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IMPLEMENTATION AND VALIDATION OF WAVE WATCH III MODEL OFFSHORE THE COASTLINES OF SOUTHERN ITALY

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ABSTRACT

The spectral third-generation ocean wind-wave model WAVEWATCH III (WW3), operational since January 2005 at the Department of Applied Sciences of the University "Parthenope" (Italy), was adopted for simulating wave propagation in the Gulf of Naples. The model was coupled with PSU/NCAR mesoscale model (MM5), which gives wind forcing at 1-h intervals. The model was implemented using a four-nested grid configuration covering the Mediterranean Sea until the Gulf of Naples, the inner mesh with higher resolution (1 km x 1 km). The simulated directional spectral waves were compared with APAT storm wave data recorded in winter 2000 offshore the Gulf of Naples and with wind and wave data collected by Servizio Idrografico e Mareografico offshore the mouth of river Sele in the Gulf of Salerno. The implementation of the wave model with reference to the December 2004 storm on the coastlines of the Gulf of Naples gives evidence of the need of a regional wind-wave model for this orographically complex area.

INTRODUCTION

The coastlines of Naples Province extends more than 150 km from the Northern bound at the mouth of Lake Patria to the Southern bound at the end of Sorrento paeninsula, including also the isles of Capri, Ischia and Procida.

The provincial Civil Protection had as objective the evaluation of the potential risk of flooding on the beaches and the establishment of a database of beaches vulnerable to wave storms. In this manner, a priority scale of the possible shore protection measures can be established and consequently, individual projects can be managed within a single framework that accounts for benefits as well as adverse impacts. A regional modelling system run by University Parthenope encompassing winds, waves and evaluation of risk of beach flooding is the backbone of the planned Civil Protection shoreline management system.

This paper describes the wave component of the comprehensive regional modelling system, which was developed by University Parthenope together with the monitoring program of winds, waves and currents. The present paper, focusing on the wave modelling, substantiates the following:

- Model implementation on the coastlines of the Naples Province;
- Model validation through a statistical comparison with wind and wave data collected on the Northern and Southern boundaries of the Gulf of Naples.

THE WAVE MODEL

WaveWatch III is a third generation wave model developed at NOAA/NCEP after the WAM wave model, as a further development of WaveWatch I, (Delft University of Technology) and WaveWatch II (NASA, Goddard Space Flight Center). The governing physical equations, the physical parametrizations and the numerical methods reflect some modifications of previous models. The solution of the governing equations is based on a first and a third order accurate numerical scheme. The breaking waves physics are not modeled, hence the applicability of this model is outside of the surf zone and on large scale. Outputs from the model include significant wave height gridded fields with the associated wave directions and periods, spectral information about wave energy at the different wavelengths.

Governing equations

The governing equations simulate variations in time and space of wave growth and decay produced by the surface wind, dissipation (e.g. due to whitecapping), and the bottom friction effects. For irregular wind waves, the random variance of the sea surface is described using variance density spectra (usually denoted as energy spectra). The variance spectrum F depends on all independent phase parameters, i.e., F (k,σ,ω), and furthermore varies in space x and time t, e.g., F(k,σ,ω,x,t), where k,σ and ω are the wave number vector, the intrinsic frequency and the absolute frequency respectively.

$$\sigma^2 = gk \tanh kd \tag{1}$$

$$\omega = \sigma + \mathbf{k} \cdot U \tag{2}$$

where U is the current speed averaged in time and space and d is the water depth. If the individual spectral components satisfy the linear wave theory (locally), the dispersion relation and Doppler type equation interrelate the phase parameters; only two independent phase parameters exist, and the local and instantaneous spectrum becomes two-dimensional. Within WWATCH the basic spectrum is the wavenumber-direction spectrum F(k,θ), which has been selected because of its invariance characteristics with respect to physics of wave growth and decay for variable water depths. The output of WWATCH, however, consists of the more traditional frequency-direction spectrum $F(f_r,\theta)$. The different spectra can be calculated from F(k,θ) using straightforward Jacobian transformations.

