Clim Dyn
DOI 10.1007/s00382-015-2659-1

Long-term changes in the frequency, intensity and duration of extreme storm surge events in southern Europe

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Received: 22 January 2015 / Accepted: 16 May 2015

Abstract Storm surges are one of the major hazards in coastal regions; positive surge events are added to tidal levels, increasing the risk of coastal flooding by extreme water levels. In this study, changes in the frequency (occurrence rate per year), intensity (magnitude of the extremes) and duration of extreme storm surge events from 1948 to 2013 are investigated using a non-stationary statistical model. To fully model extremes, the time-dependent statistical model combines the Generalized Pareto Distribution (GPD) for studying exceedances over the threshold, and the non-homogeneous Poisson (P) process for studying the occurrence rate of these exceedances. Long-term trends and the association between storm surges and the North Atlantic Oscillation (NAO) are represented in the model by allowing the parameters in the GPD–P model to be time-dependent. Different spatial patterns in the three analysed properties of storm surges are found in the Atlantic region and the Mediterranean Sea. The up to now uncharted regional patterns of storm surge duration show completely different values between the Atlantic and the Mediterranean regions, being the duration of storms surges in the Atlantic two times longer than the duration in the Mediterranean. For the last half century, we detect positive and negative spatial trends in terms of intensity of storm surge but only significant decreasing rates, of around 2 %, in the number of extreme events per year. Regarding duration, we find positive trends in certain Mediterranean areas, with durations of extreme events increasing at a rate of 0.5–1.5 h/year. Values for the 50-year return level are also estimated, showing a large spatial variability with relatively higher values along the coast. A clear sensitivity of extreme storm surges to negative NAO index is detected, specifically in the western Mediterranean basin. Results show that negative NAO phases lead to an increase in the number of extreme events and also in their intensity.

Keywords Extreme events · Extreme value model · NAO · Non-stationary · Pareto–Poisson · Storm surge

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1 Introduction

Coastal areas are specially vulnerable to climate variability and changes in sea level. Particularly, extreme sea level events have immediate impacts on the coast (Storch and Woth 2008). During the past century, storm surge events have caused considerable damage to properties and even loss of life. One of the worst natural disasters in Europe was the 1953 North Sea flood (Baxter 2005), which led to promote major studies on the strengthening of coastal defences. Over the Mediterranean Sea, there are also numerous low pressure systems, a few of which may develop a dynamical evolution similar to the one of tropical cyclones (medicanes) (see Cavicchia et al. 2014). Such storms produce severe damage in the highly populated coastal areas surrounding the Mediterranean Sea. Therefore, it is important in the general coastal planning and in flood risk assessment, to try to foresee future storm surge impacts on the coast. These extreme events are generally driven by the combination of high tides and storm surges. While astronomical tide is a deterministic component of the sea level, storm surge depends on the atmospheric pressure and wind; hence, in order to study long-term changes

Published online: 02 June 2015

in coastal risks, it is necessary to analyse this non-deterministic variable from a statistical point of view.

Various statistical techniques have been used to study changes in extreme sea level events. A basic approach is the percentile time series analysis. This technique has provided interesting information about the different behaviour of high water levels with respect to the mean sea level (e.g. Woodworth and Blackman 2004), however, it does not allow the estimation of return water levels. Focusing on extreme value models, two familiar approximations in extreme value theory are the Generalized Extreme Value (GEV) distribution from block maxima, and the Generalized Pareto (GP) distributions from the excesses over a threshold. A set of methods can be used for the selection of extreme sea levels. The classical annual maxima method (AMM) has the disadvantage of gathering a small extreme sample that could disregard extremes in the remaining data. The limitation of AMM can be overcome by methods that select maxima from shorter time blocks than a year such as monthly maxima, the r-largest values within a year, or the independent peaks over a threshold. The use of monthly maxima requires modelling the seasonal dependence for the good estimation of return periods (see Méndez et al. 2007) and the r-larger values requires defining a specific number of extremes per period (Coles et al. 2001). These techniques are, however, constrained to choosing the same number of maxima within time blocks, which can lead to a misinterpretation of climatic changes in an environment with a mean sea level rise and large inter-annual variations. Taking this into consideration, in this work we have decided to define extreme events as the exceedances over a high threshold. Two important issues that must be overcome when using the peak over threshold approach are the selection of the threshold and the minimum time span that will be required to assume the independence of consecutive storm events, since both affect the results in terms of the frequency and the exceedance estimates (see, e.g, Arns et al. 2013). Storm surge extremes have been selected from an already validated surge database (GOS database, see Cid et al. 2014) that provides, for southern Europe, a long (66 year length) and spatially uniform set of data, which is adequate to analyse long-term changes in the storm surge extremes.

The above-mentioned statistical techniques have been applied lately to analyse extreme sea level events. For example, Gräwe et al. (2012) tested different statistical methods to estimate return periods on simulated storm surges. Merrifield et al. (2013) use the AMM to investigate spatial patterns of the relative contributions from tides and non-tidal residual components. The AMM is also the approach chosen by Bernier and Thompson (2006) to calculate return levels in the north–west Atlantic. The r-largest method has been widely used in European regions (e.g. Tsimplis 1997 in the Aegean and Ionian seas, Butler et al. 2007 in the North Sea, and Marcos et al. 2009 in the Mediterranean Sea). Both methods, the AMM and the r-largest were used by Haigh et al. (2014) to estimate extreme water levels around the coastline of Australia. Finally, the peak-over-threshold (POT) approach has been recently applied to determine return water levels, as for instance, in northern Germany (see Arns et al. 2015); and specifically for storm surges, it was used by Tebaldi et al. (2012) along the US coasts, Hallegatte et al. (2011) in Copenhagen-Denmark and Bernardara et al. (2011) along the French Atlantic coasts.

The IPCC (Intergovernmental Panel on Climate Change) concludes that climate change might affect the frequency, intensity, and length of many extreme events, such as floods and storms (Church et al. 2013), which would also lead to a non-stationary behaviour of storm surges. Therefore, we propose a time-dependent extreme model that combines the Generalized Pareto Distribution (GPD) for studying exceedances over a threshold (in terms of intensity and duration), and the Poisson (P) process for studying the occurrence rate of these exceedances. Note that a point-process approach in terms of extreme value models is not commonly used to analyse variations of sea surface variables, and moreover, non-stationarity in extremes tends to be overlooked in the extreme value theory. Some exceptions can be found in the literature. The effect of temporal dependence on the frequency of storm surge in the western Mediterranean basin is explored from a non-homogeneous Poisson model in Luceño et al. (2006). The methodology to analyse climate variations at different time scales from a time-dependent monthly GEV model in extreme sea levels is described in Méndez et al. (2007). The seasonal, mean sea level rise and astronomical modulations in high water levels are explored in Menendez et al. (2009) from a time-dependent GEV as a potential extreme forecast tool. Different time-dependent extreme models are applied in Menéndez and Woodworth (2010) to a global tide-gauge dataset to conclude that the highest water levels have been increasing since the 1950s in most regions of the world mainly due to mean sea level rise, although higher regional extremes are also caused by interannual-decadal variations associated with climate fluctuations. Non-stationary extreme models have also been applied to storm surge water levels; Marcos et al. (2011) analysed the extension of GEV model to r-largest values with several time-dependent terms in order to study changes in storm surges under projections of climate scenarios. Mudersbach and Jensen (2010) used an approach based on the GEV distribution and compared the results with common stationary methods. Serafin and Ruggiero (2014) modelled extreme events of total water levels (waves, tides, and non-tidal residuals) using non-stationary extreme value distribution that includes seasonality and climate variability.

