Title: Return periods of extreme sea levels: from magnitude to frequency, duration and seasonality. Implications in a regulated coastal lagoon.

Authors: Damiano Baldan[1], Elisa Coraci[1], Franco Crosato[1], Michele Cornello[1], Maurizio Ferla[1], Sara Morucci[1], Andrea Bonometto[1*]

Affiliations:

[1]Institute for Environmental Protection and Reaserch (ISPRA), Campo S. Provolo, 4665, 30122, Venice, Italy

* corresponding author: andrea.bonometto@isprambiente.it

ORCIDs: Damiano Baldan 0000-0001-9237-4883

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

Title: Return periods of extreme sea levels: from magnitude to frequency, duration and seasonality. Implications in a regulated coastal lagoon.

Authors: Damiano Baldan[1], Elisa Coraci[1], Franco Crosato[1], Michele Cornello[1], Maurizio Ferla[1], Sara Morucci[1], Andrea Bonometto[1]

Affiliations:

[1]Institute for Environmental Protection and Reaserch (ISPRA), Venice, Italy

ORCIDs: Damiano Baldan 0000-0001-9237-4883

Abstract:

Extreme sea levels (ESLs) affect coastal ecosystems worldwide. Protection and adaptation strategies rely on the characterization of the extreme's occurrence probability in the future. However, knowledge on the occurrence rate and duration of ESLs is also needed to properly characterize the associated future risk. In this paper, we focus on the Venice lagoon, where a system of storm surge barriers can disconnect the lagoon from the sea to mitigate ESLs. Using long-term (96 years) sea level records, we model occurrence rate and duration of ESLs while accounting explicitly for seasonality and mean sea level rise. While historically ESLs occurred in the winter season, we project a significant increase (up to 10-fold with a mean sea level increase of + 100 cm) of the occurrence rate also in the summer season, when disconnections from the sea can have profound impacts on the lagoon's ecosystem. We also predict an increase in ESLs durations up to 200 hours, leading to longer disconnections of the lagoon from the sea in the future. Therefore, several adaptation strategies will be needed to limit the adverse effects of storm surge barriers on the lagoon ecosystem.

Keywords: Extreme Sea Levels, Venice Lagoon, Seasonality, ecosystem impacts

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

1. Introduction

Low-lying coastal areas are threatened worldwide by the adverse consequences of flooding hazards driven by extreme sea levels (ESLs, Nicholls et al., 2021; Vousdoukas et al., 2016). Relative sea level rise interacts synergistically with increased coastal vulnerability, affecting the exposure of coastal communities to flood risk (Vousdoukas et al., 2018). ESLs also affect coastal ecosystems, for instance by triggering erosive processes that reduce the available habitats (Leonardi et al., 2018; Mentaschi et al., 2018), and by driving seasonal saltwater intrusion in estuaries (Tian, 2019). Changes in frequency, magnitude, and seasonality of ESLs can affect the capacity of coastal ecosystems to recover after disturbances (Hanley et al., 2020).

The development of ESLs protection and adaptation strategies relies on the characterization of their occurrence probability (Boettle et al., 2016). Extreme events theory provides probability distribution functions to fit historical extremes (Coles et al., 2001). Such assessments have been widely employed to assist the design of coastal protection structures by estimating the 'worst case' design parameters that minimize the likelihood of failure (Mudersbach and Jensen, 2010). However, when the objective of the analysis is the study of the potential damages due to extreme events, 'worst case' extremes scenarios might not be sufficient, because the damage is also a function of the vulnerability of the system (Boettle et al., 2016). On the other hand, the vulnerability depends on multiple socio-economic (e.g. non-linear relationships between flood level and flooded area, Kirshen et al., 2012) and environmental parameters (e.g. sediment supply to counteract erosion, Allenbach et al., 2015) that are hardly constant over time. This is particularly true for coastal ecosystems under multiple pressures such as urbanization, altered sediment and water cycle, ecosystems overexploitation (Kane et al., 2015; Myers et al., 2019). For instance, the vulnerability of estuaries to saltwater intrusion driven by ESLs is

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

dependent on the seasonal river flow regime (Tian, 2019). Henceforth, for a proper assessment of the potential damages, functions to characterize extremes in terms of sub annual occurrence and duration are needed (Birkmann et al., 2016). Such information is particularly relevant for coastal area protected by systems of storm surge barriers.

The construction of storm surge barriers to mitigate flooding risks and related economic losses is increasingly considered as a viable adaptation option (Vousdoukas et al., 2020). Storm-surge barriers currently protect the river Scheldt estuary (the Netherlands), St. Petersburg (Russia), London and Hull (United Kingdom), New Orleans (Louisiana), and Venice (Italy), while plans for Shanghai and New York exist (Kluijver et al., 2019). Storm surge barriers temporarily disconnect the coastal zone from the sea to prevent the protected area to be affected by ESLs. The timing and duration of disconnections can have a great impact on the system. Even short disconnections can affect the water residence time (Ferrarin et al., 2013), with increased risks of hypoxia or harmful algal blooms in the summer season. Consequent impacts include changes in the macroinvertebrate community structure (Obolewski et al., 2018), with trophic-cascading implications (Young et al., 2022). Furthermore, disconnections might reduce the likelihoods of organisms exchange with the sea (Pérez-Ruzafa et al., 2019), particularly severe for organisms that rely on passive drift for dispersal. The operation of storm surge barriers also implies tradeoffs with other anthropic uses of the coastal zones, for instance when navigation is prevented during a disconnection (Umgiesser and Matticchio, 2006).

In this paper, we focus on the case study of the Venice lagoon (Northern Adriatic Sea), a paradigm of coastal flooding. The historical city of Venice and the other settlements located inside the lagoon are particularly sensitive to ESLs because of the fast relative sea level rise due to the combined effects of subsidence and eustatism (+ 2.5 mm $year^{-1}$ in the last 150 years, Biasio et al., 2020; Zanchettin et al.,

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

2021). The current long-term mean sea level is about 30 cm above the local 1897 datum (named *Zero Mareografico di Punta della Salute*, ZMPS: average local sea level for the period 1885-1909). As a result, an increase in the frequency and magnitude of ESLs causing flooding of the city of Venice was recorded (Umgiesser et al., 2021). The events with the highest recorded sea levels occurred on November 4th, 1966 (+ 194 cm), and November 12th, 2019 (+ 189 cm, Lionello et al., 2021). Of the 25 events with a sea level > 140 cm (considered as exceptional) occurred since 1885, 15 occurred since 2000, and 7 occurred since 2018 (Comune di Venezia-CPSM ISPRA CNR-ISMAR, 2022). In November 2019, the sea level was above 140 cm for 4 days (Umgiesser, 2020). To protect the city of Venice and the other settlements in the lagoon from ESLs in the future, a system of mobile barriers (MOSE) consisting of 78 independently oscillating gates located at the three inlets was built. The MOSE system was first activated to prevent the flooding of Venice in October 2020, and full disconnections to prevent the flooding of the city occurred 28 times until December 2021.

Given the challenges highlighted above, the aims of this paper are: a) to develop a proper statistical representation of the duration and frequency of occurrence of ESLs in the Venice lagoon accounting for seasonality, and b) predict future changes in ESLs characteristics under relative sea level rise.

