TÉCNICO LISBOA

IDENTIFICATION OF EXTREME STORMS ON THE PORTUGUESE COAST

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1. Introduction

Over time, the Portuguese population moved from inland regions to coastal and estuarine areas, resulting in a densification of the main cities. Several studies have been made for cases of river flooding, alerting the population in general for the risk and consequences of floods. However, considerably less attention has been paid to floods in coastal areas and estuaries, which are due to the temporary rise in sea level. Tide levels can be changed by weather systems such as hurricanes or mid-latitude cyclones, which can then originate storm surges. However, only in a few towns, people are aware of the almost constant risk of living in these places. The exposure of other mid-latitude coastal areas to frequent intense low-pressure systems (e.g. the British Islands) may be higher than in Portugal. It is also known that the impact of mid-latitude system on the coast is generally lower than that of tropical cyclones (Barry, 2010). Nevertheless, there are still many reports of abnormal sea level rise and of the consequent property and personal loss.

Storm surges are among the major events affecting the Portuguese coast (Gama *et al.*, 1994). Using more than 30-years of data, there will be a deeper knowledge of the phenomenon, and by analyzing more than one site it is possible to extrapolate this information into other locations along the coast.

Anintegrated methodology was applied to sea level records, evaluating harmonic constituents parameters and focusing on obtaining well-established meteorological residuals. Qualitative and quantitative analyses are conducted to the previous datasets, comparing the results with other shore spots, where storm surge phenomena are deeply characterized and regularly forecasted.

The aim of this work is also to investigate how weather systems affected sea levels records along the Portuguese coast during the last decades. The synoptic circulation patterns and the frequency of some basic circulation weather types (WTs) are presented (Trigo and DaCamara, 2000). The WTs that favor the occurrence of storm surges in the western coast of the country are characterized and related to the sea level recorded at the tide gauges. Surface pressure anomalies are also calculated, understanding storm formation patterns leading to extreme surge levels.

The most important storm surge events are identified. Storm-tracking analysis are conducted to the three most onerous events, for each tide gauge station. Although the surge phenomenon consists in a multi-effecting variable, it was decided to focus this study on pressure and wind effects. Correlation factors are calculated for different periods and data specifications. Based on those factors and well known past events, annual estimates (time and order of magnitude assessments) are produced.

In order to proceed the coastal flooding studyingto a computational modeling step, this work is set to bound the most important periods of time and reveal future research topics. Keeping in mind the prospect of holding regular estimates of storm surge elevation values on the Portuguese coast, key points are featured in a cause-effect approach.

2. Data acquisition

Sea level records from Viana do Castelo, Aveiro and Cascais tide gauges were obtained from the National Institute of Cartography (IGP) and Hydrographic Institute (IH). Tide level datasets frequently present gaps, which is not unusual in sea level datasets. The locations of gauges and data statistics are presented in Table 1.

Table 1. Geographic location and data information of tide gauges of Viana do Castelo, Aveiro and Cascais.

Station	**Latitude (ºN)**	**Longitude (ºW)**	**Years of data**	**Data %**
Viana do Castelo	41.69	8.84	32	92.00%
Aveiro	40.64	8.75	33	83.76%
Cascais	38.69	9.38	35	90.53%

Tidal harmonic analysis is carried out using T-Tide software package(Pawlowicz *et al.*, 2002). Firstly, a year through year analysis was performed, in order to extract the tidal harmonic constituents' amplitudes and phases, as referred in literature (Pugh, 1996). After a statistical analysis of the results, it was decided to use, for each tide gauge record, the harmonic constituents of the most recent recorded year with no data missing. This procedure allowed the standardization of the data input, in accordance with the generalized good practices of tide analysis. Sea levels, in consequence of tide effects, were obtained using the algorithm T-Predict in T-Tide. The corresponding meteorological residuals were calculated by subtracting the astronomic tide from the records. Another important parameter that has been analyzed is the signal to noise ratio (SNR) that limits the number of constituents to be used in the harmonic analysis. The influence of that parameter on the residuals calculation was carefully investigated, leading to a value of 500 for SNR. Figure 1 resumes the methodology used. Although the year-by-year analysis is not present, Table 2 shows the harmonic constituent's amplitude used for each station.

