https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Discussions

Extremes floods of Venice: characteristics, dynamics, past and future evolution

Piero Lionello[1], David Barriopedro[2], Christian Ferrarin[3], Robert J. Nicholls[5], Mirko Orlic[4], Fabio Raicich[6], Marco Reale[7], Georg Umgiesser[3], Michalis Vousdoukas[8], Davide Zanchettin[9]

[1]University of Salento, DiSTeBA - Department of Biological and Environmental Sciences and Technologies, via per Monteroni, 165, Lecce, Italy and EuroMediterranean Center on Climate Change
[2]Instituto de Geociencias (IGEO), CSIC-UCM, C/Doctor Severo Ochoa 7, 28040 Madrid, Spain
[3]CNR - National Research Council of Italy, ISMAR - Marine Sciences Institute, Castello 2737/F, 30122, Venezia, Italy
[4]Department of Geophysics, Faculty of Science, University of Zagreb, Croatia
[5]Tyndall Centre for Climate Change Research, University of East Anglia. Norwich NR4 7TJ, United Kingdom
[6]CNR, Institute of Marine Sciences, AREA Science Park Q2 bldg., SS14 km 163.5, Basovizza, 34149 Trieste, Italy
[7]Abdus Salam ICTP and National Institute of Oceanography and Applied Geophysics - OGS, via Beirut 2-4, Trieste, Italy
[8]European Commission, Joint Research Centre (JRC), Ispra, Italy
[9]University Ca' Foscari of Venice, Dept. of Environmental Sciences, Informatics and Statistics, Via Torino 155, 30172 Mestre, Italy

Correspondence to: Piero Lionello (piero.lionello@unisalento.it)

Abstract

Floods in the Venice city centre result from the superposition of several factors: astronomical tides, seiches and atmospherically forced fluctuations, which include storm surges, meteotsunamis, and surges caused by planetary waves. All these factors can contribute to positive sea-level anomalies individually and can also result in extreme sea-level events when they act constructively. The largest extreme sea level events have been mostly caused by storm surges produced by the Sirocco winds. This leads to a characteristic seasonal cycle, with the largest and most frequent events occurring from November to March. Storm surges can be produced by cyclones whose centers are located either north or south of the Alps. The most intense historical events have been produced by cyclogenesis in the western Mediterranean, to the west of the main cyclogenetic area of the Mediterranean region in the Gulf of Genoa. Only a small fraction of the interannual variability of extreme sea levels is described by fluctuations in the dominant patterns of atmospheric circulation variability over the Euro-Atlantic sector. Therefore, decadal fluctuations of sea-level extremes remain largely unexplained. In particular, the effect of the 11-year solar cycle appears to be small, non-stationary or masked by other factors. The historic increase in the frequency of extreme sea levels since the mid 19th Century is explained by relative sea level rise, with no long term trend in the intensity of the atmospheric forcing. Analogously, future regional relative mean sea level rise will be the most important driver of increasing duration and intensity of Venice floods through this century, overwhelming the small decrease in marine storminess projected during the 21 century. Consequently, the future increase of extreme sea levels covers a large range, partly reflecting the highly uncertain mass contributions to future mean sea level rise from the melting of Antarctica and Greenland ice-sheets, especially towards the end of the century. In conclusion, for a high emission scenario the magnitude of 1-in-100 year sea level events at the North Adriatic coast is projected to increase up to 65% and 160% in 2050 and 2100, respectively, with respect to the present value, and subject to continued increase

thereafter. Local subsidence can further contribute to the future increase of extreme sea levels. This analysis shows the need for adaptive planning of coastal defenses with solutions that can be adopted to face the large range of plausible future sea-level extremes.

1. Introduction

This paper reviews current understanding on the extreme water levels that are responsible for the damaging floods affecting the Venice city center, such as the event on 4th November 1966, which produced estimated damages of 400 million euros (De Zolt *et al.*, 2006), or the event on 12 November 2019 (Cavaleri *et al.*, 2020), with estimated damage of 460 million euros[1] and extensive global media coverage. Future extreme floods could produce dramatic damages and losses of a unique monumental and cultural heritage. Potential damages have been often linked to future relative sea level rise. They have been estimated billion euros by the mid of this century if relative sea level rise (RSL) continues at the observed rate for the 20th century (an unrealistic scenario based on recent trends and model projections) and reach 8 and 16 billion euros in severe and high-end RSL rise scenarios, respectively (Caporin and Fontini, 2016). These estimates ignore adaptation options. However, they show the large exposure and the values at stake. In order to prevent damages and losses of a unique monumental and cultural heritage, in 1994 the Italian government approved the construction of a system of mobile barriers (MoSE, Modulo Sperimentale Elettromeccanico) to prevent the flooding of Venice during high sea level events. MoSE's construction was initiated in 2003 and it has been successfully tested in October 2020. The understanding of the dynamics leading to extreme water levels and the future evolution of their height and frequency is of paramount importance for an accurate assessment of present and future risks. This can provide information for efficient management of implemented defence systems (see also Umgiesser et al., 2020, in this special issue), assessing their effectiveness in the framework of the future increase of extreme sea levels and the development of new strategies to cope with future scenarios (see also Zanchettin et al., 2020, and Lionello et al., 2020 in this special issue).

A clear relationship exists between the frequency of floods and RSL rise. However, this is not the only factor playing a role in flooding. Section 2.1 provides a general framework for the identification of the different contributors to RSL anomalies. They include a diversity of factors acting at different time scales. Extreme water levels are caused by weekly to hourly atmospheric forcing, and affected by long-term (seasonal to decadal) sea level variability, which in turn depends on the long-term (centennial) RSL trends (section 2.1). The timing of the surges produced by the atmospheric forcing with respect to the phase of astronomical tide and free oscillations (seiches) can substantially affect the actual maximum sea level (sections 2.1 and 2.2). In fact, the length of the basin and the average speed of barotropic shallow water waves combine in such a way that the period of the free oscillations is close to the diurnal and semidiurnal components. Therefore, the basin is close to resonant conditions and the North Adriatic has the largest tides in the Mediterranean Sea (more than 1 m at the northern end of the basin), which is relevant for extreme sea levels in Venice (Figure 1). The combination of all these forcings largely explains the historical floods, which are to some extent heterogeneous in terms of the leading factors(see section 2.2 and appendix A1). Storm surges often yield the largest contribution to extreme sea levels and in the Adriatic Sea they are caused by cyclones (as described in section 3.1). An important characteristic of the Adriatic Sea (particularly its northern area) is its proximity to the cyclogenesis area in the western Mediterranean Sea, where cyclones initiate their south-eastward propagation along the Mediterranean storm track and (in a small number of

[1] https://repository.tudelft.nl/islandora/object/uuid:ea34a719-79c1-4c6e-b886-e0d92407bc9d?collection=education

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

cases) towards central Europe (e.g., (Lionello *et al.*, 2016). In autumn and winter, the area around the Adriatic Sea is frequently crossed by these cyclones. The resulting south-easterly wind (Sirocco) when channeled along the main axis of the basin by the action of the Apennines and Dinaric Alps is essential for producing the storm surge contribution to the extreme sea levels in the northern Adriatic Sea and floods of Venice. Extreme sea levels have also been associated with large-scale atmospheric variability and astronomical (solar) forcing. Available evidence of these links and their dynamics are reviewed in 3.2.and 3.3.

A major concern is the future evolution of sea level extremes. Section 4 is devoted to past and future changes in the frequency and magnitude of sea level extremes, and the relative roles of RSL rise and atmospheric forcing at different time scales. Section 4 also considers the most recent estimates of the future extreme sea levels and their dependence with the climate scenarios. The last section 5 provides a general assessment of the existing knowledge and indications on major gaps and needs for future research.

2. Dynamics and characteristics of sea level evolution during an extreme flood

2.1. Tides, seiches and atmospherically forced sea level anomalies

This section describes the factors that contribute to sea level anomalies in the North Adriatic Sea: astronomical tides, seiches and atmospherically forced fluctuations (which include meteotsunamis, storm surges and surges caused by planetary waves) and relative sea level rise (RSLR). They are characterized by different dynamics and time scales. In general, they do not have the same importance in terms of contribution to extreme sea level events, which have mostly been attributed to large storm surges, whose effect was reinforced or attenuated by the remaining factors. The classification of the atmospherically forced fluctuations in three categories is based on the scale of the meteorological forcing process: mesoscale (tens of kilometres, minutes to hours), synoptic scale (thousands of kilometres, days) and planetary scale (tens of thousands of kilometres, weeks to months). At longer time scales, inter-decadal, inter-annual and seasonal (IDAS) sea level variability, natural and human induced land subsidence, and sea level rise (SLR) also contribute to sea level extremes by modulating the long-term evolution of relative sea level.

