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Remote Sensing of Small-Scale Storm Variations in Coastal Seas

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ABSTRACT

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Estimating extreme values of significant wave heights (SWH) is a necessity in many branches of coastal science and engineering. Storm intensity, however, is not a smooth varying quantity, but it oscillates with random variations around a generally regular trend; the estimated value of extreme sea states is, therefore, necessarily affected by the sampling time of the available data. This is especially important when making use of synthetic data deriving from weather and wave simulation systems, which artificially smoothen the SWH record history. Active remote sensing provides valuable help to overcome this problem: the work described here very briefly recalls the available satellite SWH and wind measurements and shows how such data may help clarify and reduce a possible cause of error in wave climate evaluation, and especially so along coastal areas.

ADDITIONAL INDEX WORDS: *Altimeter SWH, extreme events, Tyrrhenian Sea, Arabian/Persian Sea, wave model, gustiness, small-scale storm variations.*

INTRODUCTION

Extreme wave storm statistics are an essential tool of ocean engineering, especially so in relation to coastal engineering. The traditional—and until recently the prevalent—source of data is the historical wave buoy record: by analysing long time series of significant wave height (SWH), average and peak wave period (T_m and T_p), or other spectral parameters deriving from sampled wave records, and by fitting appropriate extreme value distributions such as Gumbel, Fisher-Tippet, *etc*., a SWH versus return time (RT) curve can often be fitted to provide a satisfactory design tool for a given site. Some recent developments are reported by Komar and Allan (2008); Li *et al*. (2011); and Pugliese Carratelli *et al*. (2007), among others.

An appropriate choice of the sampling frequency of the wave records is an important aspect of this kind of investigation: it is a well-known fact that intensity of a storm—as measured by its SWH, for instance—is not a smooth varying quantity, but it randomly oscillates around a generally slowly varying trend. As a consequence, the use of data with a lower resolution (such as a 3 h sampling, for instance) would cause a considerable reduction of the extreme value of the computed SWH as a function of the RT. Figure 1 provides an example of the effect of different sampling intervals: by making use of 18 years of recorded buoy data, the maximum SWH/RT curve was calculated first with the smallest available sampling interval (30′) and then by degrading the data to a sampling interval of 3 hours.

This clearly shows that the use of low time resolution data can cause a very serious bias in the definition of the design climate in a given site; this, however, does not pose any problem in current coastal engineering practise—as long as a wave buoy has been present in the intended site for an adequate number of years—since most of the available time series are nowadays produced and supplied with a high enough sampling frequency (usually 20 or 30 min).

The situation is quite different for locations where there is no instrumentation, as is the case not only in developing countries, but also in many coastal areas where the land morphology makes the transposition of nearby buoy data subjective and unreliable. Even more critical is the reconstruction of wave climate for the design of platforms and for coastal sea route planning. The use of different technologies to produce "synthetic" data is therefore a necessity; in addition, the design requirements have become more stringent so that the methods to estimate wave climate must be constantly updated.

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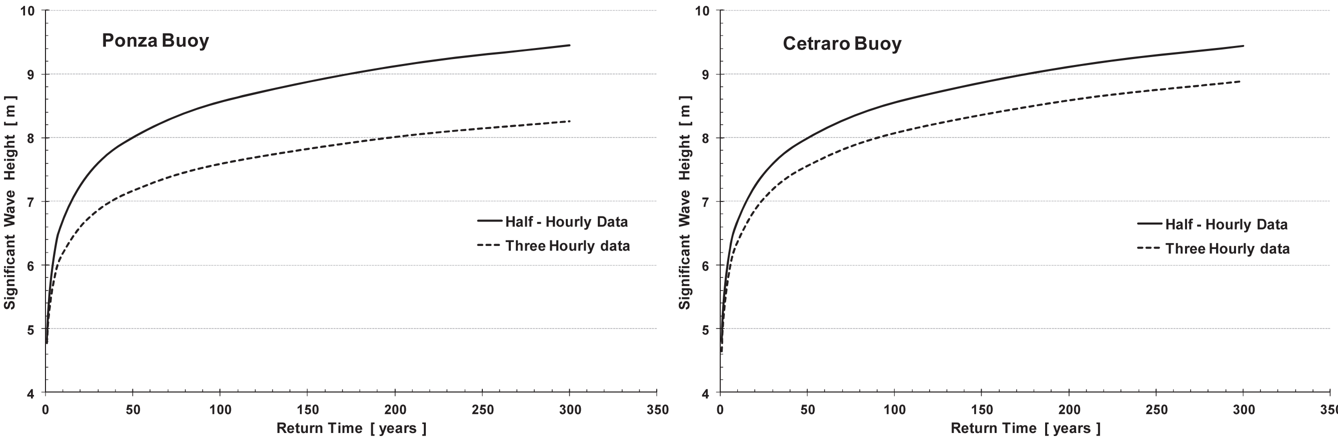

Figure 1. Extreme SWH as a function of the RT computed with half-hourly (solid line) and 3 hourly (dashed line) for Ponza (left) and Cetraro (right) wave buoys. Peak over threshold (POT) method with threshold = 4 m. Wave buoy data from Italian Environmental Agency (ISPRA).

PRESENT TRENDS FOR EXTREME SEA STATE EVALUATION

It has now become common practise in coastal and ocean engineering to analyse the wave climate by using archived data from spectral wave models, driven in turn by global and regional weather models. The quality of the extreme SWH estimate depends of course on the quality of the whole weather models and wave models chain (WM+WM); global WM+WM are run mostly by national and international weather services, such as the United Kingdom Meteorological Office (UKMO), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the National Oceanic and Atmospheric Administration; local area models are also run by private companies, and the results are widely accessible at a price.

WM+WM have been, and still are, the object of intense research work aimed at improving their accuracy. Calibration and assessment studies have been carried out for years, and the results are regularly published; no extensive review of the literature is here possible, or indeed useful, but the interested reader may find the relevant information in ECMWF (2012) library, which is constantly updated, while Accadia *et al*. (2007), Inghilesi *et al*. (2012), and Violante-Carvalho *et al*. (2012), among others, provide remarkable examples. However, most of the calibration and validation studies are aimed at improving the forecasting or hindcasting performance of the systems, rather than at estimating SWH for very high return periods. Where this has been attempted, it has been done either by using high sampling intervals wave meter data, as for instance in Mittendorf, Sweetman, and Zielke (2008), or by smoothing out altimeter data (about 5 km resolution) to better match the resolution of the model (Hanafin *et al*., 2012). At present, WM+WM data cannot provide a reliable estimate of extreme SWH sea states over short timescales.

It is quite obvious that size of the spatial computational grid $\Delta\varphi$ and $\Delta\lambda$ and the strictly related computational steps Δt are of paramount importance: if the size or the duration of a meteorological phenomenon are smaller than the sampling interval, the estimated probability of a given extreme event will certainly be biased. This is particularly true for enclosed or semienclosed seas such as the Mediterranean, and in general coastal areas where the local effects of topography and temperature gradients are more relevant.

In coastal engineering practise, an important practical aspect must be taken into account, *i.e*., that the constraint in accuracy is often given by the archiving procedure of the data rather than by the computational algorithms, as schematically shown in Figure 2, the storage interval Δts is by far larger than the computational steps in time Δt, and it is a much more important limiting factor than space resolution.