2. Methods

2.1 Study site

The Venice lagoon is the largest Mediterranean lagoon; covering a length of 50 km along the coast, with an area of 500 km^2 (Fig. 1).The lagoon is connected to the sea by the three inlets of Lido (820 m wide, 6 - 12 m deep), Malamocco (380 m wide, 14 m deep) and Chioggia (360 m wide, 11 m deep). The tide regime is semi-diurnal, with mean tidal range from 50 cm during neap tide to 100 cm during spring tide (Umgiesser et al., 2021). Spring and neap conditions occur twice each month. The sea level inside the

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

lagoon is determined by the tide and the meteorological surge, driven by atmospheric phenomena at different temporal and spatial scales (Lionello et al., 2021) with storm surges being the dominant drivers of extreme sea levels (Ferrarin et al., 2022). Storm surges are often associated with the two dominant winds regimes: the *Sirocco* wind which blows along the main axis of the Adriatic sea (SE direction), and the *Bora* wind (NE direction). Extreme sea levels that lead to the partial flooding of the city occur when the sea level is greater than + 110 cm.

2.2 Tide gauge data

We used sea level data recorded at the *Punta della Salute* gauge station (Fig. 1) covering the period 1924 – 2019. The float-operated tide gauge is located inside a still well; measurements were acquired mechanically until 1988 and electronically from 1989 onwards. Until 1989, semidiurnal maxima and minima are available (4 measurements per day); then data were recorded hourly in the period 1989 - 1994, every half hour in 1995 - 2006, every ten minutes in 2007 – 2019. To assess changes in the tide characteristics due to MOSE operations, the sea level measured at *Punta della Salute* is compared with the undisturbed value measured at *Piattaforma Aqua Alta*, a gauge located outside the lagoon, 15 km off the coast (Fig. S1).

2.3 Extreme events and cluster definition

A peak is a sequence of sea level values above a threshold. Peaks independence cannot be assumed, as several peaks might occur in a short amount of time because of the interaction of tides (spring tide), meteorological conditions (storm surge), or seiches (Ferrarin et al., 2022). For this reason, we first identified clusters of peaks, i.e. sequences of sea level values both above and below 110 cm that are separated by more than 78 hours, corresponding to the average decay time of seiches in the Northern Adriatic (Raicich et al., 1999). For example, the event recorded in April 2019 was a single peak; while in

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

November 2019, 15 peaks were detected, belonging to two clusters (Fig. 2a, 2b). In this work, we consider clusters to be independent extreme events. We calculate the duration of an event as the sum of the duration of the single peaks that compose the cluster.

The decision to operate the MOSE is based on the forecasted sea level in correspondence of a peak exceeding 110 cm (Umgiesser et al., 2021), while the barriers are activated when the sea level is generally + 70 cm (Fig. S1). Thus, we calculated two clusters durations: the duration above 110 cm and the duration above 70 cm.

Since a large fraction of data was not collected with a sufficient frequency to estimate the duration directly, we setup two statistic relationships linking the duration of a peak (in terms of time the sea level is above 110 cm and 70 cm) with the maximum sea level measured for that peak:

$$d = a + b\sqrt{z - c} \qquad (1)$$

Where d is the duration (hours), z is the sea level (cm), c is either 110 or 70, and a and b are the coefficients of the regression. We used 1995 – 2019 data to develop the relationships, and calculated the duration of each peak for the whole dataset.

2.4 Point Process for extremes occurrence frequency

A point process defined on a set *S* is a stochastic rule for the occurrence position of point events. If *S* represents a period of time, a point process can be used to describe the occurrence of sea levels above a certain threshold. The point process can be statistically characterized by defining a set a non-negative integer random variables *N(A)* for each $A \subset S$. When the random variables *N(A)* are Poisson-distributed, the process is a Poisson process, and the probability distribution function of N is expressed as:

$$Pr(N = k) = \frac{\Lambda^k e^{-\Lambda}}{k!} \qquad (2)$$

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

Where $\Lambda = \Lambda(A)$is the process intensity.When S represents time (one-dimensional process), the intensity defined on the interval $A = [t_1,t_2] \subset S$ is related to the process rate (λ, the average number of events in the time interval A) via: $\Lambda = \lambda(t_2 - t_1)$.When the rate is variable, the process is non-homogeneous, and the process intensity is calculated via integration of the process rate (Coles et al., 2001).

In this paper, we fitted a non-homogeneous Point Process (NHPP). We accomplished this by specifying the process rate to be dependent from covariates:

$$\ln(\lambda) = \beta_0 + \beta_1 \cos\left(2\pi \frac{jday}{365}\right) + \beta_2 \sin\left(2\pi \frac{jday}{365}\right) + \beta_3 \cos\left(4\pi \frac{jday}{365}\right) + \beta_4 \sin\left(4\pi \frac{jday}{365}\right) + \beta_5 ln(msl) \quad (3)$$

Where $jday$ is the Julian day (e.g. 1 for January, 1st; and 365 for December, 31st), and msl is the yearly mean sea level. Following (Menendez et al., 2009), we included annual and semiannual harmonic terms to account for seasonality. We fitted the NHPP with the package 'NHPoisson' (Cebrián et al., 2015) in R v4.1.2 computing environment (R Core Team, 2021). We used a stepwise procedure based on the likelihood ratio test to select the model with appropriate complexity (Coles et al., 2001). We validated the models by examining the residual autocorrelation, the autocorrelation function, and the quantile-quantile plots (Cebrián et al., 2015). As a further validation, we used a Monte Carlo Markov Chain approach to calculate the probability distribution of the number of events over periods of 10 years, which we compared with the empirical occurrence rate for summer (April-September) and winter (October-March).

2.5 Point process for the duration of extreme sea levels

The point process framework can be used also to model the magnitude and duration of extreme events. Extreme value theory provides probability distribution functions that are suitable for modeling values with low occurrence rate in a dataset. The Block Maxima (BM) approach considers the distribution of

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

the maxima of the set X_1, …, X_n over blocks of length *n*: $M_n = max\{X_1, \ldots, X_n\}$ and assesses $Pr(M_n > z)$, i.e. the probability that the random variable M_n is greater than z. Block Maxima follow the Generalized Extreme Value (GEV) probability distribution function (see theorem 3.1 in Coles et al., 2001):

$$Pr(M_n > z) = exp\left\{ - \left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]_+^{-1/\xi} \right\} \quad (4)$$

where $a_+ = max\,(a,0)$, μ is the location parameter (proportional to the first-order moment of the distribution and interpreted as the 1-year return level), σ is the scale parameter (always positive, proportional to the second-order moment of the distribution), and ξ is the shape parameter. When extremes are selected as threshold exceedances (Peaks over the Threshold, POT), the Generalized Pareto Distribution (GPD) is used as approximation of the GEV tail behavior.

A similar distribution for extremes can be derived in a point process approach. Assuming that the point events are exceedances over a sufficiently high threshold *u*, a two-dimensional point process can be defined on sets of the form $(t_1,t_2) \times (u,\infty)$. The related process intensity is factorized as (see theorem 7.1.1 in Coles et al., 2001):

$$\Lambda((t_1,t_2) \times (z,\infty)) = n_y(t_2 - t_1)\left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi} \quad (5)$$

where n_y is the number of events per year (normalization constant), and the location, scale and shape parameters correspond to the GEV parameters of the annual BM distribution.

The point process framework also allows for assessing the extremes' return period. First, the probability that the random variable describing extremes' magnitude is greater than the value z> u is expressed as (see theorem 4.1 in Coles et al., 2001):

$$\Pr\,(Z > z) = \frac{1}{n}\left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi} \quad (6)$$

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

where n is the number of observations per year. The parameterization in eq. 6 is justified by the GEV-asymptotic behavior of threshold exceedances. The return period corresponding to the return level z_m is:

$$Tr(z_m) = \left[1 - Pr(Z > z_m)\right]^{-1} \quad (7)$$

We explicitly model non-stationarity by allowing the location and logarithm of the scale parameters to vary according to the full model defined in eq. 3. We use the maximum likelihood criterion to fit the parameters of the PP on extremes duration with the 'extRemes' package (Gilleland and Katz, 2016). We used a stepwise procedure based on the likelihood ratio test to select the model with appropriate complexity (Coles et al., 2001). We validated the fitted models with visual inspection of the quantile-quantile plots.