Without currents, the variance (energy) of a wave packet is a conserved quantity. With the addition of currents the energy or variance of a spectral component is no longer conserved, due to the work done by current on the mean momentum transfer of waves (Longuet-Higgins et al., 1961). In a general sense, however, wave action $A \equiv E/\sigma$ is conserved (Whitham,1965 Bretherthon and Garrett, 1968). This makes the wave action density spectrum $N(k, \theta) \equiv F(k, \theta)/\sigma$ the spectrum of choice within the model. Wave propagation then is described by

$$\frac{DN}{Dt} = \frac{S}{\sigma} \tag{3}$$

where D/Dt represents the total derivative (moving with a wave component) and S represents the net effect of sources and sinks for the spectrum F.

In a numerical model, a Eulerian form of the balance equation (3) is needed. The balance equation for the spectrum $N(k,\theta,x,t)$ in a spherical grid as used in WWATCH is given as (for convenience of notation, the spectrum is henceforth denoted simply as N)

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{x} N + \frac{\partial}{\partial k} \dot{k} N + \frac{\partial}{\partial \theta} \dot{\theta} N = \frac{S}{\sigma} \tag{4}$$

$$\dot{x} = c_g + U \tag{5}$$

$$\dot{k} = -\frac{\partial \sigma}{\partial d} \frac{\partial d}{\partial s} - \mathbf{k} \cdot \frac{\partial U}{\partial s} \tag{6}$$

$$\dot{\theta} = -\frac{1}{k} \left[-\frac{\partial \sigma}{\partial d} \frac{\partial d}{\partial m} - \mathbf{k} \cdot \frac{\partial U}{\partial m} \right] \tag{7}$$

where c_g is the group celerity and θ is the wave direction, s is a coordinate in the direction θ and m is a coordinate perpendicular to s. The equation (4) is valid for a Cartesian Grid, but WWATCH III can be run on either a Cartesian or spherical grid (the latter is used for large scale applications).

Source terms

The net source term is generally given by summing up a wind-wave interaction term S_{in}, a nonlinear wave-wave interactions term S_{nl} and a dissipation ('whitecapping') term S_d,. In shallow water additional processes have to be considered, most notably wave-bottom interactions S_{bot} (e.g., Shemdin et al., 1978). This defines the general source terms used in WWATCH as

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} \tag{8}$$

Nonlinear interactions are optionally modelled using the Discrete interaction approximation (DIA, Hasselmann et al., 1985), or the Webb-Resio-Tracy method (WRT). The model includes two source term options: the first one is based on WAM model cycles 1 through 3 (WAMDIG 1988); the second one is based on Tolman and Chalikov (1996). The source term parameterizations are selected at the compile level.

Input and output

Input to WW3 can consist of wind, current, water level, temperature and ice concentration fields on the spatial wave model grid. In this study, input data used include bathymetry, wind field data and a number of input parameters required by the model.

WW3 model gives various types of output:

- Fields of mean wave parameters on the spatial grid and input fields driving the model (wave height, maximum wave height, primary and secondary wave direction, primary and secondary wave period, sea height, swell height, sea period, swell period, sea direction, swell direction, and whitecap probability);
- Spectral data at output points defined by user;
- Spectral data along selected tracks in space and time;
- Restart files containing spectral parameters and some additional mean wave parameters;
- Files with boundary data for nested models.

Implementation

The MM5/WW3 model domains cover four areas (from regional ocean to small scale):

- DOMAIN 1 (Mediterranean sea)
- DOMAIN 2 (Seas around Italy)
- DOMAIN 3 (Tyrrhenian sea)
- DOMAIN 4 (Gulf of Naples)

Information about the spatial dimension of four domains is summarized in Table 1:

	Latitude range (deg)	Longitude range (deg)	Latitude Increments (deg)	Longitude Increments (deg.)
DOMAIN 1	30.02 47.84	-5.53 41.83.	0.24	0.24
DOMAIN 2	36.11 48.31	3.76 22.41	0.08	0.08
DOMAIN 3	39.80 41.67	12.50 16.47	0.03	0.03
DOMAIN 4	40.41 41.08	13.72 14.69	0.01	0.01

Table 1 – Spatial information about the four domains

An example of the nested grids is reported in figure 1 (domains 3 and 4).