Δts for ECMWF available data (be it analysis or reanalysis such as ERA-40) is presently 6 hours, quite unsuitable for these kinds of applications; other agencies (*e.g*., UKMO) provide data with a higher sampling rate (down to 1 h). ECMWF is now (J.

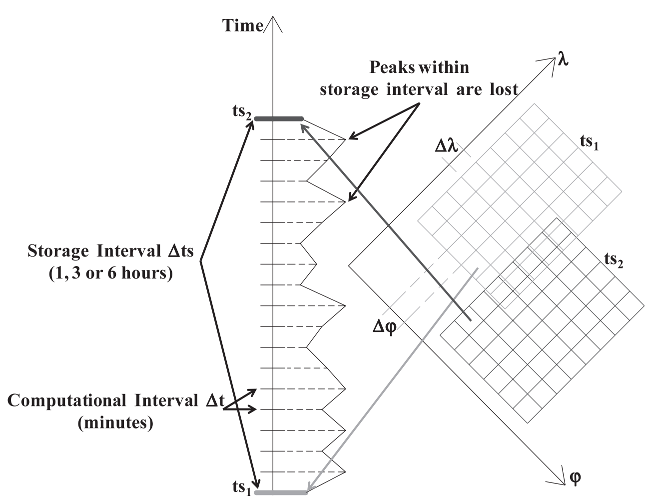

Figure 2. Storage and computational intervals in weather models and wave models chain (WM+WM).

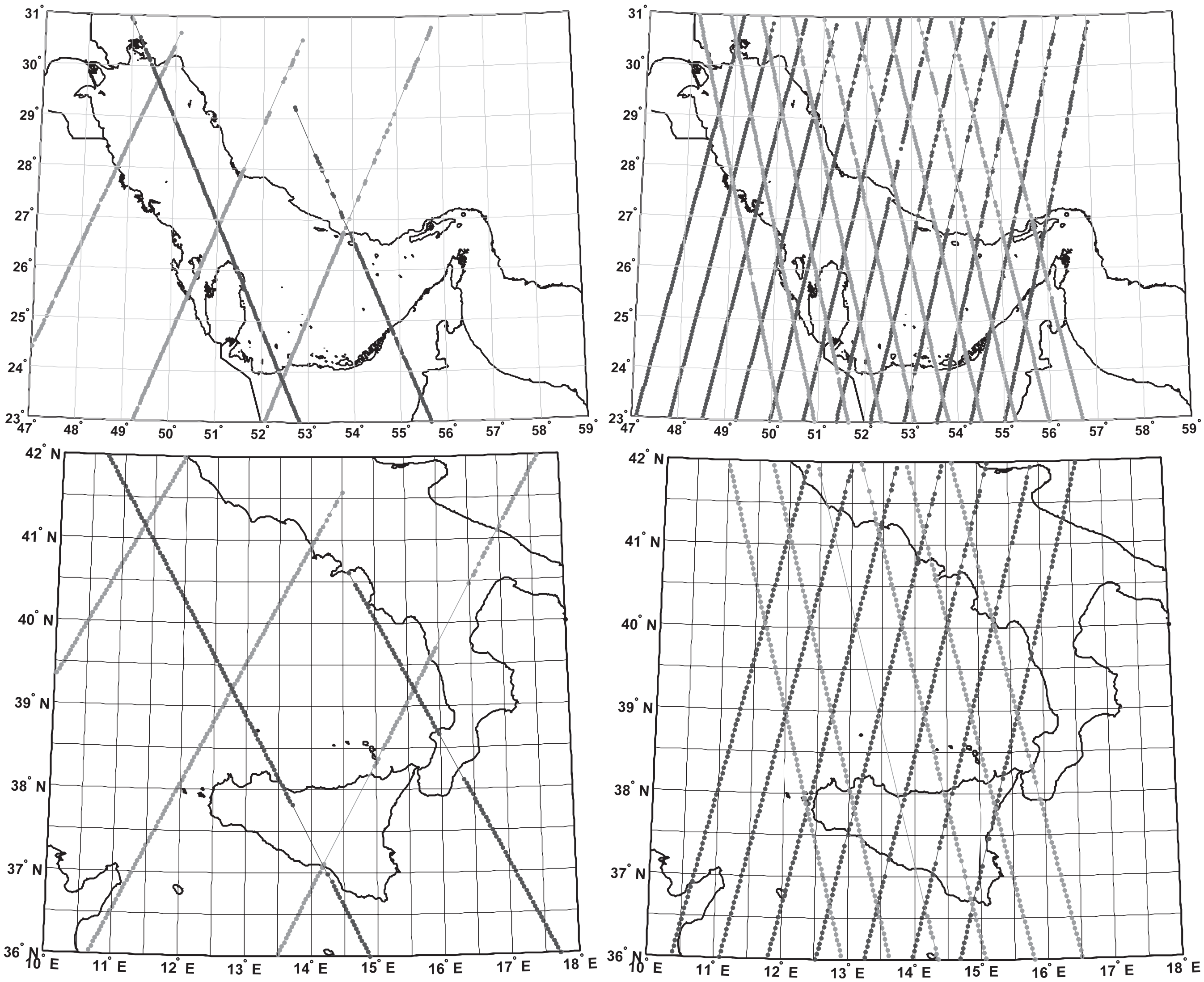

Figure 3. *Jason-1* (left) and *Envisat* (right) tracks on Arabian/Persian Gulf (top) and South Tyrrhenian Sea (bottom).

Bidlot, *personal communication*) considering improving this aspect by storing and supplying not only wave data at the fixed time steps but also their maximum values within the storage interval Δts.

This is of paramount importance in the context of ocean and coastal engineering, since extreme sea states are influenced by the irregular wind structure at sea level (gustiness), which produces in turn small-scale storm variations (SSSV), *i.e.*, local and temporal reinforcement of the sea state. The term "small scale" refers here to the smallest resolvable scales of an atmospheric dynamic model, although still much larger than the typical wave period. The problem discussed here is not linked to the so called "freak" or "anomalous" wave.

Numerical operators systematically oversmooth wind values (Chèruy *et al*., 2004), so that weather models will always filter out scale phenomena smaller than a certain scale—and such a scale is often much larger than the grid size. Frehlich and Sharman (2004) show the effects of spatial filtering in mesoscale models. No matter how fine the computational mesh, certain phenomena are inherently random and will never be the object of deterministic forecast or hindcast.

The present trend toward finer grids and shorter computational time steps as well as the general improvement in the technology are certainly leading to increasing overall accuracy: Tisler *et al*. (2007) describe the necessity of downscaled atmospheric fields, and it has indeed been proven that higher-resolution models lead to higher wind speeds, especially in coastal areas (Cavaleri and Bertotti, 2006; Chen *et al*., 2010; Gaslikova and Weisse, 2006).

