EXTREME STORM EVALUATION: integratinG DATA SOURCES AND

METHODOLOGIES

*VALUTAZIONE DELLE MAREGGIATE ESTREME: INTEGRAZIONE DELLE METODOLOGIE E DELLE SORGENTI DI DATI*

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***Abstract esteso***

*Negli ultimi due o tre decenni le sorgenti di dati ondametrici hanno subito uno sviluppo senza precedenti. Oltre all’incremento numerico e qualitativo degli strumenti puntuali come le boe ed i radar, sono emerse tutta una serie di nuove tecnologie che hanno completamente cambiato gli strumenti disponibili per la progettazione delle strutture costiere e offshore.*

*Gli altimetri radar satellitari sono da tempo, la principale fonte di misure dell'altezza d'onda significativa; le loro orbite coprono l'intera superficie terrestre molte volte al giorno, e la loro affidabilità è garantita dal confronto con la verità del mare, per lo più acquisita attraverso le boe ondametriche.*

*Allo stesso tempo, i modelli di simulazione del moto ondoso, guidati dai sistemi di previsioni meteorologiche, sono in grado di fornire dati spettrali dettagliati a intervalli fissi su una rete regolare di località. Tali modelli sarebbero però di scarso valore se non fossero supportati da un flusso continuo di dati sperimentali “assimilati”, forniti per lo più forniti da altimetri radar satellitari.*

*Le tre principali fonti di dati sono quindi indissolubilmente collegate tra loro: è quindi essenziale - per qualsiasi applicazione ingegneristica -comprenderne i principi di base al fine di stimare correttamente il clima del moto ondoso - e in particolare i suoi valori estremi*

*L’articolo presenta, in maniera essenziale, i metodi necessari per integrare queste fonti.*

**ABSTRACT**

In the last two or three decades the sources of wave data have increased enormously. Beside the ever larger number of punctual instruments such as wave buoys and local radars, a whole set of new technologies have emerged and have completely changed the tools available for the design of coastal and offshore structures.

Radar satellites are now- and have been for quite some time – a fundamental provider of Significant Wave Height measurements along orbits which cover the whole Earth many times per day. The reliability of such measurements is guaranteed by sea truth data- mostly acquired by wave buoys.

At the same time wave simulation models, driven by meteorological weather forecast systems, are able to supply detailed spectral wave data at regular intervals on a regular net of locations. Such models however are of little value unless they are supported by a continuous flow of assimilated experimental data, mostly provided by satellite radar altimeters.

The three main sources of wave data are thus inextricably connected to each other. It is therefore essential that in order to correctly estimate the wave climate – and specially so the extreme values - for any engineering purpose, the basic principles should be clearly understood.

The paper presents an outline of the methods needed to integrate these sources.

1. Background

The evaluation of extreme storms must of course be based upon an adequate time series of sea state data. In the following, the main sources are briefly described

* 1. *Point data*

In situ wave meters are certainly the most well-known, and possibly still the most reliable source of information of sea state data. The traditional buoys, as well as pole or platform gauges and sometimes pressure gauges, are kept on site and constantly technologically improved, providing very detailed information such wave spectra, significant wave height (SWH) and sometimes maximum single wave. (Reale et al 2018 gives a quick review of these techniques). New developments have led to the availability of land and platform-based sea state radars, working either on X or S bands (Serafino et al., 2022), sometimes making use of Doppler techniques (Lyzenga et al 2010). Research is currently being carried out on the possibility of applying HF radar systems, which are presently to measure sea currents, to also evaluate SWH; another interesting perspective is also the application of seismographic recordingswhich, after careful elaboration and calibration, could provide good estimates of SWH.

Despite the quality and the reliability of these local systems, they present obvious limitations when the objective is the estimation of SWH for very high return periods (TR). In the first place, by their nature, they only supply data on the location where the device is installed, and in any case, there are relatively few sites which have monitored long enough to provide long enough time series to allow a reliable statistical analysis. Besides, some buoy values of SWH are often obtained from hourly spectral analysis of 20-min records, and as a consequence they might miss high intensity SWH peaks.