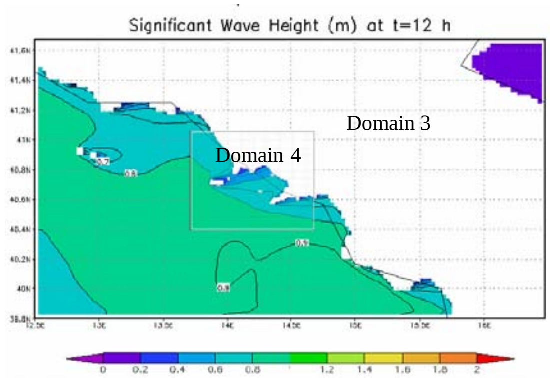

Figure1 – Example of Significant wave height for domains 3 and 4

DATASET

Data used to validate the model are the following:

- Wave data collected in years 1999 and 2004 from the APAT stations of Ponza and Capo Linaro located offshore the Gulf of Naples, in activity since 1989 and 2001, respectively;
- Wind data collected in year 2000 at the University Parthenope station of Licola, in activity since 1990.
- Wind and wave data collected in year 2000 at the Sele river mouth station, in activity from 1998.

In this paper a preliminary comparison between simulations and measurements during severe storm events is reported; then, a more systematic verification of the model reliability will be done.

In figure 2 and 3 monthly significant wave height, wind speed and direction measurements are given for November and December 2000. Wave data were collected at Ponza and Sele river mouth stations, while wind direction and speed data were collected at Licola and Sele river mouth station, respectively.

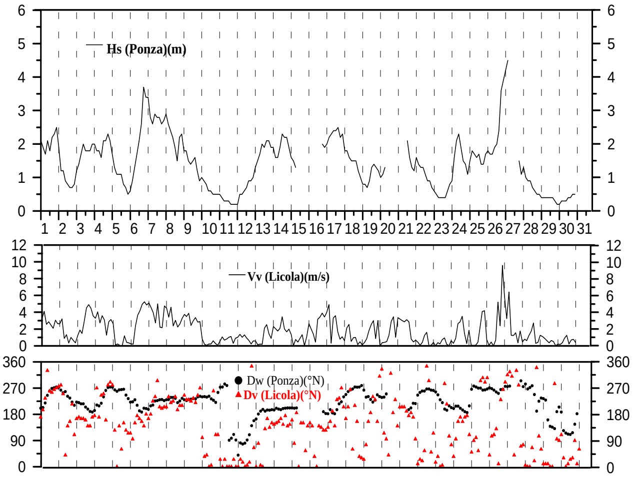

Figure 2 - Significant wave height (Hs) and wave direction Dw time series recorded offshore Ponza, wind direction (Dv) and wind speed (Vv) time series recorded at Licola in November 2000.

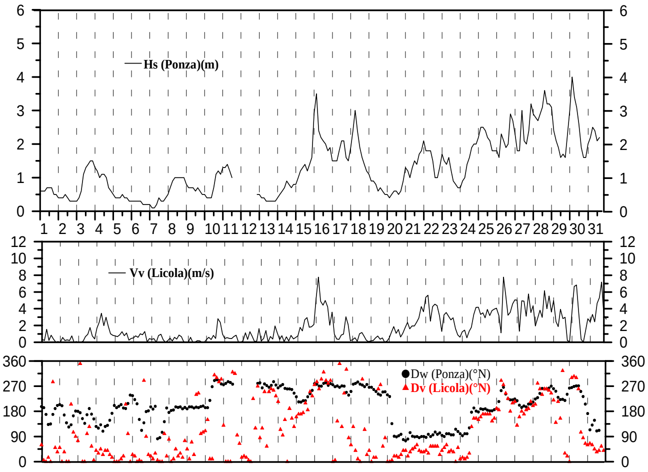

Figure 3 – Significant wave height (Hs) and wave direction Dw time series recorded offshore Ponza, wind direction (Dv) and wind speed (Vv) time series recorded in Licola, December 2000.