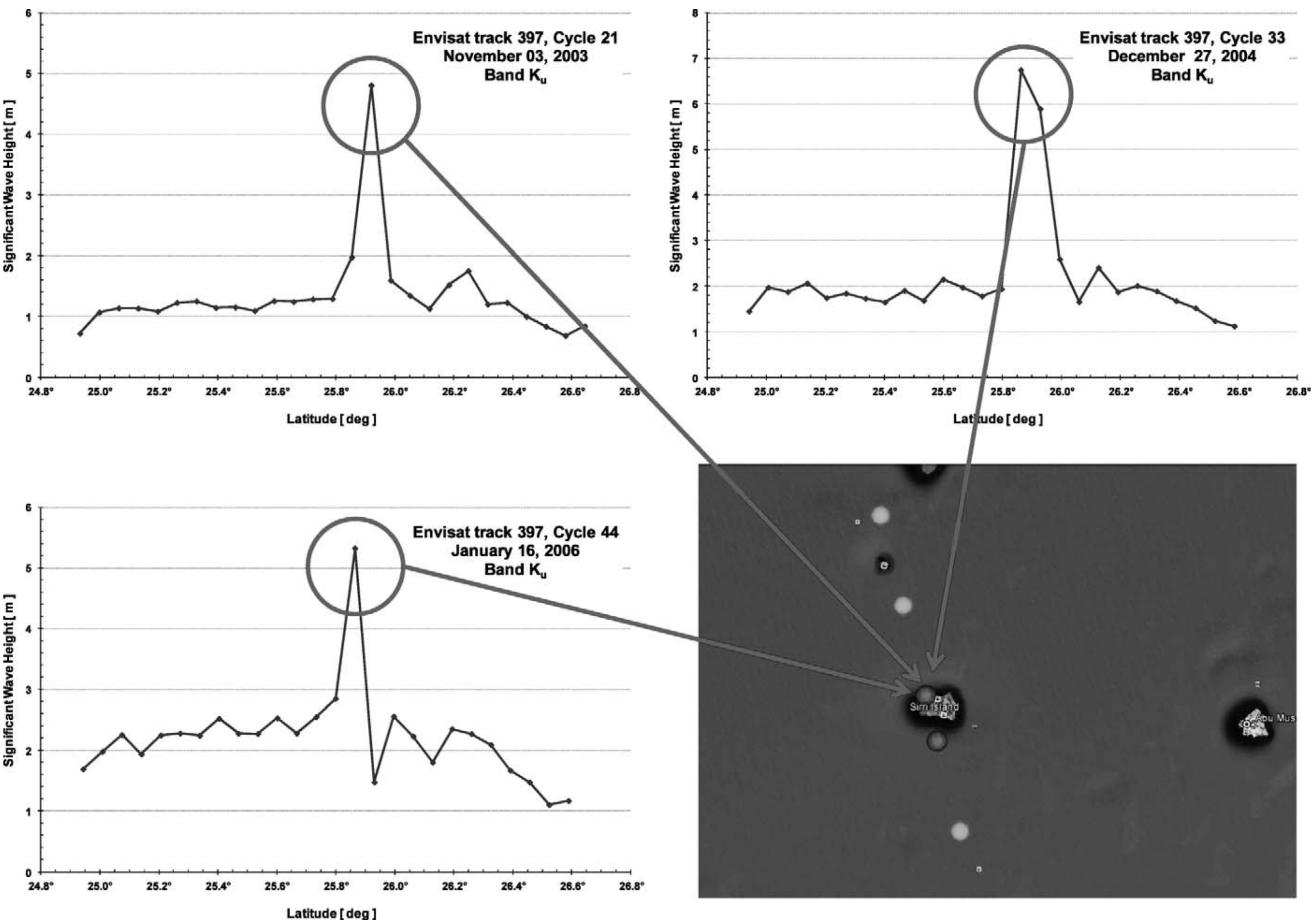

Figure 4. Spurious SWH value induced by presence of a small island. (Color for this figure is available in the online version of this paper.)

THE ROLE OF REMOTE SENSING

Remote sensing data have been of paramount importance in wave hindcasting and forecasting for many years. Active sensors, in particular, such as synthetic aperture radar (SAR), radio altimeters, and scatterometers, provide wave and wind measurements that are routinely assimilated and/or used to assess the reliability of wave model forecast.

Klemas (2009) examined the use of satellite and airborne remote sensors to evaluate costal effects of storms; SAR applications are described in a vast literature, such as in Pugliese Carratelli, Dentale, and Reale (2006, 2007).

Altimeter data in particular are an important element of wave climate studies: *TOPEX/Poseidon*, *ERS-2*, *Jason-1*, *Envisat*, *Jason-2*, and now *CryoSat* have been providing radio altimeter wind and SWH data for many years and for all the seas of the word. A classical description of radar altimeter characteristics, parameters, and limitations is reported by Chelton *et al*. (2001); more recent developments are given by Bouffard *et al*. (2008), Clarizia *et al*. (2012), and Pugliese Carratelli *et al*. (2008). Note that radar impulses are normally 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. Such data are routinely used by weather centres to improve prediction or to verify the analysis of sea state. They have also been often used to produce wave climate studies, which are far too numerous to be reviewed here: some notable examples are given by Feng *et al*. (2006); Sarkar, Mohan, and Kumar (1997); and Woolf, Cotton, and Challenor (2003).

A satellite altimeter pass provides practically instantaneous information of spatial changes (SSSV in space), while a wave buoy supplies a local description of SSSV in time—as has been shown above. Even though the two are obviously related, it is too early at this stage to determine a relation between the two aspects. The present work is aimed at showing that satellite altimeter data can provide useful indication about the entity and extent of spatial SSSV.

DATA, APPLICATIONS, AND EXAMPLES

Two distinct coastal seas have been taken as test sites: the first in the Southern Tyrrhenian Sea (STS), where an excellent record of wave buoy measurements and WM+WM results is