2.6 Sea level rise scenarios

We used the fitted models to predict the changes in the frequency and duration of ESL clusters under relative sea level rise. We explored scenarios of sea level rise ranging from + 10 cm to + 100 cm with 10 cm increments (current mean sea level is approximately + 32 cm). Such increments can be related with IPCC scenarios of + 50 – 55 cm in 2050, and + 90 – 105 for 2100 for RCP 4.5 and 8.5, respectively (Masson-Delmotte et al., 2021). To predict changes in the frequency of occurrence of ESLs with the NHPP model, we generated a 10-years long covariates vector, and used a Monte Carlo Markov Chain (1000 repetitions) to sample empirically the number of clusters realizations (Cebrián et al., 2015). To predict changes in clusters duration with the GPD models, we fixed the covariates values, we calculated the distribution's parameters, and the quantiles corresponding to 5 years return period.

3. Results

The NHPP models for clusters occurrence and duration explained that include the effect of covariates on the process intensity and position parameter were better fit to the data than models that did not

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

include it. The likelihood ratio tests (comparing the non-homogeneous selected model and its homogeneous correspondent) was: LR = 291.83, $\chi^2(4) = 9.49$, $p < 2\ 10^{-16}$ for the model for occurrence; LR = 293.42, $\chi^2(4) = 9.49$, $p < 2\ 10^{-16}$ for the model for cluster duration above + 70 cm; and LR = 209.92; $\chi^2(6) = 12.59$, $p < 2\ 10^{-16}$ for the model for cluster duration above + 110 cm (see Fig. S2 – S5 for the quantile-quantile plots). Harmonic (seasonality effects), and mean sea level covariates were retained in every model (Table 1). The selected PP models for events duration were including only covariates on the location, not on the scale parameter.

Clusters occurrence in the past increased for both summer (from 0 events in 1924-1930 to 3 events in 2010 - 2020) and winter (from 1 event in 1924 – 1930 to almost 40 events in 2010 -2019). All historic occurrence rates fall into the modeled interval of confidence and are close to the expected values (Fig. 3).

Under relative sea level rise, the model predicts an increase in the occurrence of events above 110 cm (Fig. 4), with an average number of about 100 events per decade with + 40 cm (10 of which occurring in the summer season), and about 300 events per decade with + 100 cm (35 in summer).

NHPP models for cluster duration predict smaller clusters durations in summer than in winter for both sea level thresholds. This is in line with the 2000 – 2019 observed data that report mean cluster durations of 2.4 hours in summer and 5.6 hours in winter for levels above + 110, and durations of 7.7 hours in summer and 17 hours in winter for levels above +110 cm. With a mean sea level of + 40 cm, the modeled cluster duration above 110 cm ranges between 4 hours in summer and 22 hours in winter, while the cluster duration above 70 cm ranges between 5 hours in summer and more than 50 hours in winter (Fig. 5). Values of mean sea level below + 30 cm have very low likelihoods of occurrence of clusters in the summer season. When the mean sea level is at +100 cm, the cluster duration for sea

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

218 levels above +110 cm increases until 30 – 47 hours (summer – winter), and the cluster duration for sea
219 levels above +70 cm increases until 220 – 260 hours.

220 **4. Discussion**

221 **4.1 Changes in the occurrence of extreme sea levels**

222 Our results show that the NHPP is a viable approximation for modeling the frequency of occurrence of
223 ESLs: the fitted process rate is able to represent properly the long-term historical trend for both summer
224 and winter, as well as its dependence from sea level rise. The yearly occurrence of ESLs is projected to
225 increase almost up to 10-fold compared to current conditions with a mean sea level of + 80 cm, reaching
226 values higher than 20 clusters per year. With a mean sea level of + 80 cm (+ 50 cm above current mean
227 sea level), an excursion of ± 30 cm (comparable to the average tidal amplitude) would be enough to
228 reach the + 110 cm threshold leading to the flooding of the city. This means that almost every spring
229 tide conditions could lead to a cluster of extreme events, with two MOSE closures likely every day. For
230 sea levels above + 100 (Umgiesser, 2020), a stabilization of the occurrence rate due to the spring-neap
231 cycle is supposed to occur, affecting the hypothesis of NHPP, as the clusters are considered statistically
232 independent.

233 The model for extremes occurrence frequency that accounts for seasonality can support the analysis of
234 the impacts of extreme events, as it allows for linking the extremes occurrences with periods of higher
235 vulnerability. Seasons that currently are unlikely to be impacted from ESL events could experience
236 values higher than + 110 cm several times for years. This could lead to new and not yet experienced
237 source of impact on environmental and human activities, a consequence of multiple and prolonged
238 MOSE closures.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

An increase in the frequency of extreme sea levels leading to the disconnection of the lagoon can have important consequences on the water circulation and renewal. The exchange of water with the sea through the three inlets controls water circulation under normal conditions (Ferrarin et al., 2013). When the storm surge barriers are activated, the water circulation is driven by differential wind setups (Mel et al., 2019). Changes in water circulations patterns are likely to affect the transport, accumulation, and deposition of organic matter, with cascading on biotic populations and communities (Maggiore and Keppel, 2007; Tognin et al., 2022, 2021). The sensitivity of the biota to changes in frequencies is expected to be higher in the summer season, more exposed to eutrophication and anoxic crisis.

From the geomorphological perspective, MOSE closures, combined with strong winds that typically occur during storm-surge events, can significantly increase the amount of sediment resuspended from the lagoon bed (Tognin et al., 2022). Seasonality can play a role also here because barrier closures are more likely in the late fall and winter when the biomass of both seagrass and benthic biofilm is reduced because of seasonal dynamics, thus offering relatively little protection against wind-induced sediment erosion of the lagoon bottom.

4.2 Changes in the duration of extreme sea levels

Besides the occurrence, the duration of each cluster (event) is needed to fully estimates the overall impact of extreme event under sea level rise. The duration is closely related to the selected threshold, that in the Venice lagoon depend on the MOSE managing (e.g. closures) protocols.

The NHPP model on clusters duration predicts an increase in the 5-years-return period duration of clusters for both thresholds (+ 70 and + 110 cm), with negligible likelihood of events occurrence in summer for mean sea levels below + 40 cm This is consistent with historical data, as spring/summer ESLs were uncommon. Sea level rise can lead to different extremes duration in the future. The predicted

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

length of ESLs is consistent with a multi-peaked clusters occurrence also in summer. For instance, while the likelihood of summer events is null with a mean sea level of + 40 cm, a duration of the closure around 25 hours (above the + 70 threshold) , predicted already with a mean sea level of + 50 cm suggest that the ESL cluster contains multiple peaks, and that multiple MOSE operations can occur within few hours. An increased duration of disconnections has impacts on the lagoon morphology, on its ecosystem and on its anthropic use.

Tognin et al. (2021) analyzed the role of surge events in supplying the sediment in flooding and supplying sediment to saltmarshes, observing that storm-surge-barriers can heavily hinder sediment deposition, needed for saltmarshes to offset increasing sea levels. An optimal operation strategy enabling to close the barriers at higher activation thresholds could provide significative benefits. They estimated that an activation threshold 20 cm higher than the current limits the reduction in sedimentation. Here the difference between the duration of the disconnection above + 70 and + 110 cm ranges between 130 and 150 hours for a mean sea level of + 100 cm, and can be up to 25 hours with a mean sea level of + 40.

