Sea storms which affected central Tyrrhenian coasts of the Italian peninsula in 2002

S. Palmieri[1], A. M. Siani[1], G. R. Casale[1], E. Sansone[2], G. Budillon[2], B. Buonocore[2] & M. Bencivenga[3]
[1]*University of Rome "La Sapienza", Dep. of Physics, Rome, Italy*
[2]*University of Naples "Parthenope",*
Institute of Meteorology and Oceanography, Naples, Italy
[3]*Agency for the Protection of Environment and*
Technical Services (APAT), Rome, Italy

Abstract

A diagnostic evaluation of several sea storms in the West coasts of Italy during 2002 was carried out considering the atmospheric characteristics of the storms and the interaction between the motion of atmosphere and the sea. The application of various diagnostic tools indicates common features as well as differences among the cases analysed. The role of latent heat transfer from the sea to the atmosphere is considered. The observing network of buoys moored by the Institute of Meteorology and Oceanography of the University of Naples "Parthenope" and by the Agency for the Protection of Environment and Technical Services (APAT) is useful for the analysis of sea-wave generation as a response to wind forcing and the impact on the coastal environment.
Keywords: sea storms, Tyrrhenian coasts, air-sea interaction, impact on the coastal environment.

1 Introduction

A complex marine and coastal observing system along Italian shores has been recently implemented. It consists of a buoy national network run by the Agency for the Environment Protection and Technical Services (APAT) and a more detailed local network run by the Institute of Meteorology and Oceanography of the University of Naples "Parthenope", which includes a coastal buoy, a tide gauge and a number of meteorological stations. The meteo-oceanographic buoy

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was placed in the Bay of Naples in July 2002. It was equipped with conventional meteorological and oceanographic sensors (temperature at -1, -3 and -18 m; dissolved oxygen and conductivity at -3 m; current speed and direction at -3 and -18 m).

This prompted interest in the assessment of coastal climate and vulnerability to sea storms. The work was a follow up of a previous study described by Palmieri et al. [1] in which a large number of sea storms from Central Mediterranean area were considered. The attention is now focused on the Tyrrhenian coast of the Italian Peninsula within 40 to 42 degrees N range.

2 Research line: data and meteorological fields

The selection of the storms, which affected the indicated area, was based on the following criterion: significant sea wave height > = 1.5 m and duration > = 12 hours determined at a coastal buoy station.

Date and time of storm life cycle, significant wave height and period are reported in Table 1.

Table 1: Date and time (UTC) of storm life cycle, significant wave height (cm) and period (s).

Storm n.	Date	Time	Date	Time	Sign. Height	Period
1	21 Jan	0500	21 Jan	2200	196.98	7.32
2	24 Jan	2000	25 Jan	1300	212.33	9.73
3	23 Feb	2100	25 Feb	0400	262.15	
4	04 Apr	2200	5 Apr	1500	229.89	12.03
5	28 Mag	1000	29 Mag	0500	224.29	8.33
6	07 Aug	0700	07 Aug	1800	215.39	7.64
7	23 Sep	1400	24 Sep	1400	226.88	7.16
8	18 Nov	2200	19 Nov	1100	182.15	7.51
9	22 Nov	0900	23 Nov	0000	202.86	7.21

In addition to the data collected by the local available stations, analysis fields provided by the National Center for Environmental Prediction (NCEP, USA) have been used throughout the study. The analysis horizontal resolution is about 0.7 x 0.7 degrees Lat. Long, while 42 levels are used to interpolate observational data along the vertical up to the top of the atmosphere (about 2 hPa). Details on the NCEP data assimilation system are indicated in Derber et al. [2] and in Parrish and Derber [3]. Fluxes are determined by a procedure described in Charnock [4] and in Zeng et al. [5]. A bulk aerodynamic formula is used to calculate the fluxes once the turbulent exchange coefficients are obtained

$$F = \rho\ Cq\ L\ \ Va\ (qs - qa)$$

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where ρ is air density, Cq the non dimensional turbulent exchange coefficient, L the latent heat of condensation, Va the wind speed, qs and qa the saturation specific humidity at sea surface temperature and at air temperature respectively.

The analysis of each of the 9 events considered was based on an 850 hPa map (roughly equivalent to 1500 m) with wind flags and superimposed isotherms. A complete documentation of the events was collected. For obvious reasons not all maps can be included, only the November storm is supported by a limited set of maps (Figures 1 and 2).

3 Meteorological description of storms

In this section "Tyrrhenian Sea" is indicated by TS. Some physical parameters characterising each storm considered are reported in Tables 2 and 3: sea surface temperature (SST), latent and sensible heat flux (LHF and SHF respectively), cyclostrophic component (CC), wind direction in proximity of coasts (WD), large scale curvature vorticity (VO), Rossby number (RO).