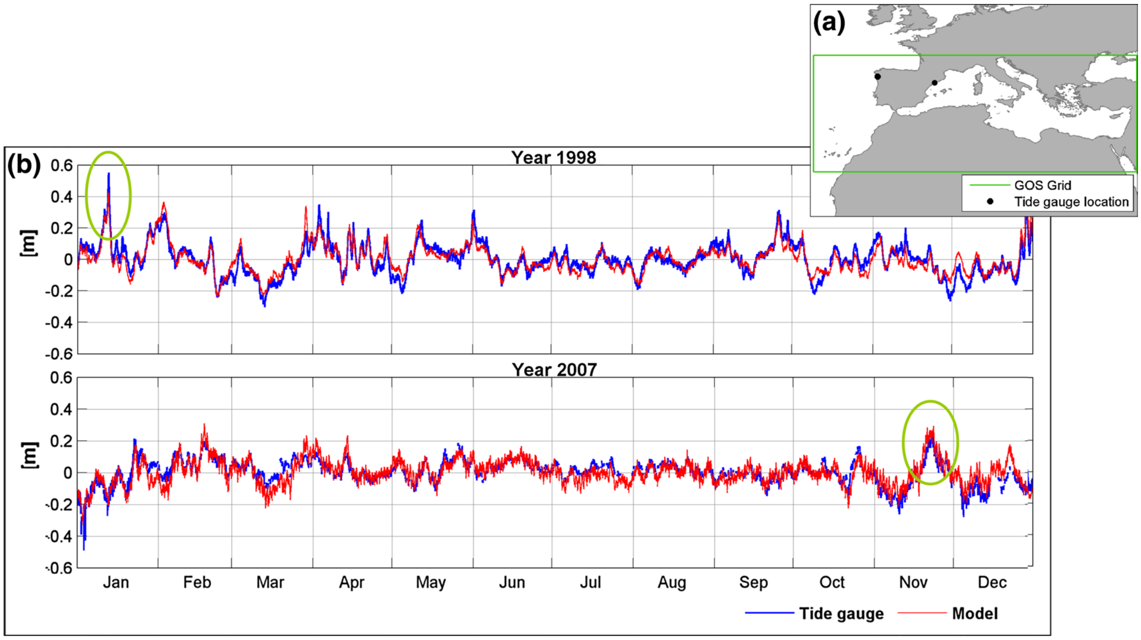

Fig. 1 Panel **a** shows the model domain (*green box*) and the location (*black dot*) where data are compared. **b** Storm surge comparison (m) at Vigo (*top*) and Barcelona (*bottom*) tide gauges for years 1998 and 2007, respectively. Measured data (*blue line*) versus modelled data (*red line*). *Green circles* encompass instants of high surge levels

The main goal of this work is the analysis of changes in extreme storm surges (i.e. changes in extreme sea levels produced by the effect of wind stress and pressure gradients over the sea surface). Following this purpose, a statistical framework to study extreme surges is established. Extreme events have been chosen using a POT technique, which allows us not to limit the number of extremes to a certain amount, but to consider all the events above a threshold. A spatial description of these storm surge extremes in terms of intensity, duration and frequency is given. In a second step, trends were studied by means of a time-dependent GPD–Poisson model, where time variability is included by adding linear trends on the scale parameter of Pareto and on the Poisson parameter. The use of a time-dependent GPD–P model has enabled us to estimate long-term trends, not only in terms of the magnitude of the extremes but also in the frequency. Specifically, significant trends in the intensity, frequency and duration of the extreme storm surge events, as well as the value of the 50-year return level were estimated at every grid-point of the model domain. Sensitivity of frequency and magnitude of extreme surges to monthly NAO index was also studied.

Following this purpose, the next section describes briefly the database used for selecting the extremes (Sect. 2). The methodology applied for defining and fitting the extremes is explained in Sect. 3. Section 4 describes the extremes in terms of intensity, frequency and duration and also gives the results of implementing the statistical model, in terms of trends, sensitivity to NAO and the estimation of 50-year return levels. Finally, a summary and a discussion are provided in Sect. 5.

2 Database description

Extreme events have been selected from a 66-year (1948–2013) high-resolution surge hindcast named GOS 1.1, which describes the sea level variation due to the effect of wind stress and pressure gradients (Cid et al. 2014). Although the database in Cid et al. (2014) ends in 2009, for this work GOS 1.1 has been updated until December 2013. It has been performed for southern Europe using the Regional Ocean Modelling System (ROMS) of Rutgers University. ROMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged NavierStokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation with a split-explicit time stepping algorithm (Haidvogel et al. 2000; Shchepetkin and McWilliams 2005; Haidvogel et al. 2008). It uses a horizontal curvilinear Arakawa C grid and vertical stretched terrain-following coordinates. The model domain (see green box on subplot at Fig. 1) encloses southern Europe, including the Mediterranean Sea and the Atlantic area in southern Europe, with a horizontal resolution of 1/8° (∼14 km). GOS 1.1 was driven with hourly meteorological data of wind and atmospheric pressure from the

SeaWind I hindcast (Menendez et al. 2014). The *SeaWind I* dataset is a high-resolution (30 km) atmospheric dynamical downscaling from NCEP global atmospheric reanalysis focused on offshore surface wind fields. The ROMS model was run in barotropic mode and the inverted barometer effect was imposed at the open boundaries of the domain (north and west edges), using a free surface Chapman condition and 2D Flather condition for momentum. The GOS 1.1 database was exhaustively validated with tide gauges and satellite data, reaching high correlation coefficients and small root mean square errors all over the domain, except for three semi-enclosed areas (northern Adriatic, Gulf of Gabes and Aegean Sea) where the hindcast overestimates satellite measures. An example of the general agreement between measured and modelled data can be seen in Fig. 1 for Vigo and Barcelona tide gauges. The modelled surge data (red line) are well correlated with the tide gauge measures (blue line), where statistics show a root mean square error of 6.5 cm and a correlation factor of 0.88 (see Cid et al. 2014). A good agreement is also observed when referring to extreme values, as can be seen from the data within green circles. Note that GOS 1.1 grid-points have a spatial resolution of about 14 km and therefore they do not exactly represent in-situ values in shallow water depths at the coast (i.e. tide gauge records).

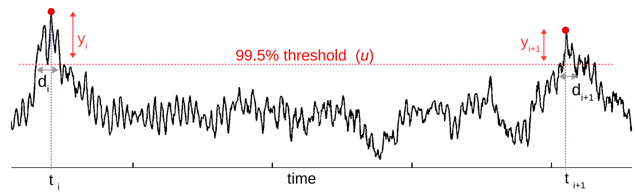

Fig. 2 Peak over threshold technique. *Red dots* are extreme events, values over the 99.5 %. Each of the selected extremes occurs at a specific time t_i, has a specific duration of d_i and exceeds the threshold by an amount of y_i

3 Extreme value model

3.1 Selection of the extreme events

Surge time series are extracted from the hourly database at every grid cell of the domain. Following the Peak Over Threshold (POT) technique, all data over the threshold of 99.5 %, derived from the entire period, are considered exceedances. The threshold selection is made taking into account that the number of events above the threshold is sufficient not to violate the basis of the model (i.e. an average of around two events per year, following the experience of previous works, e.g. Menéndez et al. 2008)

Figure 2 represents the applied method to characterise storm surge extremes. Red dots indicate the peaks of two events (excesses y_i and y_{i+1}) that happen at time t_i and t_{i+1} ; the duration of each extreme event is given by d_i and d_{i+1} , respectively. The statistical model used to estimate trends requires the extremes to be independent. Thereby, the independence between consecutive events is achieved by imposing that extremes must be separated by at least 3 days in between. This value has been chosen taking into account that the average lifetime of the cyclones in the Mediterranean is 28 h and the typical values for the North Atlantic are 3 days (Trigo et al. 1999). Therefore, the value of 3 days is selected to ensure independence between storms in the region. The maxima sample data is then introduced in the extreme model. Results of the extreme statistical analysis in terms of number of events per year and duration will be shown in Sect. 4.