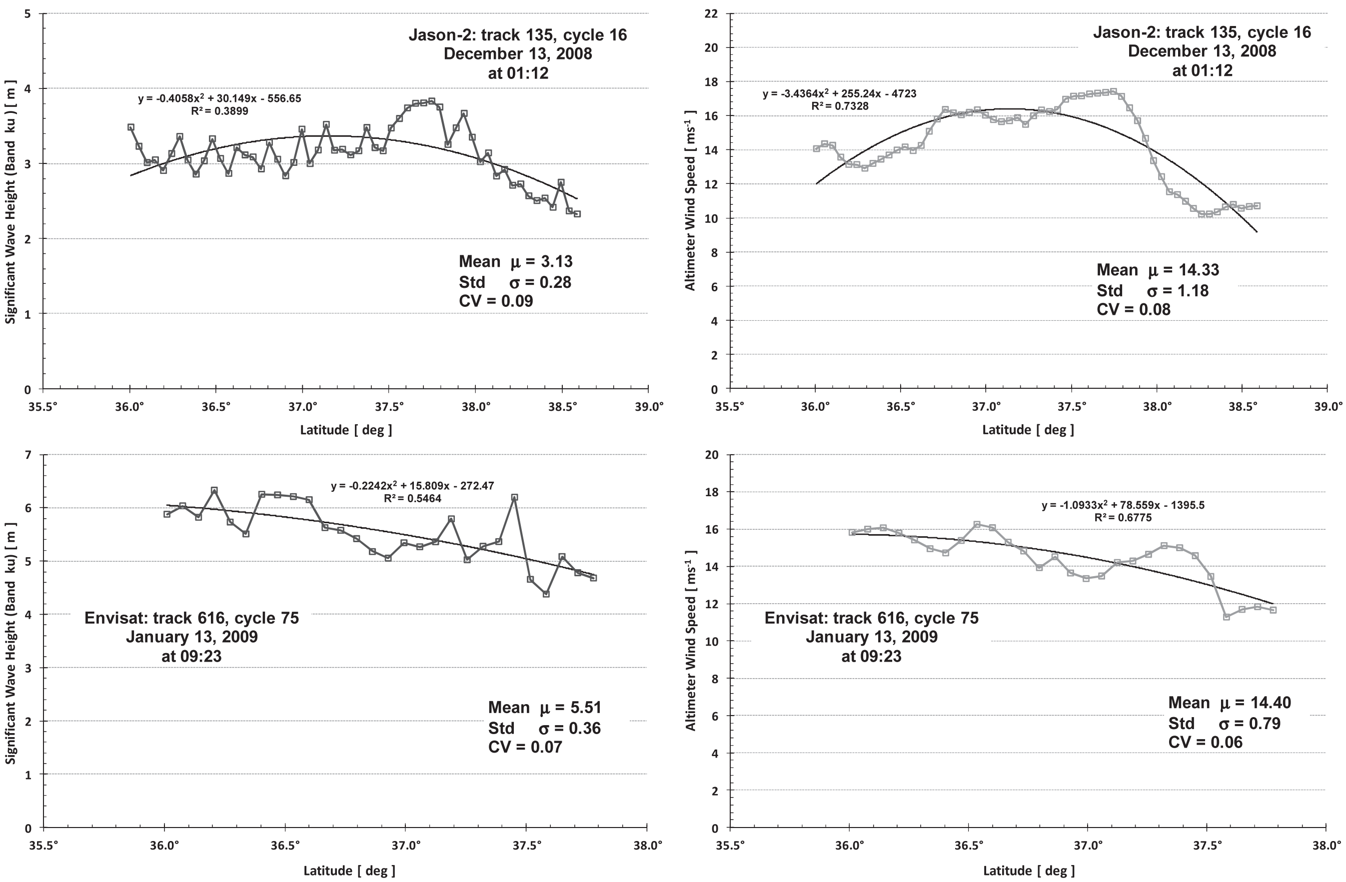

Figure 5. South Tyrrhenian Sea altimeter data (left, SWH; right, wind speed; curve, best fit parabola).

available, and the second in the Arabian/Persian Sea (PG), 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*, *Jason-2* (five in the PG and five in the STS), and *ESA Envisat* (22 in PG and 13 in STS) altimeter satellite tracks were considered (Figure 3). All the available passes for such tracks were examined, and those where SWH was consistently above 1 m (PG) and 2 m (STS) were taken into account.

Not all the altimeter signals are necessarily related to real variations of the wave height, since its response is affected by many errors, especially in the vicinity of a coast: Figure 4 shows how the presence of a small island can give a spurious SWH value. Some care was therefore taken to eliminate this kind of disturbance by comparing subsequent passages over the same track. A further effect is linked to the loss of accuracy in the transition from land to sea: a discussion of such effects is reported by Goìmez-Enri *et al.* (2010); all the passages employed here have been depurated form the part affected by this transition.

Rain effects and/or slicks (Tournadre *et al.*, 2006) may also confuse the results, so all the passages where available second band values (C band for *Jason-1* and *Jason-2* and S band for *Envisat*) were inconsistent with the Ku band were excluded from the present analysis. Most of the remaining oscillation around the trend is thus certainly a measure of the oscillations of storm intensity, over a spatial scale between 10 and 25 km, related to wind reinforcements (gustiness).

After this preliminary phase, SWH and wind velocity data for each passage were plotted in space, and an interpolating curve (trend) was calculated. Examples for STS and PG are shown in Figures 5 and 6, respectively. This allows one to visualise the presence of random oscillations, in both wind (gustiness) and SWH (SSSV), on both seas.

The oscillations are thus measured with reference to the interpolating curve, which necessarily involves some degree of arbitrariness; it is thus also necessary to get a better understanding of which space and time scale SWH values can confidently be considered as deterministic, *i.e.*, reliably estimated by the model, and which must be considered to be purely random in nature.

Some indication of the scale, *i.e.*, of the typical dimension of a SSSV, can indeed be obtained by considering the spatial autocorrelation $C(i)$ of the normalized SWH and wind data, that for a generic discrete real waveform Y (be it SWH or wind velocity) is given by Eq. 1.