* 1. *Satellite data*

Satellite radar measurement of both surface wind and SWH have been available since the launch of Geosat in 1985 (Ribal and Young 2019). Since then there has been a continuous coverage of global altimeter data (see Fig. 1).

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**Figure 1 -** Durations of satellite missions included in the combined database (From Ribal and Young 2019)

**Fig. 1** - *Durata delle missioni satellitari incluse nel database combinato (Ribal and Young 2019)*

The altimeter footprint is between 5 and 10 km in range (across satellite path) and about the same in azimuth for the older satellites, while the most recent altimeters make use of Doppler technology to provide an azimuth resolution of a few hundred metres.

The quality and the reliability of altimeter measurements has been repeatedly tested against buoy measurement by many Authors over the years.

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| (a) | (b) |

Figure 2 - Q–Q plots between the Envisat altimeter and NDBC buoy data. Shown are (a) wind speed and (b) significant wave height (from Young et al 2017)

Fig. 1 – Diagramma Q–Q tra l'altimetro Envisat e i dati della boa NDBC. Vengono mostrati in (a) la velocità del vento e in (b) l'altezza significativa dell'onda (da Young et al 2017)

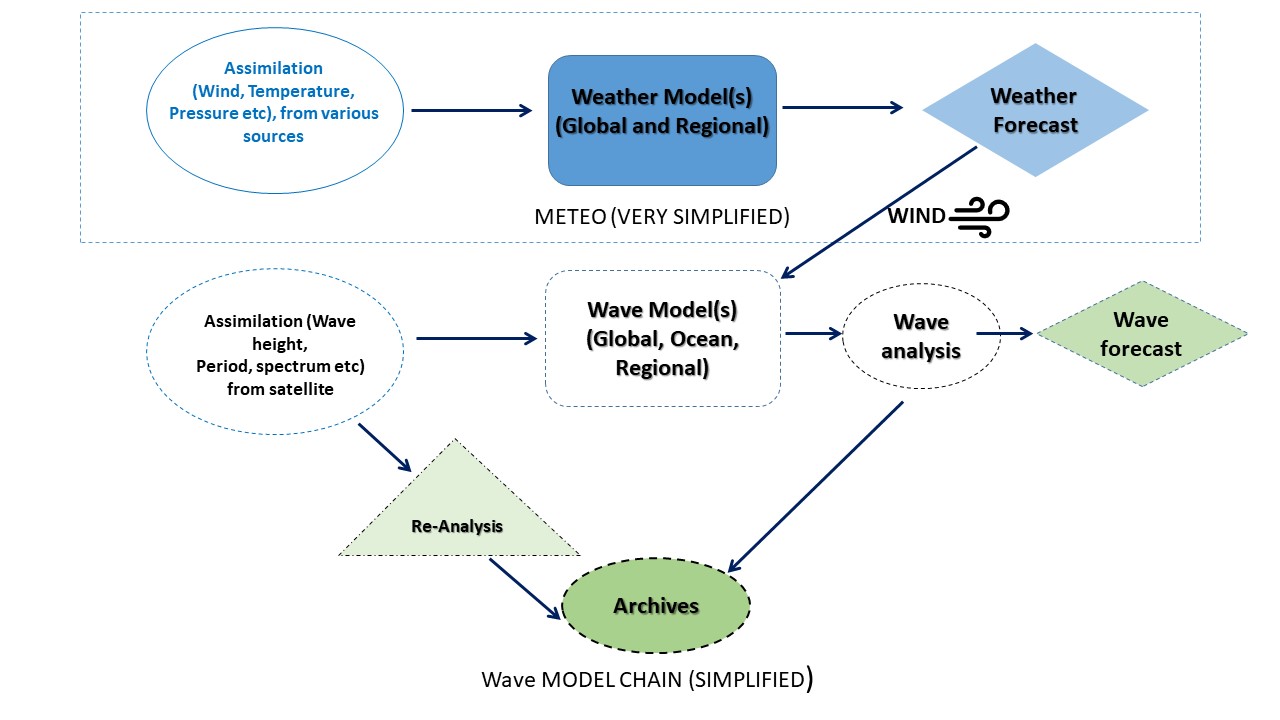
Figure 2 shows an example of the results by Young et al. (2017), who validated a database consists of altimeter data over the period 1984–2014, from 23 different satellites against an independent buoy dataset, and cross validated at crossover points with other satellite systems. Similar controls and calibration are constantly carried out to verify and to improve the reliability of the satellite instrumentation to the point that the reliability of their measurements can now be considered equal or even higher to that of buoy wave meters (Timmermans et al., 2022).

