

Severe sea storms along Italian coasts

S. Palmieri¹, S. Corsini³, G.R. Casale² & A.M. Siani¹

¹*University of Rome "La Sapienza", Dep. of Physics, Rome, Italy*

²*Consulting meteorologist; c/o S. Palmieri*

³*Servizio Idrografico e Mareografico Nazionale, Rome, Italy*

Abstract

An analysis of 82 severe sea storms which affected the coasts of Italian Peninsula from 1990 up to 2001, documented by systematic observations carried out by a buoy national network, is performed with the aim to identify the main features of meteorological fields and to describe their development. For each of the 82 cases a standardised minimum documentation is collected, consisting of both 1000 hPa maps and surface wind speed fields covering the whole Mediterranean area. Storms are then classified according to the location of the low pressure centre, by means of a k-means cluster analysis. Thereafter the time development of representative events of each cluster is investigated considering time sequences of various fields starting from the early stage of the storms. The boundary layer structure in areas of wave generation is finally considered (vertical wind-shear, static stability, Richardson number). Concluding remarks are referred to the peculiar meteorological features of Mediterranean sea storms.

1 Introduction

The study has been inspired by the implementation, under the Department of National Technical Services (Servizio Idrografico e Mareografico Nazionale), of a national network of buoys along the coasts of the Italian Peninsula to monitor and report in real time the state of the sea and its wave motion (Appendix 1). About ten years of continuous observations are now available (1990-2000). The list of sea storms occurred during this time span, together with values of some wave parameters, were provided by the Civil Engineering Department of the 3rd Rome University, that stimulated and sponsored the present research, aiming to offer a meteorological characterisation of the events. A sea storm, in the contest

of this study, is defined as a coastal storm characterised by sea waves reaching the buoy site from a sector not exceeding 60 degrees, height greater than 1 m. Storms in sequence are considered as two individual events if separated by a time interval of at least 48 hours.

2 Steering line of the study: atmospheric quantities and data

Sea storms, although defined on the basis of wave motion, are the result of the atmospheric forcing on the sea, which is effective in a region (*generation area*) whose boundaries are both coasts and some geometric features of the wind and/or pressure fields. The momentum of the wind over the sea surface is transferred very effectively to the wind waves, and waves develop with time and space, until a *saturated* condition is eventually attained.

The “*fetch*”, a well known basic quantity used in reference to sea-atmosphere interaction, is a measure of the linear dimension of the generation area in the direction of the wind. Although the use of concepts such as fetch or generation area are fruitful in characterising the impact of a disturbance at a specific site, they are not particularly appealing in classifying meteorological aspects of storms. Another important point to be stressed is that the available atmospheric documentation of past cases, such as that retrievable by NCEP (National Center for Environmental Prediction; Kalnay [1]) offers a very consistent representation of atmospheric fields, in a landscape in which larger scale features are dominant, while small scale features, like extreme winds or coastal local effects, are absent. The processes that generate kinetic energy on the mesoscale (topographic forcing and/or mesoscale instabilities) may be taken into consideration in detailed case studies, only when very dense observations allow a high space resolution of meteorological fields.

The 82 events have been divided in five classes according to the geographical co-ordinates by means of an objective methodology shortly described in the next section.

Cyclonic development stages are described and analysed for representative storms of each cluster.

Moreover for the purpose of this research the adoption of a parameter capable of identifying the space scale of storms, within the so called “synoptic” and “small synoptic scale” range, was considered a good start. After a number of trials $V^2/(Rf)$ was selected, where V is the surface wind speed, R is the radius of curvature of streamlines or isobars, f is the Coriolis parameter. In the operational estimate the wind speed is determined in the centre of the area of maximum wind, while R is the curvature radius of the low pressure measured at the centre of the maximum wind area.

3 Time and space distribution of events

For each year, months in which sea storms occurred are indicated in Figure. 1. It may be seen that November, December and January are the most critical ones,

while from February to June cases are scattered. In Summer sea storms are nearly absent.