3.2 The time-dependent GPD–Poisson model

As already mentioned, the statistical model chosen to estimate long-term trends in the frequency (extremes occurrence rate), intensity (sea level reached above the threshold) and duration (number of hours where the level is above the threshold) of storm surge events is a time-dependent version of the Peak Over Threshold model (Méndez et al. 2006). This model combines the Generalized Pareto Distribution (GPD) (see Eq. 1) for studying exceedances over a threshold, and the Poisson Distribution (P) (see Eq. 2) for studying the occurrence rate of exceedances.

$$G(x;\sigma,\xi) = 1 - \left(1 + \xi\frac{x}{\sigma}\right)^{-1/\xi} \tag{1}$$

$$P(n;\lambda) = e^{-\lambda}\frac{\lambda^n}{n!} \tag{2}$$

The basic idea is to choose a high threshold (u) and to study the statistical properties of all the exceedances over u; specifically, the number of events (n) every year, the amounts by which the threshold is exceeded (threshold excesses, i.e. y_i) and the duration over that threshold (d_i).

The number of events (n) over the level u in any given year follows a Poisson distribution with annual mean λ . The intensity and duration of the extremes will be the variables analysed by the GPD distribution. The combination of Poisson model for frequency and the GPD model for intensity (or duration) can be expressed as shown in Eq. 3.

$$H(x,n;\sigma,\xi,\lambda) = \exp\left\{-\lambda\left(1 + \xi\frac{x}{\sigma}\right)^{-1/\xi}\right\} \tag{3}$$

where $\lambda > 0$ is the Poisson parameter (mean number of events over a period of time), and $\sigma > 0$ and ξ $(-\infty < \xi < \infty)$ are the scale and shape Pareto parameters,

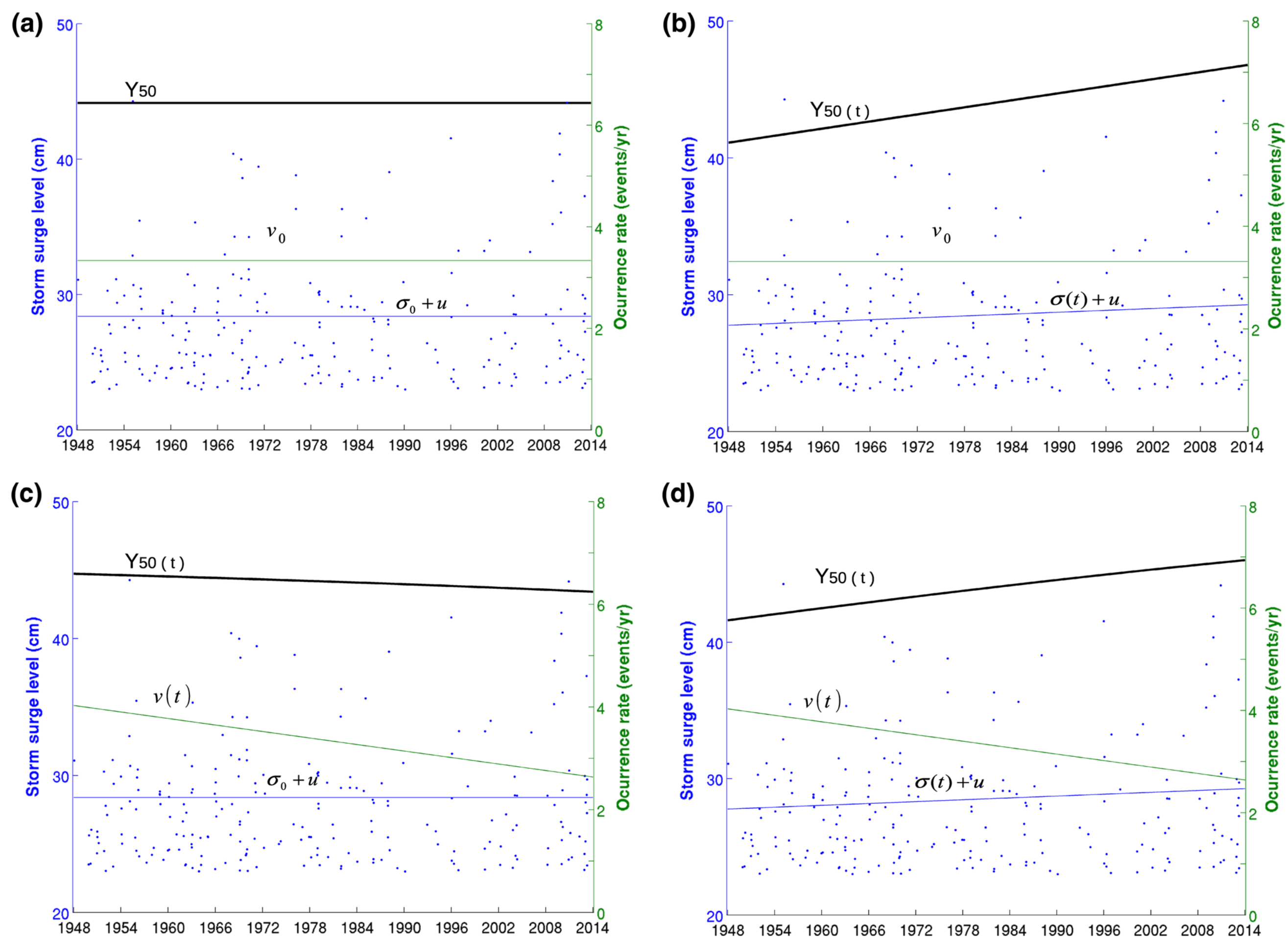

Fig. 3 Effect of the time-dependent parameters. *Blue dots* extreme events; *blue line* scale Pareto parameter; *green line* Poisson parameter; *black line* 50-year return level. **a** Stationary case. **b** Time-dependent scale Pareto parameter. **c** Time-dependent Poisson parameter. **d** Both Pareto and Poisson parameters are time-dependent

respectively. x corresponds to the threshold excess (or the duration) of the selected extreme events.

For this purpose, the GPD–P model is run twice; in one case the variable of the GPD distribution (x) is the sample of the independent peaks (i.e. y_i) and in a second run the GPD variable is the sample of durations of the independent events (i.e. d_i). In both cases the Poisson variable is the occurrence of the extreme events (i.e. t_i).

The main idea of the approach in this work is to consider that the exceedance probability of a certain extreme event varies through time. Consequently, variability is represented in the model by allowing the parameters in the GPD–P to be time-dependent, using linear parametric expressions for the scale Pareto parameter (Eq. 4) and the Poisson parameter (Eq. 5).

$$\sigma(t) = \sigma_0 + \sigma_1(t - t_0) \tag{4}$$

$$\lambda(t) = \int_{t_0}^{t_f} \nu(t)\, dt\,; \qquad \nu(t) = \nu_0 + \nu_1(t - t_0) \tag{5}$$

where $\nu(t)$ represents the rate of occurrence of independent events over the threshold every year. $\sigma(t)$ accounts for the mean value and the variance of the exceedances.