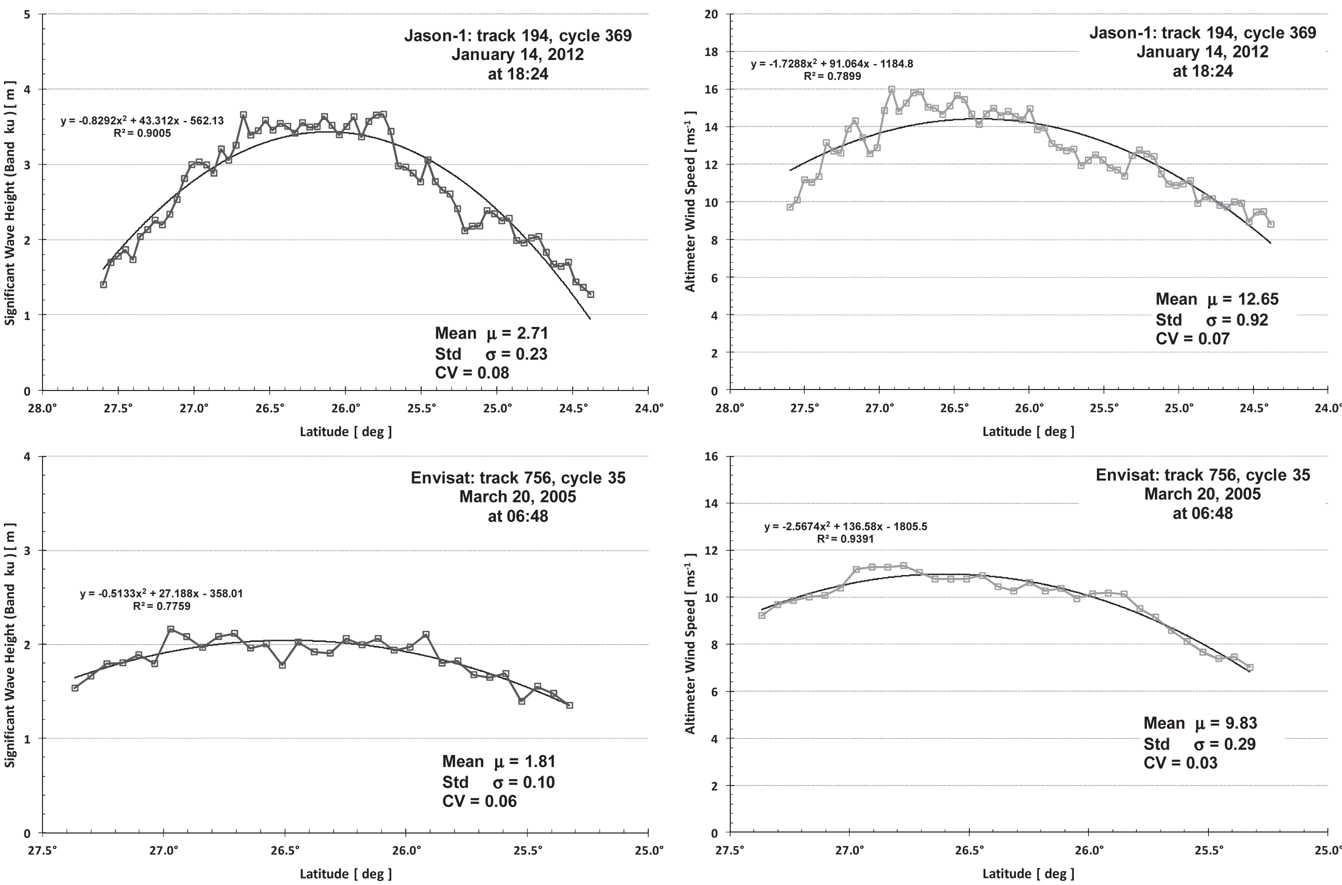

Figure 6. Persian Gulf altimeter data (left, SWH; right, wind speed; curve, best fit parabola).

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

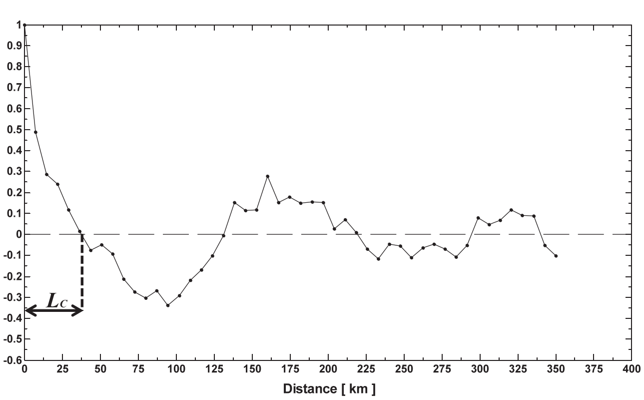

Figure 7. Spatial correlations of SSSV.

where N is the length of the discrete waveform.

The distance L_C of the first zero-crossing of $C(x)$ (see Figure 7) can be taken to be an indicator of the space scale. Figures 8 and 9 show some examples.

It is interesting to note that while the Tyrrhenian data yield L_C values that may range up to about 50 to 60 km, the Gulf data considered generally show a much smaller correlation distance. Some insight can also be gained by analysing the along track spectra of altimeter 1 Hz SWH values (Figure 10). It appears that, at least for the cases examined, which are all taken in enclosed seas, there is a consistent amount of irregular fluctuations for $1/L > 0.025$, *i.e.*, for $L < 40$ km, and it is to be expected that this could be the threshold below which the fluctuations should be considered random. This could be very different for open oceans.

Quantitative information on SSSV indication can be obtained by considering the standard deviation σ of both wind and wave (Eq. 2):

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

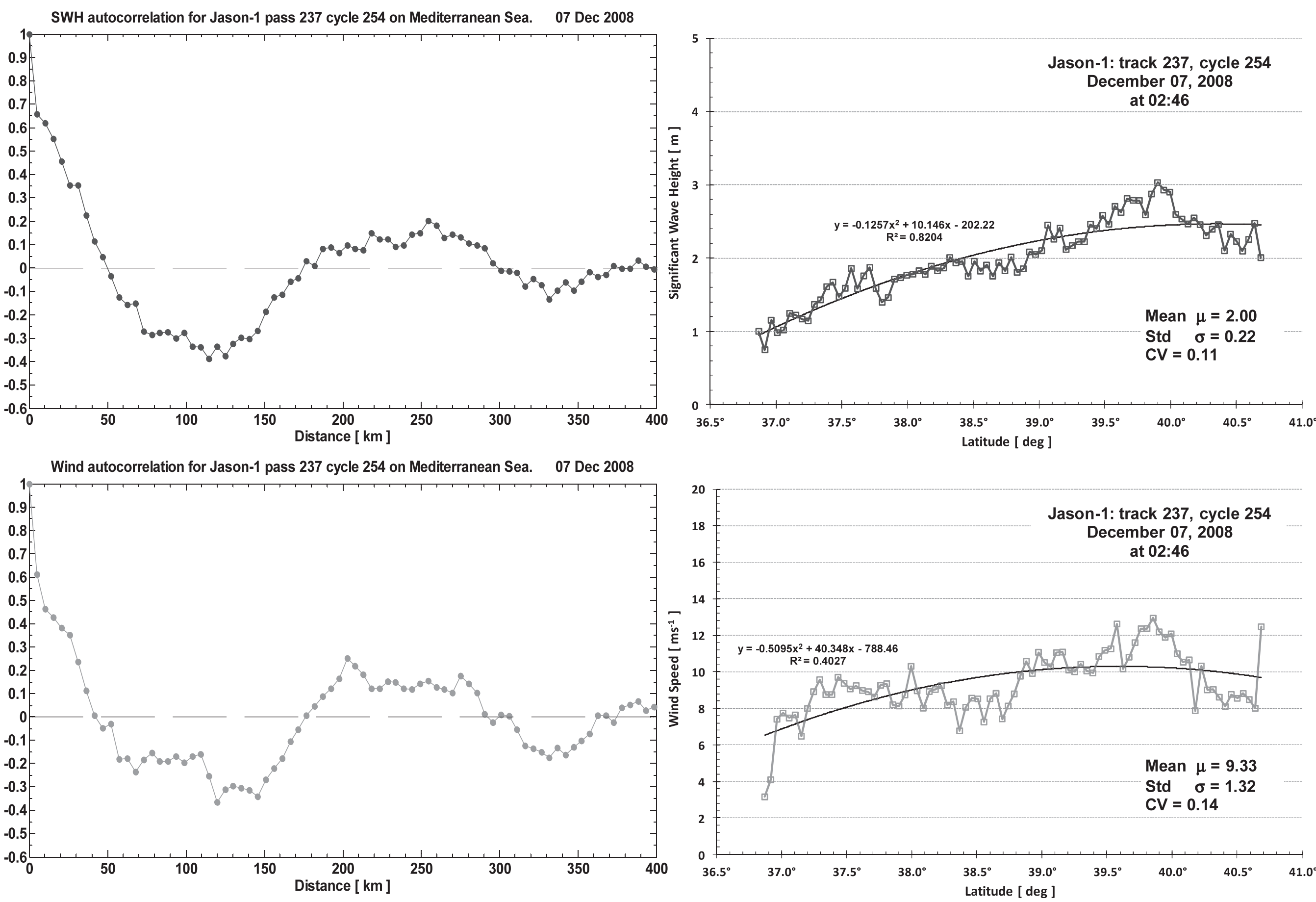

Figure 8. Spatial correlations of SSSV for Mediterranean storms.

where Y_i is the measured value of sample (wind speed or SWH), T_i is the value of the average trend line at the same position, and N is the number of (1 Hz) measurements. A scatter index $CV = \sigma/\mu$ for each pass was also considered, by taking μ as the mean of all the N values of the passage (N in the cases examined varies between 20 and 90). The scatter indexes CV can be treated in turn as random variables, and Figure 11 shows their empirical frequency distributions as well as their cumulate functions.

