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# SATELLITE ALTIMETER DATA TO IMPROVE THE UNDERSTANDING OF WAVE STORM STATISTICS

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**Abstract**: Satellite altimeter data provide useful information about short term oscillations of storm intensity, a phenomenon which might bear a relevant effect on the estimation of extreme value SWH. However, while such data are now easily and readily available, their application is not at all straightforward: problems like the size of the sampled area, the presence of rain and the influence of land or floating objects, may confuse the results and have to be taken into account. The paper and the discussion will deal with recent research in this field and will provide results on gustiness effects as estimated from both satellite data and wave meter measurement.

Keywords: altimeter; wave-heigth; gustiness; wave-climate.

## INTRODUCTION

The evaluation of wave climate and particularly of storm extremes is one of the most important aspects of sea related activities, such as coastal and offshore constructions, civil protection of coastal areas and sea route planning. As new and more accurate sources of data become available and at the same time the design requirements become more stringent, the methodologies needed to estimate wave climate parameters must be constantly updated.

On sites with a long historical record of wavemeter data, the use of measured data is the obvious choice; however, on most locations over the world there is no adequate instrumentation, so the use of "synthetic" data is a necessity.

In the last few years a new procedure has become nearly standard, due to the general availability of global and local weather and wave models. The method is based upon synthetic data deriving from the chain:

1. Global Forecast System (GFS) Archive Data.
2. Local Area Weather Model (LAM).
3. Wave Generation and Propagation Model (WAM).
4. Statistical analysis of the synthetic wave data on the site.

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Steps 2 and 3 can be split into sub-steps by making use of nested grid and models. Wave transformation on shallow water can be added to either step 3 or 4. Storage of data can be carried out at any step or sub-step.

GFSs are ran mostly by National or International Weather services, while LAMs and wave models can also be implemented and run by private companies, and the results are widely accessible at a price. The whole procedure is heavily dependent on weather forecasts and analyses, which are necessarily limited in spatial as well as in time accuracy, and this reflects on the quality of the estimation of extreme waves such as are required in coastal engineering; grid size and time steps are thus of paramount importance.

It is quite obvious, for instance that if the size or the duration in time of a meteorological phenomenon is smaller than the sampling interval, the estimated probability of a given extreme event is certainly biased. This especially affects coastal areas and enclosed seas, where the local effects of topography and temperature gradients are more relevant.

Bertotti et al. (2009), for instance showed that GFS+WM analyses (ECMWF in their example) cannot capture the detailed structure of the wind in the vicinity of the coasts, and they advocate the use of high-resolution models. Similar conclusions emerge from the work of Chen et al. (2010).

However, although the present trend toward finer grids and shorter computational time steps and the general improvement in the technology are certainly leading to ever increasing overall accuracy, it is likely that that there will always be some bias due to the presence of small scale phenomena which produce local and temporal reinforcement of the sea state.

The objective of the paper is to show how satellite altimeter data can clarify the behaviour of storms over short periods scales and therefore provide a useful tool to improve wave climate analysis.

## DATA AND METHODS

Satellites wind and SWH measurements have been widely available for many years. Since 1985 a number of satellites (Geosat, ERS-1, TOPEX/Poseidon, ERS-2, Jason-1, Envisat, Jason-2, CryoSat) have been providing radio altimeter data for all the seas of the word. A classical description of Radar Altimeter characteristics, parameters and limitations is reported in Chelton et al. (2001).

It is enough here to recall that impulses are averaged over about 1 second to provide 1 Hz measurements, i.e. about 7 km apart from each other, with a footprint about 12 km long and 6 km wide.

Satellite altimeter data are widely available, and they are routinely assimilated by Weather Centres in order to improve prediction and analysis of the sea state; they have also been often used to produce wave climate studies, as for instance by Woolf et al. (2003) and by Cavaleri and Sclavo (2006).

A more recent application of such data (Abdalla and Cavaleri, 2002, Pugliese Carratelli et al., 2008, Al Ragum et al., 2009) is to provide an indication of Small Scale Storm Variability (in the following SSSV), largely due to the irregular wind structure at the sea level ("gustiness").

In this paper some statistical parameters of SSSV, as measured by satellite altimeters in enclosed seas, are calculated and compared with similar statistics from Meteo/Wave models and from wave buoy data.

## APPLICATIONS AND EXAMPLES

Two distinct coast semi enclosed seas are considered here: the first in the Southern Tyrrhenian Sea, where good wave buoy measurements and weather/wave modelling results are available, and the second in the Arabian/Persian Sea (in the following Persian Gulf), which provides an interesting test area because of the low occurrence of rain – a well known factor of disturbance for altimeter data.
A number of Jason-1 and ESA Envisat altimeter satellite passes were considered during local storms; SWH and wind velocity data were plotted in space and an interpolating curve (trend) was calculated for each episode. An example is shown in figure 1 and 2.