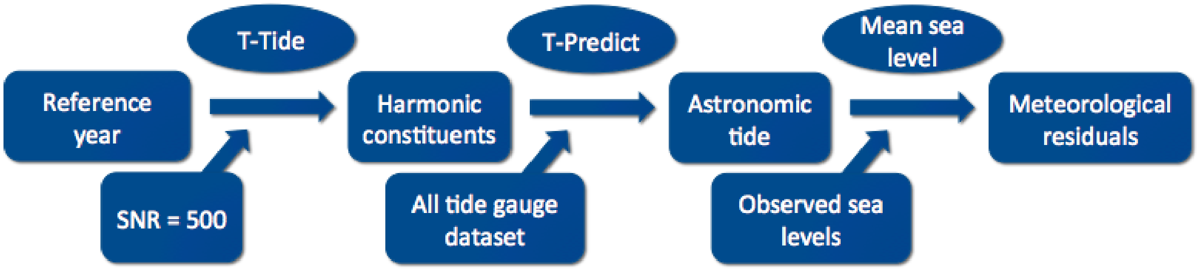


Figure 1. Meteorological residuals calculation diagram

Table 2. Tidal harmonic constituents used in T-Predict algorithm.

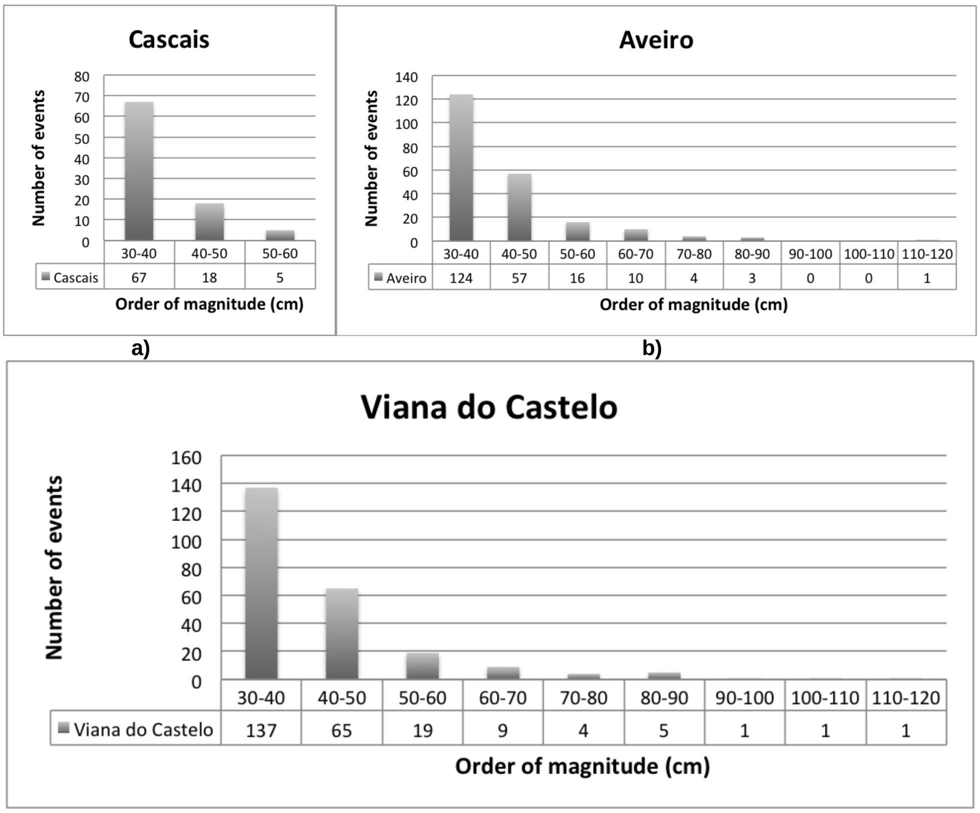
Station	**Year**	**Tidal harmonic constituents amplitude**							
		O1	**K1**	**N2**	**NU2**	**M2**	**S2**	**K2**	**M4**
Aveiro	1999	5.66	6.03	20.34	-	96.93	33.43	-	3.83
Cascais	1998	6.33	6.87	21.81	-	101.47	35.69	-	-
Viana do Castelo	2008	6.31	7.00	22.17	4.07	104.16	36.46	10.26	-