The average SWH CV values are found to be around 0.1: if a normal distribution is assumed, a SWH value 30% higher than the trend is to be expected with a 2.5% probability, while the empirical cumulate functions suggest only a 20% increase with the same probability level: in any case this is by no means a negligible effect for all practical purposes related to coastal engineering.

In order to provide a specific guidance to engineering practise, more extensive site-specific data should be gathered; it is, however, reasonable to assume that if the objective of the analysis is the design of a rigid structure (*i.e.*, sensitive to wave actions of a short duration), the extreme SWH values resulting from model data should be increased by assuming an extra random effect according to the distributions suggested above.

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

There seems to be no doubt that the main cause of SSSV is gustiness: a number of theoretical results prove such a connection. Hsu and Blanchard (2007) used the gust factor concept to improve the friction velocity estimates. Abdalla and Cavaleri (2002) actually simulated SSSV by feeding synthetic gusty wind series to a wave model and provide some evidence of SSSV with CV values not unlike those found in the present work. On a large scale similar effects have been found by using SAR on the North Sea (Pleskachevsky, Lehner, and Rosenthal, 2012).

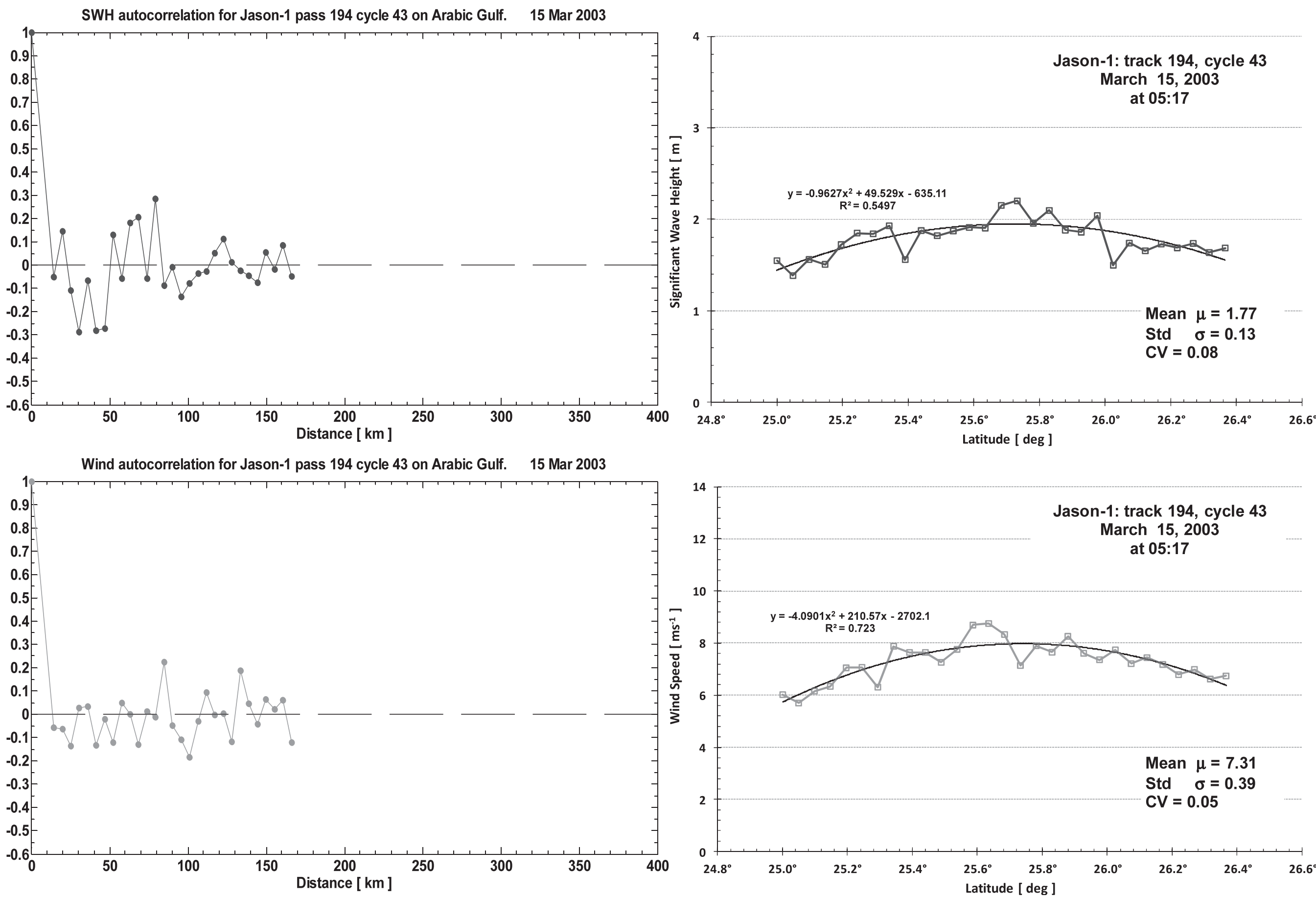

Figure 9. Spatial correlations of SSSV for Persian Gulf storms.

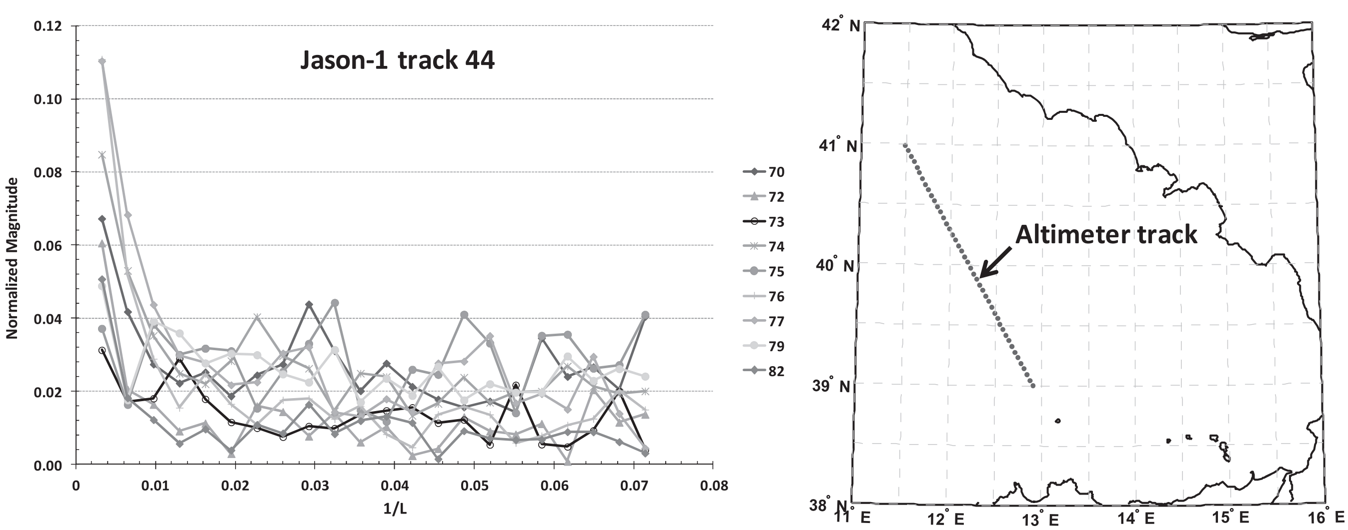

Figure 10. Along track spectra of altimeter 1 Hz SWH for different cycles of *Jason-1* track 44 in the South Tyrrhenian Sea. (Color for this figure is available in the online version of this paper.)