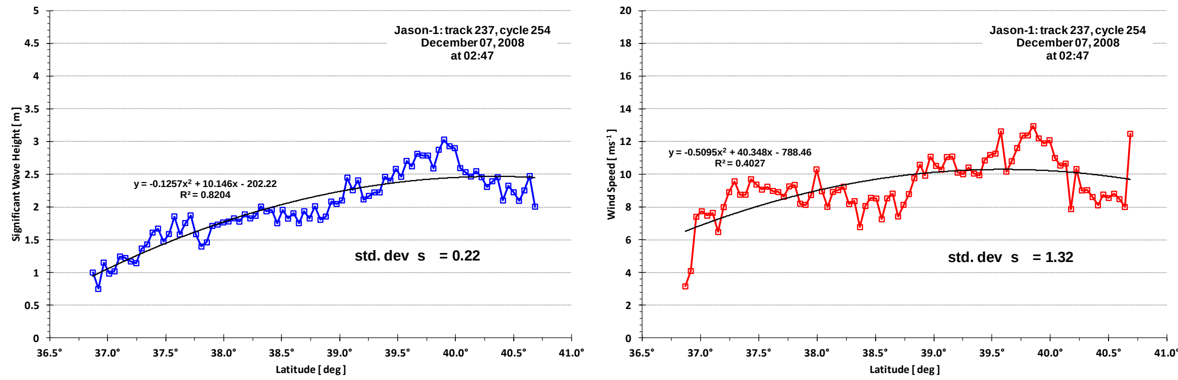



**Fig. 1. Jason altimeter data in the Southern Tyrrhenian Sea. Left: SWH; right: wind speed; curve: best fit parabola.**

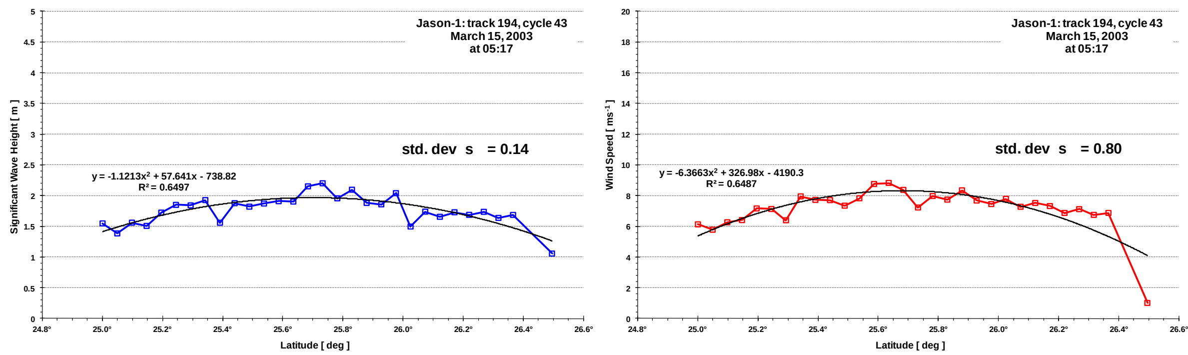



**Fig. 2. Jason altimeter data in the Persian/Arabian Gulf. Left: SWH; right: wind speed; curve best fit parabola.**

The presence of SSSV is evident in both wind and SWH, on either seas.
The standard deviation $\sigma$ of both wind and wave data around the generally regular trend was estimated by assuming Eq. 1:

$$\sigma = \sqrt{\frac{\sum_{1=1}^{N}(Y_i - T_i)^2}{(N-1)}} \qquad (1)$$

$Y_i$ being the measured value of sample i, $T_i$ the values of the trend at the same position, and N the number of (1 Hz) measurements. A coefficient of variation $\sigma/A$ for each pass was also considered, by taking A as the mean of all the N values of the passage (N varies between 20 and 90). The scatter index $\sigma/A$ (standard deviation normalized by the mean of the data) varies between 0.10 and 0.20, very similar to the values already presented for the Tyrrhenian sea by Pugliese Carratelli et al. (2008).

Assuming a normal distribution, this implies a 2.5% probability of a SWH value 30% higher than the trend - by no mean a negligible effect, for all practical purposes.

Not all the signal behaviour is necessarily related to real variations of the wave height since the altimeter response is affected by many errors, especially in the vicinity of a coast: a discussion of such effects is reported in Gómez-Enri et al. (2010); most of it, however is certainly a measure of the oscillations of wave agitation, related to atmospheric instability. Abdalla and Cavaleri (2002) simulated SSSV by feeding synthetic gusty wind series to a WAM model, with σ/A values similar to those found in the present work. They also presented an example of satellite altimeter SSSV and gustiness data in the western Mediterranean, with apparently a longer fetch and a longer spatial scale around the trend than those presented here.

An indication of the scale, i.e. of the typical dimension of a SSSV, can indeed be obtained by considering the spatial autocorrelation $\mathrm{C(i)}$ of the normalized SWH and wind data with $\mathrm{C(i)}$ that for a generic discrete real waveform $\mathrm{Y}$ is given by the following expression (Eq. 2):

$$C(i) = \frac{\sum_{m=-\infty}^{+\infty} Y(m) \cdot Y(i+m)}{\sum_{j=1}^{N} Y_j^2} \tag{2}$$

The distance $L_C$ of the first zero-crossing of $C(x)$ (See Fig. 3) can be taken to be to be an indicator of the space scale of the SSSVs.