Astronomical tides in the Adriatic Sea consist of two Kelvin waves oppositely travelling along the basin at semidiurnal periods (Hendershott and Speranza, 1971) and of topographic waves travelling across the basin at diurnal periods (Malačič, Viezzoli and Cushman-Roisi, 2000). They are adequately reproduced by a number of numerical models (e.g. (Janeković and Kuzmić, 2005; Lionello, Mufato and Tomasin, 2005; Ferrarin, Maicu and Umgiesser, 2017). Diurnal and semidiurnal components have their maximum amplitude at the northern shore of the basin. The semidiurnal components have an amphidromic point in the centre of the Adriatic (Franco *et al.*, 1982).

Seiches in the Adriatic are standing waves with a node at the southern boundary of the basin and an antinode at the northern shore. The periods of the basic modes are estimated at about 21.3 h and 10.8 h (Manca, Mosetti and Zennaro, 1974) and their pattern mimics the diurnal and semidiurnal tides, respectively. Seiches are commonly produced after a surge, when the wind drops or switches from Sirocco (south-easterly) to Bora (north-easterly) and the water accumulation in the north Adriatic is ceases to be supported by the wind stress. The Adriatic seiches are damped relatively slowly, with the decay time of fundamental mode amounting to 3.2 days (Cerovečki, Orlić and Hendershott, 1997), due to a weak frictional dissipation inside the basin and a small energy loss to the Mediterranean Sea. There is a long tradition of numerical modelling of the Adriatic seiches, e.g. (Lionello, Mufato and Tomasin, 2005), but more accurate predictions of their periods and decay are still needed, e.g., (Bajo *et al.*, 2019).

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Storm surges in the Adriatic have been extensively studied due to the need to forecast the floods of Venice (Robinson, Tomasin and Artegiani, 1973), see Umgiesser et al., 2020 in this issue for a review. The response of the sea to air pressure forcing is close to the inverted barometer effect at daily time scales , e.g., (Karabeg and Orlić, 1982). However, the surge magnitude is mostly determined by the wind blowing over the shallow water areas over the North Adriatic Sea. The wind contribution to sea level along the Northern coast is typically 10 times larger than the inverse barometer effect (Bargagli *et al.*, 2002; Conte and Lionello, 2013; Lionello, Conte and Reale, 2019). Surges are produced by two main winds: Sirocco blowing over the whole basin and a combination of Bora over the north Adriatic and Sirocco over the south Adriatic. Depending on the structure of the wind field, flooding is more pronounced along the west or the east Adriatic coast (Međugorac *et al.*, 2018).

Meteotsunamis are meteorologically-generated long ocean waves in the tsunami frequency band (Vilibić and Šepić, 2009; Šepić, Vilibić and Belušić, 2009). They are generated by mesoscale air pressure disturbances that resonantly generate a traveling sea level anomaly, when their speeds of propagation approach that of the shallow-water barotropic waves. Meteotsunamis pose a major hazard on the eastern Adriatic coast, where their resonant periods are close to those of the normal modes of the bays/harbors.

Long planetary atmospheric waves (PAW) propagate slowly and with wavelengths ranging from 6000 to 8000 km. They produce a long-term meteorological forcing and eventually long-lasting sea level anomalies (***PAW surges***), which establish favorable day-lasting conditions for flooding (Pasarić and Orlić, 2001).

The combination of storm surge, meteotsunamis and PAW surge represents the direct action of the meteorological forcing on extreme sea levels and it is collectively termed **surge** in this manuscript, when no distinction is possible among the different contributions.

The factors considered so far allow an interpretation of a typical flood (“aqua alta”, e.g. Robinson et al., 1973). When a cyclone moves from western Mediterranean towards the Adriatic, low air pressure and Sirocco wind support an increase of sea level in the northern Adriatic Sea and potential flooding of the area. When the cyclone leaves the Adriatic area, air pressure increases while the Sirocco slackens or changes to Bora. Consequently, sea level decreases and seiches may be generated. Therefore, in the Adriatic storm surges and seiches represent two distinct phases of the response to the atmospheric forcing, one in which sea level rises under direct atmospheric forcing, and the other in which sea level relaxes – possibly through a series of damped oscillations. If a successive storm surge develops before the attenuation of the seiches induced by a previous event, a constructive or destructive superposition may occur (Bajo *et al.*, 2019). Analogously, the phase of tide during the period when the storm surge is large, can substantially increase or decrease the actual sea level maximum.

The contribution of meteotsunamis and PAW surges to extreme sea-level events in Venice has not been thoroughly investigated to date. However, the recent 12 November 2019 event uncovered their important role in flooding in Venice. Therefore, in general, the hazard and probability of an extreme sea level should also include these two contributions.

RSLR represents a long-term process (see Zanchettin et al. 2020, in this special issue, for a comprehensive review of its past and future evolution). It has been the dominant factor responsible for the significant increase of frequency of floods of the Venice city centre (Lionello *et al.*, 2012b). This is further modulated by IDAS sea-level variability.

Natural Hazards and Earth System Sciences
Discussions

2.2. A description of the largest past events

Regular instrumental observations in Venice started in 1871. Since 1919 sea-level values have been referred to the mean sea level over the 1884-1909 period (central year 1897),which is usually called 'Zero Mareografico Punta Salute' (ZMPS), and referred to as relative sea level (RSL). The history of Venice tide gauges, their reference planes and the related geodetic connections were described and discussed by (Dorigo, 1961a) and (Battistin and Canestrelli, 2006). (Battistin and Canestrelli 2006) reviewed the observations from 1872 to 2004 and provided a complete list of high and low sea-level data with the relevant primary data sources. Sea-level data are also available in the web sites of the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Servizio Laguna di Venezia (www.venezia.isprambiente.it), and the Centro Previsione e Segnalazione Maree of Venice municipality (www.comune.venezia.it/content/centro-previsione-e-segnalazione.maree).

The Venice Municipality defines a high RSL event ('aqua alta') when relative sea level (RSL) exceeds 80 cm (above ZMPS), a severe event when it exceeds 110 cm and an exceptional event when it exceeds 140 cm. Since 1872, the 140-cm threshold has been exceeded during 18 events. Depending on the phase of the astronomical tide and of other factors, very high RSL can or cannot correspond to very high storm surge. Table 1 list the highest RSL events[2] alongside the contributions of various factors (in a similar way as previously done by (Orlić, 2001):

RELATIVE EXTREME SEA LEVEL: STORM SURGE + PAW SURGE + METEOTSUNAMI + ASTRONOMICAL TIDE + SEICHE + IDAS VARIABILITY + RSLR

For computing the values in table 1, the long-term water level time series of Punta della Salute was processed with a tidal harmonic analysis tool based on the least squares fitting (Codiga, 2011) to separate the tidal from the other contributions to the total sea level. The residual sea levels were detrended for RSLR using a 10-year centered running mean. The other contributions (storm surge, PAW surge, meteotsunami, local setup, seiche, IDAS variability) were estimated using digital filters (low pass, band pass and high pass, as described in Ferrarin et al., 2020) in the time domain assuming Fourier decomposition. The value separating storm surge and PAW surge was set to 10 days and that the corresponding value for storm surge and meteotsunami (including also local set-up in the lagoon) was set to 10 hours. The separation between the PAW surges and IDAS variability was achieved by applying a low pass filter with the cut-off period placed at 120 days.

Overall, the events listed in Table 1 agree with the ones compiled in other studies since the beginning of instrumental observations (Dorigo, 1961b; Livio, 1968; Canestrelli *et al.*, 2001). The event of 4 November 1966 corresponds to both the highest surge and the highest RSL. Other outstanding events are those observed on 22 December 1979 and 12 November 2019.

The event of 29 October 2018 consists of two peaks that occurred 6 hours apart, with similar RSL values (148 and 156 cm), but quite different phases of the astronomical tide, so that the higher water level corresponds to the lower storm surge. This is the only example in 147 years of two such high RSL peaks in such a short time interval. November 2019 is also peculiar because four RSL peaks with at least 140 cm height occurred on 12, 13, 15 and 17. The event of 12 November 2019 was particularly severe, reaching 189 cm RSL. This was the second highest ever recorded RSL. In this case the storm surge was relatively modest, and the exceptional water level was caused by the superposition of PAW surges,

[2] Some significant surges may have been missed before 1933 due to lack of information, while all the high RSL events are available since 1872.

positive astronomical tide and an unprecedented contribution caused by a meteotsunami. It should be stressed that four of the eight highest RSL values since 1872 were observed during the autumn seasons of 2018 and 2019.

The amplitude of the astronomical tide makes it an important contribution to the actual sea-level extreme and time lag between the surge peak and the nearest astronomical tide maximum may make a substantial difference. Considering the events described in Appendix 1, if surge and tide had peaked together, the observed RSL, based on the linear superposition of the different factors (a reasonable first-order approximation for the Adriatic Sea) would have approximately been 220 cm, both on 4 November 1966 and 29 October 2018 (second peak), and 215 cm on 12 November 1951. Particularly, for the second peak of 29 October 2018 the large magnitude of negative astronomical tide contribution has an essential role to limit the impact of the event. On the contrary, the coincidence of a moderate storm surge with a preexisting seiche and a high astronomical tide level produced the sixth highest level in the records.