From the point of view of the anthropic use, increased lengths of disconnection can impact the activities of the harbor located inside the lagoon, as the movement of ships across the three inlets is prevented by the presence of the gates (Umgiesser and Matticchio, 2006).

Both issues will be affected more in the future. The length of closures is currently limited to some tens of hours per year, but under sea level rise the value is expected to increase. Umgiesser (2020) calculated potential future closures based on 2001 – 2003 tide data shifted for different mean sea level values, reporting a yearly duration of closures increasing from 30 hours/year for a mean sea level of +30 cm, to 1400-1800 hours/year for +70 cm, and 4000-5000 hours/year for +100 cm. Using a similar approach

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

and tide data from 2000 - 2019, the study from Mel et al. (2020) reports a yearly duration of closures of 1000-3000 hours/year for + 70 cm, and 3100 – 5500 hours/year for +100 cm. Our study is consistent with these findings. By multiplying the average number of clusters (Fig. 4) by the average cluster duration with a return period of 5 years (Fig. 5), we could provide a rough estimate the yearly disconnection duration. We estimate disconnection durations of 40 hours/year for +30 cm, 1700 hours/year for + 70 cm, and 7000 hours/year for + 100 cm, in line with existing studies. With a mean sea level of +70 cm (i.e. 50 cm higher than current values), the lagoon would be disconnected from the sea 25% of the time, and almost all the time when the mean sea level is + 100 cm (i.e. 70 cm higher than current values). Our results show that simple statistical models based on historical data are able to represent the occurrence of extremes in the near future, in substantial agreement with hydrodynamic-based models.

4.3 Future perspectives

Out work shows the importance to move from the 'worst case' estimation of ESLs to the related frequency of occurrence and duration when the focus of the analysis is in the assessment of impacts on both environment and human activities. The 'worst case' approach is the most used approach for the design of structures (Razmi et al., 2017). Existing methods can be adapted to account for non-stationarity due to sea level rise or other causes (Baldan et al., 2022). Further research is needed to investigate whether the interaction between the sea level rise and the tide structure is the only cause for the increase in frequency of ESLs, or weather other causes can be identified, such as potential changes in the meteorological forcing at multiple spatial scales leading to storm surges (Ferrarin et al., 2022; Lionello et al., 2021).

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

However, when the focus is on environmental analyses, the “worst case” approach provides limited information. This is particularly true for lagoon systems and their morphological and ecological features, due to their resilience to stressors. Here, the frequency and duration of extreme events play a crucial role in driving the morphological and ecological trajectories (Carniello et al., 2016; Fagherazzi, 2014; Leonardi et al., 2018).

Our study highlighted that the sea level rise will yield an increase in the duration of ESLs, and some potential changes to their timing. Future studies should aim at charactering the vulnerability of the system and at assessing mitigation measures based on the development of new protocols for operating the MOSE gates. In this regard, it is important to remark that our results are based on observed data, while the decisions to disconnect the lagoon and the duration of the disconnection are based on the forecasts of the water level in the city of Venice. Current uncertainty in the forecasts is approximately 10 cm (Umgiesser, 2020; Umgiesser et al., 2021). In order to reduce the number and duration of closures, improved predictions are needed for two reasons. First, the risk of activating the MOSE system for events that would not lead to the flooding (prediction of ESLs magnitude) of the city can be reduced (i.e. a reduction of false alarms). Second, the duration of the disconnections can be reduced by acting on the closure levels (e.g. activating the system when the water level is + 90 cm instead of + 70 would reduce the length of closures): in this case the prediction of the timing of the peak is very important.

An improved understanding of the potential ecological impacts of disconnections is also needed to properly characterize the flooding risk and the associated damages. Impacts of disconnections on the water residence time and water circulation need to be studied further, with a particular emphasis on the seasonal dynamics (Ferrarin et al., 2013), the related impacts on sediment and organic matter cycles (Tognin et al., 2022), the implications for the biota (Tagliapietra et al., 2009), and potential increases in

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

eutrophication risks (Sfriso and Facca, 2007). Finally, impacts of disconnections on the functioning of the lagoon ecosystem, for example as nursery for many Adriatic fish species (Ghezzo et al., 2013) should be studied.

Our work can support studies on the ecological impacts of ESLs. The changes in ESLs occurrence presented in this paper are relative to periods of 10 years to ensure a stable projection. Ecological analyses would require an higher temporal resolution. For instance, the stress increases when the inter-arrival time between consecutive ESLs is smaller than the recovery time of the system. Future work could focus on investigating the likelihood of occurrence as a function of meteorological and climatic forcing at finer temporal scales (e.g. yearly), and on the inter-cluster changes (e.g. the number of peaks that constitute a cluster, duration of single peaks).

5. Conclusions

In this work, we modeled extreme sea levels duration and frequency of occurrence with a non-homogeneous Point Process, including explicitly the effects of seasonality and mean sea level. Changes in extreme sea levels duration and magnitude could be related to the seasonality. Our approach allows for extending extreme events analysis to endpoints that are easily relatable to the variable vulnerabilities of the system. Similar analyses can be implemented for different coastal area protected by storm surge barriers, but the methodology is general and could be implemented whenever there is the interest in the quantification of differential, season-dependent effects of extreme events.

Aknowledgements

This work was supported by the EU-INTERREG project ADRIACLIM (grant number IT-HR 10252001)

Data availability

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

Data used in this work are freely available from the portal of the Italian Institute for Environmental Protection and Research (ISPRA): https://www.venezia.isprambiente.it/rete-meteo-mareografica

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

References

Allenbach, K., Garonna, I., Herold, C., Monioudi, I., Giuliani, G., Lehmann, A., Velegrakis, A.F., 2015. Black Sea beaches vulnerability to sea level rise. Environ. Sci. Policy 46, 95–109.

Baldan, D., Coraci, E., Crosato, F., Ferla, M., Bonometto, A., Morucci, S., 2022. Importance of non-stationary analysis for assessing extreme sea levels under sea level rise. EGUsphere 1–23.

Biasio, F. De, Baldin, G., Vignudelli, S., 2020. Revisiting Vertical Land Motion and Sea Level Trends in the Northeastern Adriatic Sea Using Satellite Altimetry and Tide Gauge Data 1–25.

Birkmann, J., Wenzel, F., Greiving, S., Garschagen, M., Vallée, D., Nowak, W., Welle, T., Fina, S., Goris, A., Rilling, B., Fiedrich, F., Fekete, A., Cutter, S.L., Düzgün, S., Ley, A., Friedrich, M., Kuhlmann, U., Novák, B., Wieprecht, S., Riegel, C., Thieken, A., Rhyner, J., Ulbrich, U., Mitchell, J.K., 2016. Extreme Events, Critical Infrastructures, Human Vulnerability and Strategic Planning: Emerging Research Issues. J. Extrem. Events 03, 1650017. https://doi.org/10.1142/s2345737616500172

Boettle, M., Rybski, D., Kropp, J.P., 2016. Quantifying the effect of sea level rise and flood defence – A point process perspective on coastal flood damage. Nat. Hazards Earth Syst. Sci. 16, 559–576. https://doi.org/10.5194/nhess-16-559-2016

Carniello, L., D'Alpaos, A., Botter, G., Rinaldo, A., 2016. Statistical characterization of spatiotemporal sediment dynamics in the Venice lagoon. J. Geophys. Res. F Earth Surf. 121, 1049–1064. https://doi.org/10.1002/2015JF003793

Cebrián, A.C., Abaurrea, J., Asín, J., 2015. NHPoisson: An R package for fitting and validating nonhomogeneous Poisson processes. J. Stat. Softw. 64, 1–25.