After calculating the residuals for every year with available records, the statistical percentiles are calculated and presented in Table 3. It can be observed that the storm surge elevations are higher northwards, as expected, as severe storms are formed in upper Atlantic areas, near Island. As mentioned before, sea level records are missing frequently, which most of the time happens with adverse meteorological situations (Esteves *et al.*, 2010). In this way, the real percentile values may be a little higher than the calculated ones.

Table 3. Storm surges elevation percentiles for each tidegauge.

Surge (cm)	Cascais	Aveiro	Viana do Castelo
Percentile 50	5.1	5.8	4.9
Percentile 75	10.4	12.6	12.0
Percentile 85	13.7	17.4	16.9
Percentile 95	21.2	28.4	28.6

A quantitative analysis, based on New York City procedure (Colle *et al.*, 2010), was conducted to the number of events registered on the tide gauges, using a 0.1m discretization –Figure 2. Results show a significant difference on Cascais events' number and intensity, compared with levels registered in Aveiro and Viana do Castelo (Araújo *et al*, 2011).



a) b)

c)

Figure 2. Event's number and intensity: a) Cascais; b) Aveiro; c) Viana do Castelo

Based on Trigo and DaCamara (2000) procedure, which adapted the characterization of circulation Weather Types (WTs) to mainland Portugal, the time-series of daily circulation patterns affecting western Iberia were reproduced. This characterization made use of a set of indices associated with the direction and vorticity of geostrophic flow, determined from mean sea level pressure (SLP) fields. These indices were computed using daily-average sea level pressure (SLP), with values being obtained from the 16 grid points (p1-p16) shown in Figure 3. Weather types were then calculated using several conditions, leading to a total of 26 types. In order to statistically analyzethe information, the hybrid situations were distributed to either pure directional or vorticity-based types, setting the 10 basic types showed in table 4.

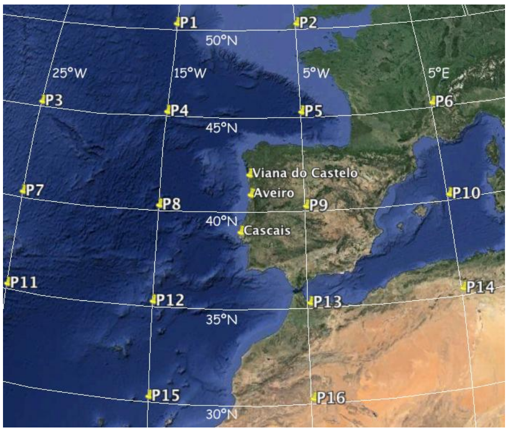


Figure 3. Grid points used for WT calculation and geographic location of tide gauge stations

WTs	Symbol
Anticlyclonic	A
Cyclonic	C
Northeasterly	NE
Easterly	E
Southeasterly	SE
Southerly	S
Southwesterly	SW
Westerly	W
Northwesterly	NW
Northerly	N

Table 4. Ten basic WT used to characterize pressure data

3. Pressure-surge relation

To understand the formation and origin of the surge events, concerning 95-percentile situations on the gauge record, anomaly pressure fields for each WT are obtained. A similar approach to Trigo and Davies (2002) is adopted, where four days, three days, two days and 24 h lag is considered. In Figure 4, an example of anomaly fields, for Viana do Castelo, using a 24h lag is displayed for the southwesterly WT conditions. For each WT, pressure anomalies are calculated using Eq.[1]:

$$Anomaly = SLP_{peak\ situations} - SLP_{climatology} \qquad [1]$$

where, $SLP_{climatology}$is the mean of pressure values for the winter season period (October-March) in all-record period and $SLP_{peak\ situations}$contains all the pressure values situations in which the 95-percentile was reached.

