Sirocco winds.

In the first case the "stormy conditions" that may produce wave events have been defined as:

- Mean sea level pressure difference between Rimini and Brindisi > 0 mbar.
- Wind direction at Rimini included into the range 270°-120°.

Under these conditions a positive trend has been recorded till the middle 2000s (figure 3.8), when the trend inverted its sign to negative. It is possible to highlight that till the middle 1990s the trend mildly increases (sometime it seems to be steady or even negative), but during the period middle 1990s - middle 2000s the positive trend increased much faster than the years before.

When considering only waves produced by Bora winds, the "stormy conditions" that may produce wave events have been defined as:

- Mean sea level pressure difference between Rimini and Brindisi > 0 mbar.
- Wind direction at Rimini included into the range 0°-90°.

Under these conditions the long-term SYNOP datasets show a positive trend (figure 3.13) till the middle 2000s, when the sign inverted to negative.

In the end, considering only waves produced by Sirocco winds, the "stormy conditions" that may produce wave events have been defined as:

- Mean sea level pressure difference between Rimini and Brindisi < 2 mbar.
- Wind direction at Rimini included into the range 90°-180°.

These constrains lead to a small and mild positive trend (figure 3.17) during the period 1960-2016, with large interannual variations but with a mildly ten-years moving average.

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