Coles, S., Bawa, J., Trenner, L., Dorazio, P., 2001. An introduction to statistical modeling of extreme values. Springer.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

372 Comune di Venezia-CPSM ISPRA CNR-ISMAR, 2022. Previsioni delle altezze di marea per il bacino San Marco e
373 delle velocità di corrente per il Canal Porto di Lido - Laguna di Venezia.

374 Fagherazzi, S., 2014. Storm-proofing with marshes. Nat. Geosci. 7, 701–702.

375 Ferrarin, C., Ghezzo, M., Umgiesser, G., Tagliapietra, D., Camatti, E., Zaggia, L., Sarretta, A., 2013. Assessing
376 hydrological effects of human interventions on coastal systems: Numerical applications to the Venice
377 Lagoon. Hydrol. Earth Syst. Sci. 17, 1733–1748. https://doi.org/10.5194/hess-17-1733-2013

378 Ferrarin, C., Lionello, P., Orlić, M., Raicich, F., Salvadori, G., 2022. Venice as a paradigm of coastal flooding
379 under multiple compound drivers. Sci. Rep. 1–11. https://doi.org/10.1038/s41598-022-09652-5

380 Gilleland, E., Katz, R.W., 2016. extRemes 2.0: An Extreme Value Analysis Package in R. J. Stat. Softw. 72, 1–39.
381 https://doi.org/10.18637/JSS.V072.I08

382 Hanley, M.E., Bouma, T.J., Mossman, H.L., 2020. The gathering storm: optimizing management of coastal
383 ecosystems in the face of a climate-driven threat. Ann. Bot. 125, 197–212.

384 Kane, H.H., Fletcher, C.H., Frazer, L.N., Anderson, T.R., Barbee, M.M., 2015. Modeling sea-level rise vulnerability
385 of coastal environments using ranked management concerns. Clim. Change 131, 349–361.
386 https://doi.org/10.1007/s10584-015-1377-3

387 Kirshen, P., Merrill, S., Slovinsky, P., Richardson, N., 2012. Simplified method for scenario-based risk assessment
388 adaptation planning in the coastal zone. Clim. Change 113, 919–931.

389 Kluijver, M., Dols, C., Jonkman, S.N., Mooyaart, L.F., 2019. Advances in the Planning and Conceptual Design of
390 Storm Surge Barriers-Application to the New York Metropolitan Area. Henry, Hydraul. Eng. Repos. - Coast.
391 Struct. 9, 326–336. https://doi.org/10.18451/978-3-939230-64-9

392 Leonardi, N., Carnacina, I., Donatelli, C., Ganju, N.K., Plater, A.J., Schuerch, M., Temmerman, S., 2018. Dynamic
393 interactions between coastal storms and salt marshes: A review. Geomorphology 301, 92–107.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

394 Lionello, P., Barriopedro, D., Ferrarin, C., Nicholls, R.J., Orlić, M., Raicich, F., Reale, M., Umgiesser, G.,
395 Vousdoukas, M., Zanchettin, D., 2021. Extreme floods of Venice: Characteristics, dynamics, past and
396 future evolution (review article). Nat. Hazards Earth Syst. Sci. 21, 2705–2731.
397 https://doi.org/10.5194/nhess-21-2705-2021

398 Maggiore, F., Keppel, E., 2007. Biodiversity and distribution of polychaetes and molluscs along the Dese estuary
399 (Lagoon of Venice, Italy). Hydrobiologia 588, 189–203.

400 Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L.,
401 Gomis, M.I., 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to
402 the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC Geneva, Switz.

403 Mel, R., Carniello, L., D'Alpaos, L., 2019. Addressing the effect of the Mo.S.E. barriers closure on wind setup
404 within the Venice lagoon. Estuar. Coast. Shelf Sci. 225, 106249.
405 https://doi.org/10.1016/j.ecss.2019.106249

406 Menendez, M., Mendez, F.J., Losada, I.J., 2009. Forecasting seasonal to interannual variability in extreme sea
407 levels. ICES J. Mar. Sci. 66, 1490–1496. https://doi.org/10.1093/icesjms/fsp095

408 Mentaschi, L., Vousdoukas, M.I., Pekel, J., Voukouvalas, E., Feyen, L., 2018. Global long-term observations of
409 coastal erosion and accretion 1–11. https://doi.org/10.1038/s41598-018-30904-w

410 Mudersbach, C., Jensen, J., 2010. Nonstationary extreme value analysis of annual maximum water levels for
411 designing coastal structures on the German North Sea coastline. J. Flood Risk Manag. 3, 52–62.
412 https://doi.org/10.1111/j.1753-318X.2009.01054.x

413 Myers, M.R., Barnard, P.L., Beighley, E., Cayan, D.R., Dugan, J.E., Feng, D., Hubbard, D.M., Iacobellis, S.F.,
414 Melack, J.M., Page, H.M., 2019. A multidisciplinary coastal vulnerability assessment for local government
415 focused on ecosystems, Santa Barbara area, California. Ocean Coast. Manag. 182, 104921.
416 https://doi.org/10.1016/j.ocecoaman.2019.104921

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

417 Nicholls, R.J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A.T., Meyssignac, B., Hanson, S.E., Merkens, J.L., Fang, J.,
418 2021. A global analysis of subsidence, relative sea-level change and coastal flood exposure. Nat. Clim.
419 Chang. 11, 338–342. https://doi.org/10.1038/s41558-021-00993-z

420 Obolewski, K., Glińska-Lewczuk, K., Astel, A., 2018. Lost connectivity between a coastal lagoon and the sea –
421 implications of floodgate closure for benthic macroinvertebrates. Estuar. Coast. Shelf Sci. 211, 77–89.
422 https://doi.org/10.1016/j.ecss.2018.02.012

423 Pérez-Ruzafa, A., De Pascalis, F., Ghezzo, M., Quispe-Becerra, J.I., Hernández-García, R., Muñoz, I., Vergara, C.,
424 Pérez-Ruzafa, I.M., Umgiesser, G., Marcos, C., 2019. Connectivity between coastal lagoons and sea:
425 Asymmetrical effects on assemblages' and populations' structure. Estuar. Coast. Shelf Sci. 216, 171–186.
426 https://doi.org/10.1016/j.ecss.2018.02.031

427 R Core Team, 2021. R: A Language and Environment for Statistical Computing.

428 Raicich, F., Orlic, M., Malacic, V., 1999. A case study of the Adriatic seiches (December 1997). Nuovo Cim. della
429 Soc. Ital. di Fis. C 22.

430 Razmi, A., Golian, S., Zahmatkesh, Z., Zahmatkesh ZahraZahmatkeshAliabadi, Z., 2017. Non-Stationary
431 Frequency Analysis of Extreme Water Level: Application of Annual Maximum Series and Peak-over
432 Threshold Approaches. Water Resour Manag. 31, 2065–2083. https://doi.org/10.1007/s11269-017-1619-
433 4

434 Sfriso, A., Facca, C., 2007. Distribution and production of macrophytes and phytoplankton in the lagoon of
435 Venice: comparison of actual and past situation, in: Lagoons and Coastal Wetlands in the Global Change
436 Context: Impacts and Management Issues. Springer, pp. 71–85.