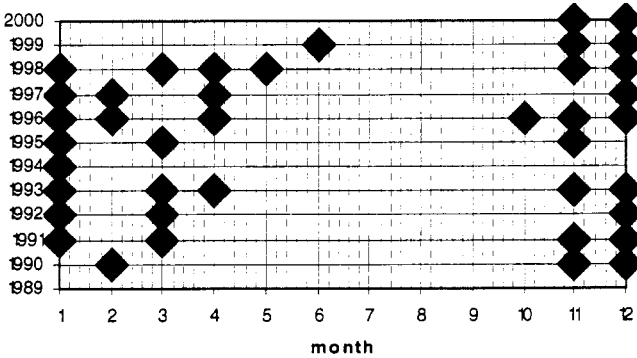


Figure 1 : months in which sea storms are reported

Space distribution of events is analysed by means of a cluster analysis, a well known statistical technique which allows to organise data in separate structures (clusters). The “k-means” method adopted in this case, requires the number of clusters to be prescribed. By means of an iterative algorithm the data are distributed in the different clusters in a way to minimise the variance within each cluster and to maximise that between individual clusters. Means and Euclidean distances, statistics for each cluster, as well as a list of cluster members, are the output elements useful for the interpretation of results.

Since each sea storm event is invariably associated to an atmospheric depression, in order to obtain an objective framework of the space distribution of cases, geographical co-ordinates of the cyclone centre are the input variables considered in the analysis.

The results indicate three groups with cyclone centres in the Mediterranean Basin - central, western, eastern - respectively and two more groups collecting cases characterised by depression centred outside the Basin at higher latitudes. The analysis output (containing the area where the centre is located) may be summarised as follows

- cluster 1: 12 cases, 15% (North-eastern Europe)
- cluster 2: 30 cases, 37% (Central Mediterranean)
- cluster 3: 11 cases, 13% (North -western Europe)
- cluster 4: 19 cases, 23% (Western Mediterranean)
- cluster 5: 10 cases, 12% (Eastern Mediterranean)

By far the largest fraction of events with an impact on the coasts of Italy is associated to depressions centred in adjacent sub-basins, as might be expected. Nevertheless low pressure areas with centres in other parts of Mediterranean

(western section in particular), as well as outside the Basin, do account for a considerable frequency.

Each cluster may be characterised by a virtual centre, whose latitude (longitude) is the mean of latitudes (longitudes) of the cases involved. The event at the minimum distance (Euclidean distance in the latitude-longitude plane) from the virtual cluster centre may be regarded as the most representative element of the whole cluster. Representative elements of each cluster are listed below (name of the station which reported the storm and date):

- cluster 1: Ponza 28/12/1999
- cluster 2: Pescara 16/02/1997
- cluster 3: La Spezia 06/11/2000
- cluster 4: Mazara 01/03/1993
- cluster 5: Monopoli 28/02/1997

4 Features of the cyclonic development for the typical storm of each cluster

Storm history is outlined by means of maps of meteorological fields. It has to be stressed that the described events shall be regarded as examples only. Although the factors favouring the formation, deepening and movement of storms may be different within each cluster, some common characteristics derive from large scale topographical effects which are common to each group. The 850 hPa contours for clusters 1,2, 3 and 4 are shown in Figure 2.

Cluster 1: Ponza 28/12/1999

On Dec 26 a vigorous nearly straight jet stream is present over the Atlantic from the Labrador coasts to central Europe. The flow is a powerful conveyor belt of shear vorticity toward Europe. The inertial fluido-dynamic instability (Haltiner & Martin [2]; Lindzen & al, [3]; Uccellini, [4]) is presumably responsible for the appearance of an ondulation over the Bay of Biscay.

The two cyclone formations occurred in western Europe on Dec 26 and 27 nick-named “Lothar” and “Martin” by the German Weather Service, caused local winds of record-breaking intensity at several synoptic stations (Ulbrich & al, [5]). On the 28 cold air masses are spreading into northern Mediterranean through southern France and a depression in the lee of the Alps sets in. The new development is a consequence of the deformation of the thermal field due to the barrier effect of the Alpine Range bringing about a favourable geometry of the thermal advection over northern Italy. This is a typical lee-cyclogenesis process in which mountains play a major role (Buzzi & Tibaldi, [6]). The Tyrrhenian coasts are affected by a strong “mistral” flow.