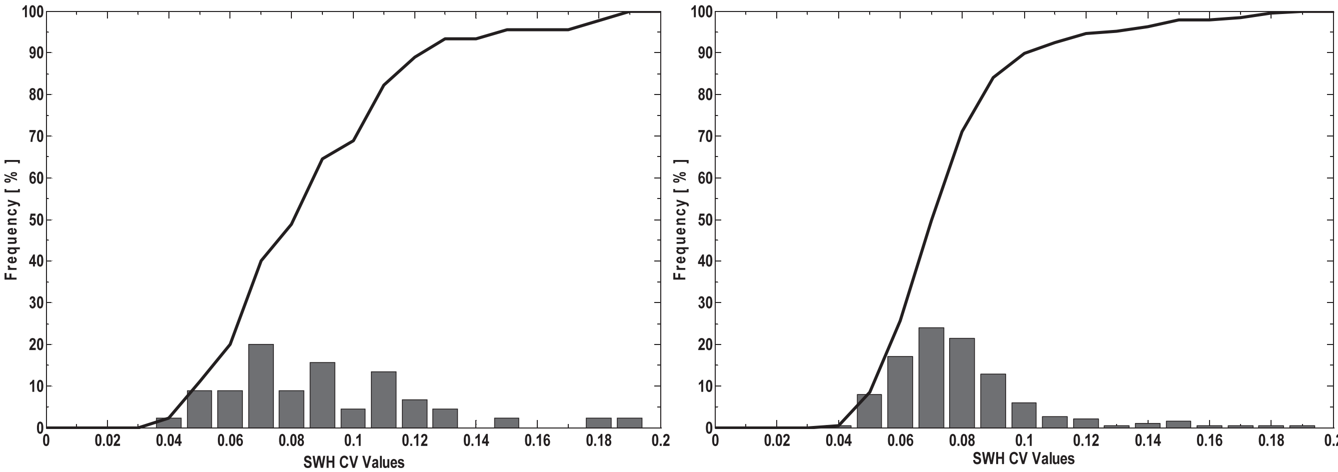

Figure 11. Empirical frequency distribution and cumulate function for SWH *CV* values in the South Tyrrhenian Sea (left) and Persian Gulf (right).

Since the physical effects and the reconstruction algorithms for SSSV are radically different and independent from each other, a confirmation of the connection between gustiness and SSSV can be found by considering the scatter index *CV* for altimeter wind speed (Figure 12), which shows a similar behaviour to the *CV* of SWH.

In any case the existence and the importance of subgrid oscillation is obvious; it is worth asking if improvements of model resolution might lead to simulation of such oscillations. A number of tests were therefore carried out on a storm that took place in the Southern Tyrrhenian Sea in November 2010 by making use of the results of NETTUNO model.

NETTUNO is a high-resolution (0.05°) WAM application developed by the Italian Meteorological Centre (CNMCA) in cooperation with the Italian National Research Council (ISMAR-CNR). (Bertotti *et al*., 2010) and driven by the COSMO-ME (Consortium for Small-Scale Modelling-Mediterranean) atmospheric model. COSMO-ME, presently at 7-km resolution, is based on the COSMO model, the standard regional weather forecasting tool of Italian, German, and many other national meteorological offices. Information about it is available at http://www.cosmo-model.org.

The storm was monitored by four wave meters run by the Italian Wavemeter Network (Ponza and Cetraro buoys) and by the Campania Region Civil Protection Department (Capri and Cilento), and three altimeter satellite passes are available (*Jason-1*, *Envisat*, and *ERS-2*). Figure 13 shows the time behaviour of SWH as recorded by one of the buoys

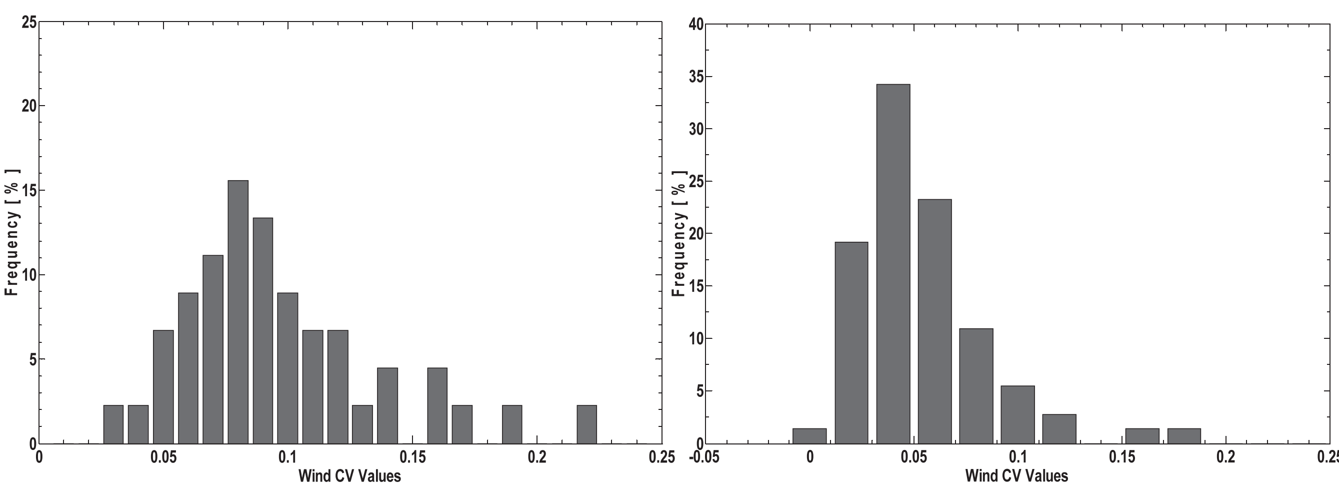

Figure 12. Empirical frequency distribution for wind speed *CV* values in the South Tyrrhenian Sea (left) and Persian Gulf (right).