In conclusion, the comparison among the different contributions in Table1 shows that storm surge represents often the largest contribution, but, in several cases, also other factors play a fundamental role. Particularly, in the case of 12 November 2019, the second highest ever-recorded sea level has been produced by comparable contribution from several factors, with a storm surge value, which was not particularly high.

The meteorological and marine conditions that led to major surge events have been assessed with reanalyses and dedicated model simulations, including the catastrophic storm surges of 4 November 1966 (De Zolt *et al.*, 2006; Roland *et al.*, 2009; Cavaleri *et al.*, 2010), 22 December 1979 (Cavaleri *et al.*, 2010), 1 December 2008 (Međugorac, Pasarić and Orlić, 2016), 1 November 2012 (Međugorac, Pasarić and Orlić, 2016), 12 November 2019 (ISPRA and CNR-ISMAR, 2020). Bertotti *et al.* (2011) modelled five important events that occurred between 1966 and 2008. Appendix 1 includes the descriptions of major surge and RSL events and related meteorological situations.

The frequency of storm surges follows a strong seasonal cycle (Lionello *et al.*, 2012b). The most intense events (with maxima above the 99th percentile) occur in November and December, with November concentrating the largest number of intense events. However, severe events (maxima above the 80th percentile) can occur from late September to early May, and, very rarely also in summer.

2.3. The propagation of the sea-level signal in the interior of the lagoon

North Adriatic sea-level anomalies first propagate into the lagoon through the three inlets, and then follow the tidal channels. The major channels are up to 10 meters deep, and this results in a propagation speed of about 10 m/s (Umgiesser *et al.*, 2004). The water then expands laterally into the shallow flats, where propagation of the wave is much slower.

Astronomical tides in the southern and central basins of the lagoon are slightly amplified with respect to the inlets, because of resonance effects between the tide (both diurnal and semidiurnal) and the size of the basin. In the northern part of the lagoon, characterized by mud flats, islands and salt marshes, dissipative processes dominate over the resonance condition, so that the tidal wave shows an attenuation of about 50 % of the incoming tide (Ferrarin *et al.*, 2015). As a consequence of natural and anthropogenic morphological changes that occurred in the lagoon in the last century, the amplitude of major diurnal and semi-diurnal tidal constituents grew significantly, with a consequent increase in extreme high sea levels in Venice (Ferrarin *et al.*, 2015).

The surge signal, once it has entered inside the lagoon, is able to propagate nearly without damping to the city center, where sea levels are comparable to the ones close to the inlets with a typical 1 hour delay (Umgiesser *et al.*, 2004). Other more remote areas of the lagoon show a higher phase shift with respect to the inlets of up to 3 hours.

With strong NE (Bora) or SE (Sirocco) winds, the difference between sea levels in the south and the north side of the lagoon may exceed 50 cm (Mel, Carniello and D'Alpaos, 2019). The Venice city center is relatively little affected by these differences, since it is close to the node of the oscillation of the water level. However, the strong setup at the southern part of the lagoon can lead to flooding in the city of Chioggia.

3. Atmospheric patterns associated with extreme storm surges

3.1. Characteristics of cyclones producing storm surges and floods of Venice

The Mediterranean region is one of the areas in the Northern Hemisphere where cyclone activity is more frequent due to a wide range of factors and mechanisms acting in the region which favor several cyclogenesis processes (Trigo, Davies and Bigg, 1999; Lionello *et al.*, 2006a; Ulbrich, Leckebusch and Pinto, 2009; Lionello *et al.*, 2012a; Ulbrich *et al.*, 2012; Lionello *et al.*, 2016). These systems are often associated with extreme weather events (Jansa *et al.*, 2001; Lionello *et al.*, 2006a; Toreti *et al.*, 2010; Ulbrich *et al.*, 2012; Reale and Lionello, 2013) and, more specifically, with large storm surges along the Mediterranean coastline and floods of Venice (Canestrelli *et al.*, 2001; Trigo and Davies, 2002; De Zolt *et al.*, 2006; Lionello *et al.*, 2012b; Lionello, Conte and Reale, 2019). Cyclones produce storm surges by two mechanisms: the inverse barometric effects (resulting from the decrease of atmospheric pressure during the cyclone transit over the area) and the wind set-up (caused by the intense cyclonic air flow, typically Sirocco, channelled by the topography along the main axis of the Adriatic Sea, which piles up water masses against the coast of the Northern Adriatic (Lionello, Conte and Reale, 2019).

Figure 2 shows the temporal evolution of mean sea-level pressure (MSLP) fields during intense storm surge events. It is a composite based on the floods with storm surge higher than 50 cm in Venice in the period 1979-2019 (Table 1) using the hourly MSLP fields of ERA5 reanalysis (Hersbach *et al.*, 2020). The time lags chosen for the composites is 36, 24 , 12 hours before and 12, 24 hours after the peak of the event (reported in Table 1). Figure 3 shows the same information, though it is based on the remaining events in table 1, when the storm surge component did not exceed 50cm. In both figures at the peak of the event, the pressure minimum is located in the Gulf of Genoa, but in figure 2 the cyclone is deeper and the SLP gradient along the Adriatic Sea is larger. Further, the evolution of the cyclone before and after the peak of the sea-level anomaly is different. In figure 2 cyclogenesis occurs in the western Mediterranean Sea (as noted in (Lionello *et al.*, 2012b), close to the Iberian coast, as a minimum well separated from the background field. In figure 3 cyclogenesis occurs in the northwestern Mediterranean Sea within the flow produced by a preexisting cyclone, whose center is located north of the Alps. In both figures the lee cyclogenesis processes and the generation of a secondary minimum is evident (Trigo and Davies, 2002; Lionello, 2005; Lionello *et al.*, 2012b; Lionello, Conte and Reale, 2019) and the pressure gradient along the Adriatic Sea intensifies and becomes almost parallel to the basin coastlines. This synoptic configuration produces a decrease of the atmospheric pressure above North Italy and an increase of intensity of atmospheric flow in the Adriatic Sea directed towards its northern coast, which results in the increase of sea level in Venice e.g. (Lionello *et al.*, 1998).

Figure 4 shows the density (contours) of tracks of cyclones (measured as % relative frequency of cyclones in each cell of 1.5 degree) producing relative sea level higher than 110 cm (https://www.comune.venezia.it/it/content/grafici-e-statistiche) in the period 1979-2019. The figures report also the tracks of all cyclones that are listed in table 1 (cyan colour), of November 4th 1966 (blu line), the Vaia storm 29 October 2018 (red line) and of 12 November 2019 (green

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Discussions

line). Cyclone tracks shown in Figure 4 have been identified with an automatic detection and tracking scheme (Lionello, Dalan and Elvini, 2002) to the ERA-5 MSLP fields.

The density of track shown in Figure 4 is characterized, in the Atlantic sector, by a peculiar north-west/south-east direction which is different from the usual south-west/north-east direction observed in Atlantic (Neu *et al.*, 2013; Ulbrich *et al.*, 2013; Reale *et al.*, 2019). Moreover, the density of track has a maximum in the Western Mediterranean. As shown in Lionello et al., 2012 the tracks of cyclones producing the strongest event (Table 1 and Figure 2) have distinctive characteristics with respect to the majority of cyclones crossing the Mediterranean Sea. As shown in Figure 4 many of these systems enter the region from the West/South West and follow a North-East direction. On the other hand, the majority of Mediterranean cyclones originate in the gulf of Genoa and follow a South-East direction (Trigo, Bigg and Davies, 2002; Trigo, Davies and Bigg, 1999; Lionello *et al.*, 2006b; Ulbrich *et al.*, 2012; Lionello *et al.*, 2016). More recent studies suggest that a phase-locking of the cyclone with respect to the basin seems to be critical to provide the optimal conditions for surge events, with small variations in its position inducing a veering of the onshore wind and even opposite responses in sea level (Lionello, Conte and Reale, 2019).

The diversity of triggering cyclones is also evidenced from a cluster analysis of the daily atmospheric fields associated with autumn surge events in Venice (Figure 5). When all extreme surges are considered (Fig. 5a), the resulting pattern resembles that of Figures 2 and 3 at the peak of the event, since the majority of extreme surge events occur in autumn (see next section). However, the composite has a considerable spread (as measured by the root mean squared difference, RMSD), which can be reduced by progressively discriminating types of events with a k-means analysis (Fig. 5b). Two clusters bring the steepest decrease in the RMSD distribution and capture the distinction between cyclones to the north and south of the Alps (Figs. 5c,d) already reported by (Lionello, 2005).