Cluster 2: Pescara 16/02/1997

The event is a good example of storms which influence the Adriatic coasts. A meteorological disturbance of medium intensity born two days before over Britain moved through the Mediterranean and is present, in the upper air maps, as a trough over southern Italy. On February 16 an outbreak of cold air from eastern Europe feeds new energy into the system. Thermal advection is again a leading factor in storm intensification.

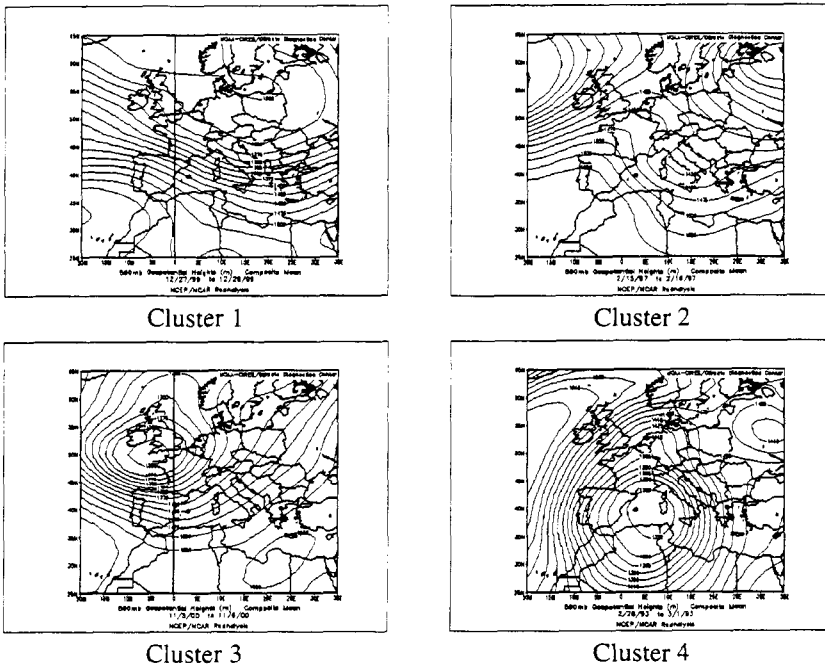


Figure 2 : Typical 850 hPa contour patterns of clusters 1, 2, 3 and 4

Cluster 3: La Spezia 06/11/2000

This is a typical event characterised by a depression centred outside Mediterranean Basin. The cyclone over France is very deep and wide. The system is thermally symmetric at all levels and is likely to persist and dominate the European flow pattern for a few days. The southern edge of this huge circulation system influences the western Mediterranean Basin determining a large wave generation area elongated in Southeast Northwest direction.

Cluster 4: Mazara 01/03/1993

The depression over western Mediterranean is formed as a response to a large scale circulation pattern characterised by an extreme amplitude of the large scale pattern (low index). Azores anticyclone is displaced northward, favouring an unusual south pointing jet along European Atlantic coasts.

On March 1st the Mediterranean low pressure area is concentrated in space, thermally isolated, deep and violent.

Cluster 5: Monopoli 28/02/97

The geometry of meteorological fields is similar to that of the typical storm of cluster 2, although the low pressure is now located over Ionian sea. Another peculiar difference is that cold advection from Northeast is not active as in the previous event. The intensification is presumably due to convective instability and release of latent heat.

Two examples are shown (28/12/99 and 16/02/97) which are classical prototypes of depressions generated or intensified in the Mediterranean as a consequence of cold outbreaks and topographical effects. For other storms (01/03/93 and 28/02/97) cyclogenesis and intensification of surface circulation is probably supported also by convective instability and latent heat release. Recent studies have shown that huge amount of moisture may be imported in the Mediterranean either from Arabian sea (Krichak & Alpert [7]) or from tropical Atlantic (Reale & al. [8]) . The possible effect of a very intense disturbance located outside the Basin is finally well represented by the event of 06/11/00.

5 Atmospheric boundary layer in wind maxima

Some elements useful for an analysis of the boundary layer (surface-1500 m) are provided in Table1. Parameters are computed right in the centre of wave generation areas (wind maxima) where the interaction sea- atmosphere is more effective.