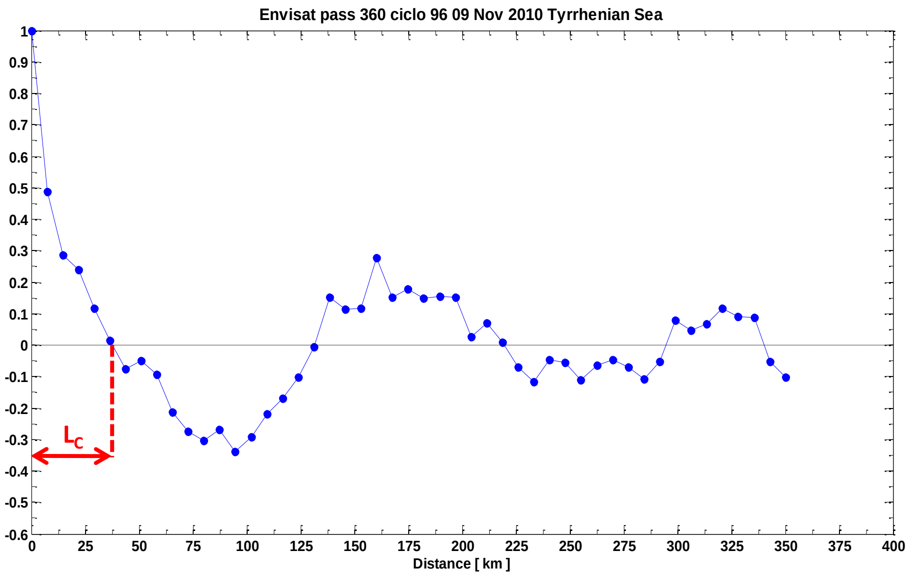
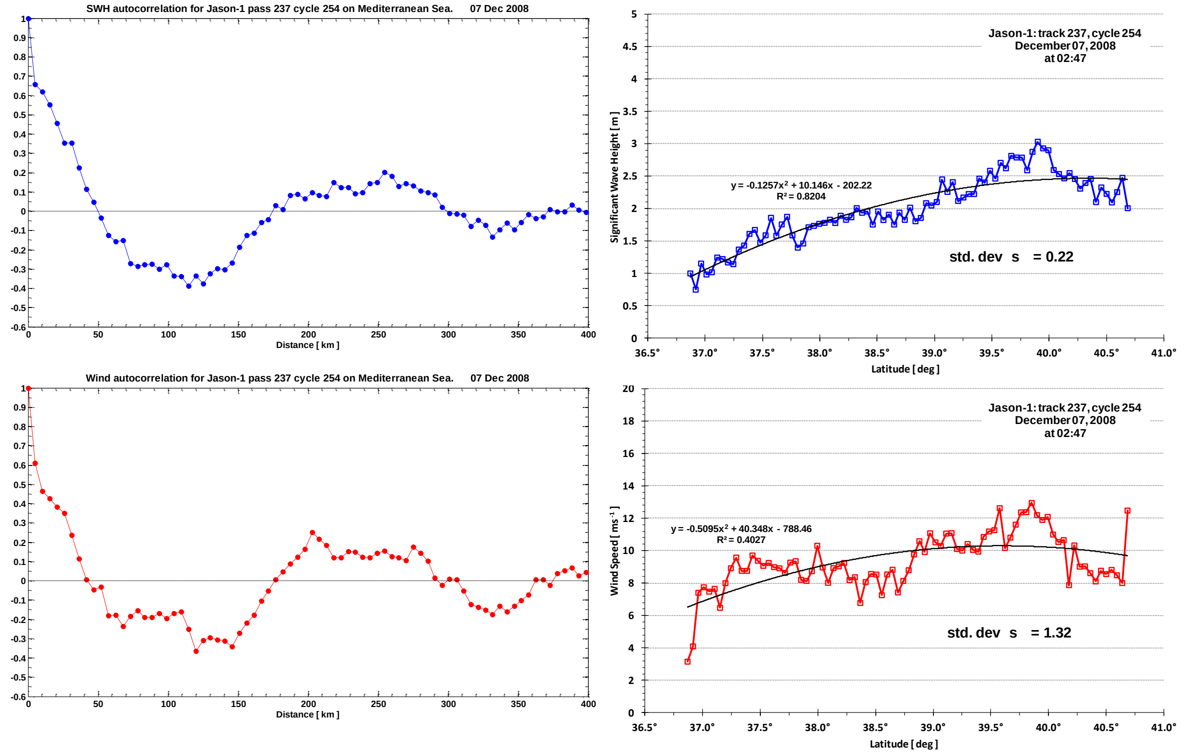



**Fig. 3. Spatial correlations of SSSV.**

It is interesting to note that while the Tyrrhenian data yield LC values which may range up to about 50 km, the Gulf data considered so far show a very small correlation distance, i.e. nearly no coherence at all. It should also be remembered that at very short correlation distances the analysis becomes meaningless, since altimeter measurements are in any case an average over a few kilometers.