3.2. Links to large scale patterns

Several studies have investigated links between the main modes of atmospheric circulation variability and high surges in Venice (Fagherazzi *et al.*, 2005; Lionello, 2005; Zanchettin *et al.*, 2009; Barriopedro *et al.*, 2010; Martínez-Asensio, Tsimplis and Calafat, 2016).

The North Atlantic Oscillation (NAO) has been found to exert no significant influence on extreme surges, which are linked to a different large scale circulation pattern (Lionello, 2005), being the East Atlantic (EA; (Martínez-Asensio *et al.*, 2014; Martínez-Asensio, Tsimplis and Calafat, 2016) or the East Atlantic Western Russia (EAWR; (Fagherazzi *et al.*, 2005) the teleconnection patterns that exert the largest influence on their seasonal characteristics. Another study found that the negative phase of the NAO is associated with both high mean sea level and floods in Venice (Zanchettin *et al.*, 2009), although this signal is absent in autumn (when surges are larger). Differences in the large-scale seasonal mean atmospheric circulation between active years (autumns with at least one high surge) and quiet years (autumns with no high surge) have been reported (Barriopedro *et al.*, 2010). The favorable seasonal pattern for the occurrence of autumn surges displays a wave train with a negative pressure center in central Europe bounded by two high pressure anomalies.

The aforementioned relationships are often weak, though, and hence potentially sensitive to metrics, thresholds and analyzed periods. This blurred influence of teleconnection patterns is not surprising, taking into account that seasonally averaged indices do not necessarily capture short-term fluctuations, and that favorable synoptic conditions (see Fig. 5) might occur under different large-scale configurations. To avoid this, a Weather Regime (WR) approach is adopted herein, which predefines a number of recurrent large-scale atmospheric circulation patterns and assigns each day to one of them.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Following (Garrido-Perez *et al.*, 2020), we considered eight WRs, which yields a fair representation of the variability all-year round. Almost half of the extreme sea levels[3] in Venice are associated with the Atlantic Low (AL) WR (Figure 6a), whose canonical pattern (Figure 6b) strongly resembles that of Fig. 5d and of Figure 8.6 of (Lionello 2005). The remaining cases (arguably many of the Mediterranean cyclones included in Fig. 5c) occur under different WRs without a clear preference, although some anticyclonic WRs (e.g. the Atlantic High) are unfavorable for extreme sea levels. Despite the strong association with AL on daily scales, the seasonal frequency series of AL days yields little skill on the corresponding occurrence of extreme surges (rho=0.26 for 1948-2018, $p<0.05$), which is similar to that obtained from other less influential WRs (e.g. Zonal Regime, rho=0.27; $p<0.05$). This illustrates that the interannual variability of seasonal extreme sea levels cannot be well described by fluctuations in the dominant patterns of atmospheric circulation variability over the Euro-Atlantic sector.

3.3. The role of solar cycles on extreme floods

Some studies have reported decadal fluctuations in the frequency of extreme surges in phase with the 11-yr solar cycle during the second half of the 20th century, such that periods of high solar activity have coincided with more frequent and persistent extreme surges in Venice (Tomasin, 2002; Lionello, 2005; Barriopedro *et al.*, 2010) and other Mediterranean coastal stations (Martínez-Asensio, Tsimplis and Calafat, 2016). This signal results from the atmospheric forcing on sea level, as revealed by hindcasts of a barotropic ocean model forced with observed atmospheric pressure and winds (Martínez-Asensio, Tsimplis and Calafat, 2016).

An unanswered question is how such small solar forcing modulates the tropospheric circulation over the Euro-Atlantic sector. Several hypotheses have been proposed, including decadal variations of the regional atmospheric circulation that promote the constructive interference with the favorable pattern for the occurrence of extreme surges during periods of high solar activity (Barriopedro *et al.*, 2010). Other studies claim for a solar modulation of the stratospheric polar vortex and a lagged response of the NAO, e.g. (Thiéblemont *et al.*, 2015) and reference therein). However, this mechanism would mainly affect the winter NAO, rather than the decadal variability of autumn extreme surges in Venice. In addition, modeling studies reveal negligible impacts of the 11-yr solar cycle on the NAO and demonstrate that decadal variations of the NAO can eventually vary in phase with the 11-yr solar cycle by random chance (Chiodo *et al.*, 2019). Given the lack of mechanistic understanding, the null hypothesis of internal variability cannot be rejected.

Indeed, an updated analysis of the longest series of daily RSL in Venice (Raicich, 2015) shows that the 11-yr solar signal is no longer evident in the frequency series of autumn extreme surges since the ~2000s, nor it was present before the ~1950s (Figure 7 top panel). Significant correlations are limited to the period from 1970 to 2000 (Figure7, bottom panel) and give rise to strong co-variability during the second half of the 20th century, coinciding with the Grand Solar Maxima covered by most studies. Further, there is no indication of the presence of a 11-year periodicity in the mean sea level and its extremes (figures III.1 and III.2). Therefore, either the solar signal is non-linear, non-stationary (arguably masked by other sources variability) or the decadal variability of extreme surges is due to other causes, likely internal variability. It is reasonable that, superimposed on the uncontroversial increasing frequency of Venice flooding due to the mean sea-level rise, large interannual-to-decadal variations will continue in the future, the causes of which are still uncertain.

[3] Events with maximum sea level above the 99.5th percentile of the 1948-2018 distribution

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

4. Past and future evolution

4.1. Past evolution and recent trends of floods and extreme sea levels

(Enzi and Camuffo, 1995) presented the most complete compilation of pre-instrumental extreme sea-level events observed in Venice by reviewing hundreds of historical documents, thus obtaining a sequence of over 100 events in the 787-1867 period. The long-term evolution has been studied by (Camuffo and Sturaro, 2004) combining information from documentary sources and instrumental observations. From 1200 to 1740 the flood frequency was <0.1 yr^{-1}, except for the Spörer period (1500-1540), when it was 0.63 yr^{-1}. Subsequently, the frequency increased from 0.19 yr^{-1} in 1830-1930 to 1.97 yr^{-1} in 1965-2000.

Former studies of recent trends (Trigo and Davies, 2002) found that in the second half of the 20th century the local mean sea-level rise compensated the decreasing frequency of storms, leading to no change in the frequency of floods. Other studies, found a significant positive trend of moderate surges in Venice and Trieste during the second half of the 20th century (1951-1996), that was attributed to increases in the frequency of Sirocco wind conditions over the central and southern Adriatic (Pirazzoli and Alberto, 2002). A more recent study considered data in the period 1940-2007, reporting a 4% reduction of all surges, but no significant increase in the frequency or intensity of the most extreme events if the effect of RSLR is subtracted to the sea-level data (Lionello *et al.*, 2012b). According to(Ferrarin *et al.*, 2015), the detected increase in amplitude of the tidal waves enhanced the occurrence of extreme high sea levels in Venice in the period 1940-2014, while changes in storminess had no significant long-term impact. Observations made in Venice and Chioggia allowed to extend the series of storm surges back to the second half of the 18th century (Raicich, 2015). For this longer period, the time series of surge frequency did not exhibit a significant long-term trend, but strong inter-annual and inter-decadal variability. In summary, the amount of current evidence shows that while the frequency of floods has clearly increased in time, there is no clear indication of a trend in either the frequency or the severity of extreme surge events. The long term increase of flood frequency is largely caused by the relative mean sea-level rise (connected to both climatic change and land subsidence, see Zanchettin et al 2020 in this special issue).

4.2. Future evolution of extreme sea levels

Several past studies considered the future evolution of storm surges in the Adriatic Sea. A first analysis was based on a doubled-CO_2 scenario and a single climate simulation (Lionello, Nizzero and Elvini, 2003). Successive studies adopted the SRES scenarios and multiple simulations (Marcos *et al.*, 2011; Lionello, Galati and Elvini, 2012; Troccoli *et al.*, 2012; Mel, Sterl and Lionello, 2013). The most recent studies have considered the whole Mediterranean Sea or large parts of it and an ensemble of simulations (Conte and Lionello, 2013; Androulidakis *et al.*, 2015; Vousdoukas *et al.*, 2016; Lionello *et al.*, 2017; Mentaschi *et al.*, 2017; Vousdoukas *et al.*, 2017; Vousdoukas *et al.*, 2018). All studies show a remarkable agreement on suggesting non-significant changes or even a significant reduction of the intensity of future surges, which might reach about 5% for the RCP8.5 emission scenario at the end of the 21st century. However, the future increase of relative mean sea level has been shown to be the dominant factor (Lionello *et al.*, 2017; Jackson and Jevrejeva, 2016; Jevrejeva *et al.*, 2016; Vousdoukas *et al.*, 2017; Vousdoukas *et al.*, 2018) and it will cause increase of frequency and height of floods. Only a very low rate of future sea-level rise, such as that hypothesized in (Troccoli *et al.*, 2012), might prevent future increase of floods. However, such a low future rate of rise is very unlikely (Jordà, Gomis and Marcos, 2012). It is lower than the global sea-level rise under the low RCP2.6 scenario in the IPCC SROCC (Oppenheimer *et al.*, 2019) and it would require relative sea level in Venice during the 21st century to be lower than observed during the 20th century (see also Zanchettin et al. 2020, in this issue).