The storm from 6 to 8 November 2000 was characterized by wave directions coming from South. This storm was particularly severe for the Northern Tyrrhenian

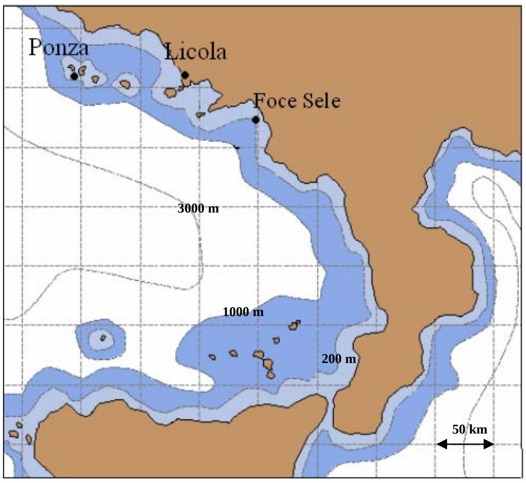

Figure 4 – Wind and wave data measurement stations

and the Ligurian sea, reaching the maximum value of Hs of 5.80m measured by the APAT buoy located offshore La Spezia. The maximum value of Hs measured by the APAT buoy located offshore Ponza was 3.70 m. at 06/11/2000 18.00 GMT. The storm from 27 to 29 December 2000 was characterized by wave directions coming from S-W (194-270°N – Ponza) and from S-W, W and N-W (200-270°N, Licola). The maximum value of Hs measured by the APAT buoy of Ponza was 3.60 m. at 28/12/2000 15.00 GMT.

		Mean	Maximum	Minimum
Licola	DDv (M)	207.0	295.0	140.0
	Vv (M)	3.8	5.2	2.2
	DDv (S)	232.0	270.6	194.0
	Vv (S)	9.7	14.8	4.4
Ponza	DDw (M)	220.0	238.0	197.0
	Hs (M)	2.6	3.7	1.5
	DDw (S)	228.0	238.0	216.0
	Hs (S)	2.8	3.57	2.01
Sele	DDv (M)	197.0	272.0	146.0
	Vv (M)	9.2	13.61	4.78
	Hs (M)	1.9	3.15	0.96
	DDv (S)	227.0	269.1	188.0
	Vv (S)	9.9	14.7	1.5
	DDw (S)	236.0	245.3	220.0
	Hs (S)	2.1	3.1	1.4

Table2 - Mean, maximum and minimum values - November 2000 - M=measured S=simulated. DDv and DDw are in °N; Hs is in meters.

		Mean	Maximum	Minimum
Licola	DDv (M)	259.6	320.0	205.0
	Vv (M)	4.0	6.2	2.0
	DDv (S)	274.7	305.5	197.4
	Vv (S)	9.1	12.6	3.3
Ponza	DDw (M)	241.5	270.0	206.0
	Hs (M)	3.0	3.6	2.4
	DDw (S)	237.6	270.9	210.1
	Hs (S)	2.6	3.4	2.0
Sele	DDv (M)	240.8	279.0	208.0
	Vv (M)	8.4	10.0	6.3
	Hs (M)	1.9	2.4	1.4
	DDv (S)	242.9	266.1	210.5
	Vv (S)	9.2	13.1	3.8
	DDw (S)	241.1	249.5	231.1
	Hs (S)	2.4	3.1	1.7

Table3 - Mean, maximum and minimum values - December 2000 - M=measured S=simulated. DDv and DDw are in °N; Hs is in meters.