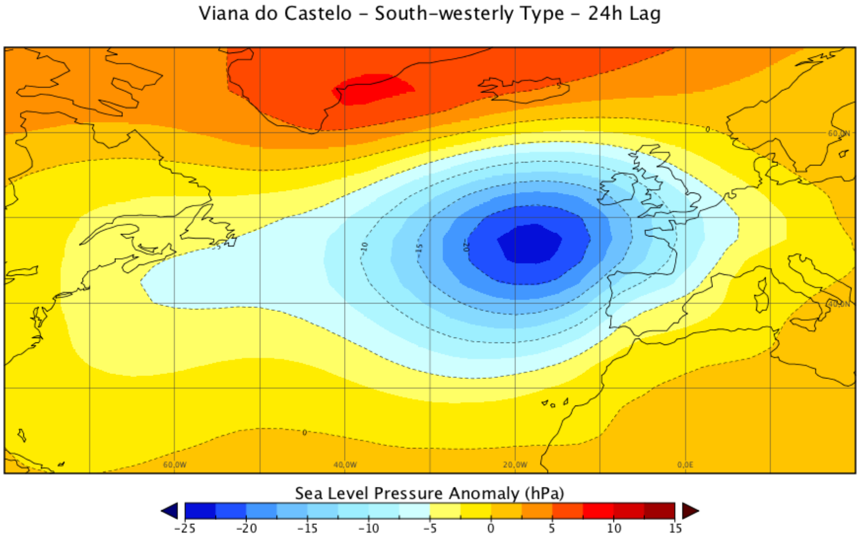


Figure 4. Southwesterly type pressure anomaly using a 24h lag in Viana do Castelo tide gauge

Results shown that the center of negative anomalies varies as we change the WT. Cyclonic ones are located near the tide gauges but demonstrates less intense negative anomaly values compared with SW and W types. Southwesterly and westerly negative anomaly centers are located further north. The common aspect in all types is the positive anomaly values above 70ºN latitudes.

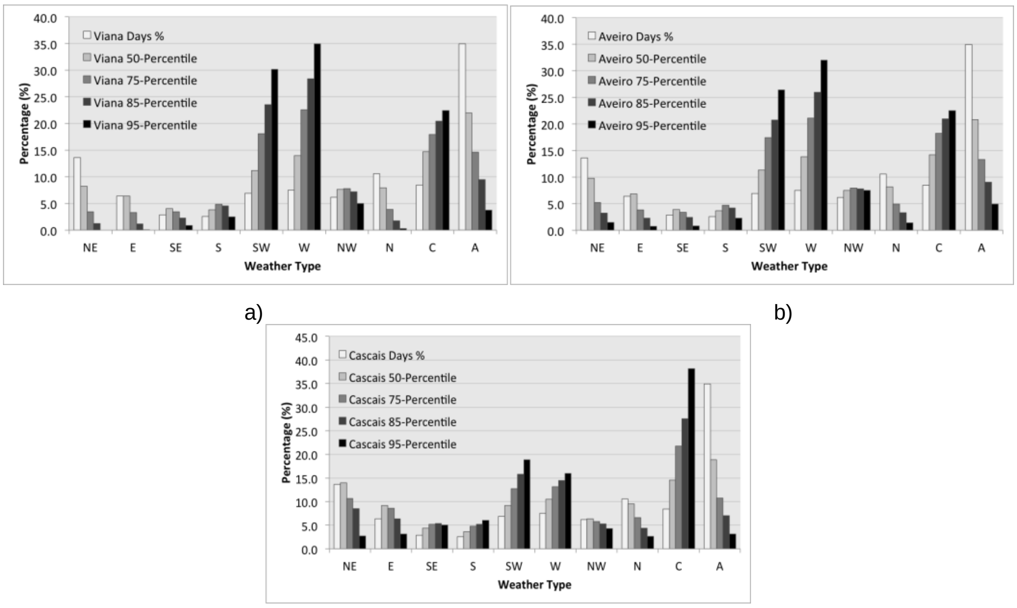
In order to validate the developed WT classification, long-term comparisons are made between the daily circulation types and the storm surge elevation data. The aim of the analysis is to determine whether the results would agree with those obtained from synoptic experience and SLP maps observation.Although anticyclonic type is the most frequent one, it is generally associated with good and calm weather, becoming a non-surge type. Southwesterly, westerly and cyclonic WTs are considered to be strong surge types, as they meet the following condition: "%days' < '#-percentile occurrences", for all the four percentiles calculated. As presented in Table 5, these three WTs together represent at least three quarters of all the storm surges occurrences above 95-percentile.