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

The future variation of amplitude of tides and surges in response to sea-level rise will depend how the coast is adapted (Bamber and Aspinall, 2013) – protection versus retreat. (Lionello, Mufato and Tomasin, 2005) showed that a full compensation strategy (protection), preserving the present coastline by dams, would reduce the amplitude of tides and storm surges, while a no compensation strategy, allowing permanent flooding of the low coastal areas (retreat), would increase the amplitude of the diurnal components and the amplitude of storm surges at the North Adriatic coast. These effects are small, but not completely negligible, being about 10% for the diurnal component in case of 1-m sea-level rise.

Projections of extreme sea levels were produced combining dynamic simulations of all relevant components during the present century, and under RCP4.5 and RCP8.5 scenarios. They include: mean sea-level rise and sea-level anomalies driven by tides, surges and wind wave set-up (Vousdoukas *et al.*, 2017; Mentaschi *et al.*, 2017; Vousdoukas *et al.*, 2018). MSLs were produced through a probabilistic process-based framework (Jackson and Jevrejeva, 2016; Jevrejeva *et al.*, 2016), incorporating the large uncertainties originating from the Greenland and Antarctic ice sheets under RCP8.5 (Bamber and Aspinall, 2013). Values for different return periods were estimated using non-stationary extreme value statistical analysis (Mentaschi *et al.*, 2016). Here, the spatially average values along the north-west Adriatic coast (i.e. from the Po delta to the Gulf of Trieste) have been extracted from the above datasets, which have pan-European or global coverage.

The 100-year extreme sea level (100y-ESL) (Figure 8) at the North Adriatic Sea by 2050 is very likely (5-95th percentile) to rise by 5 to 23 cm under the RCP4.5 moderate-emission-mitigation-policy scenario and by 17 to 62 cm under the RCP8.5 high emissions scenario (Vousdoukas *et al.*, 2018). Similarly, rise to 20-38 cm and 48-175 cm, respectively, by the end of the century.

Breaking down the contributing factors to the increase in 100y-ESLs (Figure 9), thermal expansion accounts for 45% and 38% (median values) of the projected rise towards the end of the century, under RCP4.5 and RCP8.5, respectively while the Antarctica and Greenland ice sheet melting contribution vary from 15% to 23% (median values). However, the combined contributions from ice mass-loss from glaciers, and ice-sheets in Greenland and Antarctica together, are the dominant factor by 2100, contributing to 54% and 50% (median values) of the 100y-ESL increase under a moderate-emission-mitigation-policy scenario (RCP4.5) and a high emissions scenario (RCP8.5), respectively.

The increase in 100y-ESLs corresponds to more frequent occurrence of present 100y-ESL values. By the year 2050, the frequency of present-day 100-year events is projected to increase by 2 or 10 times (50 or 10 years) depending on the emissions scenario. By the end of this century, events with the severity of current 1-in-100-year ‘acqua alta’ would occur at least every 5 years under the RCP4.5 and more than once the RCP8.5 scenario, respectively.

5. Conclusions and outlook

There is a widespread view that extreme sea levels in the Venice city center are mostly caused by storm surges and that the actual maximum sea level depends substantially on the timing of the storm surge peak with respect to the phase of the astronomical tide. Consequently, efforts have traditionally focused on the correct simulation of the intensity, timing and spatial variability of the wind (mainly the Sirocco) for the accurate reproduction of sea-level extremes. This review confirms the paramount importance of storm surge, which produced the highest recorded flood (4 November 1966), but also identifies other phenomena that, though they individually produce lower sea-level anomalies than storm surge, can act constructively and yield extreme water levels. The event of 12 November 2019 (the second highest ever recorded flood) provides a good example. Therefore, research is required on PAW and meteotsunamis, the other synoptic drivers

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

of surges, including their joint distributions, in order to better understand the likelihood of compound events as that of November 2019.

Another poorly addressed factor is the influence of wave-set up and its effect on the sea-level anomalies inside the Venice lagoon. Some studies have considered it during individual storms affecting Venice (Bertotti and Cavaleri, 1985; LIONELLO, 1995; De Zolt *et al.*, 2006) and in 100y-ESL projections (Vousdoukas *et al.*, 2016; Vousdoukas *et al.*, 2017). These studies show that the wave set-up contribution at the shoreline can exceed 10 cm, but the relevance for the flooding of Venice city center was never analysed.

The long-term RSLR is modulated by sea-level variability at shorter time scales (from seasonal to decadal). Similarly, the occurrence of storm surge events also displays strong interannual to decadal variability. Evidences linking this variability with astronomical (e.g. the solar cycle) and climate patterns (e.g. North Hemisphere teleconnections) remain elusive, from both statistical and theoretical approaches. These issues are important for the development of seasonal predictions of sea-level extremes, understanding of observed trends and their attribution to long term anthropogenic climate change (and local subsidence). Longer records and better understanding of the sea-level responses to atmospheric forcing and remote influences would contribute to fill these knowledge gaps.

The synoptic conditions leading to extreme storm surges at Venice are clearly documented, as they are produced by cyclogenesis occurring in the western Mediterranean Sea. There is consensus on the secondary role that the meteorological forcing and marine storminess play in the long-term changes of major floods. This influence may decrease further in the future with the projected attenuation of storm surges. However, the confidence on future weakening of storm surges depends on the capability of climate models to correctly reproduce this process under climate change. In addition, storm surges do not account for the full atmospheric forcing of extreme sea-level events. Literature on projections of PAW surges and meteotsunamis is presently unavailable and progress on these factors is urgently required as their changes may be different from those of storm surges. Therefore, while presently available studies agree on the future attenuation of storm surges, analyses including all atmospheric forcings of extreme sea-level events are missing and deserve investigation.

This review confirms the consensus concerning the key control of historic and future RSLR on the frequency and severity of floods in Venice. Hence, understanding and predicting the future evolution of extreme sea levels in Venice depends critically on the availability of RSLR projections with lower uncertainty than at present. A large fraction of such uncertainty is related to the future emission scenario. Adopting a moderate-emission-mitigation-policy scenario (RCP2.6), or a high emissions scenario (RCP8.5) would imply a 30% difference in the projected 100y-ESL at the end of the 21st century. Another major source of uncertainty concerns the melting of ice-sheets, which accounts for the largest increase of the 100y-ESL at the end of this century, particularly for a high emission scenario. Local anthropogenic and long term natural subsidence can further contribute to the future increase of extreme sea levels (see Other factors, such as changes in storminess or the deviation of the Mediterranean mean sea level from that of the Subpolar North Atlantic (caused by steric effects and redistribution of mass within the Mediterranean Sea) appear to be less important (see Zanchettin et al., 2020 in this special issue).

Reducing uncertainty in the future projections of sea-level extremes is only one aspect of the research needed. The other aspect is adaptive planning of coastal defences to consider the large uncertainty of future sea-level extremes. A moderate scenario suggests a 10% and 30% increase of 100y-ESL in 2050 and 2100, respectively. A high emission scenario shows a 25% increase already in 2050, reaching 65% in 2100. These ranges are further enlarged by the uncertainty in scenario projections (leading to 100y-ESL increase up to 65% and a 160% in 2050 and 2100, respectively), which should be further expanded to higher values including high-end RSLR scenarios (see Zanchettin et al., 2020 in this issue). The large range of possible changes, especially after 2050 is not expected to be reduced substantially in the upcoming years, as it largely relies on human decisions and pervasive modeling uncertainties, which limits the generation of constrained climate information and poses major challenges for policy-making decisions on the development of effective adaptation measurements. These results (see also Lionello et al. 2020 in this special issue) stress the need for planning and implementing defense strategies of Venice that can be adapted to face the large range of plausible future sea-level extremes.

Acknowledgements

M. Reale has been supported in this work by OGS and Cineca under HPC-TRES award number 2015-07 and by the project FAIRSEA (Fisheries in the Adriatic Region - a Shared Ecosystem. Approach) funded by the 2014 - 2020 Interreg V-A Italy - Croatia CBC Programme (Standard project ID 10046951).The work of M. Orlić has been supported by Croatian Science Foundation under the project IP-2018-01-9849 (MAUD). Scientific activity by DZ and GU performed in the Research Programme Venezia2021, with the contribution of the Provveditorato for the Public Works of Veneto, Trentino Alto Adige and Friuli Venezia Giulia, provided through the concessionary of State Consorzio Venezia Nuova and coordinated by CORILA. D. Barriopedro was supported by the Spanish government through the PALEOSTRAT (CGL2015-69699-R) and JEDiS (RTI2018-096402-BI00) projects.