The added value of this extreme model in the estimation of trends on return values is shown in Fig. 3. In this figure, blue dots represent the excesses of the selected extreme events for a grid cell located at the south-west of Cyprus (31.5° in longitude and 34.23° in latitude), blue line corresponds to scale Pareto parameter, green line is the Poisson parameter and black line is 50-year return level estimated as shown in Eq. 6.

$$Y_{50}(t) = u - \frac{\sigma(t)}{\xi}\left[1 - (\nu(t)\ T)^{\xi}\right] \tag{6}$$

where $\sigma(t)$, ξ and $\nu(t)$ are the GPD–P parameters; T is, in this case, 50 years and $Y_{50}(t)$ is the time-dependent 50-year return level.

A visual inspection of the maxima sample (blue dots) on Fig. 3 shows a slight increase in magnitude and a clear decrease in the frequency of the events throughout the analysed period (1948–2013). Figure 3a shows the stationary approach, where the GPD–P parameters are constant ($u = 23$ cm; $\hat{\sigma_t} = \hat{\sigma_0} = 5.4$ cm; $\hat{\nu_0} = 3.3$ events/year). The estimated flat 50-year return level is 44.15 cm. The increase in the magnitude of the peaks is depicted in Fig. 3b, where a trend of 0.86 mm/year in $\hat{\sigma_t}$ indicates that 42.5 cm is a storm event of the 50-year period during the sixties whilst 46 cm is the 50-year return level from the 2000s. Panel c shows the results if we only take into account time dependence in the occurrence rate of extreme events. A decrease in the occurrence rate of events per year is detected, with about 4 events/year until the seventies to within three events/year nowadays. This decrease in the frequency of extreme events also affects the 50-year return level, which results in 44.5 cm during the sixties and a slightly lower value (43.5 cm) at the end of the 2000s. Figure 3d highlights the time dependent analysis taking into account significant trends in both, Pareto and Poisson parameters. The combination of an increase in the magnitude of extreme events and a decrease in the occurrence rate leads to a rise of the 50-year return value through time. Therefore, Fig. 3 evidences the importance of using a point-process approach since resulting trends may have opposite signs depending on the feature (magnitude/frequency) allowed to be time-dependent.

In order to investigate if the estimated trends are partly due to interannual-decadal fluctuations, the statistical relationship between climate indices and storm surge extremes is studied. A linear term is added to the scale parameter of Pareto (Eq. 7) and the Poisson parameter (Eq. 8) to estimate the sensitivity of the storm surge exceedances to climate patterns. The North Atlantic Oscillation index (monthly NAO index, available from the Climate Research Unit http://www.cru.uea.ac.uk/cru/data/nao) was chosen to be used as a covariate in the model since its phase and strength has been widely linked to storm surges in Europe. Positive NAO phases lead to an increase in the storms magnitude and frequency towards north–east Europe, while negative NAO phases lead to a shift and weakening of the storms towards southern Europe. This causes a negative correlation between the sea level and the NAO index along the Mediterranean and eastern North Atlantic (e.g. Calafat et al. 2012; Woolf et al. 2003). Most of the English Channel is weakly and negative correlated to NAO, but from the Straits of Dover up to the North Sea, strong and positive correlations are found (e.g. Haigh et al. 2010; Woodworth et al. 2007).

$$\sigma(t) = \sigma_0 + \sigma_2 \mathrm{Cov}(t); \tag{7}$$

$$\lambda(t) = \int_{t_0}^{t_f} \nu(t)\, dt\,; \qquad \nu(t) = \nu_0 + \nu_2 \mathrm{Cov}(t); \tag{8}$$

where $\mathrm{Cov}(t)$ is the covariate defined by the monthly NAO index.

3.3 Statistical inference

The maximum likelihood estimation (MLE) method is chosen to estimate the GPD–P model parameters. If the N exceedances x_1, x_2, ..., x_N are observed at days t_1, t_2, ... t_N over a T-year period, the log-likelihood function for the time-dependent GPD–Poisson model is expressed as shown in Eq. 9.

$$l_{x,t}(\theta) = \sum_{i=1}^{N} \left\{ \log\, \nu(t_i) - \lambda(t_i) - \log \sigma(t_i) - \left(1 + \frac{1}{\xi}\right) \log\left(1 + \xi \frac{x_i}{\sigma(t_i)}\right) \right\} \tag{9}$$

where x_i is the threshold excess (or the duration over the threshold) on day t_i and θ is a vector of regression parameters.

Statistical significance of the time-dependent terms compared with the stationary case, is estimated according to likelihood ratio test which relates the deviance function (see Eq. 10) to the Chi squared distribution (see Coles et al. 2001).

$$Ds = 2\left\{ l(\theta^a) - l(\theta^b) \right\} \tag{10}$$

where $l(\theta^a)$ and $l(\theta^b)$ are two log-likelihood functions that differ only in the number of regression parameters contained in θ.

Grid points where the analysed trends or the NAO covariate are not significant above the 90 % confidence level, will show a white dot in the maps of obtained results.

4 Results

4.1 Descriptive statistics of the storm surges

The spatial characteristics of the storm surge in southern Europe can be described from the aforementioned variables of the extreme model, i.e. the value of the 99.5 % threshold, the mean number of events per year and the duration of each selected event over and above the threshold. Figure 4 shows these estimated variables from the latter half of the twentieth century to the present and for each grid point of the GOS dataset. Figure 4a shows the threshold value above which we have considered surge events as extremes. As can be seen, there is a latitudinal gradient; values of the 99.5 percentile are higher than 30 cm at latitudes above 40∘ N and decrease gradually to the south, reaching values of around 10 cm nearby the Canary Islands. It is also noticeable how surge values are greater throughout the continental shelf due to the wind set-up. This is clearly visible at the