The following figures 4 and 5 show some examples:

Jason-1: track 237, cycle 254. Mediterranean Sea 07 Dec 2008




Jason-1: track 120, cycle 255. Mediterranean Sea 12 Dec 2008

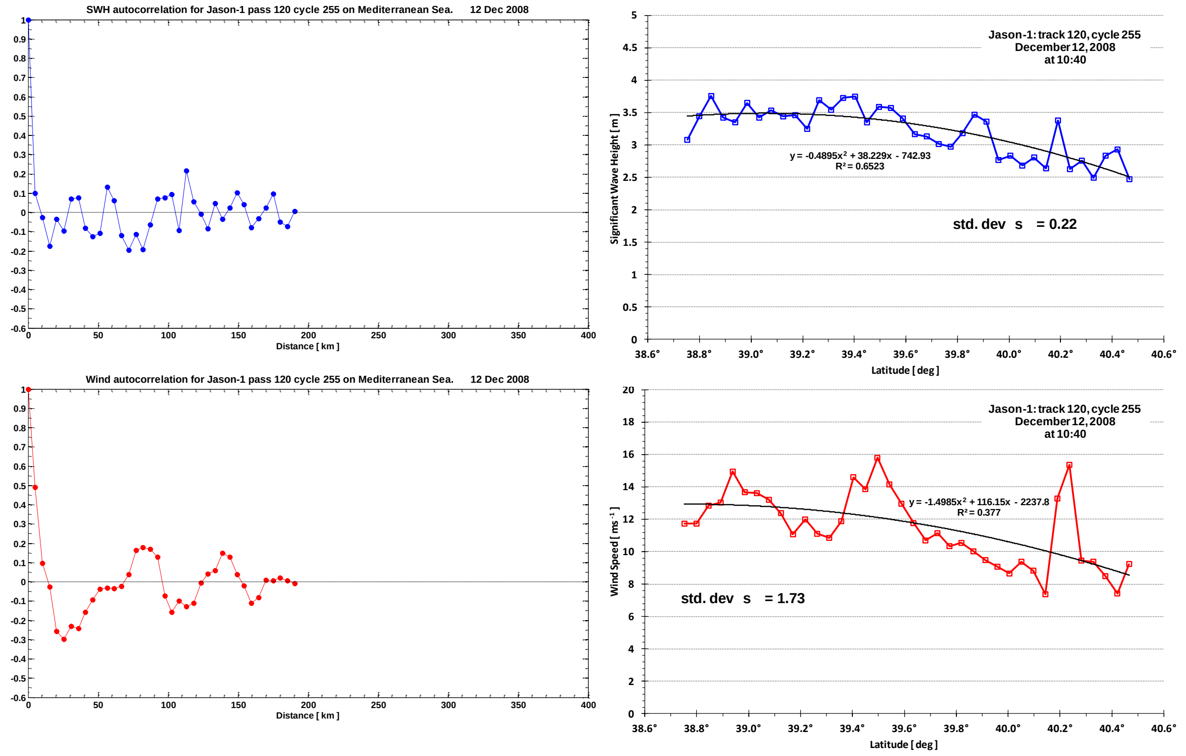
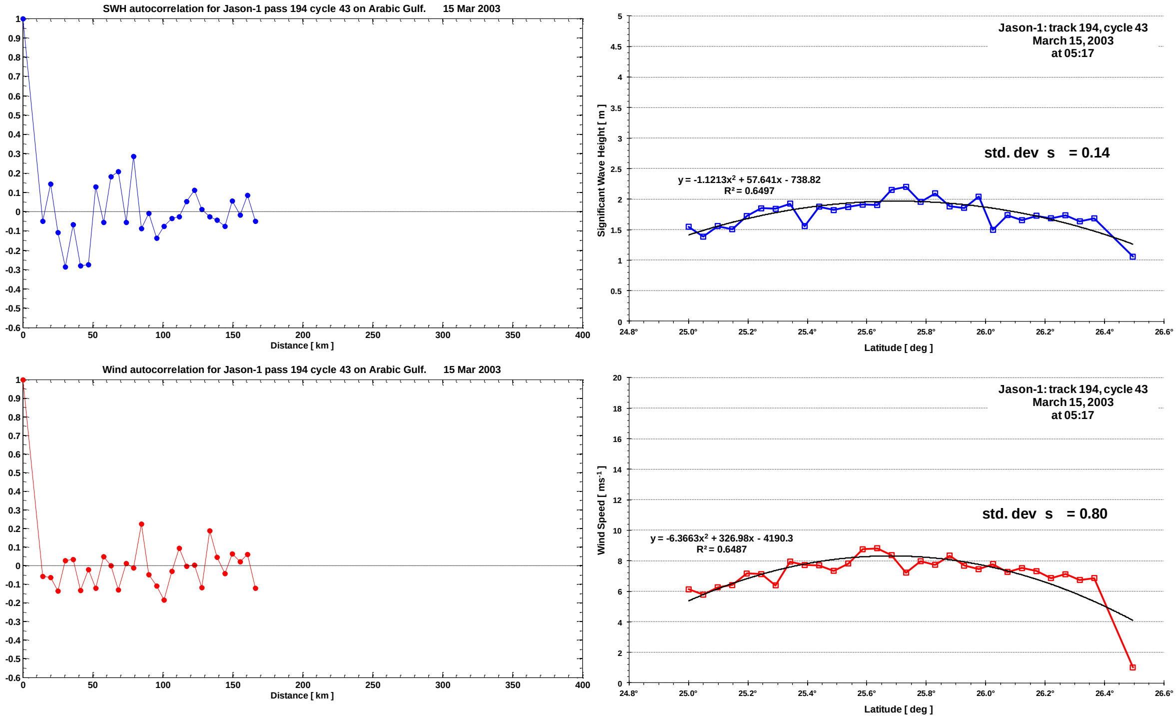