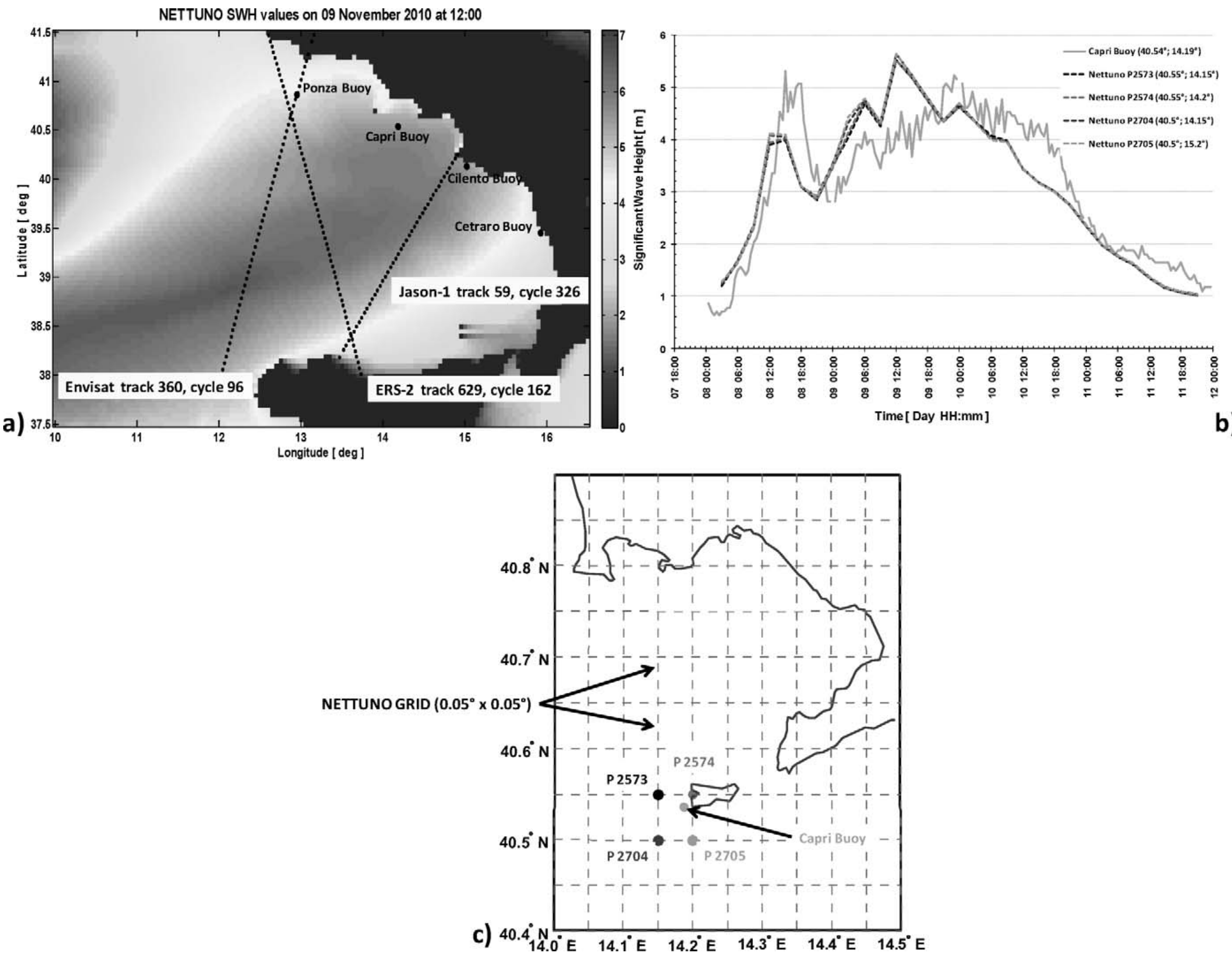

Figure 13. (a) CNMCA NETTUNO SWH simulation on 09 November at 12:00. (b) Comparison between Capri buoy and NETTUNO model grid points. (c) Location of buoy and grid points.

(Capri) and by the four NETTUNO model grid points around it.

In Figure 14 satellite-measured SWH data for ERS-2 track 629 and corresponding simulated NETTUNO values in the same area are shown.

By comparing altimeter data in space, as well as wave buoy data in time, with the NETTUNO forecast, it appears that while—apart from the bias—the general trends seem to match quite well, there are virtually no small-scale oscillations in the model results, which obviously dampens all oscillation with a wavelength of 20 km or more. These results seem to show that—as stated above—certain local phenomena cannot be simulated in a model, and highlight the opportunity of making use of satellite altimeter data in order to take SSSV into account.

CONCLUSIONS AND PERSPECTIVES

Small-scale storm variations can affect extreme significant wave height; the importance of taking this aspect into account when analysing extreme wave climate must not be overlooked. By analysing satellite altimeter tracks it appears that the present numerical modelling techniques are unable to evaluate such variations of both wind (gustiness) and sea sate. The problem can only be partially solved by increasing the resolution of the computational schemes. As a consequence, in order to correctly evaluate extreme sea states, the use of synthetic data must necessarily be supplemented by stochastic information on the effect of gustiness. Satellite altimeter data can supply useful information about the intensity of SSSV phenomena both in wind and in wave intensity.

Remote sensing data are therefore a vital tool to improve the understanding of extreme wave heights, and especially so in

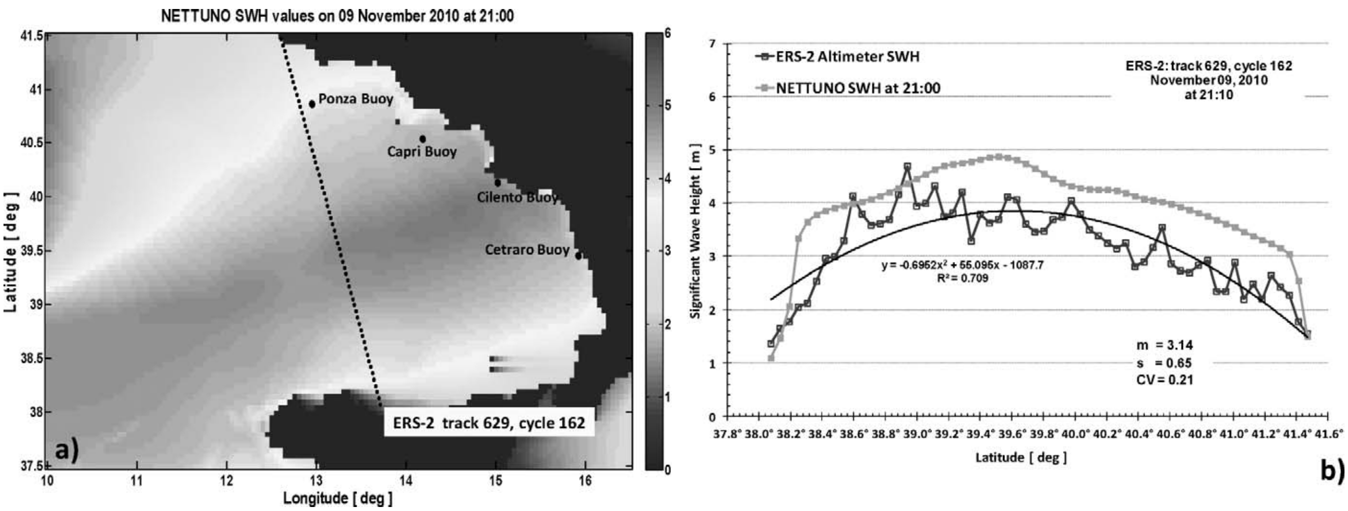

Figure 14. (a) CNMCA NETTUNO SWH simulation on 09 November 2010 at 21:00, with *ERS-2* track 629. (b) Comparison between SWH ERS-2 track 629 altimeter data and corresponding CNMCA NETTUNO simulation. Simulated data are collocated along the altimeter track.

enclosed seas and in the vicinity of the coast. From the limited investigation carried out so far, it is already possible to derive some cautionary suggestion about SWH extreme values.

Further developments should be aimed at correlating space dependent SSSVs as revealed by satellite altimeter measurement to time variation as measured by wave buoys.

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