Author contribution

PL coordinated the paper. Specific contributions to the sections are as follows (LA = leading author, CA = contributing author). Section 1: LA: PL; CA: RJN, DZ. Section 2: LA: MO and FR; CA: PL, GU, CF. Section 3: LA: MR and DB, CA: FR and PL. Section 4: LA: MV, CA: FR, PL. Section 5: LA: PL, CA: RJN, DZ, DB. Figure 1, 2,3 and 4 MR, Figures 5 and 6 DB; figures 7 and 8 MV. Table 1:CF; table 2: FR; Appendices: AI: FR; AII :MR; AIII: DB ; Figure III1 and III2, DB.

Competing Interest

The authors declare that they have no conflict of interest.

6. Appendix I: Selected major events

Here we present a short description of extreme sea-level events based on original reports. Each description is based on the cited sources, which often include synoptic weather maps and diagrams of relevant meteorological parameters (see table A.1)

A1.0. 15 January 1867

On 15 January 1867, that is just few years before the beginning of regular sea-level records a remarkable storm surge occurred. Although no tide gauge data are available, contemporary sources reported measurements taken at local hydrometers.

Zantedeschi (1866-67), quoting the local Civil Engineering Office (Ufficio del Genio Civile), reported that the maximum observed height was 1.59 m 'above the common ordinary high water marked at the royal hydrometer in the Grand Canal'.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

The 'common ordinary high water' is also known as the 'comune marino' (CM), that is the upper edge of the green belt formed by algae on quays and walls, often indicated by an engraved horizontal mark and/or a 'C' (Rusconi, 1983; Camuffo and Sturaro, 2004). According to Dorigo (1961a) the ZMPS is 22.46 cm below the CM of 1825, upon which the tide gauge zero at S. Stefano was based. Therefore, under the hypothesis that the same CM was adopted at the royal hydrometer and at S. Stefano, the maximum RSL should have been approximately 181 cm above ZMPS.

However, later sources gave different figures. Annali (1941) reported 132 cm above the 1825 CM, therefore the height would turn out to be 154 cm (153 is reported, maybe due to rounding). Dorigo (1961) also reported 153 cm, probably quoting Annali (1941).

If the 181-cm height was correct, the 1867 height would be the third highest RLS ever measured in Venice, not too far from the 187 cm of 12 November 2019 and the 194 cm reached on 4 November 1966. Note, however, that in the 1860's the relative MSL was about 30 cm lower than at present, which makes the 1867 event very remarkable.

A1.1. 16 April 1936

A cyclone affected the western and central Mediterranean, with a minimum SLP around 990 hPa in the Gulf of Lions, causing strong southerly winds blew over the Adriatic. In Venice wind mostly blew from the first quadrant but it veered to SSW near the surge peak, with gust speed over 25 m s^{-1}; in the meantime the SLP dropped to 990 hPa.

The RSL reached 147 cm; at that time it represented the second highest value ever recorded, the first having been observed on 15 January 1867 (see Appendix 2). The RSL peak occurred about 2 hr after the astronomical tide maximum. The surge contribution was about 94 cm.

A1.2. 12 November 1951

From 10 to 12 November a deep cyclone formed in the Ligurian Sea where SLP dropped from 1008 to 984 hPa. On the Ionian Sea and the Balkans SLP was higher than 1012 hPa, and the strong SLP gradient induced strong southerly winds over the Adriatic Sea, up to over 20 m s^{-1} in Venice. As a result, the RSL in Venice increased both because of the wind-induced surge and the local IB effect. Luckily, the surge peak occurred at the astronomical tide minimum; if it had occurred at the next high tide, 5 hr later, the observed RSL would have been about 65 cm higher. The RSL peak was 151 cm and it exceeded the official danger level of 110 cm for about 9 hr. The surge peak attained 84 cm.

A1.3. 4 November 1966

On 3 and 4 November 1966 the SLP field over the Mediterranean was characterized by a cyclone to the west and an anticyclone to the east. The cyclone centre deepened and slowly moved from the northwest Mediterranean to northeast Italy, while the zonal SLP gradient increased over the Adriatic. As a consequence, strong and persisting southerly wind affected the Adriatic Sea. In Venice Sirocco speed reached 20 m s^{-1} with gusts up to 28 m s^{-1}, and the SLP dropped to 992 hPa.

The RSL height of 194 cm and the surge height of 143 cm are the highest values in the whole record. The RSL remained over 110 cm for 22 hr. Economic losses for the city of about 400 hundred millions euros have been estimated.

Note that two elements limited the RSL peak, namely the fact that the astronomical tide was near zero at the time of the maximum surge, and that in those days the Moon phase was close to last quarter, making the astronomical tide amplitude relatively small, around 30 cm. Had the surge peak occurred 5 hr earlier, the RSL would have attained about 220 cm.

A1.4. 22 December 1979

This event was connected with a cyclone whose minimum was less than 990 hPa, that moved on 21 and 22 December from the Algerian coast to the Gulf of Genoa. The combination with higher SLP over the Balkans enabled southerly wind blow over the central and southern Adriatic, with gusts up to 20 m s^{-1}, while in the northern Adriatic Bora prevailed with gusts over 20 m s^{-1}. The local SLP was not particularly low (1001 hPa) thus the surge was mainly attributed to wind.

The surge peak reached 108 cm and came 3 hr before the astronomical tide maximum: nevertheless, the RSL was remarkably high, namely 166 cm which represents the third highest observed value. A RSL higher than 110 cm lasted for 7 hr.

A1.5. 1 February 1986

The synoptic situation consisted of cyclone over the western Mediterranean, this time centred in the Gulf of Lions, and an anticyclone over eastern and northern Europe. A southerly wind flow affected the whole central Mediterranean, including the Adriatic Sea, but a Bora component was present over the northern Adriatic. Southerly wind was particularly strong in the southern Adriatic (almost 30 m s^{-1} gusts in Bari), while in Venice Bora gusts were faster than 20 m s^{-1}.

This event is characterised by the fourth highest RSL ever measured in Venice, that is 159 cm. The event severity was the result of a moderate surge of 70 cm, that occurred just 1 hr after a 35 cm astronomical tide maximum. Overall, the surge exceeded 60 cm for 15 hr.

A1.6. 6 November 2000

This event was caused by the combined effect of a large cyclone affecting the whole western Europe and an anticyclone over eastern Europe. The lowest SLP was observed in the English Channel with values lower than 970 hPa. The eastward movement of the cyclone caused the whole Adriatic to experience a remarkable SLP decrease in the 24 hr preceding the surge, up to a 27-hPa drop in Venice.

As on 1 February 1986, during this event the storm surge and the astronomical tide maximum almost coincided. The observed RSL attained 144 cm and the surge grew up to 89 cm. The RSL remained above 100 cm for over 7 hr.

A1.7. 1 December 2008

An intense cyclone, with strong westerly flow affected the western Mediterranean Sea. The day before the surge a small-scale cyclonic circulation developed over the Gulf of Genoa and moved eastward into the River Po valley. This caused surface wind over the Tyrrhenian and Adriatic Seas to veer from W to SW, then to S, intensifying in the meantime and reaching the maximum intensity in the early hours of 1 December. In the afternoon, the cyclonic circulation began weakening and the intensity of the associated wind in the Adriatic Sea progressively decreased.

From the late afternoon of 30 November to the early morning of 1 December, SLP in Venice dropped by about 13 hPa in 9 hr, reaching 994 hPa. The wind veered from NNE to SE around 01:30 UTC, with speed between 15 and 20 m s^{-1} for the following 7-8 hr.

The RSL attained 156 cm, that is the fifth highest value since 1872. The maximum surge height was 61 cm and it occurred less than 1 hr before the astronomical tide maximum.

A1.8. 29 October 2018

The event was caused by the combined action of a cyclone, centred between the Gulf of Lions and the Gulf of Genoa, whose minimum SLP was lower than 985 hPa, and an anticyclone over northeastern and eastern Europe. This configuration enabled strong Sirocco along the Adriatic, with speed around 15 m s^{-1} and gusts up to 25 m s^{-1} from the late morning to the evening in Venice, where SLP reached a minimum of 996 hPa.

The strength and persistence of southerly winds caused the sea level to remain particularly high. The highest RSL was reached at 13:40 UTC with 156 cm (fifth value in the history of the observations in Venice), a couple of hours later than the astronomical tide maximum, then the RSL decreased to 119 cm at 16:35 UTC at rose again up to 148 cm at 19:25 UTC. The surge level peaked at 92 cm together with the maximum RSL and to 117 cm at 19:20 UTC, in coincidence with the astronomical tide minimum. The 117 surge level represents the second highest ever observed and the 119 cm value the highest minimum RSL. Overall, the RSL was higher than 120 cm for 14 hr, as on 4 November 1966.