Table 5. Relative frequency of the three onerous WTs in surge occurrences.

(SW+W+C) WTs	% Days	50% percentile	75% percentile	85% percentile	95% percentile
Viana do Castelo	22.9	39.9	58.6	72.4	87.5
Aveiro		39.3	56.8	67.7	80.9
Cascais		34.2	47.6	57.9	73.1

When analyzing the differences between the tide gauge stations, it was noticed that the relative frequency of cyclonic WT decreases when moving north, in comparison with southwesterly and westerly types, which become more often. This result was already expected as the WTs were calculated having as reference the latitude of mid-Portuguese territory, where Cascais tide gauge is located. In fact, if the reference point used in each station has the same latitude of the station, the previous variations might not be seen, since that is a consequence of the relative position of the gauge with respect to the dominant flow. This suggests that, in Aveiro and Viana do Castelo storm surge cases, the center of the low-pressure system might be located further north than in Cascais events.

Figure 5 shows the evolution of relative frequency when moving from weak to severe surge elevation values, for the three tide gauge stations analyzed. It can be seen that C, SW and W weather types have a positive growth, whereas A, NE and N types have a negative growth, being rare their appearance in 95-percentile values.



a) b)

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Figure 5. Evolution of relative frequency along storm surge percentiles: a) Viana C.; b) Aveiro; c) Cascais.

4. Storm-Tracking and Correlation Coefficients

With the relation between SLP field camps and storm surge elevations being well-established, the study continue focusing on finding the storm-related variables strongly correlated with the phenomenon. The applied methodology initiated by selecting the relevant stormy periods of the whole dataset range. Using the conditions (i) at least one selected period by year and (ii) all the events that produced a 50cm storm surge value; a total of 58 periods from 1976 till 2011 were analyzed.

Based on Colle et al. (2010) characterization on New York area events, the coordinates of low-pressure systems' center were identified in figure 6, regarding the moment when the referred tide gauge reaches the maximum surge level.

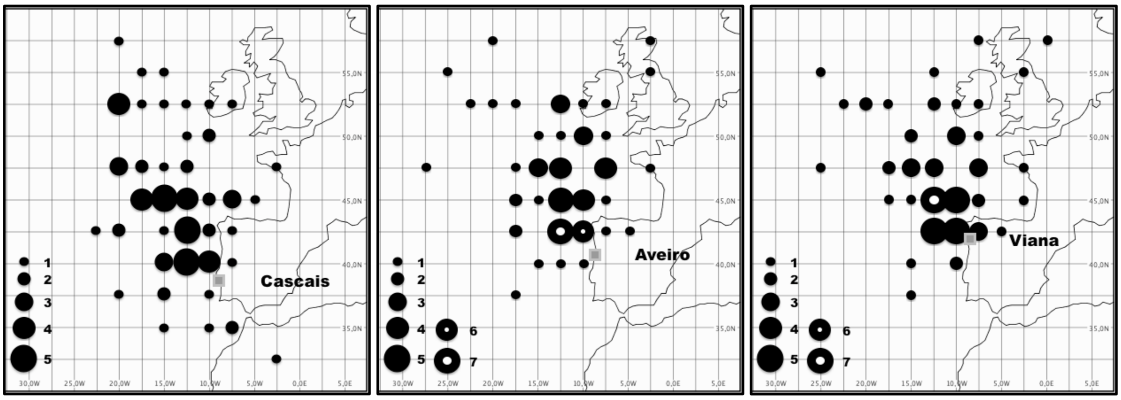

Figure 6. Low-pressure systems' center location at maximum surge level, for each tide gauge station

From the previous figure it is clear to identify the area around 45ºN/12.5ºW as the preferential for reaching the surge greatest values for all the tide gauges studied. Furthermore, for Cascais region were also affected by storms formed in Madeira Island region, although less frequent compared to the previous mentioned ones.