MODEL VALIDATION WITH WIND AND WAVE DATA

The mean, maximum and minimum values of the wind and wave data are given in tables 2 and 3 for November 2000 and December 2000, respectively.

The comparison between the simulated and measured wind speeds gives a good agreement in the mean and maximum values for the offshore measurements (Sele river mouth), while the comparison is unsatisfactory for the station located at Licola. On the other hand, the comparison between the simulated and measured wave heights gives a satisfactory agreement for both the offshore and inshore wave stations, with a better performance for the offshore measurements, and for the inshore measurements restricted to the storm of November 2000, for the reasons which will be next discussed.

The comparison between the numerical simulations and the wind data recorded in Licola and offshore the mouth of river Sele is given in fig. 5 and 6 for the storms of November and December 2000, respectively. The examination of the results shows that the model underestimates the wind measurements when data are recorded on land: the points corresponding to Licola (recorded on land) are located in the higher part of the figure (showing simulated wind velocity in excess with respect to the data), while the points corresponding to Sele river mouth exhibit a good agreement between wind simulations and data; on the other hand, a good agreement is observed for the wind direction, for both Licola and Sele river mouth.

These results are in agreement with the already discussed results of tables 2 and 3.

The comparison between the wave numerical simulations and the data recorded offshore Ponza and at the mouth of river Sele is globally given in fig. 7, while in fig. 8 and 9 the time histories of the simulated and recorded waves are given for the November 2000 storm and in fig. 10 and 11 for the December 2000 storm, respectively.

The examination of fig. 7 shows that the agreement between simulated and observed waves is more acceptable than the wind speeds, for both the deep water (Ponza) and intermediate depth conditions (Sele mouth). This result is in agreement with the comparison between the mean and the maximum values of the parameters given in tables 2 and 3.

The time histories of the simulated and recorded wave storms gives more insight into the physical aspects of the simulation: in fact, the wave simulations of the November 2000 storm (characterized by quite uniform directions spread from 200°N to 230°N) are in good agreement with the data (figg. 8 and 9), while the simulations of December 2000 storm present higher differences (figg. 10 and 11). These differences can be explained by the circumstance that there is a first stage of the storm (wave directions coming from South) in which the significant wave heights are correctly simulated, and a second stage (associated with the superposition of swell and sea waves) in which the model probably underestimates the swell waves.

Finally, the global results of the statistical comparison are given in table 4, which reports the parameters of the linear regression (intercept A, slope B and regression coefficient r), together with the standard deviation.

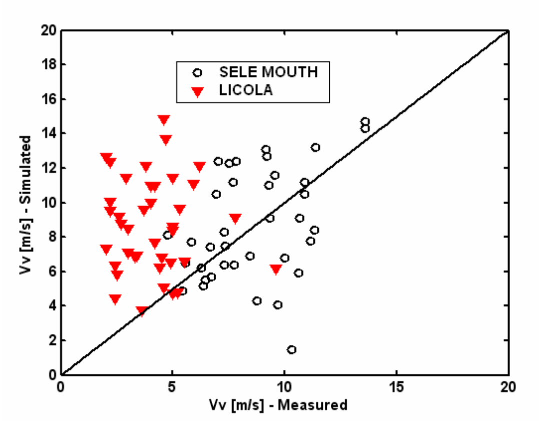

Figure 5 – Comparison between measured and simulated wind data - Licola and Sele mouth stations

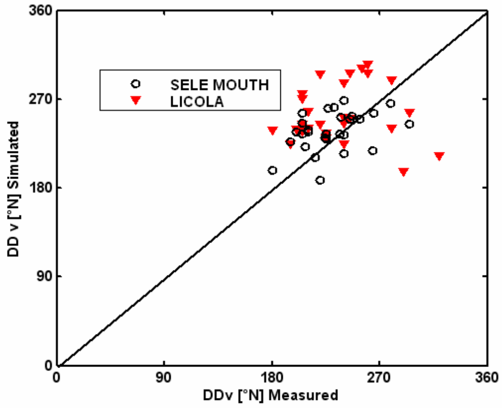

Figure 6 – Comparison between measured and simulated wave direction data - Licola and Sele mouth stations