Fig. 4. Spatial correlations of SSSV for Mediterranean storms.

Jason-1: track 194, cycle 43. Arabic Gulf 16 Mar 2003




Jason-1: track 194, cycle 80. Arabic Gulf 16 Mar 2004

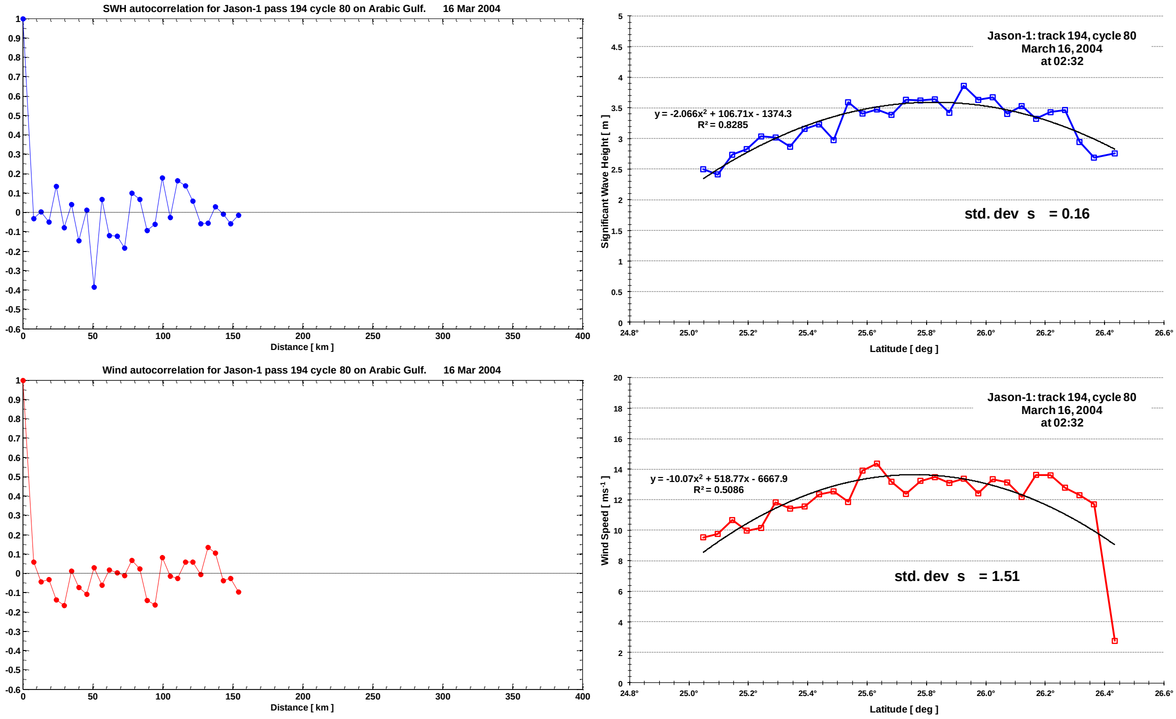



**Fig. 5. Spatial correlations of SSSV for Persian Gulf storms.**

The statistical parameters $\sigma/A$ and $L_C$ of the wind values seem be quite similar to those of the SWH, against the physical intuition which suggests that oscillation of wave height should be similar but reduced compared to those of the wind, and possibly with a larger coherence. This is an aspect which might be related to the implicit spatial averaging process of 1Hz altimeter data, and it which obviously requires further research.

In any case the existence and the importance of sub-grid oscillation is obvious; in the example shown above, the ECMWF model grid size and time step are very large, so it is worth asking if improvements of model resolution might be able to simulate such oscillations. A number of tests were therefore carried out with the NETTUNO model results on a storm which took place in the Southern Tyrrhenian Sea in November 2010. Nettuno is a high resolution (0.05°) WAM application, developed by CNR ISMAR, run by the Italian Weather Service CNMCA, and driven by the COSMOS/ME European Model. Nettuno is described in Bertotti et al. (2010).
The storm was monitored by four wavemeters run by the Italian Wavemeter Network and by the Campania Region Civil Protection Department (Fig. 6); also, three altimeter satellite passes are available (Jason-1, Envisat and ERS-2). Figure 7, instead, shows the four Nettuno model grid point around Capri buoy.