Despite the inherent importance of the maximum levels reached, a pure storm-tracking analysis was made to the 3 most onerous storms that occurred during the studied period. In figure 7 the Feb'86 storm is showed, with the particularity of being the one that caused the highest surge value ever recorded. It is possible to observe the typical west-east progression path as well as the maximum value preferential area, described before.

In order to continue the analysis to a prediction area, several meteorological-based variables were correlated with the storm surge elevation data. Data specifications were also taken into account, such as:

- Pressure grid's spatial and time displacements: by using from 2.5º till 0.75º grids, the influence of small local pressure variations were related with the surge observed at the tide gauges. On the time range, both 6-hours values and daily averages were used.
- The influence of the stormy periods, by selecting only the maritime winter period or a specific event;

Correlation comparisons were made concerning different variables and data options through the same variable (Taborda and Dias, 2000). The correlation coefficients can be found in table 6.

Considering the coefficients showed on the mentioned table, the following variables could be distinguished as strongly correlated with the surge phenomenon:

- Local sea level pressure;
- Geostrophic flow, calculated in the direction of maximum correlation coefficient;
- Local wind intensity, calculated in the same direction as geostrophic flow.

The maximum correlation direction of geostrophic flow was calculated for each tide gauge. The results are presented in figure 8, by showing its azimuth. Note that in Viana do Castelo and Aveiro's tide gauges the maximum correlation direction has a greater western component than in Cascais, mainly due to the orientation of the shoreline. Another important characteristic was the creased influence of the southern component in all stations. This might express the *Coriolis* effect, as southern currents are deviated into a more perpendicular direction into the coast, enhancing the surge elevation.

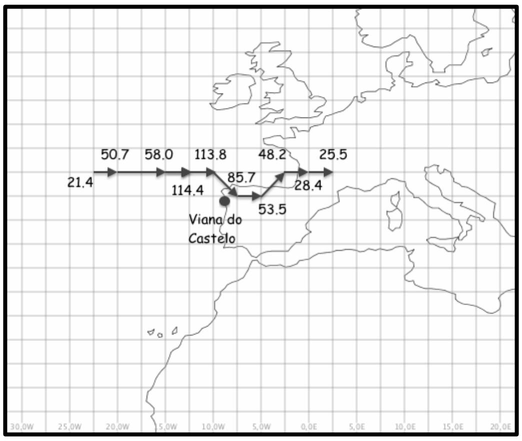

Figure 7. Viana's Feb-1986 storm-tracking with surge values registered at tide gauge for each position (cm)

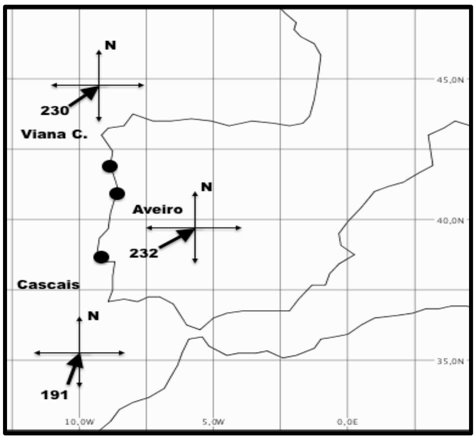

Figure 8. Maximum correlation geostrophic flow azimuth for each tide gauge

Yet the previous conclusions were important to better understand the causes of storm surge events and define the variables most linked to this temporary sea elevation, simultaneity of the different coastal dynamic processes must be taken into account. In fact, an extreme surge event occurring in a low tide period can be hardly noticed, as its real effect is not let the sea level get so low as predict. On the other hand, a perfect combination of the previous oscillations peakscan cause severe damages, as occurred during Feb'10 with cyclone Xynthia(Liberato et al., 2013). In figure 9 it is possible to compare the predicted and registered sea elevation.