However, despite the high ground resolution of each single altimeter measurement, the temporal and cross-track sampling of the whole system is very low. The satellites, at an height of about 700 km, describe an orbit that goes around the earth in a little more than an hour and they fly over the same spot at an interval, known as Repeat Cycle (RC) which may vary between 5 and 20 days while the distance between tracks at the equator varies between less than a hundred and a few hundred km – obviously the smaller the distance, the longer the RC. As a consequence, extreme storm events are under sampled and the system cannot by itself provide adequate information on extreme events – especially so in restricted closed or semi-enclosed seas. Indeed, the same consideration which apply to the effects on the evaluation of extreme storms with point measurements or by model hindcasting (see for instance Dentale et al 2016), obviously also apply to satellite altimetry.

*1.3 Synthetic data*

Over the past 30 years, thanks to the wide availability of weather models which provide both forecast and hindcast (“analysis”) data all over the world, many state and international meteorological centres, as well as some research institutes and private companies have begun to systematically run global and regional wave generation and propagation models (WWMS).

These waves are driven by the low altitude winds (generally and conventionally, at an altitude of 10 m) generated by meteorological systems. Both are constantly calibrated and corrected through the acquisition ('assimilation') of measured data. Fig 3 May help clarify the procedures.



**Figure 3 -** A very simplified schematic of weather wave modelling systems

**Fig. 3** - Schema molto semplificato dei sistemi di modellazione delle onde meteorologiche

The use of such data is now universal: forecast and analysis are published almost in real time, providing sea sate information for many vital applications: ship routing, coastal safety, and harbour operation; equally important is the formation of archives storing long time series of "synthetic data" which are today the main source of information for both forecast and for statistical analyses. Long (often as many as 40 years) records are available for every point of the sea surface, with a temporal frequency than can be as high as 1 hour, and a spatial resolution which may vary from half a degree to a few miles.

Recorded data are available from may public sites (see for instance NOAA <https://polar.ncep.noaa.gov/waves/hindcasts/nopp-phase2.php>)

It is worth remarking that WMMS wave data derive thus from a chain made up of two parts: a wave model which takes explicitly into account the geographical and morphological aspects of the wave formation and propagation, which is basically a deterministic algorithm; and a meteorological part, which provides the input winds and involves necessarily a higher degree of randomness.

3. Integration

Summarizing, as seen above, the main sources of data are three, strictly interconnected:

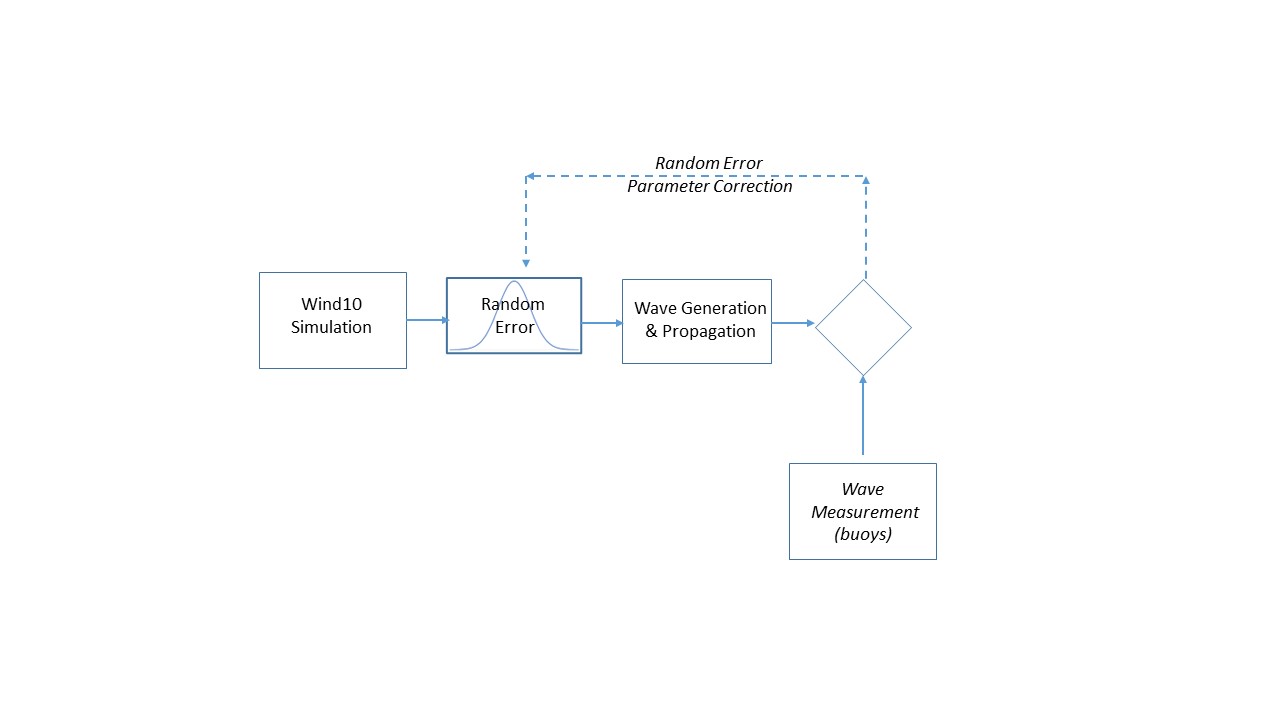
(1) point measurements (wavemeters, mainly buoys), which are relatively scarce, but provide accurate and sometime long time series in a limited number of sites. Many states organization run buoy system; the biggest network with a long-time record is probably NOAA NCEP.

(2) satellite radar system, which provide a frequent coverage all over the oceans, but with a low temporal and cross-track sampling resolution. Their reliability and accuracy are fully established and continuously calibrated and checked with buoy measurements. Their cross-track distance and their Repeat Cycle are not adequate for a reliable estimate of storm extreme value and of their probability.

(3) synthetic data, produced by WWMS. They cover all the sea surfaces of the world, and they rely massively on satellite data for assimilation and calibration. Such data are produced by many sources; the most widely used are the Climate Forecast System (CFS), run by the NOAA National Center for Environmental Prediction NCEP) and the ECMWF; for other sources, specially oriented to Mediterranean climate, see for instance Sartini et al. et al., (2015, 2016). The estimation of extreme SWH values for high return times through a synthetic data base raises various issues: apart from the obvious problem of reliability of the model chains an important aspect is the way through which ground truth wave data are assimilated into the analysis. As stated above, the assimilation procedures are carried out by making use of the measurement of satellite altimeters, whose timing and location is uncorrelated with the weather or the sea state, so the calibration is biased against the extreme weather or sea states- - extreme SWH values are therefore often missed.

Moreover, the sampling time of the models, i.e. the time interval in which the data are stored and released, is often longer than the standard sampling time of the buoys, which causes a negative distortion of the estimated extreme values ​​(Arena et al., 2013; Dentale et al. 2016). Also, their spatial resolution, i.e. the distance between computational points is often too low.

A correct analysis of wave climate can thus be only based on the interaction and synergy of the three sources of data, as conceptually shown in figure 4.