Of the small sample considered, 5 cases with winds blowing from the sector between W and S ("Libecciate") and 4 NW events ("maestrale") are listed. When the cyclostrophic component was considered as an index of storm intensity as suggested in Palmieri et al. [1], the most severe storm is n. 4 (Apr 4, 2002). The disturbance was characterised by the highest Rossby number (Table 2) which indicated that acceleration was not negligible: Coriolis and pressure gradient forces did not balance each other and the storm, meteorologically speaking, was approaching the 'small synoptic scale'.

Discussion of some cases in detail.

Storm n. 3, Feb23-24, 2002.

Streamline field of storm n. 3 (a winter NW case) shows how the western Alps separated the surface flow in two streams, one heading toward TS, the other bordering the northern slopes of the mountain range, a well known occurrence extensively described in Buzzi and Tibaldi [6]. Over Southern France the cold air outbreak into the Mediterranean is a well marked feature. The same occurred at the eastern end of the Alps. The thermal ridge over the Po Valley was due to the 'barrier' effect of the mountains. The largest significant wave height (262.15 cm, Feb 23, 2002) was attained by this storm with marked descending motion suggesting that a downward flux of momentum was contributing to the high kinetic energy in the low levels. An analysis of vertical profiles indicated high stability (Convective Available Potential Energy-CAPE = 0 m^2s^{-2}) coupled with strong anticyclonic vertical wind shear, confirming the downward flux of momentum. The relatively high precipitable water (18mm, long term monthly average 13.5mm) is also a feature to be stressed. A comparison of vertical profiles at a coastal site and upstream shows the effect of air path over sea: the boundary layer is slightly stabilised and moisture content appreciably increased. A considerable portion of the surface kinetic energy available at the outbreak into the Mediterranean was transferred to the sea wave system.

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Table 2: Physical parameters. Data are referred to 00 UTC of each event considered.

Storm number	SST°C	LHF	SHF	CC	WD	VO	RO
-	13	W/m^2	W/m^2	m/s	deg	1/s e-5	-
1	13	60	10	0.21	280	0.37	0.03
2	15	105	-5	1.66	200	1.53	0.15
3	14	110	35	1.36	260	1.28	0.12
4	18	100	20	2.55	120	1.84	0.20
5	25	200	100	0.71	310	0.71	0.06
6	23	300	100	1.05	290	1.06	0.11
7	18	250	25	1.13	260	1.25	0.13
8	17	140	0	1.66	160	1.53	0.15
9	17	200	8	1.04	200	1.11	0.10

Table 3: Synoptic storm features.

Storm number	Date	850hPa flow	Temp. advection	300hPa flow	rainfall	300hPa vert. motion
1	21 Jan	WNW	Warm	NE	-	Downward
2	24 Jan	SW	Warm	W	-	Upward
3	23 Feb	NW	No Adv.	NW	-	Downward
4	04 Apr	SW	Cold	SSW	Moderate	Upward
5	28 May	W	Cold	WSW	-	Upward
6	07 Aug	WNW	Cold	W	Light	Downward
7	23 Sep	W	No Adv.	W	Moderate	Upward
8	18 Nov	SSW	No Adv.	SSW	Heavy	Upward
9	22 Nov	WSW	Light cold	W	-	Downward

Storm n. 4, April 4, 2002

A depression was centred over Sardinia. Very active ascending motions were present over TS. Heavy rainfall was affecting the eastern sea of Corsica. In this area moderate rainfall and SE winds were the dominant features. During the morning a definite backing of winds at all levels indicated marked cold advection. Among the storms considered this April one had the maximum Rossby number (0.2), the maximum vorticity and cyclostrophic component. Vertical profiles indicated large water content (precipitable water 21mm, long term monthly average 15.5mm) and moderate instability (CAPE $32m^2$ s^{-2}). The significant wave height (229.8cm) followed closely the record of 262.1cm achieved on February, 23.

Storm n. 6, August 7, 2002

August 7, 2002 was an example of summer storm. A depression centred at the border between Austria and Romania was leading to a vigorous branch of NW flow over TS. Latent heat flux field was quite active and sensible heat flux was also factor. The concurrence of strong winds and high sea surface temperatures lead to an appreciable transfer of energy from the sea to the atmosphere increasing the storm intensity along TS coasts. The comparison of vertical profiles at the Rhone Valley mouth and downstream at Naples indicates the marked humidification of the boundary layer confirming the primary role of latent heat flux. A moderate instability (CAPE = $297m^2s^{-2}$) was associated to a nearly normal precipitable water content (24mm, long term monthly average 25mm).