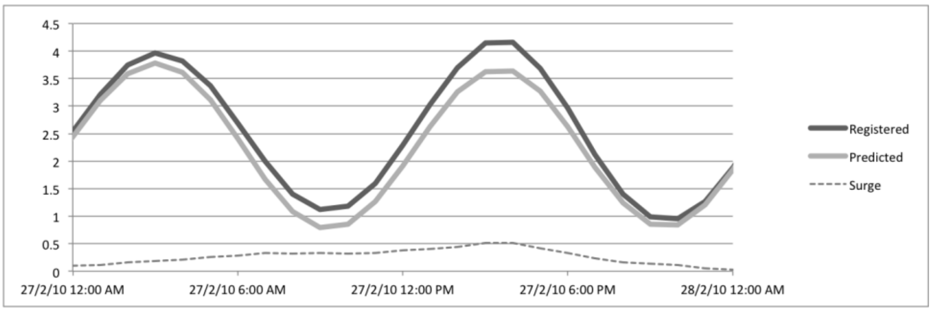

Figure 9. Predicted and registered sea levels on Cascais station during cyclone Xynthia (Feb/10)

Table 6. Correlation values summary table, for each tide gauge and under many calculation options

Variable	Calculation Point	Organization	Database	Grid	Period	Interval	Cascais	Aveiro	Viana C.
Sea level pressure	Point (40N;10W)	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	24h	0.71	0.68	0.67
Sea level pressure	Point (42.5N;10W)	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	24h	0.74	0.75	0.76
Sea level pressure	Point (42.5N;10W)	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	6h	0.68	0.75	0.76
Sea level pressure	Point (42.5N;10W)	NOAA	NCEP/NCAR	2.5ºx2.5º	Stormy Periods	6h	0.56	0.73	0.72
Tide gauge/low pressure center distance	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Stormy Periods	6h	0.22	0.20	0.12
Lowest pressure in the area	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Stormy Periods	6h	0.18	0.31	0.41
Tide gauge/low pressure's gradient	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Stormy Periods	6h	0.18	0.03	0.05
Low pressure distance/intensity factor	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Stormy Periods	6h	0.37	0.49	0.53
Lowest pressure in the area	N/A	ECMWF	ERA-Interim	0.75ºx0.75º	1st Feb till 9th Mar 2010	6h	0.08	-	-
Sea level pressure	Point (38.25N;9.75W)	ECMWF	ERA-Interim	0.75ºx0.75º	1st Feb till 9th Mar 2010	6h	0.83	-	-
Tide gauge/low pressure center distance	N/A	ECMWF	ERA-Interim	0.75ºx0.75º	1st Feb till 9th Mar 2010	6h	0.48	-	-
Local wind speed	Point (38.25N;9.75W)	ECMWF	ERA-Interim	0.75ºx0.75º	1st Feb till 9th Mar 2010	6h	0.41	-	-
Local wind direction	Point (38.25N;9.75W)	ECMWF	ERA-Interim	0.75ºx0.75º	1st Feb till 9th Mar 2010	6h	0.24	-	-
Lowest pressure in the area	N/A	ECMWF	ERA-Interim	0.75ºx0.75º	Xynthia (26th - 28th Feb 2010)	6h	0.31	-	-
Sea level pressure	Point (38.25N;9.75W)	ECMWF	ERA-Interim	0.75ºx0.75º	Xynthia (26th - 28th Feb 2010)	6h	0.97	-	-
Tide gauge/low pressure center distance	N/A	ECMWF	ERA-Interim	0.75ºx0.75º	Xynthia (26th - 28th Feb 2010)	6h	0.75	-	-
Local wind speed	Point (38.25N;9.75W)	ECMWF	ERA-Interim	0.75ºx0.75º	Xynthia (26th - 28th Feb 2010)	6h	0.94	-	-
Total flow (F)	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	6h	0.32	0.47	0.47
Total shear vorticity (Z)	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	6h	0.02	0.04	0.03
Westerly flow (WF)	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	6h	0.15	0.48	0.54
Southerly flow (SF)	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	6h	0.30	0.32	0.39
Maximum correlation geostrophic flow	N/A	NOAA	NCEP/NCAR	2.5ºx2.5º	Maritime winter (Oct-Apr)	6h	0.32	0.53	0.62
Sea level pressure	Closest point	ECMWF	ERA-40 + ERA-Int	Thickest available	Maritime winter (Oct-Apr)	6h	0.66	0.67	0.72
Maximum correlation geostrophic flow	Closest point	ECMWF	ERA-40 + ERA-Int	Thickest available	Maritime winter (Oct-Apr)	6h	0.30	0.50	0.59