A1.9 12, 15 and 17 November 2019

On November 12th, 2019, an exceptional flood event took place in Venice, second only to the one that occurred on November 4th, 1966. Moreover, with 15 high tides higher than 110 cm and 4 events above 140 cm, November 2019 was the worst month for flooding in Venice since the beginning of sea-level records.

The extreme high sea level recorded in Venice was due to the combination of the following large-scale and local dynamics: the in-phase timing between the peak of the atmospheric surge and the lower high astronomical tide; a standing low-pressure and wind systems over the Mediterranean Sea - that is associated with planetary atmospheric waves trough extending over the whole month of November - which determined a high monthly mean sea level in the northern Adriatic Sea; a deep low-pressure system over the central-southern Tyrrhenian Sea that generated south-easterly winds along the main axis of the Adriatic Sea, pushing waters to the north; a fast-moving local cyclone travelling in the north-westward direction over the Adriatic Sea along the Italian coast, generating a meteotsunami; very strong south-westerly winds over the Lagoon of Venice, which led to a rise in water levels and damages to the historic city.

The SLP minimum of the cyclone on the Tyrrhenian Sea was about 990 hPa. A small deep secondary SLP minimum formed in the afternoon, reaching 988 hPa at Venice around 21 UTC. Initially, moderate northeasterly wind was blowing over the north Adriatic (about 10 m s^{-1} at Venice), but between 21 and 22 UTC it veered to S,E then to SW, and sustained wind reinforced up to 20 m s^{-1} at Tessera airport.

The highest RSL was reached at 21:50 UTC with 189 cm, that represents the second highest value in the history of the observations in Venice, and it almost exactly coincided with the astronomical tide peak. The surge level peaked at 100 cm, representing the fourth highest value ever observed. The peak RSL was similar to the 1966 value (namely 194 cm), but, while in 1966 it was mainly the result of a huge meteorological component (143 cm, see A1.3 above), in 2019 the astronomical tide contribution also played a significant role. Moreover, in 2019 the relative sea level was 11 cm higher with respect to 1966.

On 15 November another storm surge developed in connection with a large cyclone over west Europe, having a 995 hPa SLP minimum over France, and extending into Algeria. Local pressure in Venice reached 1001 hPa and wind blew from SE at less than 10 m s^{-1}. The RSL peaked at 154 cm at 10:40 UTC and the surge peak occurred 6.5 hours later with 62 cm.

Appendix II: A note on cyclone tracking algorithm

Cyclones producing extreme surges have been identified and tracked using a cyclone detection and tracking method applied to the gridded ERA5 mean sea-level pressure (SLP) fields with a spatial resolution of 0.25o and a temporal resolution of 6 h. This dataset covers the period 1979–2018. The cyclone detection and tracking has been extensively described in previous studies (Lionello, Dalan et al. 2002, Reale and Lionello 2013, Lionello, Trigo et al. 2016). It is based on the search of pressure minima in MSLP-gridded fields. It identifies the location where each cyclogenesis process occurs and constructs the trajectory of the pressure minimum by joining the location of the low-pressure centre in successive maps until it disappears (cyclolysis). This cyclone tracking algorithm contains features that are meant to detect the formation of cyclones inside the Mediterranean and, at the same time, avoid the inflation of the number of cyclones, determined by considering small, short-lived features as independent systems. The method first partitions the sea-level pressure (SLP) field in depressions, which can be considered candidates for independent cyclones, by merging all steepest descent paths leading to the same minimum.

Appendix III Wavelet of the storm surge frequency

In order to integrate the discussion in section 5.3 on the presence of a 11-year periodicity of storm surges, Figures A.1 and A.2 show the amplitude of the wavelets of the autumn mean time series of Relative Sea Level (RSL) for 1924-2018 and of its daily extremes. In both graphics, a decadal signal consistent with the 11-year solar cycle is present only for a few decades from the 1970s to the 1990s and absent before and after this period.

References

Androulidakis, Y. S., Kombiadou, K. D., Makris, C. V., Baltikas, V. N. and Krestenitis, Y. N. (2015) 'Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions', *Dynamics of Atmospheres and Oceans,* 71, pp. 56-82.

Bajo, M., Međugorac, I., Umgiesser, G. and Orlić, M. (2019) 'Storm surge and seiche modelling in the Adriatic Sea and the impact of data assimilation', *Quarterly Journal of the Royal Meteorological Society*, 145(722), pp. 2070-2084.

Bamber, J. L. and Aspinall, W. P. (2013) 'An expert judgement assessment of future sea-level rise from the ice sheets', *Nature Climate Change,* 3(4), pp. 424-427.

Bargagli, A., Carillo, A., Pisacane, G., Ruti, P. M., Struglia, M. V. and Tartaglione, N. (2002) 'An Integrated Forecast System over the Mediterranean Basin: Extreme Surge Prediction in the Northern Adriatic Sea', *Monthly Weather Review*, 130(5), pp. 1317-1332.

Barriopedro, D., García-Herrera, R., Lionello, P. and Pino, C. (2010) 'A discussion of the links between solar variability and high-storm-surge events in Venice', *Journal of Geophysical Research Atmospheres,* 115(13).

Battistin, D. and Canestrelli, P. (2006) *1872-2004 La serie storica delle maree a Venezia*, Venice, Italy: Istituzione Centro Previsioni e Segnalazioni Maree. Available at: https://www.comune.venezia.it/sites/default/files/publicCPSM2/pubblicazioni/La_serie_storica_delle_maree_a_Venezia_1872-2004_web_ridotto.pdf.

Bertotti, L., Bidlot, J.-R., Buizza, R., Cavaleri, L. and Janousek, M. (2011) 'Deterministic and ensemble-based prediction of Adriatic Sea sirocco storms leading to 'acqua alta' in Venice', *Quarterly Journal of the Royal Meteorological Society,* 137(659), pp. 1446-1466.

Bertotti, L. and Cavaleri, L. (1985) 'Coastal set-up and wave breaking', *Oceanologica acta,* 8(2), pp. 237-242.

Camuffo, D. and Sturaro, G. (2004) 'Use of proxy-documentary and instrumental data to assess the risk factors leading to sea flooding in Venice', *Global and Planetary Change*, 40(1), pp. 93-103.

Canestrelli, P., Mandich, M., Pirazzoli, P. A. and Tomasin, A. (2001) *Wind, Depressions and Seiche: Tidal Perturbations in Venice (1951-2000)*, Venice, Italy: Istituzione Centro Previsioni e Segnalazioni Maree. Available at: https://www.comune.venezia.it/sites/default/files/publicCPSM2/pubblicazioni/Venti_depressioni_e_sesse.pdf.

Caporin, M. and Fontini, F. (2016) 'Damages Evaluation, Periodic Floods, and Local Sea Level Rise: The Case of Venice, Italy', *Handbook of Environmental and Sustainable Finance*: Elsevier, pp. 93-110.

Cavaleri, L., Bajo, M., Barbariol, F., Bastianini, M., Benetazzo, A., Bertotti, L., Chiggiato, J., Ferrarin, C., Trincardi, F. and Umgiesser, G. (2020) 'The 2019 Flooding of Venice AND ITS IMPLICATIONS FOR FUTURE PREDICTIONS', *Oceanography*, 33(1), pp. 42-49.

Cavaleri, L., Bertotti, L., Buizza, R., Buzzi, A., Masato, V., Umgiesser, G. and Zampieri, M. (2010) 'Predictability of extreme meteo-oceanographic events in the Adriatic Sea', *Quarterly Journal of the Royal Meteorological Society*, 136(647), pp. 400-413.

Cerovečki, I., Orlić, M. and Hendershott, M. C. (1997) 'Adriatic seiche decay and energy loss to the Mediterranean', *Deep Sea Research Part I: Oceanographic Research Papers*, 44(12), pp. 2007-2029.

Chiodo, G., Oehrlein, J., Polvani, L. M., Fyfe, J. C. and Smith, A. K. (2019) 'Insignificant influence of the 11-year solar cycle on the North Atlantic Oscillation', *Nature Geoscience*, 12(2), pp. 94-99.

Codiga, D. L. (2011) *Unified tidal analysis and prediction using the UTide Matlab functions.* Graduate School of Oceanography, University of Rhode Island Narragansett, RI.

Conte, D. and Lionello, P. (2013) 'Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios', *Global and Planetary Change*, 111, pp. 159-173.

De Zolt, S., Lionello, P., Nuhu, A. and Tomasin, A. (2006) 'The disastrous storm of 4 November 1966 on Italy', *Natural Hazards and Earth System Science*, 6(5), pp. 861-879.

Dorigo, L. (1961a) *Le osservazioni mareografiche in Laguna di Venezia*, Venice, Italy: Istituto Veneto di Scienze, Lettere e Arti.

Dorigo, L. (1961b) *Maree eccezionali registrate a Venezia Punta della Salute. Periodo 1867-1960*: Istituto Veneto di Scienze, Lettere e Arti.