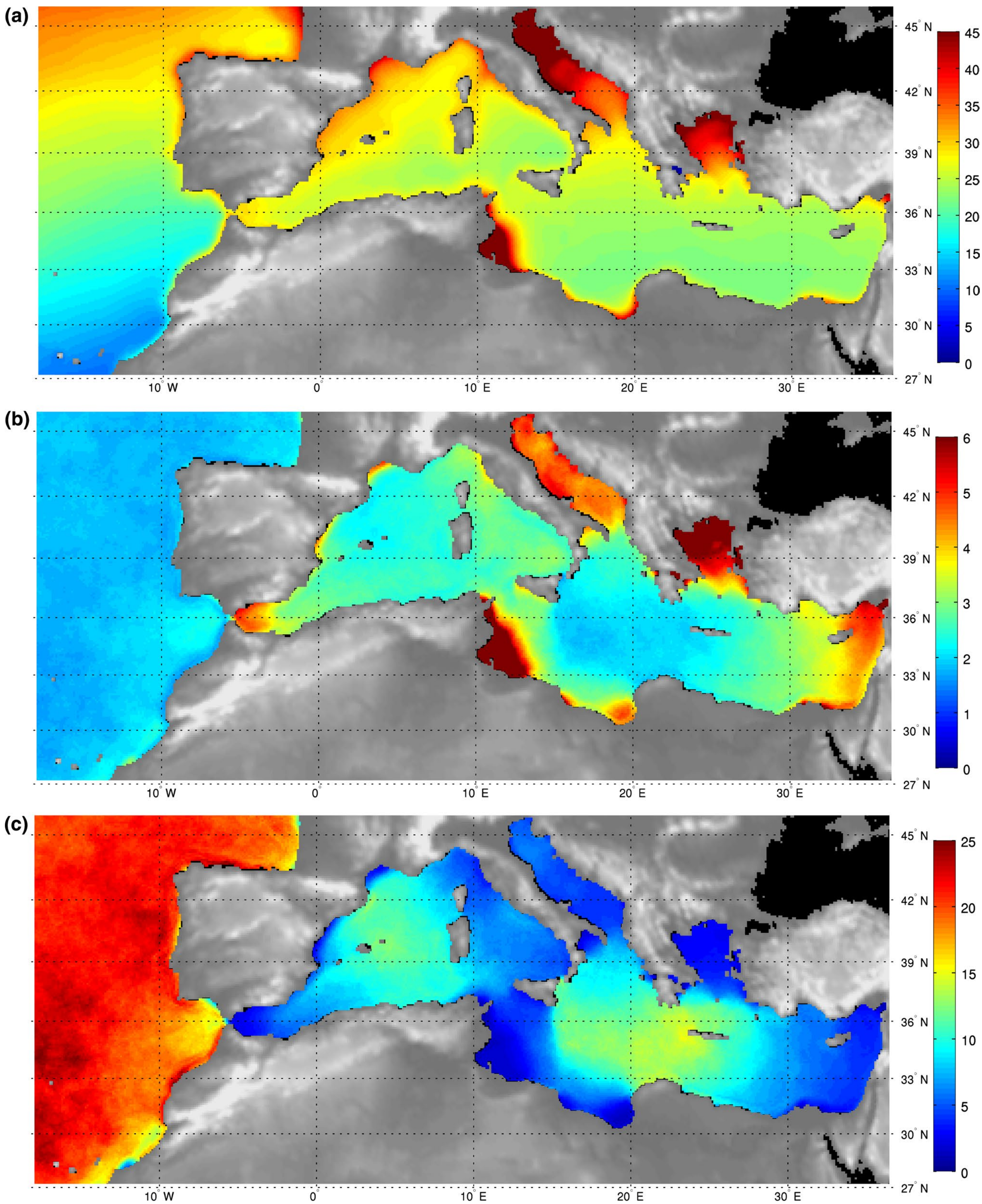

Fig. 4 Descriptive statistics of storm surge extremes. **a** Value of the 99.5 % threshold (cm). **b** Mean number of events per year (extremes/year). **c** Mean of the duration over the threshold (hours)

French coast, where its wide shelf originates surge levels of above 35 cm. At the Mediterranean sea, the 99.5 percentile is larger at the west basin, and the largest values are located at five semi-enclosed areas (Gulf of Lion, Gulf of Gabes, Adriatic Sea, Gulf of Sirte and Aegean Sea). Figure 4b depicts the mean number of extreme events per year; as can be seen, storm surge events over the 99.5 percentile are usual in semi-enclosed geographical areas every year. More than five events per year over the threshold are found in the five mentioned Mediterranean semi-enclosed areas plus the western and easternmost Mediterranean areas (i.e. the Alboran Sea and the eastern Levantine Mediterranean basin). The Atlantic part of the domain experiences less extreme events every year, with values of around two events/year. Figure 4c represents the mean duration of the extreme events. There are clearly two different patterns regarding this variable: the Atlantic and the Mediterranean. Storm surges at the Atlantic part of the domain have a duration of around 1 day while the duration at the Mediterranean is much smaller, with maximum values of 15 h in the deepest region of the Mediterranean basin. The occurrence rate and duration maps of storm surges have an inverse spatial relationship. This behaviour suggests that the relative small spatial and temporal scale of the meso-scale atmospheric circulation eddies, added to the semi-enclosed character of some coastlines, limit the duration of storm surge events and make them more frequent.

Summing up, (i) northern regions show larger magnitudes of high storm surges; (ii) coasts exposed to the Atlantic Ocean received extreme events of large duration; (iii) the semi-enclosed areas in the Mediterranean region receive the largest and most frequent storm surge events.

4.2 Long-term trends in frequency, intensity and duration of extreme storm surges

Once the GPD–P model is applied, we are able to estimate long-term trends. Figure 5 depicts the estimated trends in frequency, intensity and duration. White dots represent areas where trends have a confidence level below the 90 %.

Trends in magnitude (see Fig. 5a, mm/year) are shown through the linear trend estimated in the time-dependent 50-year return level. Except for the northern Adriatic, north–west Atlantic, and Gabes and Sirte gulfs, a general increase is estimated in most of the analysed domain. These increases are, however, significant only in the Mediterranean Levantine basin, south Greek coast and north–west Genoa gulf, with trends of around 1 mm/year, and the Alboran Sea and south coast of Sicily, with increases of about 0.5 mm/year. Negative trends of 2 mm/year are estimated at the Gulf of Gabes and Sirte and the north Adriatic. Special caution, however, related to these negative trends must be taken in the north Adriatic and Gulf of Gabes because some uncertainties in the GOS dataset were found during the validation process (Cid et al. 2014).

Trends in frequency are directly given by the non-homogeneous Poisson parameter (Fig. 5b). In this work, it is expressed as a percentage of change in the number of extreme events per year. Apart from a positive trend in the occurrence rate of events assessed in the south of Greece (increase of 1.5 %), only statistically significant decreases are obtained, mainly in semi-enclosed areas at the southern Mediterranean Sea. The largest decreases are found in the middle-south Mediterranean (i.e. Gulf of Sirte and Gulf of Gabes), at diminution rates in the number of events per year of around 2 %. Negative trends of about 1 % are found in the Alboran Sea, south of Sicily and Levantine Mediterranean basin, and slight decreases are detected in the north Adriatic and Aegean Sea.

Trends in the duration of extreme events are showed in Fig. 5c. Results indicate a general decrease in the Atlantic and a general increase in the Mediterranean. The significance of these trends is mainly relevant in the eastern Mediterranean basin. In particular, positive rates of 1.5 h/year are located at the south of Italy and Greek coasts. Less pronounced trends are found along the Italian Mediterranean coast, with increasing values in the duration of storm surges of rates of 0.5 h/year. Similar values are reached at Levantine basin, Alboran Sea and along the coasts of Turkey and Egypt.

Overall, some relevant contributions from the analysis of trends for the last half century are: (i) except for some specific regions, most of the Atlantic and Mediterranean southern Europe does not show significant increases or decreases in extreme storm surges. It may indicate that climate variations at lower time scales (seasonal, interannual) are the main drivers of changes in extreme storm surges. (ii) Only south Greek coasts show an increase of all analysed properties of extreme storm surge. It can be related to the clear significant increases of the magnitude and duration of extreme events in the easternmost Mediterranean basin and may indicate an intensification or changes in circulation patterns of cyclone activity in this region. (iii) The estimated trends for the last half century reveal a slight but clear decrease in magnitude, occurrence, and duration of extreme storm surge events in the north Adriatic. A detailed analysis should be taken for estimations of changes in Venice lagoon and surroundings due to the complex bathymetry and coastline of this area.