5. Annual most severe storms detection

With the knowledge acquired from the previous analysis (and *weather types* information), annual estimates were made to the maximum meteorological data range available – from year 1948 till 2014. These estimates will guide future dynamic modelling analysis, in order to validate the order of magnitude presented and complete the sea elevation data series.

Three types of estimates were produced, concerning the annual most severe storm period, the date and hour where the highest storm surge value was produced and the order of magnitude (to tens of centimeters) of that surge value. As previous mentioned, the factors applied to these estimates were:

- The corresponding WT: especial attention given to C, SW and W types;
- Sea level pressure values lower than 1000hPa;
- Sea level pressure drops up to 8hPa/6h;
- Geostrophic flow peaks, calculated through the maximum correlation direction;
- Local sea-land wind peaks;
- Comparison with the several storms analyzed and the storm surge values produced in them.

For each tide gauge, annual tables were produced, where the estimate values were compared to the registered values, when they were available. Although the referred tables are not reproduced here, an analysis to the 2013/14-winter period is presented. The December-13 to February-14 period was characterized by a continuous storm passage through the Portuguese coast, producing diverse changes in the coast profile and enhancing the dynamic coastal processes. The observed values were compared to the estimated ones and the results are presented in tables 7, 8 and 9, for the 3 stations.

VIANA CASTELO	Order of magnitude (cm)	Date of occurrence
Estimation	80	04/02/14 12:00
Observed	65	09/02/14 18:00
Observed at estimation date	53 (with gaps)	04/02/14 16:00

Table 7. 2013/14 maritime winter estimations vs. observations for Viana do Castelo

AVEIRO	Order of magnitude (cm)	Date of occurrence
Estimation	80	04/02/14 12:00
Observed	80	09/02/14 18:00
Observed at estimation date	50 (with gaps)	04/02/14 21:00

Table 8. 2013/14 maritime winter estimations vs. observations for Aveiro

CASCAIS	Order of magnitude (cm)	Date of occurrence
Estimation	40	09/02/14 12:00
Observed	56	06/01/14 14:00
Observed at estimation date	38	09/02/14 17:00

Table 9. 2013/14 maritime winter estimations vs. observations for Cascais

Apart from the considerable storm surge values registered, the sea elevation series analysis revealed abnormal spring tides amplitude, in which adding an extreme wave periods (more than 20 seconds) caused floods in several coastal towns. Concluding, it could be possible to say that the continuous surge values registered passed the tide's 12h-period, overlapping its effects.

6. Conclusions

The main conclusions obtained from this research were: (i) sea level data series with an average of 11% gaps, mainly in stormy periods; (ii)an average of 5% days in which storm surge values were above 25cm, along the Portuguese coast, during the last 35 years; (iii) the strong relation between the surge phenomenon and the C, SW and W *weather types*, revealing a 23% of days in which there is a considerable risk of having higher sea levels; (iv) the strong probability of occurring storm surge events above 25hPa sea level pressure anomaly; (v) the cause-effect approach from sea level pressure, synoptic flow, local wind and weather type variables to the surge phenomenon. In addition tothe previous points, the study revealed the possibility of developing regular predictions of surge levels.

As part of a larger coastal flooding study program, this work intends to be continued, into a computational modelling step. In the near future, civil protection authorities maydefend coastal populations and prevent severe property losses using these practical conclusions to guide their alerts.

7. References

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