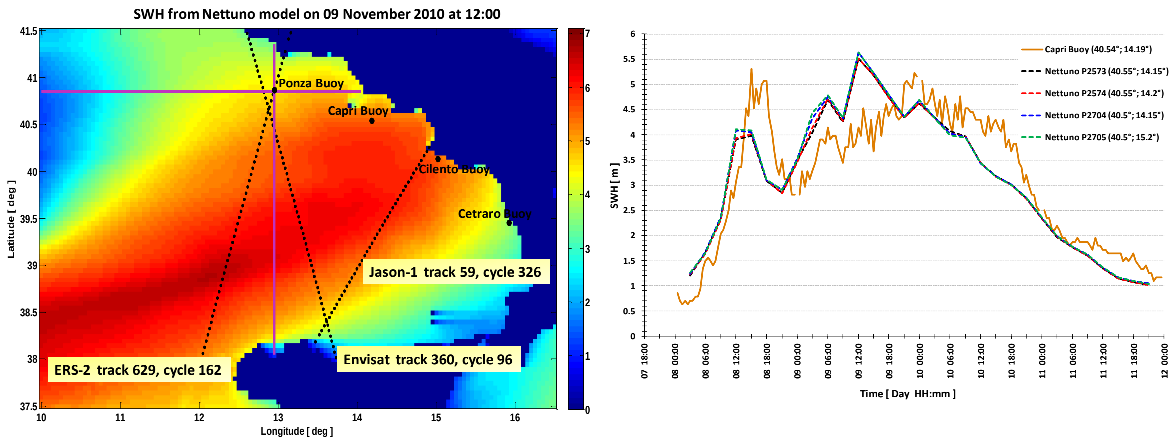



**Fig. 6. November 2010 storm in Tyrrhenian sea: CNMCA Nettuno simulation (left) and comparison with Campania Civil Protection Department Capri buoy data (right).**

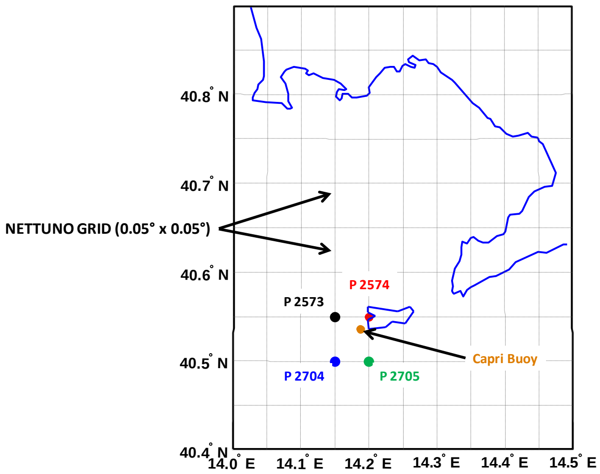



**Fig. 7. November 2010 storm in Tyrrhenian sea: CNMCA Nettuno simulation (left) and comparison**

In the following Figure 8 satellite measured data and spatial autocorrelations are shown for both ENVISAT track 360 data and simulated Nettuno values along a parallel and a meridian in the area