4.3 Relationship between NAO and extreme storm surges

Most of the Atlantic and Mediterranean southern European regions do not show significant long-term trends in extreme storm surges. One explanation for this behaviour could

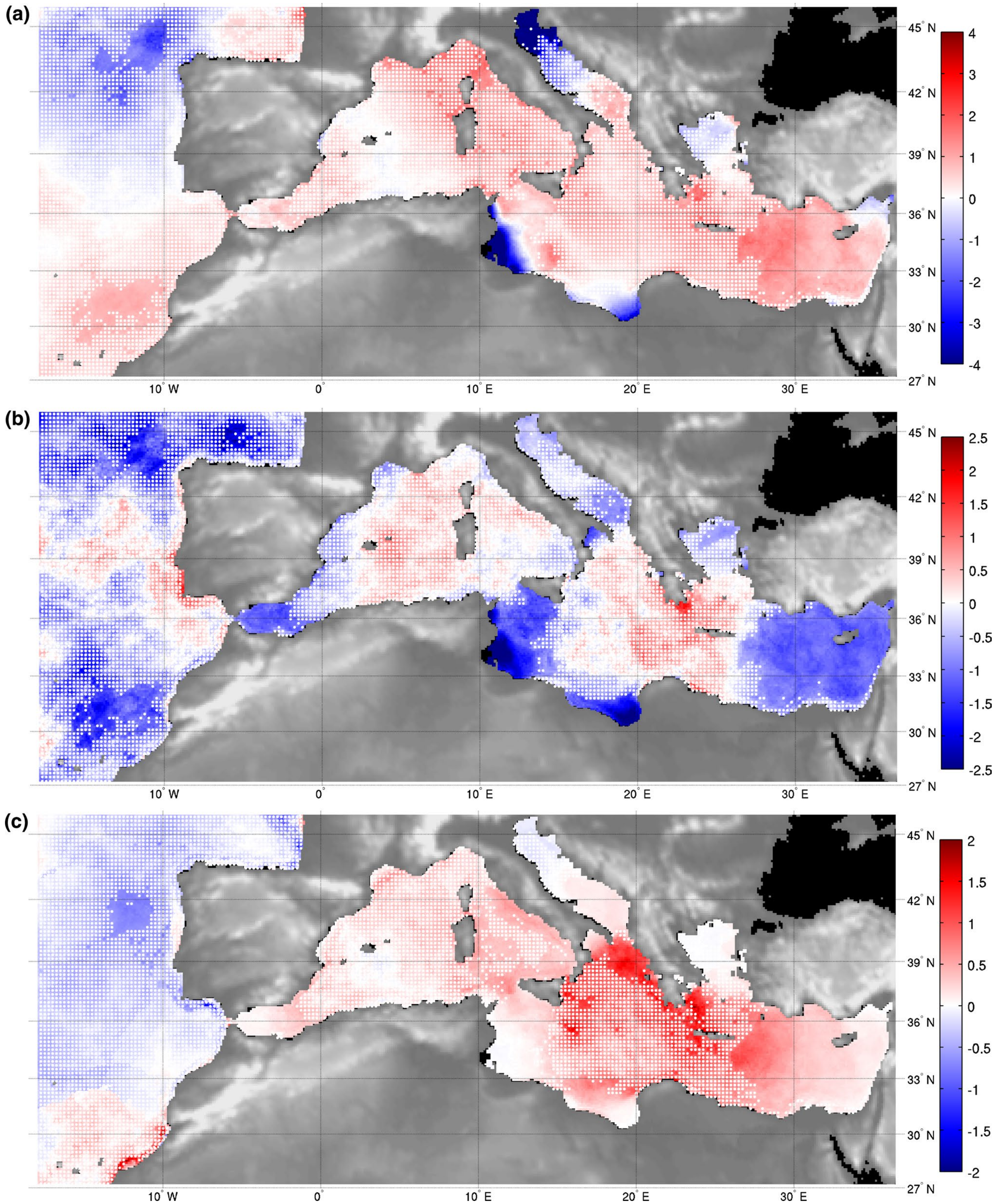

Fig. 5 Spatial distribution of the long-term trends. *White dots* represent areas where the statistical significance of the trends is lower than 90 %. **a** Trends in intensity (mm/year), obtained from the linear fitting of the yearly 50-year return level. **b** Trends in frequency (%), obtained from the time-dependent Poisson parameter and expressed as percentage by using the mean number of events per year. **c** Trends in duration (hours/year), obtained from the second run of the GPD–P model, using the duration of the extremes as the GPD variable

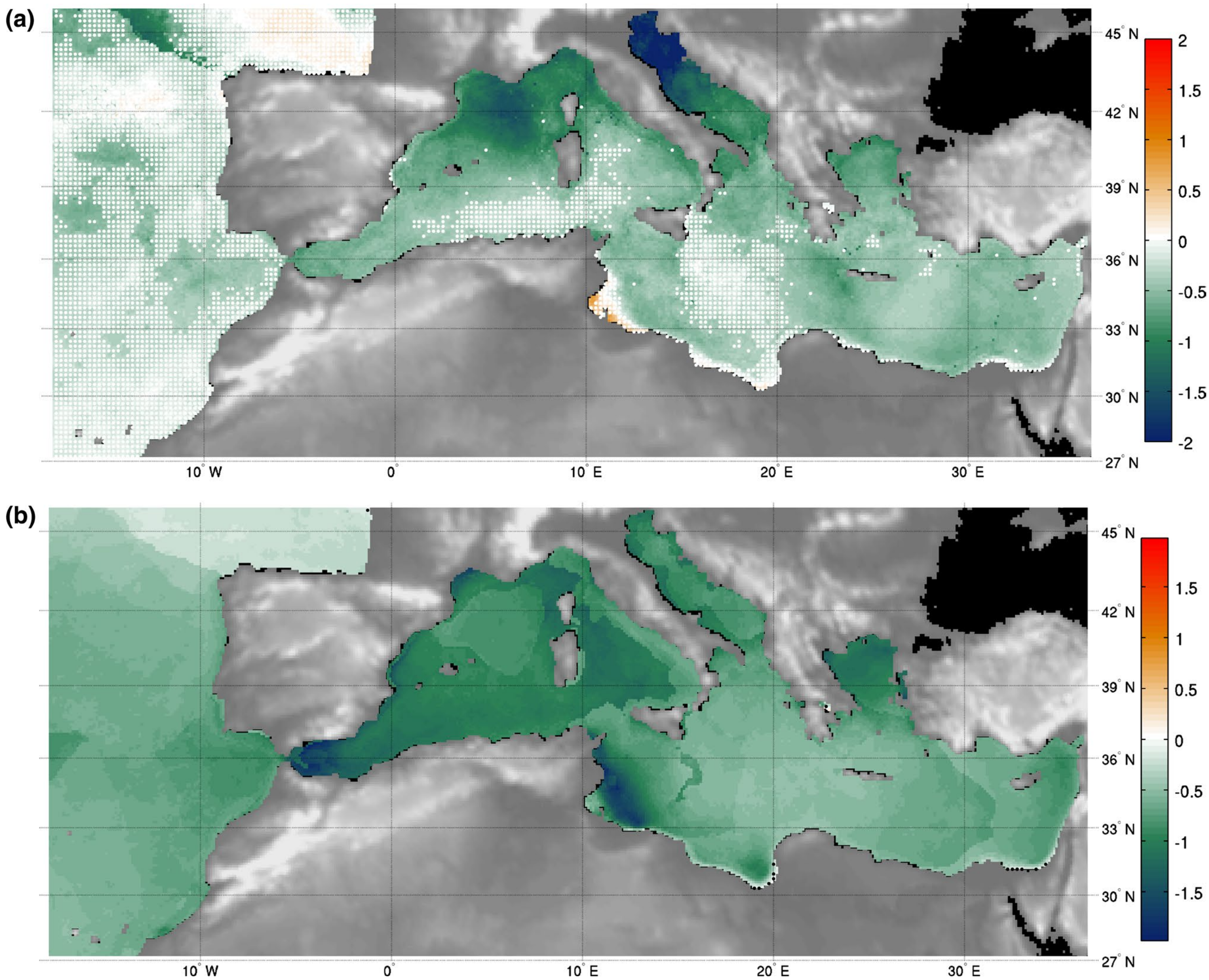

Fig. 6 **a** Sensitivity of the extremes intensity to NAO (cm/unit index). **b** Sensitivity of the extremes frequency to NAO (events per year/unit index). *White dots* represent areas where the sensitivity is lower than 90 %

be that extreme storm surges have been more affected by inter-annual and decadal variability than by climate variations at longer time scales. This was also described by Wahl and Chambers (2015) for the United States coastline, where they identify regions with considerable multidecadal extreme sea level variations unrelated to changes in mean sea level.