Table 1. Boundary layer parameters estimated for the representative storm of each cluster. Data are referred to the area of maximum wind . Cl = cluster number; VS = vertical wind shear; BV = Brunt-Vaisalla frequency; SSTT = sea surface temperature - air temperature difference; MLH = mixed layer height (data not available for 01/03/93)

Date	Cl	VS (1/s)	BV (1/s)	RN	SSTT (°C)	MLH (m)
28/12/99	1	4,3E-3	7,0E-3	2,6	0	1400
16/02/97	2	-1,3E-3	7,0E-3	27,8	+1.5	700
06/11/00	3	5,0E-3	6,5E-3	1,7	+1	1500
01/03/93	4	3,7E-3	6,9E-3	3,6	-1,5	
28/02/97	5	1,3E-3	4,8E-3	12,8	+4	1200

Turbulence is controlled by the balance between wind shear and static stability (represented by the Brunt-Vaisalla frequency). Mechanical turbulence becomes dominating and overturning of the layer occurs, when the Richardson number $[(g/\theta \, d\theta/dz)/((dV/dz)^2)]$ is close to 0.25.

The storm of 16/02/97 is that characterised by minimum turbulence. As a consequence in this case the minimum mixing height (800m) is experienced. A

relatively active mixing within the boundary layer occurred on Nov 6th, 2000 with a wind shear nearly balancing buoyancy (Richardson number approaching the critical threshold). In conclusion the analysed cases show a generally stable boundary layer and the flow may be considered to a large extent laminar, such as to hamper any serious vertical dissipation of momentum.

6 Intensity of storms, the record event of 28/02/96 (Mazara)

As mentioned the ratio $V^2/(Rf)$ allows a classification of storms based on their degree of ciclostrophy. The parameter is actually the ratio between the centripetal acceleration (V^2/R) and the Coriolis parameter and has the dimension of a wind speed. Depending on the relative magnitude of the geostrophic wind and $V^2/(Rf)$, the motion may be said to be *predominantly geostrophic* or *predominantly ciclostrophic* (Petterssen,[9]). The parameter has the tendency to increase when one of (or a combination of) the following conditions does (do) occur:

- (1) wind kinetic energy (V^2) is increasing;
- (2) the low pressure area becomes more concentrated and the curvature radius R decreases;
- (3) the cyclone is located at low latitude.

The frequency distribution of $V^2/(Rf)$ for the 82 storm ensemble is shown in Figure 3. In most cases values do not exceed 3 m/s while in one case only the threshold 4 is trespassed.

According to this criterion, the events listed in Table 2 may be considered of extreme intensity (as usual the storm name coincides with the reporting station):

Table 2. Events of extreme intensity

Station	Date	$V^2/(Rf)$ (m/s)	Cluster
Mazara	28/02/1996	4.86	4
Pescara	28/02/1997	3.75	5
Crotone	14/01/1995	3.52	5
Alghero	26/12/1993	3.14	2
Monopoli	29/01/1994	3.09	5

Extreme storms fall, in general, in cluster 5 (eastern Mediterranean), although the record-breaking one ($V^2/(Rf) > 4$ m/s) is a member of cluster 4 (western Mediterranean). They affect coasts of southern Italy.

6.1 The Mazara sea storm of 28/02/96

The Mazara storm, characterised by a deep cyclone centre over Tunisia, deserves a detailed consideration, both for its extreme intensity reminding tropical systems and its life history. The embryo of the disturbance may be traced back on February 25 at the boundary between Mali and Guinea, Niger Valley (Figure 4).

The deepening of the low pressure area occurred between 25 and 26 February east of Mauritania and Morocco. On the 28 the cyclone is centred over Tunisia and appears very concentrated and violent. At this stage a closed circulation is present at upper levels also (Figure 5).

The initial development, in spite of the very low latitude, is very likely to be produced, as in most extratropical cyclones, by the geometry of the thermal advection field (Petterssen, [9]).