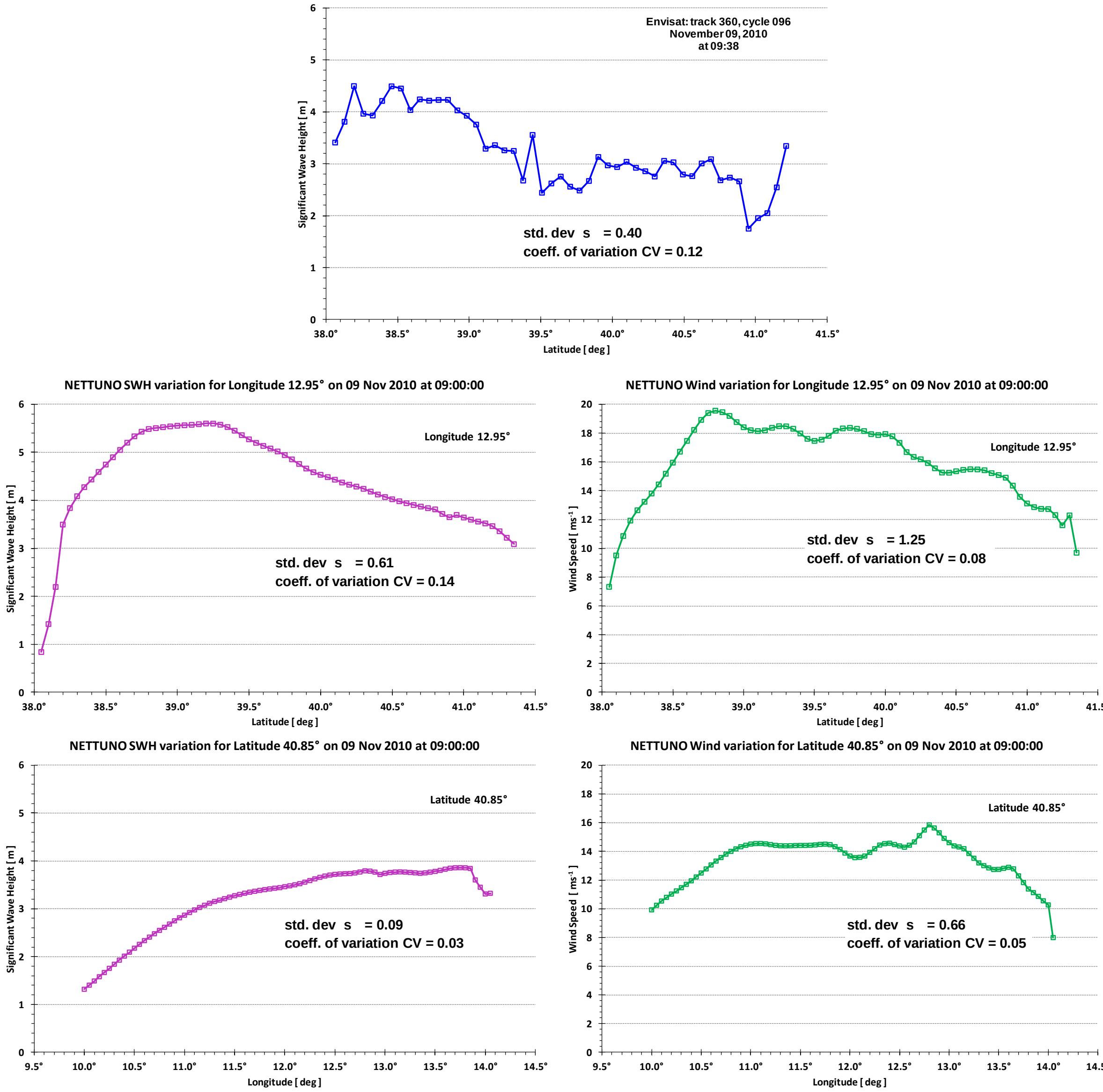



**Fig. 8. Envisat SWH data (blue) and Nettuno SWH (purple) and wind (green) simulations along a parallel and a meridian.**

By comparing Envisat data with the South/North Nettuno forecast, it is immediately obvious that while the general trends seem to match quite well, there are virtually no oscillations in the model data. These results seem to show that – no matter how small the grid – certain local phenomena cannot be simulated in a model – or perhaps not yet, at the present stage of weather modelling. It is worth recalling that numerical stabilization operators systematically over-smooth wind values (Cheruy et al., 2002). To enforce this point, the existence of a strong small scale randomness can often be proven by looking at ordinary time sampled recordings of wavemeters. The following Figure 9 represents the time behaviour of SWH at the Italian RON (National Wave Network) buoy of Catania, together with the six-hour ECMWF analyses of various grid points around it.

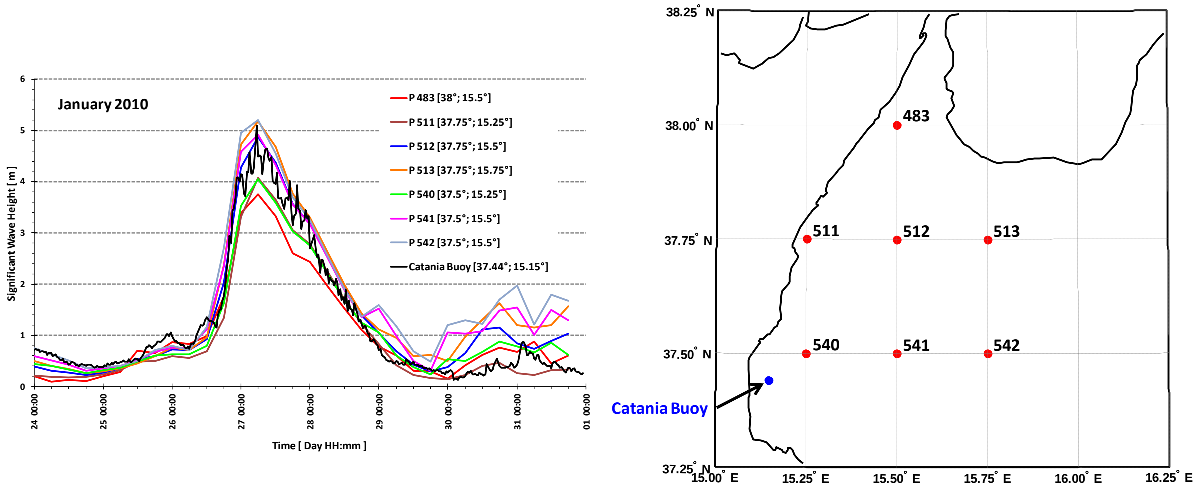



**Fig. 9. Wave buoy measures compared with adjoining ECMWF.**

The time oscillations of the recorded values are the equivalent in time of the space oscillations revealed by the satellite altimeters, and time correlation also show a time coherence similar to the spatial coherence described above. Figure 10 shows the time autocorrelation obtained from the buoy data for the Tyrrhenian November 2010 storm discussed above.