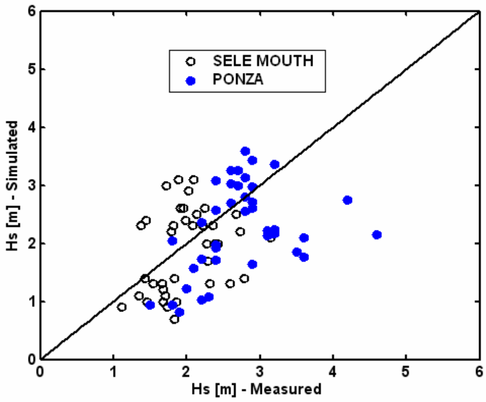

Figure 7 – Comparison between measured and simulated significant wave heights data - Ponza and Sele mouth stations.

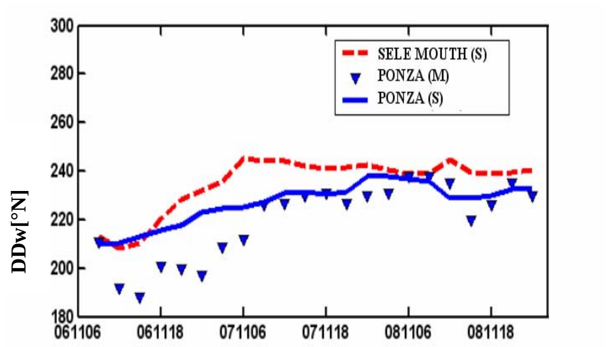

Figure 8 –Measured and simulated wave direction data - Ponza and Sele mouth stations - November 2000. M=measured S=simulated

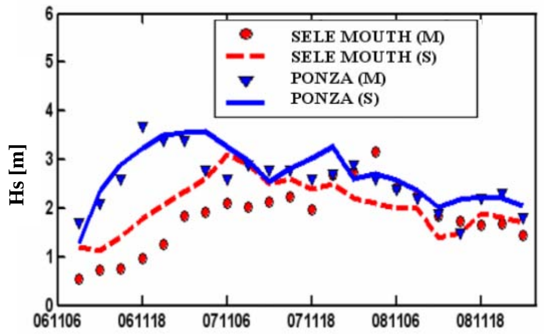

Figure 9 – Measured and simulated significant wave height - Ponza and Sele mouth stations - November 2000. M=measured; S=simulated

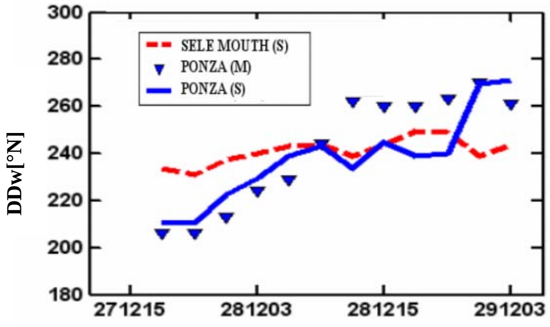

Figure 10 – Measured and simulated wave direction data - Ponza and Sele mouth stations - December 2000 M=measured; S=simulated

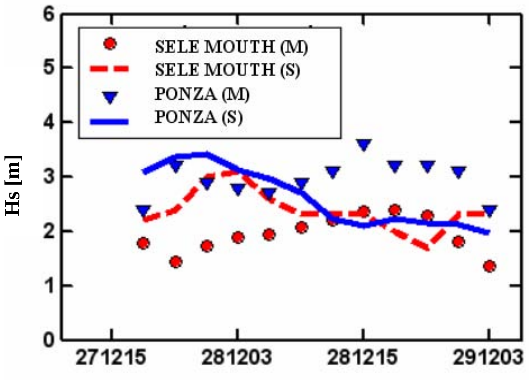

Figure 11 – Measured and simulated significant wave height - Ponza and Sele mouth stations – December 2000 M=measured S=simulated

The examination of table 4 confirms the previous considerations about the differences between the land and offshore wind measurements. In fact, the regression coefficient of the wind velocities at Licola is the lowest of all the parameters considered.