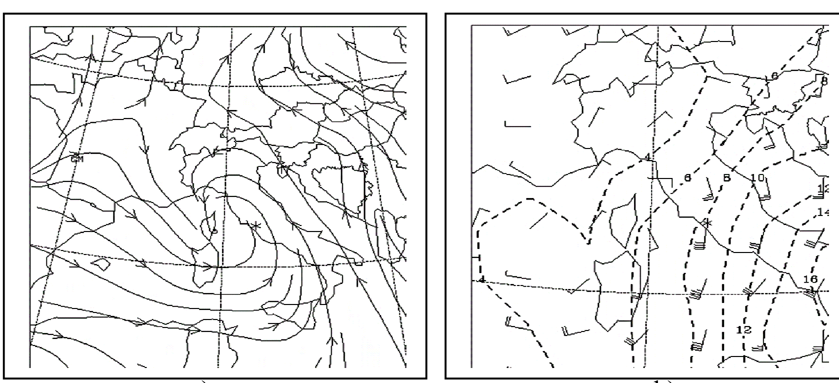
Storm n. 7, September 23, 2002

September 23, 2002 storm is another interesting case. The northerly flow over central Europe was disturbed by the Alps and a lee trough set in leading to a strong westerly flow over TS. Westerly winds, both at low levels and aloft, were blowing in the area. There were no signs of significant frontal activity and the elongated pattern of rainfall over the TS coasts probably derived from the concurrent action of low level convergence and upslope forced ascent.

The atmospheric moisture is slightly higher than normal (25mm, long term monthly average 23mm). In spite of the small buoyant potential energy (CAPE = $19m^2s^{-2}$) the existence of very dry, deep adiabatic layers below cloud base was evident from soundings. As rain begun to fall and evaporate in the sub-cloud layer, large negative buoyancy accelerated the air downward producing strong wind gusts.

Storm n. 8, November 18, 2002

This case is peculiar of SSW flow associated to frontal activity.



a) b)

Figure 1: 18 Nov 2002 12 UTC a): Surface streamlines field showing a vortex with centre between Corsica and Sardinia b) 850 hPa temperature and winds.

The storm centre was over Northern TS while a cold front was active over the eastern portion of Sardinia. Strong southerly currents affected the TS coasts (Figures 1a) and b) Cold advection over Sardinia, stationary steep temperature

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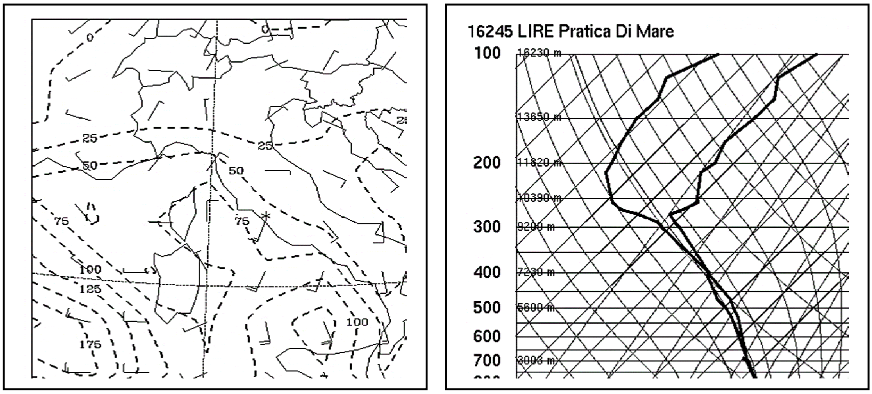
gradient from Sicily Channel). In spite of the very favourable situation the minimum sea wave height (within the small group of cases considered) was attained.

This was partly due to an active transfer of momentum upward as indicated by vertical motions and to the buoy site sheltered partly from southerly winds. Precipitable water was quite large (30mm, long term monthly average 17mm) and the atmosphere was unstable (CAPE = $54m^2s^{-2}$). It is likely that when the strong surface moist winds reach coastal areas (such as the case of storm n. 8) the convergence due to surface friction (Ekman-like pumping) drives a vertical velocity current stimulating local convection and rainfall. As a result of the mentioned favourable conditions the heavy condensation and rainfall associated with this storm released a huge amount of energy leading to further cyclonic development (Figures 2a) and b)).



a) b)

Figure 2: 18 Nov 2002 12 UTC a): Latent heat flux field W/m2. Marked fluxes are emerging SW of Sardinia; b)temperature, dew point and wind profiles.