437 Tagliapietra, D., Sigovini, M., Ghirardini, A.V., 2009. A review of terms and definitions to categorise estuaries,
438 lagoons and associated environments. Mar. Freshw. Res. 60, 497–509. https://doi.org/10.1071/MF08088

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

Tian, R., 2019. Factors controlling saltwater intrusion across multi-time scales in estuaries, Chester River, Chesapeake Bay. Estuar. Coast. Shelf Sci. 223, 61–73. https://doi.org/10.1016/j.ecss.2019.04.041

Tognin, D., D'Alpaos, A., Marani, M., Carniello, L., 2021. Marsh resilience to sea-level rise reduced by storm-surge barriers in the Venice Lagoon. Nat. Geosci. 14, 906–911. https://doi.org/10.1038/s41561-021-00853-7

Tognin, D., Finotello, A., D'Alpaos, A., Viero, D.P., Pivato, M., Mel, R.A., Defina, A., Bertuzzo, E., Marani, M., Carniello, L., 2022. Loss of geomorphic diversity in shallow tidal embayments promoted by storm-surge barriers. Sci. Adv. 8, 1–13. https://doi.org/10.1126/sciadv.abm8446

Umgiesser, G., 2020. The impact of operating the mobile barriers in Venice (MOSE) under climate change. J. Nat. Conserv. 54, 125783. https://doi.org/10.1016/j.jnc.2019.125783

Umgiesser, G., Bajo, M., Ferrarin, C., Cucco, A., Lionello, P., Zanchettin, D., Papa, A., Tosoni, A., Ferla, M., Coraci, E., Morucci, S., Crosato, F., Bonometto, A., Valentini, A., Orlić, M., Haigh, I.D., Nielsen, J.W., Bertin, X., Fortunato, A.B., Pérez Gómez, B., Alvarez Fanjul, E., Paradis, D., Jourdan, D., Pasquet, A., Mourre, B., Tintoré, J., Nicholls, R.J., 2021. The prediction of floods in Venice: Methods, models and uncertainty (review article). Nat. Hazards Earth Syst. Sci. 21, 2679–2704. https://doi.org/10.5194/nhess-21-2679-2021

Umgiesser, G., Matticchio, B., 2006. Simulating the mobile barrier (MOSE) operation in the Venice Lagoon, Italy: global sea level rise and its implication for navigation. Ocean Dyn. 56, 320–332.

Vousdoukas, M.I., Mentaschi, L., Hinkel, J., Ward, P.J., Mongelli, I., Ciscar, J.C., Feyen, L., 2020. Economic motivation for raising coastal flood defenses in Europe. Nat. Commun. 11, 1–11. https://doi.org/10.1038/s41467-020-15665-3

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., Feyen, L., 2018. Climatic and socioeconomic controls of future coastal flood risk in Europe. Nat. Clim. Chang. 8, 776–780. https://doi.org/10.1038/s41558-018-0260-4

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

462 Vousdoukas, M.I., Voukouvalas, E., Annunziato, A., Giardino, A., Feyen, L., 2016. Projections of extreme storm
463 surge levels along Europe. Clim. Dyn. 47, 3171–3190. https://doi.org/10.1007/s00382-016-3019-5

464 Young, Matthew, Feyrer, F., Fong, D., Johnson, R., Kraus, T., Larwood, V., Stumpner, E., Young, Megan, 2022.
465 Ocean connectivity drives trophic support for consumers in an intermittently closed coastal lagoon.
466 Estuar. Coast. Shelf Sci. 264, 107665. https://doi.org/10.1016/j.ecss.2021.107665

467 Zanchettin, D., Bruni, S., Raicich, F., Lionello, P., Adloff, F., Androsov, A., 2021. Sea-level rise in Venice : historic
468 and future trends (review article) 2643–2678.