	A	B	r	std
DDv Licola	133.21	0.47	0.73	24.51
Vv Licola	5.84	1.03	0.38	2.67
DDw Ponza	126.61	0.45	0.92	9.15
Hs Ponza	0.83	0.74	0.81	0.32
Vv Sele	2.87	0.77	0.55	3.16
Hs Sele	1.23	0.45	0.55	0.54

Table 4 – Global results of the statistical comparison

Besides, the comparison between the statistical parameters relative to the significant wave heights at Ponza (offshore) and Sele mouth (inshore) shows that the agreement is better for the offshore conditions, with regards to the regression coefficient and the standard deviation. This result suggests that some physical effects (like bottom friction) should be better simulated.

WAVE SIMULATIONS IN THE GULF OF NAPLES

The implementation of the wave model on the coastlines of the Gulf of Naples was exemplified for the coastal locations shown in fig.12, with reference to the simulations of the recent wave storm of December 2004.

The coastal locations were chosen in ascending order of wave vulnerability: the location 1 (Gulf of Pozzuoli) is the most sheltered; the location 2 (Torre del Greco) is in the center of the Gulf and so it is characterized by an intermediate wave vulnerability, while Massa Lubrense (location 3) presents a quite opened coastline and so it is subjected to the highest waves.

In fig.13 the wave simulations of the peak of December 2004 storm are reported for the domain 2 (coastlines of Italy) of the model.

Fig.14 and 15 show the time history of the mean wave direction and significant wave height of December 2004 storm referred to the model simulation in the three different coastal areas considered.

In the same figure the recorded waves at the APAT station of Capo Linaro, in the Central Thyrrenian Sea are given (the closer wave station of Ponza, didn't work in that circumstance).

Figure 12 – Location of coastal areas of interest in the Gulf of Naples

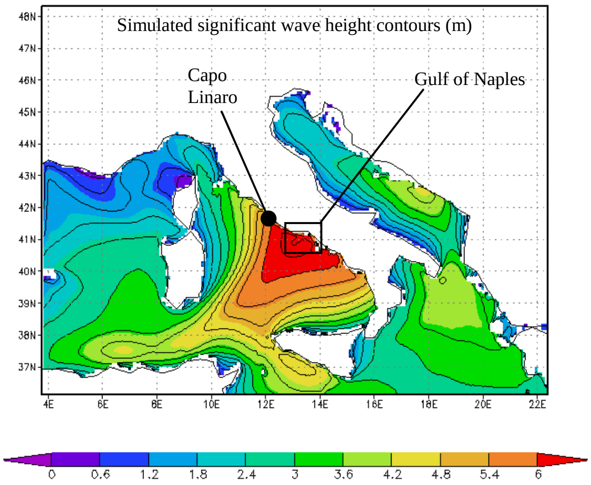

Figure 13 – Wave conditions of December 2004 storm. Gulf of Naples is in the centre of the storm (squared area), while Capo Linaro is at the northern boundary.

The examination of figg. 12 and 13 leads to the following considerations.

The SWH at the peak of the storm is maximum for the domain 4 (Gulf of Naples), while wave measurements were done by a buoy located at Capo Linaro (located approximately at 42°N, 12°E), which is at the northern boundary of the most exposed coastal area.