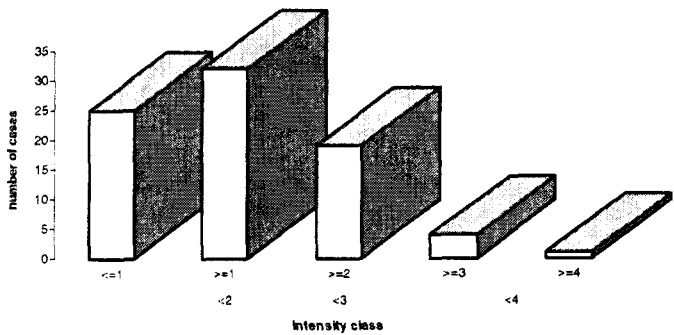


Figure 3 : storm intensity frequency distribution

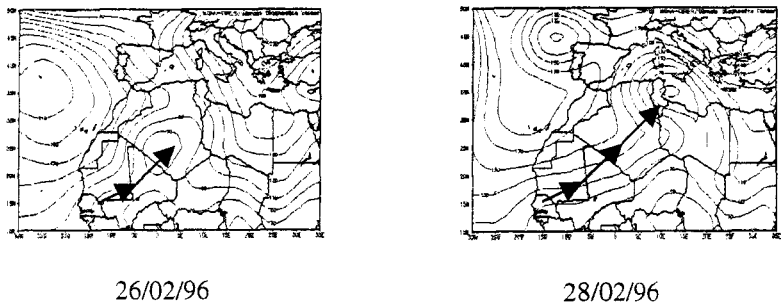


Figure 4 : 1000 hPa contours 26/02/96 and 28/02/96

The large scale surface wind field intensification is due to an increase of the southwest-northeast pressure gradient brought about by two concurrent factors: (a) the persistence of high pressure over the Balkan Peninsula favoured by the cold winter surface conditions in that region and (b) the north-eastward movement of the depression. Frictional convergence along south-facing coasts of Sicily as well as topographic convergence ('shoulder effect') in the westernmost angular shaped ridge of the Island, provide additional local amplification factors for the wind streaks.

7 Conclusion

Sea storms, although defined on the basis of wave motion, are the result of the atmospheric forcing on the sea, which is effective in a region (*generation area*) whose boundaries are both coasts and some geometric features of the wind and/or pressure fields.

First of all the 82 events have been divided in five classes according to the geographical co-ordinates by means of an objective cluster analysis. Three groups are found with cyclone centres in central, western and eastern Mediterranean Basin respectively and two more groups collecting cases with depression centred at higher latitudes, outside the Basin. The event at the minimum distance from the virtual cluster centre is regarded as the most representative element of the whole cluster. Representative elements of each cluster are discussed.

Two examples were shown (28/12/99 and 16/02/97) which are classical prototypes of depressions generated or intensified in the Mediterranean as a consequence of cold outbreaks and topographical effects. For other storms (1/03/93 and 28/02/97) cyclogenesis and intensification of surface circulation is probably supported also by convective instability and latent heat release. The possible effect of a very intense disturbance located outside the Basin is finally well represented by the event of 6/11/00.

Some elements useful for an analysis of the boundary layer (surface-1500 m) are then introduced. Parameters are computed right in the centre of wave generation areas (wind maxima) where the interaction sea-atmosphere is more effective. The considered cases show a generally stable boundary layer and the flow may be considered to a large extent laminar, such as to hamper vertical dissipation of momentum.

As a next step, a parameter capable of identifying the space scale and, at the same time, the intensity of storms, is applied. The parameter is the ratio between the centripetal acceleration (V^2/R) and the Coriolis parameter. In most cases values do not exceed 3 m/s, while in one event only the threshold 4 is trespassed (Mazara 28/02/96). This record-breaking event is then discussed in detail: a peculiar example of a storm originated in western Africa, that moved quickly toward the Mediterranean, where the system acquired new energy on account of the sensible and latent heat sources distribution in the Basin.

The large scale surface wind field intensification in the Sicily Channel is due to an increase of the south west - north east pressure gradient brought about by

two concurrent factors: (a) the persistence of high pressure over the Balkan Peninsula favoured by the cold winter surface conditions in that region and (b) the north-eastward movement of the depression. Frictional convergence along south-facing coasts of Sicily as well as topographic convergence ('shoulder effect') in the westernmost angular shaped ridge of the Island, provide additional local amplification factors for the wind streaks.

The classification and interpretation of dynamical atmospheric processes which lead to severe sea storms along the coasts of Italian Peninsula is a necessary step to improve local prediction and at the same time to reduce hazards and vulnerability of coastal environments.

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