469

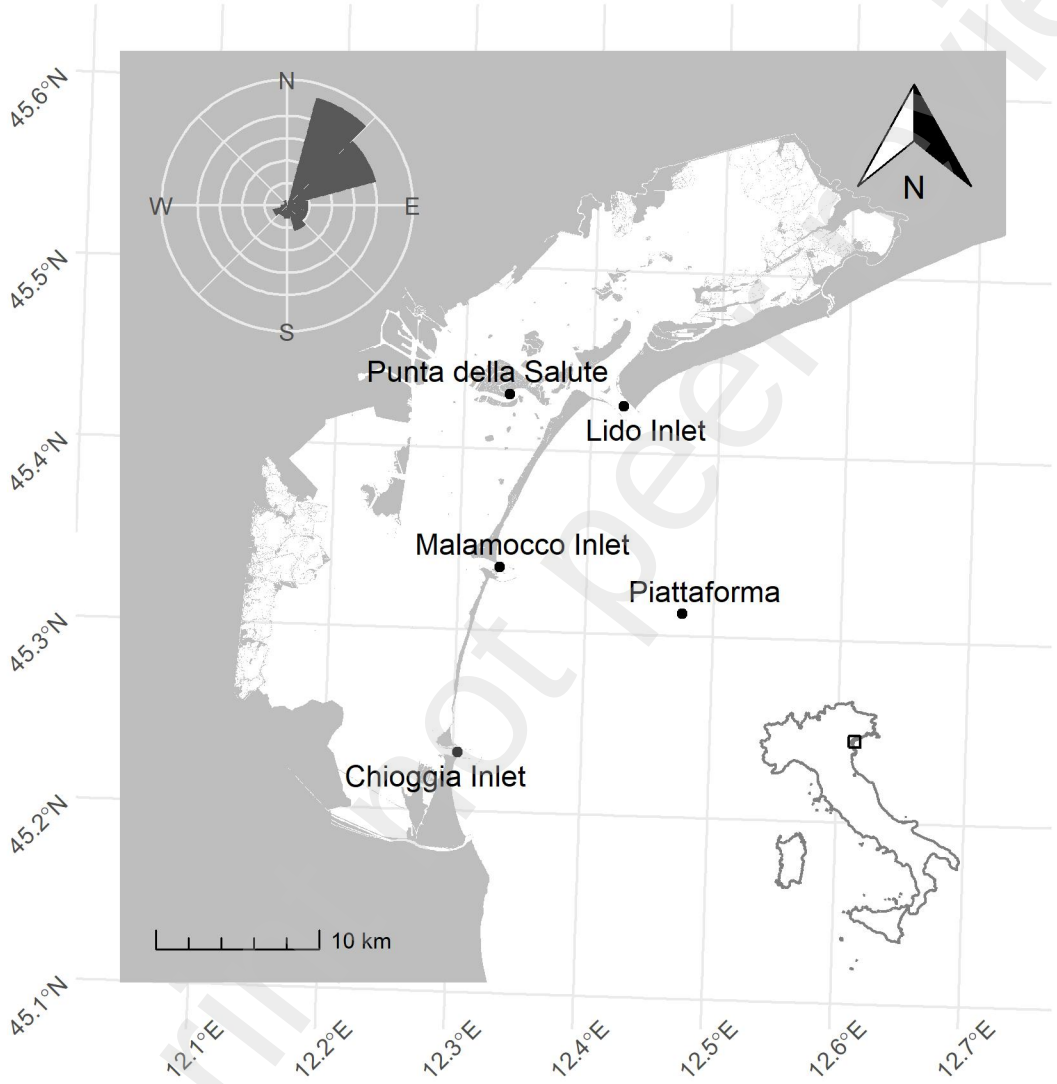
470

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

Figures

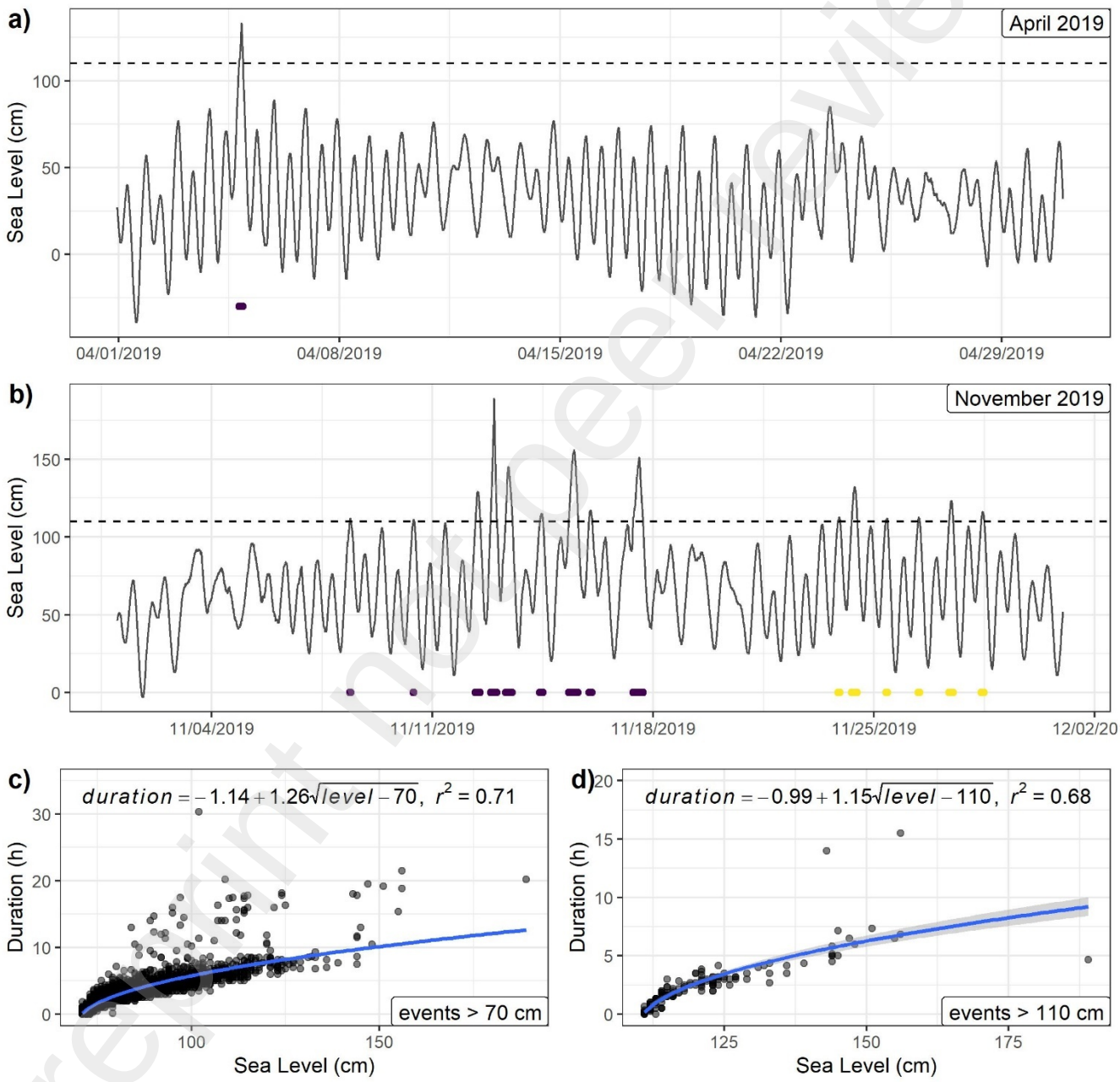
Figure 1 – Map of the Venice Lagoon with the position of the three inlets and the two tide gauges used in this study. The top-right insert is the wind direction for wind speeds greater than 5.5 m/s (class 4 in Beaufort scale) measured at Piattaforma station for the period 2010 - 2021. Note the prevalence of NE winds (*Bora*).



Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

477 **Figure 2** - Tide characteristic with highlighted clusters (a, b), regressions used to fill the time series (c,d). The
478 dashed line in plots a) and b) is the + 110 cm threshold for the flooding of the city. The colored lines below the
479 graph represent the peaks (sea level > + 110 cm). Different colors highlight different clusters. Note that the
480 cluster in April 2019 has a single peak, while the two clusters in November 2019 have multiple peaks each.