The comparison between the wave directions simulated in the different coastal zones for the December 2004 storm is given in fig. 14. The results show that even in case of a storm of uniform direction (coming from South and South-West 180-230 °N) the simulated wave directions are quite different in space: in locations 2 and 3, the simulated directions follow the wave measurements at Capo Linaro more closely, while in the sheltered location 1 (Pozzuoli) the waves are more forced to follow the coastal configuration which is opened only to Southern waves.

Fig. 15 gives the comparison between the significant wave heights simulated in the different coastal zones of fig.12. The results of the simulations show a good agreement with the measurements, in particular for Pozzuoli, while the waves simulated in locations 2 and 3 are significantly higher. This result is in a quite good agreement with fig.13, which shows the peak of the storm located offshore the Gulf of Naples. The good agreement with the simulated waves at Pozzuoli is due to the circumstance that this location is partly sheltered, so the simulated waves agree with the measured ones at Capo Linaro (which is just outside the most exposed coastal area). On the other hand, the local great storm severity was confirmed by the occurrence of a lot of damages to the harbours and to the beaches recorded in the Naples and Salerno Provinces.

In other words, a so high level of damages would not have been explained with the wave heights recorded offshore Capo Linaro.

It is evident from these results that the wave measurements, although very useful, cannot cover all the possible situations of wave occurrence in a complex coastal area like the Gulf of Naples, and that a regional wave hindcasting service is needed.

CONCLUSIONS

The implementation and validation of a regional modelling system run by University Parthenope of Naples encompassing winds and waves for the wave simulation and propagation in the Gulf of Naples gave the following main results.

A good agreement was obtained between the simulated and recorded winds over the sea surface, while systematic errors were noted for winds measured on land.

The best agreement was obtained for the offshore wave simulations, especially for storms of uniform direction, as the simulations are more critical in case of swell and sea wave superposition.

A good agreement was also obtained for the inshore wave simulations, although a better tuning of the bottom friction effects should improve the results.

The wave simulations for the December 2004 storm gave evidence of the significant importance of a regional wind-wave model for a complex coastal area like the Gulf of Naples.

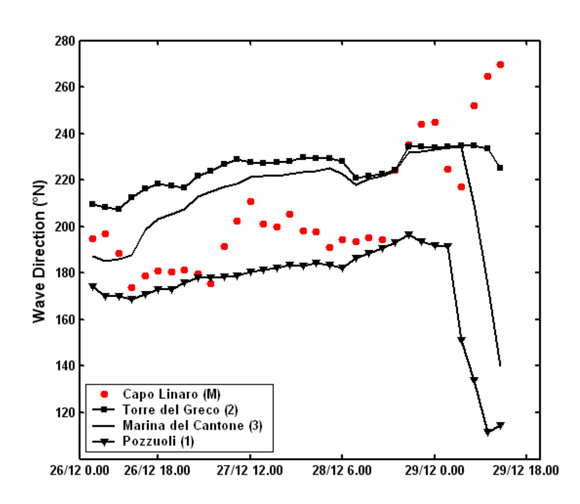

Figure 14 – Time history of the December 2004 storm – Wave Direction

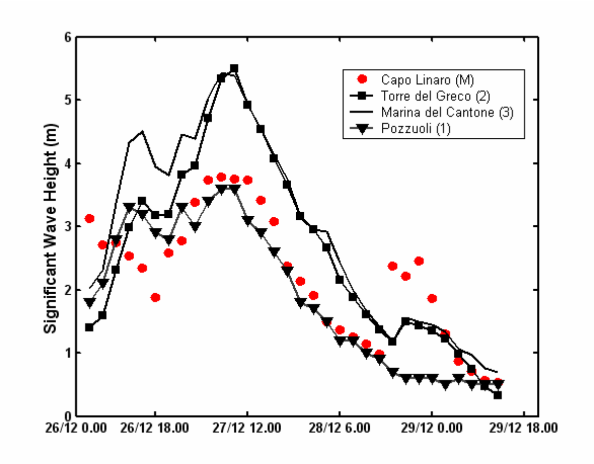

Figure 15 – Time history of the December 2004 storm – Significant wave height

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