Since storm surges are directly forced by changes in the zonal circulation of the atmosphere and meridional wind components, the relationship between the main coupled ocean-atmosphere mode of variability in the area, the North Atlantic Oscillation (NAO), and extreme storm surges is investigated.

Here, we use the monthly NAO to analyse the relationship between this climate index and extreme surges. Note that we focused on NAO conditions whenever the selected extreme surge events happened and not only during the winter season. A mainly negative relationship is found both in terms of intensity and frequency, which means that extreme storm surges are more intense and more frequent when NAO phase is negative. This is an expected result since negative NAO phases are characterised by a shift of storms tracks towards lower latitudes, and by the low pressure system over the Azores area being higher than during positive NAO phases, which leads to an increase in the sea level related to the inverse barometer effect. The opposite occurs from the northernmost English Channel to northern European Seas, where positive NAO phases lead to higher sea levels due to more intense storm surge events (Wakelin et al. 2003; Woodworth et al. 2007; Yan et al. 2004).

Although sensitivity to NAO is generally negative, there is a relevant difference of NAO influence patterns in magnitude and frequency of surge extremes. As can be seen from Fig. 6, where white dots represent areas with less

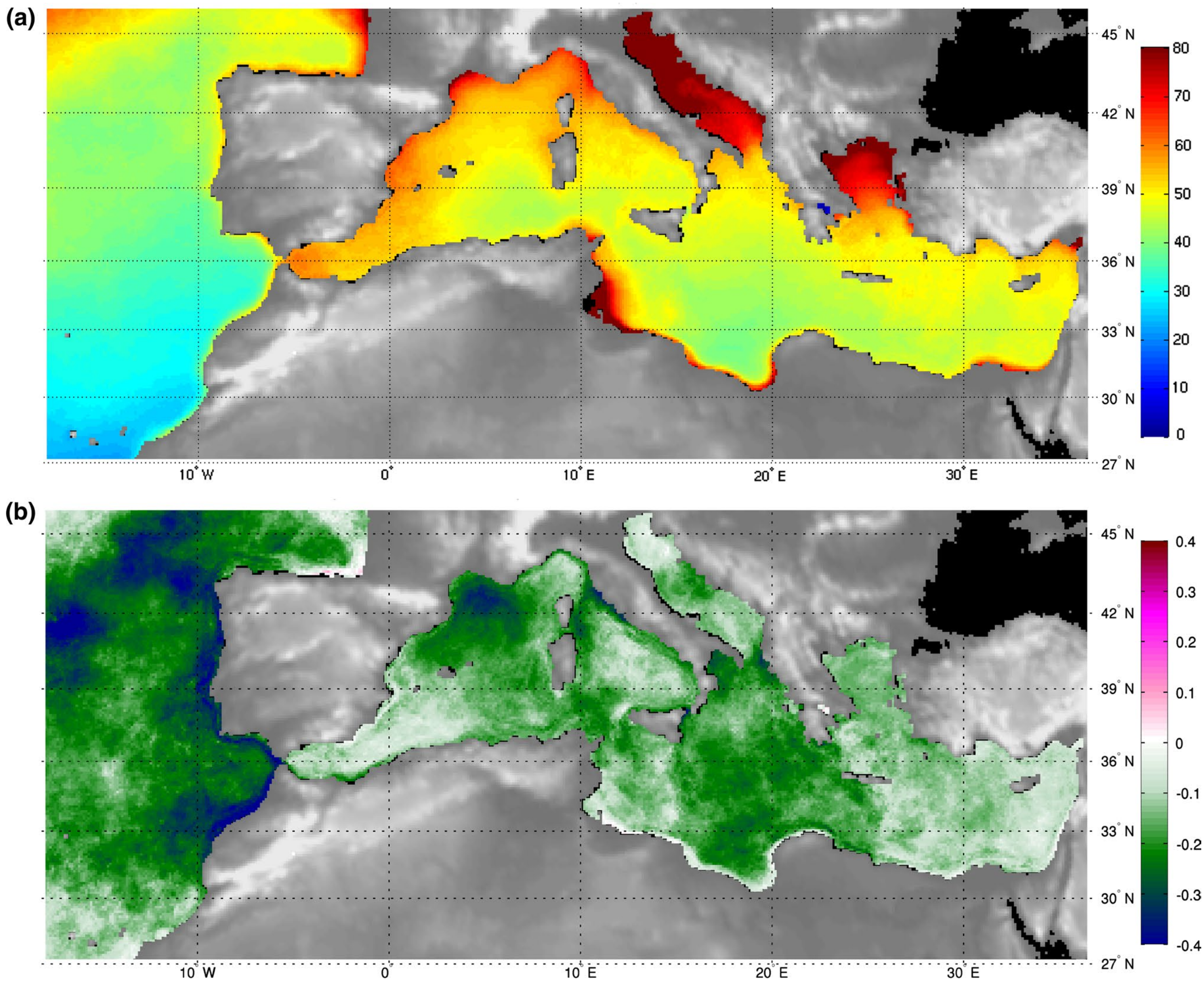

Fig. 7 **a** Current 50-year return level (cm). **b** Shape pareto parameter (non-dimensional)

than 90 % of statistical significance, most southern Europe shows a significant influence of negative NAO phase in the occurrence of extreme events (see Fig. 6b) while sensitivity of extremes magnitude is below 90 % in most of the Atlantic basin and some areas of the Mediterranean Sea (see Fig. 6a). The difference in the statistical significance of NAO influence in the properties of the extreme events may be explained in terms of the local-regional scale; the magnitude of the extremes is more affected by the orography or the complex coastline than the occurrence of the event. The highest teleconnections to NAO are found in the western Mediterranean basin. Gulfs of Lion and Genoa and northern Adriatic are the areas where the magnitude of extreme surges is more affected by the NAO index; Alboran Sea and Gulf of Gabes are the areas where the frequency of extremes is more affected by NAO index. These results can be explained by the fact that the occurrence of cyclones in the western Mediterranean basin is partly due to incoming low pressure systems from the Atlantic through the Gulf of Biscay and Iberian peninsula (Trigo et al. 1999) and because the cyclones often remain on the belt-shaped coastal area from the Alboran Sea through the Gulf of Lion and the Gulf of Genoa to the Adriatic Sea (Bartholy et al. 2009).

Figure 6 has, therefore, proven that extreme events in southern Europe (their magnitude and their occurrence rate) are significantly affected by NAO, with its negative phase being one of the main drivers of the extreme storm surge events, especially in the western Mediterranean basin.

4.4 50-year return level

Extreme value models enable the estimation of very unusual extreme events from a relatively short data period.

This is often referred as return values and return periods, estimations required to design defence structures and to quantify risk.