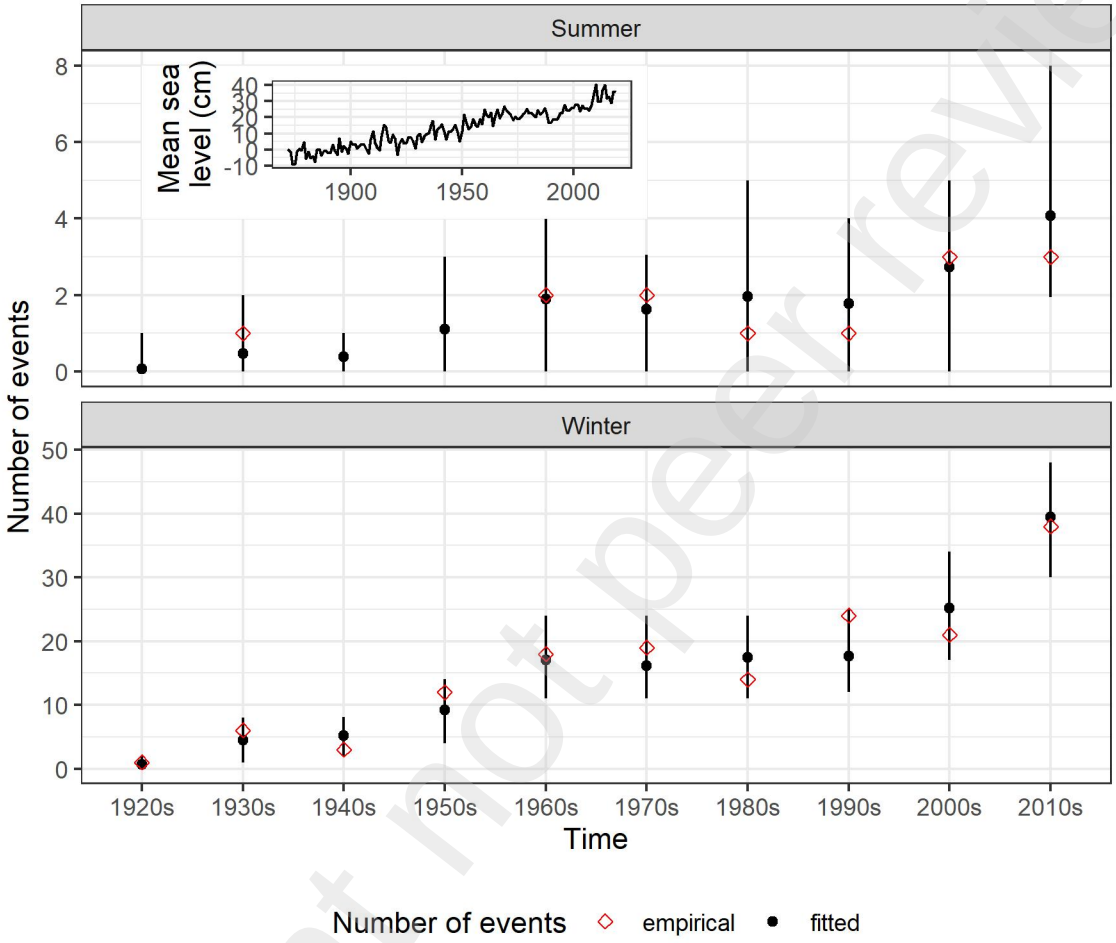
481

482

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

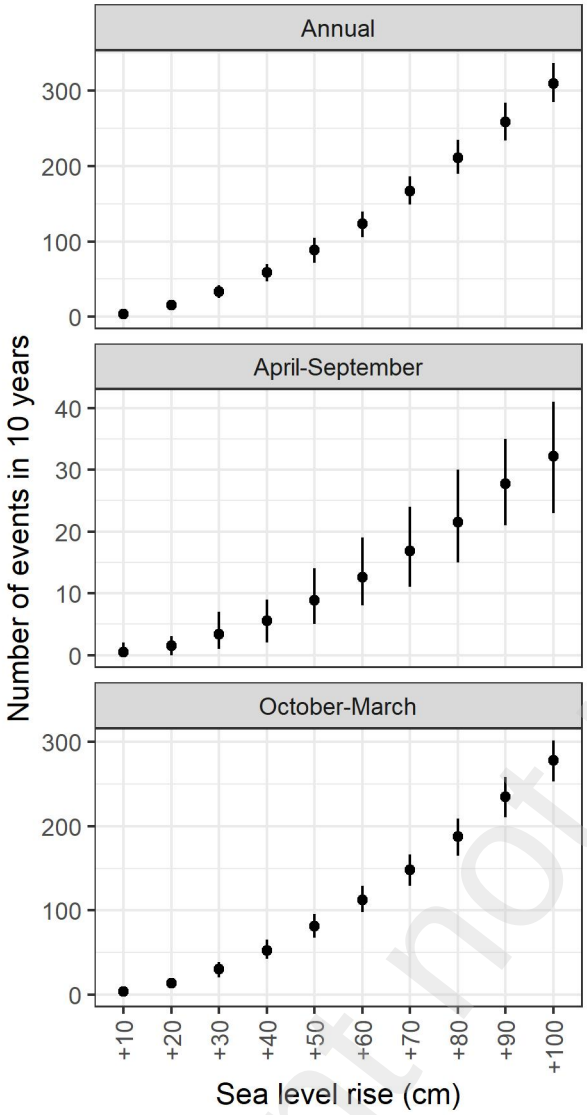
Figure 3 – Comparison between fitted and empirical number of clusters aggregated by decade. Summer refers to April – September period, Winter refers to November – March. The insert represents the annual mean sea level trend for the last 150 years. In decades where no extreme sea levels were recorded, the empirical data point is not shown.



Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

Figure 4 – Number of clusters (mean and confidence bounds) occurring in a period of 10 years for different values of sea level rise.

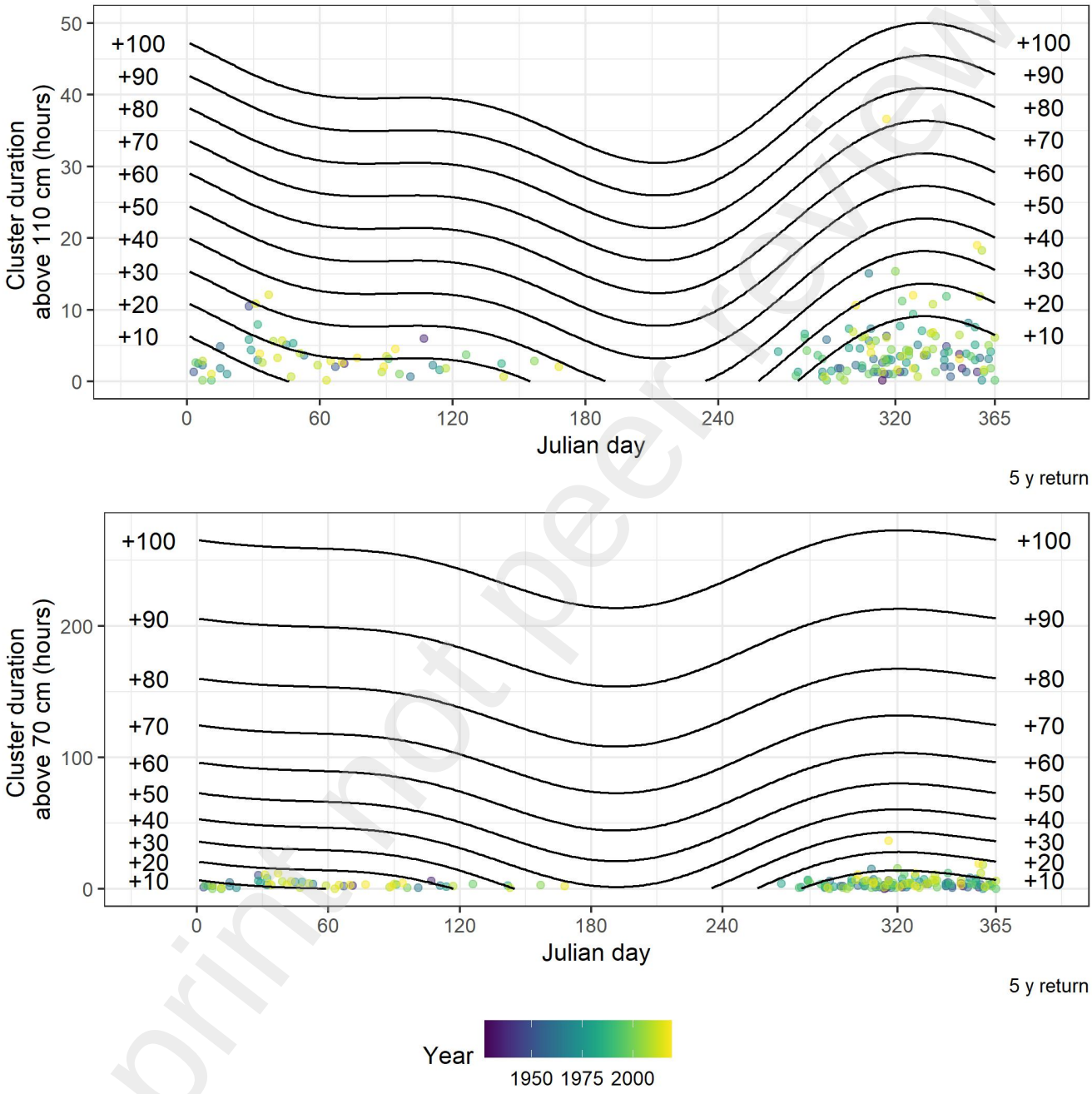


Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

493 **Figure 5** – Duration of clusters predicted under different sea level rise values. The dots represent the peacks over

494 the threshold used to fit the point process on duration.



495

496

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619

497 **Tables**

498 **Table 1** – Coefficients of the covariates for the Point Process models for extremes frequency and duration. Refer
499 to Eq. 3 for the terms to which coefficients refer. Numbers in the parenthesis represent the confidence interval
500 from the maximum likelihood estimation.

Model	Parameter	β_0	β_1	β_2	β_3	β_4	β_5
Frequency	$\ln(\lambda)$	-12.1 (-13.7,-10.6)	2.09 (1.539,2.64)	-	-0.52 (-0.86,-0.19)	-0.79 (-1.03,-0.56)	1.92 (1.45,2.39)
Duration > 70 cm	μ	-29.4 (-42.1,-16.7)	25.5 (12.9,38.2)	-1.68 (-6.4,3.05)	-8.1 (-13.9,-2.24)	-5.46 (-10.0,-0.84)	1.08 (0.73,1.44)
	$\ln(\sigma)$	1.26 (0.65,1.87)	-	-	-	-	0.03 (0.01,0.05)
Duration > 110 cm	μ	-11.1 (-14.3,-7.7)	7.36 (5.52,9.2)	-0.49 (-1.89,0.91)	-3.91 (-5.41,-2.4)	-	0.45 (0.33,0.58)
	$\ln(\sigma)$	4.11 (3.61,4.62)	-	-	-	-	-

501

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4188619