4 Oceanographic aspects of storms

In sub paragraphs 4.1 and 4.2 both sea level and bottom-surface ocean dynamics are analysed using the data from available observations.

4.1 An analysis of sea level parameters

The physical effect of a storm on the surface of the sea is the increase of the wave motion due to the wind stress. The increase or decrease of water level is also caused by changes in atmospheric conditions that affects sea level.

Sea level changes were analysed considering, for 2002, the hourly time series of water height determined by the bottom pressure gauge, placed close to the

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shore line of Piano di Sorrento (Naples) equipped with a quartz crystal sensor whose oscillating frequency is a function of the absolute pressure it receives.

The Meteorological Tide (MT) and atmospheric pressure are plotted in Figure 3. The MT is the difference between the observed sea level and the predicted astronomical tide computed by the harmonical analysis.

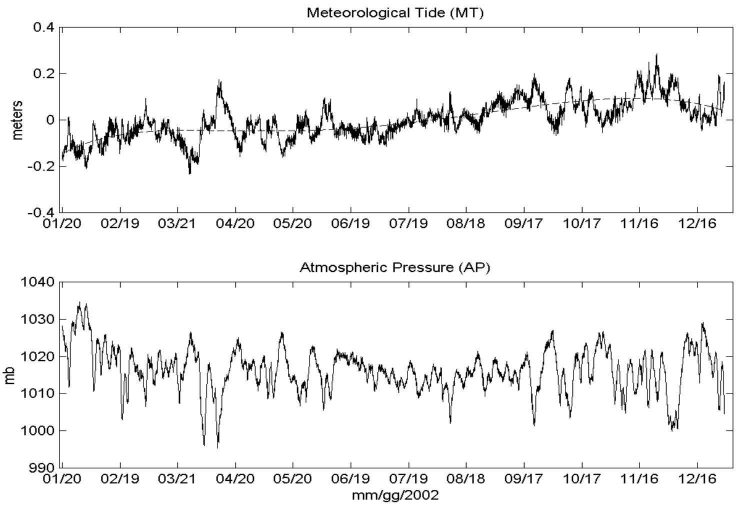

Figure 3: Meteorological tide and atmospheric pressure for the 2002.

Therefore the MT represents the changes of sea level after filtering tides. The dotted line indicates the Mean Sea Level (MSL), computed by the mean square method. The difference between the MT and the MSL consists the hourly time series of Residual Sea Level (RSL). In Table 4 the lowest and the highest value for each signal and their difference are reported.

The comparison between the graphs of Figure 3 clearly shows the well known inverted pressure effect: a 1hPa increase of atmospheric pressure causes 1 cm decrease of the sea level and vice versa to achieve an hydrostatic balance as indicated in Pirazzoli and Surges [7]. In fact the response of sea level to atmospheric forcing is only partially hydrostatic and not always instantaneous.

The correlation analysis between atmospheric pressure and sea level allows the estimate of the time delay between the meteorological forcing and sea level changes.

The correlation coefficients are in most cases close to one with a time delay ranging from 0h (event 2 ,5) to a few hours (event 4, 6, 7, 8, 9). Events 3 and 6 show respectively a low and an anomalous value of the correlation coefficients (r= -0.35; r = 0.12).

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Table 4: Minimum (MIN), maximum (MAX) values, difference of each signal.

	MIN (m)	MAX (m)	DIFF. (m)
Tide (observed)	4.39	5.18	0.78
Mean sea level	-0.15	0.09	0.24
Residual sea level	-0.19	0.22	0.41
Astronomical tide	-0.20	0-22	0.42
Atmospheric pressure	995.3	1034.7	39.40

4.2 Some features of ocean dynamics

The dynamical ocean regime of the storm n. 6 was characterized by low values of kinetic energy. At surface layer the water temperature decreased of 1°C in 24 hours. An unexpected behaviour was detected in the sub-surface layer (-18 m) where the temperature dropped at the beginning of the storm from 25°C to 21°C. During the storm the water temperature oscillated within a range of 1.5°C at the semidiurnal frequencies. 48 hours after the cooling, the temperature increased to 25° reaching surface values similar to those before the storm. Consequently, the effect of this storm was to increase the stratification of the water column. This may be related to a change in the dynamical regime of the Gulf of Naples during the storm which advected cold waters in the bottom layer (-18 m).

A different behaviour was observed in September (storm n. 7) and November 2002 (storms n. 8 and n. 9) when, despite a stronger atmospheric forcing in terms of kinetic energy, the water column didn't show any significant changes. Actually, in September the cooling was only of 0.6°C, while in November only the surface layer showed a limited decrease in temperature (about 0.3°C). In particular during the storm n. 8 the surface layer showed a small cooling (-0.2°C) in contrast with the bottom layer which showed an opposite warming (+0.2°C).