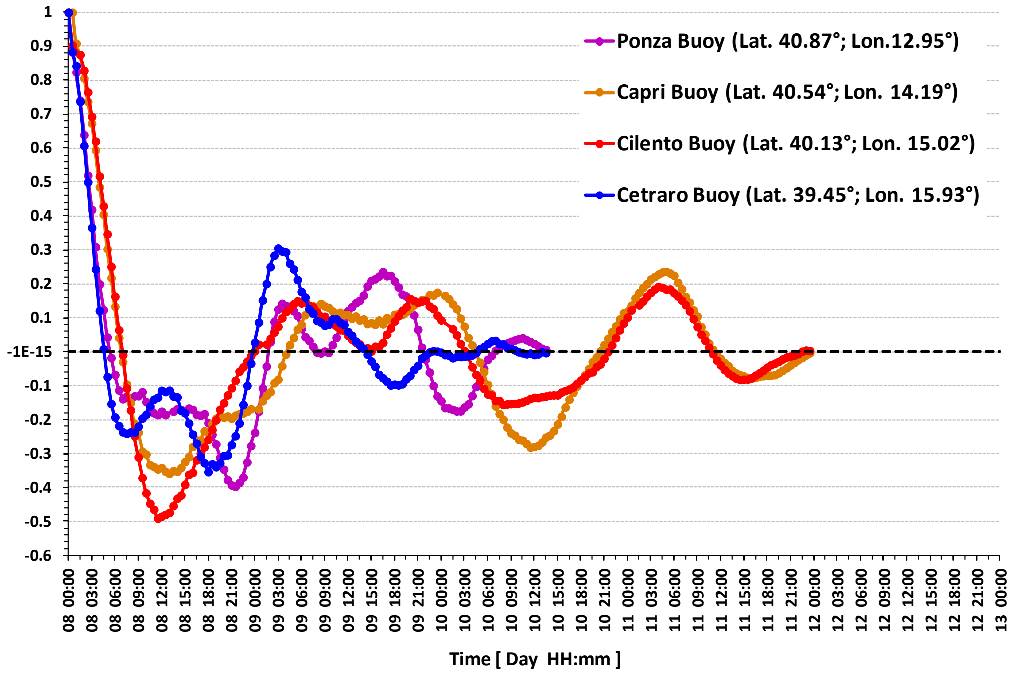



**Fig. 10. Time autocorrelation, November 2010 storm; (RON and Campania Civil Protection Department buoy data)**

The importance of taking SSSV into account when considering extreme SWH must not be overlooked. The following example, also based on wavebuoy data, highlights the bias deriving from employing data too coarsely sampled.

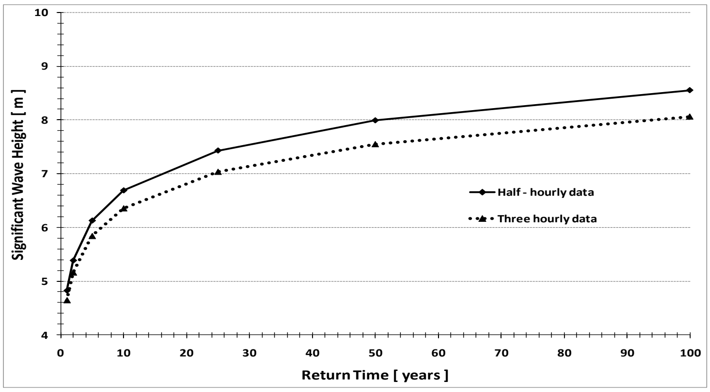



**Figure 11. Extreme events as computed with half-hourly and three hourly data at Cetraro; Peak Overt Threshold, wave height threshold = 4 m. (data from Cetraro RON wavemeter).**

The continuous curve yields the Significant Wave Height (SWH) as a function of the return time, extrapolated from data collected at half hours interval, while the dots show the results of the same calculations, with a three-hours sampling of the data. By the same token, overlooking the effects of SSSV when making use of synthetic data deriving from Meteo/Wave systems can lead to an even stronger bias.

## CONCLUSIONS

As stated in the beginning, SSSV was studied by Abdalla and Cavaleri (2002), "gustiness", mostly by making use of random realisations of the input wind fields. Data and examples provided here have shown such variability on a scale that is far lower than the resolution of meteorological models – present, and probably also future.

SSSV cannot be overlooked when estimating extreme wave distribution; even though no practical guideline can be provided yet, an important - if perhaps obvious – caveat is that weather model data employed for historical SWH analysis should have the highest possible resolution in time and space. Since this cannot be applied to archive data, which are normally computed on coarse grids and stored at a few hours intervals, research is needed to correlate statistical extremes to sampled data. The long history of altimeter wind and SWH data, acquired at intervals of a few kilometers, are extremely useful for this purpose.

However, while such data are now easily and readily available, their application is not at all straightforward: problems like the size of the sampled area, the presence of rain and the influence of land or floating objects, may confuse the issue and have to be carefully taken into account.

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Wavemeter: RON (Italian National Wavemeter Network) and Campania Regional Civil Protection

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