Figure 7 displays the estimated results for the present 50-year return storm surge level, together with the estimated shape parameter of the extreme value distribution for the study region. The shape parameter determines the upper tail of the distribution and consequently describes the behaviour of the most unusual extreme events. In general, negative values are found, indicating a bounded upper tail. This can be a consequence of one of two reasons: either regularly-occurring intense extreme events (e.g. the north–west Iberian Peninsula and the Gulf of Lion), or the scarce occurrence of extreme values (e.g. north Atlantic African shelf and Ionian Sea). There are also regions where the shape parameter is close or equal to zero (e.g. northern Adriatic and eastern Biscay Gulf), indicating an exponential behaviour of the upper tail and, therefore, higher magnitudes for the most unusual extreme events.

Values for the current 50-year return level were calculated, as shown in Eq. 6, using the non-stationary Pareto–Poisson model. According to the 99.5 % threshold spatial pattern represented in Fig. 4a, the largest 50-year return values are found at the northern Adriatic, Aegean Sea, Gulfs of Gabes and Sirte, the Gulf of Lion and along the Egyptian coast, reaching more than 75 cm. A similar north–south spatial gradient is detected, although it is less pronounced. In contrast, the 50-year return level provides less intense values at the north–west coast of the Iberian Peninsula and larger magnitudes at Alboran Sea and the easternmost Mediterranean basin.

5 Summary and discussion

In this study, a storm surge hindcast (GOS database) spanning from 1948 to 2013 and a time-dependent Pareto–Poisson model are used to characterise and analyse climate variations in intensity, frequency and duration of extreme storm surge events. Non-stationarity is included into the extreme model by allowing time-dependent parameters through covariate NAO and linear trends.

The climatological analysis of not only the magnitude of the maximum extreme values, but also their duration and frequency of occurrence throughout the time, has allowed a better characterisation of the extreme storm surges. A general north to south gradient is found over the entire domain with respect to the selected 99.5 % threshold value (approximately from 30 to 10 cm at the Atlantic and from 30 to 20 at the Mediterranean). This spatial pattern is obviously correlated to the wind speed over this area, as can be checked from Menendez et al. (2014). Higher storm surge values are located in coastal areas due to water piling induced by onshore winds (values of around 35 cm). The mean number of events per year is mainly lower at the Atlantic part of the domain than at the Mediterranean coasts (2 vs. 4–5 events/year). Regarding the duration of the extremes over the threshold, there are clearly two different areas; higher values at the Atlantic with mean durations of 24 h, and lower values at the Mediterranean Sea with maximum durations of 15 h. This is because, as pointed out by Trigo et al. (1999), Mediterranean lows are, in general, less intense and are associated with smaller spatial scales and with shorter life cycles than Atlantic synoptic systems. Therefore, durations of storm surges are also smaller in the Mediterranean than in the Atlantic. An inverse relationship between the duration and the number of extreme events has been found. This is, extremes last longer offshore, while close to the coast, and specially along semi-enclosed Mediterranean coasts, extreme events are shorter but present a higher occurrence rate every year.

Regarding trends, results show negative patterns throughout the domain when studying the frequency of storm surge events (mean values between 1 and 1.5 %), except for the south coast of Greece where the number of events per year tends to increase at rates of 1.5 %. There are more areas with positive trends in frequency but they do not reach the 90 % of significance. Regarding intensity, both positive and negative trends are found; intensity of storm surges has increased mainly at the easternmost Mediterranean basin (1 mm/year) while decreasing rates at the coast are mostly reduced to semi-enclosed areas such as the Gulf of Sirte (2 mm/year), Gulf of Gabes and northern Adriatic. With respect to duration, two different trend patterns are present: positive in the Mediterranean and negative in the Atlantic, although at coastal areas significant trends are only positive within a range of 0.5–1.5 h/year. In summary, most of the southern European region does not show significant trends in extreme storm surges; an exception to this are regions as the Alboran Sea, gulfs of Gabes and Sirte, northern Adriatic and the easternmost Mediterranean. The spatial patterns of the trends in duration indicates an increase in the Mediterranean and a decrease in the Atlantic but the mean duration of the extremes is higher in the Atlantic than in the Mediterranean. It is worth noting that decreasing trends found in the northern Adriatic for the three analysed variables are in agreement with results from local studies as for example Trieste, where Raicich (2003) found that during the period 1939–2001, strong surges became less frequent. The period of study is a key factor when studying trends; in areas where the inter-annual or decadal variability is of great importance, the sign of trends may even change depending on the temporal coverage of study. For instance, trends in magnitude around the Alboran Sea switch from negative (not shown) to positive (Fig. 5a) when the study period is 1948–2009 or 1948–2013, respectively. Therefore, the analysis of linear trends is a simplistic approximation and it is totally dependent on the analysed time period. The Alboran sea is an example of an area with a strong interannual-decadal variability.

To test if this interannual-decadal variability of storm surges is related to the North Atlantic Oscillation, we have studied the response of sea level to the NAO index. This relationship has been analysed previously at different time scales, most of them focused on north–west Europe (e.g. Haigh et al. 2010; Woodworth et al. 2007). Studies analysing a bigger domain (e.g. Woolf et al. 2003), found that sea level is generally higher around north–west Europe in NAO positive winters, while it is generally lower around the Azores and southern Europe. We have found an inverse (negative) connection between NAO and extremes, both in terms of intensity and frequency, consistent with the strong and negative correlation found by Calafat et al. (2012) between tide gauge records and NAO when studying sea level decadal variability. For southern Europe and specifically for the atmospheric contribution to sea level, Gomis et al. (2008) found a negative correlation between NAO and surge monthly means. Marcos et al. (2009) also obtained negative correlations between winter NAO and storm surge values for the same domain. The significant connection found in this work between NAO and extremes proves that NAO contributes to changes in the extreme storm surges. Therefore, the latest tendency of the NAO index to positive phases since the 80's, could lead to negative trends in the magnitude and the occurrence rate of extremes, as we have found here. Hence, in this study we provide details of the relationship of the North Atlantic Oscillation with the extreme storm surges at an homogeneous spatial domain and for both, magnitude and occurrence of extreme events.

Other indexes as the Mediterranean Oscillation Index (MOI), Western Mediterranean Oscillation (WEMO), East Atlantic pattern (EA), East Atlantic/Western Russian (EA/WR), Atlantic multidecadal oscillation (AMO), could also have an influence in the Atlantic and the Mediterranean basin. Thus, a further study including these climatic indexes should be carried out.

The study of the 50-year return level has shown a general north to south gradient at both the Atlantic and Mediterranean basins. Some exceptions to this are found along coastal areas in the Mediterranean African coast, reaching values up to 70 cm for instance at the Gulf of Lion or Libyan and Egyptian coasts. A similar spatial pattern for the 50-year return level was obtained by Marcos et al. (2009) where they also found higher values along the Tunisian and Egyptian coasts.

Finally, in this study, we have presented a statistical framework (GPD–P time-dependent model) to study extreme storm surge events, and we have used it to estimate long-term trends; showing that not only the intensity of the extremes affect the value of the 50-year return level but also does the frequency with which the extremes occur. We have also used the North Atlantic Oscillation index as a covariate in the statistical model, addressing the influence of the North Atlantic Oscillation index into the long-term trends. The results found in this work can be of great help in the estimation of the total water level (tide + surge + wave set up) in coastal areas: extremes of storm surges together with wave height extremes, can be a valuable information in the assessment of the flooding risk.

Acknowledgments The authors thank Puertos del Estado (Spanish Ministry of Public Works) for providing the tide gauge records. This work has been partially funded by the Spanish Ministry of Economy and Competitiveness under the research project PLVMA (TRA2011-28900) and the FP7 European project CoCoNet (287844). We also thank the reviewer Dr. Ivan Haigh and an anonymous referee for their valuable comments and suggestions to improve the quality of this paper.

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