For both n. 6 and n. 8 events, in the Gulf of Naples, the bottom layer dynamics appeared disconnected from that of the surface layer. A possible explanation may be the following: in both cases, the bottom dynamics was able to renew the deep layer completely carrying a new water mass, colder than the surface layer in summer and warmer in autumn, to the coast. As a consequence the water column stability was enhanced in the first case and diminished in the second one.

5 Impact of storms on coastal environments

The Tyrrhenian coast of the Italian Peninsula within Lat. 40 and 42 degrees N is considered. The Tiber estuary is a critical area in which the shore recedes overtime. The ribbon of low lands (height below 10m) is very large and intensive developments including the international airport of Rome "Leonardo da Vinci", as well as residential area, are present. The area is particularly vulnerable to wind storms and wind tide floods. At lower latitudes the coast is characterised by a complex topography. In the area of Naples, either the carbonate highground of the Sorrentina peninsula or the volcanic build up of the Somma-Vesuvio have often slopes with a topographic gradient in the 30°to 50° range. When the

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amount of rainfall surpasses a certain limit landslides are likely. These phenomena may occur in the form of piroclastic melted layer flows or as the collapse of rocks and volcanic tufa blocks. An outline of the impact of some 2002 storms on the coastal environment follows:

Storm n. 3, Feb 23-24, 2002
Limited damages due to the wind. In Naples a model of the Maschio Angioino Castle in Plebiscito Square (made of aluminium cans) was demolished by a wind gust.

Storm n. 4, Apr 4, 2002
Although meteorologically the storm appeared very intense, the reported damages were limited. Only minor floods in small confined areas of coastal towns occurred. It is very likely that severe weather affected mostly the open sea between Sardinia and the Italian peninsula and perhaps the E coasts of Corsica.

Storm n. 6, August 7, 2002
No serious damages reported.

Storm n. 7, September 23, 2002
Severe flooding of many sections of Naples. More than 500 calls to the fire brigade. Many cars blocked up in the mud. Damages mostly due to rainfall and landslides.

Storm n. 8, November 18, 2002
Catastrophic damages reported. In the Naples area sea waves and winds destroyed fishing fleets and tourist/sporting facilities. A huge number of greenhouses on the surrounding hills were swept away by the wind. A major landslide was reported at Amalfi where the state road was interrupted. At the Tiber estuary artificial reef collapsed and some residential sections were flooded and isolated. In the northern part around the 42 degrees latitude, beeches, tourist facilities and boats were swept away by the sea storm.

6 Results and conclusions

The 2002 synoptic experience supports the notion that autumn storms, associated to a moderate flux of latent heat in the boundary layer and a high precipitable water, are likely to affect more severely TS with both strong winds and rainfall. Vulnerability in these cases is large for flat coasts open to SW-SE. Storms become particularly dangerous where orography and fragmentation of the coast give rise either to upslope motions or to an active frictional drag. This in turn stimulates convergence and an Ekman pumping mechanism within the atmospheric boundary layer. Moreover rain evaporation in the sub-cloud layer, leads in some cases to large negative buoyancy which accelerates the air downward producing strong wind gusts. Vulnerability is in this case due not solely to wind and ground slope, but also to rainfall and tends to increase if the

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area is prone to landslides. South wind component at all levels, atmospheric instability, high sea surface temperatures, saturated soils, are features affecting the severity of autumn sea storms.

Within the coastal ribbon more vulnerable sub-areas may be identified by searching for maxima of the topography induced vertical motion. This may be achieved by means of schemes in which surface wind velocity (direction and speed) as well as atmospheric stability and topographic gradients are involved.

The local geostrophic vorticity at the top of the boundary layer, when available from meteorological models, is a valuable fingerprint of the boundary layer pumping. Winter sea storms, characterised by a stable boundary layer favouring in most cases the concentration of kinetic energy in the lower atmosphere, cause damages in flat sections of the coasts by sea waves and winds. Vulnerability in this case is higher in land areas with elevations not greater than 10 m. Winter storm features which are more effective in magnifying damages are: wind component perpendicular to the coast line, downward flux of momentum, frequency and intensity of wind gusts, sea waves (large significant height).

Among the various parameters considered to evaluate storm potential in its impact to coastal environment, the atmospheric precipitable water deserves the utmost attention. In general, the interaction of convective phenomena and surface wind field shows how these two aspects concur in determining damages to coastal environment.

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