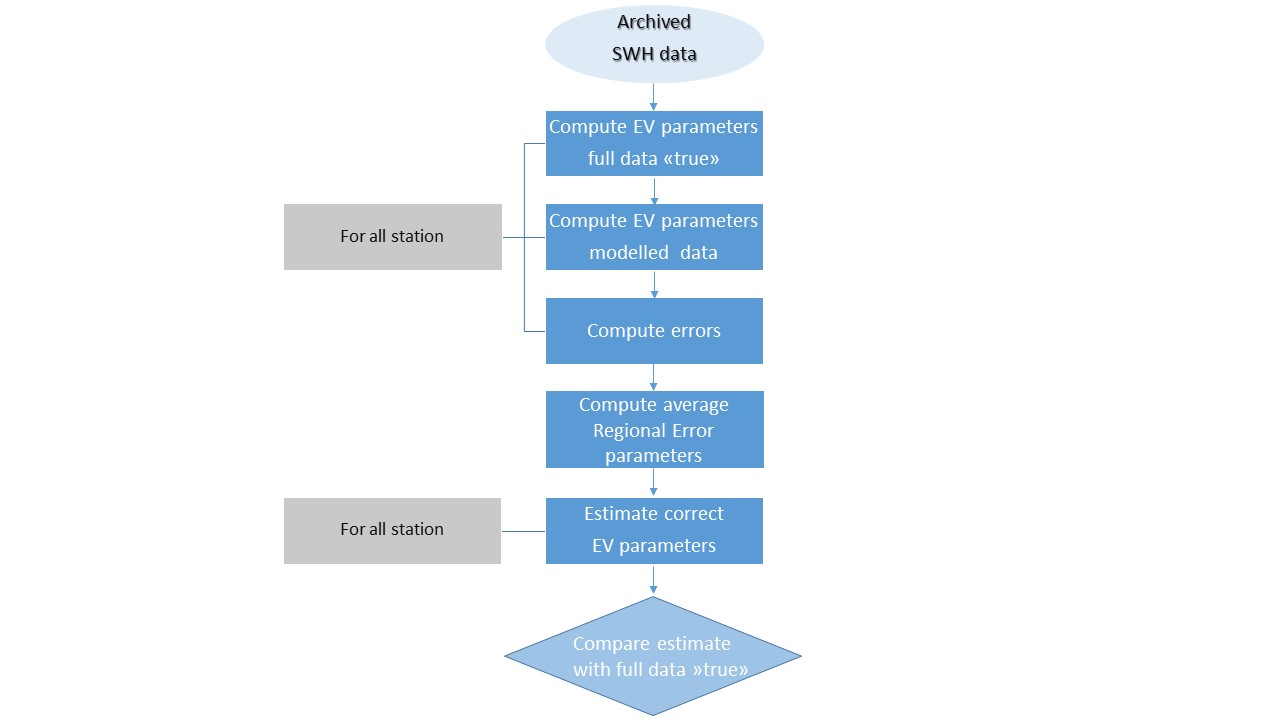
**Figure 4 -** Error estimating procedure

**Fig. 4** – Procedura di stima dell’errore

When the objective of the analysis is the determination of average wave climate, as it is required in coastal erosion or wave energy investigation, the procedure has been well tested and can provide reliable results as long as enough data are available (Sannino et al. 2011).

The problem is far more delicate (see for instance De Leo et al. 2022) when the objective of the work is the evaluation of extreme storm (EV); as stated above, all three sources of data are biased in one way or another when high return period estimation is required. In such cases, a procedure integrating synthetic and experimental data is required.

One such procedure has been proposed and tested by Dentale et al. (2018, 2020). Its basic idea is the assumption that the parameters of any SWH(TR) function, linking SWH with its return time TR, are themselves randomly distributed so that that the distribution of such parameters – rather than their definite value - can be estimated by integrating the data from the model with those from the buoys in the area.



**Figure 5 -** Integrated procedure for the evaluation of Extreme Storm Values (EV)

**Fig. 5** – Procedura integrata per la valutazione dei Valori Estremi (EV)

**Conclusions**

The modern complex technologies have completely changed the methods through which wave climate can be assessed – and particularly so when extreme SWH values are required. Local measurements, global satellite survey and synthetic data production are closely related to the point that no correct analysis can be carried out without a full understanding of their interconnections. The ever-increasing diffusion of the data must be supported by the development of new techniques that will make full use of the recent developments. The paper gave a brief outline of these possibilities.

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