Enzi, S. and Camuffo, D. (1995) 'Documentary sources of the sea surges in Venice from ad 787 to 1867', *Natural Hazards*, 12(3), pp. 225-287.

Fagherazzi, S., Fosser, G., D'Alpaos, L. and D'Odorico, P. (2005) 'Climatic oscillations influence the flooding of Venice', *Geophysical Research Letters*, 32(19).

Ferrarin, C., Maicu, F. and Umgiesser, G. (2017) 'The effect of lagoons on Adriatic Sea tidal dynamics', *Ocean Modelling*, 119, pp. 57-71.

Ferrarin, C., Tomasin, A., Bajo, M., Petrizzo, A. and Umgiesser, G. (2015) 'Tidal changes in a heavily modified coastal wetland', *Continental Shelf Research*, 101, pp. 22-33.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Discussions

Ferrarin, C., Bajo, M., Benetazzo, A., Cavalari, L., Chiggiato, J., Davison, S., Davolio, S., Lionello, P., Orlić, M., Umgiesser, G. (2020b). “Local and large-scale controls of the exceptional Venice floods of November 2019”, submitted to *Progress in Oceanography*.

Franco, P., jefti ć , L., Malanotte Rizzoli, P., Orli ć , M. and Purga, N. (1982) 'Descriptive Model of the Northern Adriatic', *Oceanologica Acta,* 5(3), pp. 11.

Garrido-Perez, J. M., Ordóñez, C., Barriopedro, D., García-Herrera, R. and Paredes, D. (2020) 'Impact of weather regimes on wind power variability in western Europe', *Applied Energy,* 264, pp. 114731.

Hendershott, M. C. and Speranza, A. (1971) 'Co-oscillating tides in long, narrow bays; the Taylor problem revisited', *Deep Sea Research and Oceanographic Abstracts,* 18(10), pp. 959-980.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R. and Schepers, D. (2020) 'The ERA5 global reanalysis', *Quarterly Journal of the Royal Meteorological Society,* 146(730), pp. 1999-2049.

ISPRA, C. a. and CNR-ISMAR (2020) *Un mese di alte maree eccezionali. Dinamica e anomalia dell'evento del 12 novembre 2019*. Available at: www.comune.venezia.it/content/le-acque-alte-eccezionali (Accessed: 30 September 2019).

Jackson, L. P. and Jevrejeva, S. (2016) 'A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios', *Global and Planetary Change,* 146, pp. 179-189.

Janeković, I. and Kuzmić, M. (2005) 'Numerical simulation of the Adriatic Sea principal tidal constituents', *Ann. Geophys.,* 23(10), pp. 3207-3218.

Jansa, A., Alpert, P., Buzzi, A. and Arbogast, P. (2001) 'MEDEX, cyclones that produce high impact weather in the Mediterranean', *Avalaible at http://medex. aemet. uib. es*.

Jevrejeva, S., Jackson, L. P., Riva, R. E. M., Grinsted, A. and Moore, J. C. (2016) 'Coastal sea level rise with warming above 2 °C', *Proceedings of the National Academy of Sciences,* 113(47), pp. 13342-13347.

Jordà, G., Gomis, D. and Marcos, M. (2012) 'Comment on “Storm surge frequency reduction in Venice under climate change” by Troccoli et al', *Climatic change,* 113(3-4), pp. 1081-1087.

Karabeg, M. and Orlić, M. (1982) 'The influence of air pressure on sea level in the North Adriatic—a frequency-domain approach', *Acta Adriatica,* 23(1/2), pp. 21-27.

Lionello, P. (1995) 'Oceanographic prediction for the Venetial Littoral', *NUOVO CIMENTO DELLA SOCIETA ITALIANA DI FISICA C-GEOPHYSICS AND SPACE PHYSICS,* 18(3), pp. 245-268.

Lionello, P. (2005) 'Extreme storm surges in the gulf of venice: Present and future climate', *Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge.*, pp. 59-69.

Lionello, P., Abrantes, F., Congedi, L., Dulac, F., Gacic, M., Gomis, D., Goodess, C., Hoff, H., Kutiel, H., Luterbacher, J., Planton, S., Reale, M., Schröder, K., Vittoria Struglia, M., Toreti, A., Tsimplis, M., Ulbrich, U. and Xoplaki, E. (2012a) 'Introduction: Mediterranean climate-background information', *The Climate of the Mediterranean Region*, pp. xxxv-xc.

Lionello, P., Bhend, J., Buzzi, A., Della-Marta, P. M., Krichak, S. O., Jansa, A., Maheras, P., Sanna, A., Trigo, I. F. and Trigo, R. (2006a) 'Cyclones in the Mediterranean region: climatology and effects on the environment', *Developments in earth and environmental sciences*: Elsevier, pp. 325-372.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Lionello, P., Bhend, J., Buzzi, A., Della-Marta, P. M., Krichak, S. O., Jansà, A., Maheras, P., Sanna, A., Trigo, I. F. and Trigo, R. 2006b. Chapter 6 Cyclones in the Mediterranean region: Climatology and effects on the environment. *Developments in Earth and Environmental Sciences.*

Lionello, P., Cavaleri, L., Nissen, K. M., Pino, C., Raicich, F. and Ulbrich, U. (2012b) 'Severe marine storms in the Northern Adriatic: Characteristics and trends', *Physics and Chemistry of the Earth,* 40-41, pp. 93-105.

Lionello, P., Conte, D., Marzo, L. and Scarascia, L. (2017) 'The contrasting effect of increasing mean sea level and decreasing storminess on the maximum water level during storms along the coast of the Mediterranean Sea in the mid 21st century', *Global and Planetary Change,* 151, pp. 80-91.

Lionello, P., Conte, D. and Reale, M. (2019) 'The effect of cyclones crossing the Mediterranean region on sea level anomalies on the Mediterranean Sea coast', *Nat. Hazards Earth Syst. Sci.,* 19(7), pp. 1541-1564.

Lionello, P., Dalan, F. and Elvini, E. (2002) 'Cyclones in the Mediterranean region: the present and the doubled CO2 climate scenarios', *Climate Research,* 22(2), pp. 147-159.

Lionello, P., Galati, M. B. and Elvini, E. (2012) 'Extreme storm surge and wind wave climate scenario simulations at the Venetian littoral', *Physics and Chemistry of the Earth,* 40-41, pp. 86-92.

Lionello, P., Mufato, R. and Tomasin, A. (2005) 'Sensitivity of free and forced oscillations of the Adriatic Sea to sea level rise', *Climate Research,* 29(1), pp. 23-39.

Lionello, P., Nizzero, A. and Elvini, E. (2003) 'A procedure for estimating wind waves and storm-surge climate scenarios in a regional basin: The Adriatic Sea case', *Climate Research,* 23(3), pp. 217-231.

Lionello, P., Trigo, I. F., Gil, V., Liberato, M. L. R., Nissen, K. M., Pinto, J. G., Raible, C. C., Reale, M., Tanzarella, A., Trigo, R. M., Ulbrich, S. and Ulbrich, U. (2016) 'Objective climatology of cyclones in the Mediterranean region: A consensus view among methods with different system identification and tracking criteria', *Tellus, Series A: Dynamic Meteorology and Oceanography,* 68(1).

Lionello, P., Zampato, L., Malguzzi, P., Tomasin, A. and Bergamasco, A. (1998) 'On the correct surface stress for the prediction of the wind wave field and the storm surge in the Northern Adriatic Sea', *Nuovo Cimento della Societa Italiana di Fisica C,* 21(5), pp. 515-532.

Lionello, P., Nicholls, J.R., Umgiesser,G., Zanchettin, D. (2020) 'Venice flooding and sea level: past evolution, present issues and future projections' *Natural Hazards and Earth System Sciences (submitted)*

Livio, D. (1968) *Le alte maree eccezionali a Venezia*, Venice, Italy: Ufficio Idrografico del Magistrato alle Acque156).

Malačič, V., Viezzoli, D. and Cushman-Roisin, B. (2000) 'Tidal dynamics in the northern Adriatic Sea', *Journal of Geophysical Research: Oceans,* 105(C11), pp. 26265-26280.

Manca, B., Mosetti, F. and Zennaro, P. (1974) 'Analisi spettrale delle sesse dell'Adriatico.', *Bolletino di Geofisica Teorica ed Applicata,* 16, pp. 10.

Marcos, M., Jordà, G., Gomis, D. and Pérez, B. (2011) 'Changes in storm surges in southern Europe from a regional model under climate change scenarios', *Global and Planetary Change,* 77(3), pp. 116-128.

Martínez-Asensio, A., Marcos, M., Tsimplis, M. N., Gomis, D., Josey, S. and Jordà, G. (2014) 'Impact of the atmospheric climate modes on Mediterranean sea level variability', *Global and Planetary Change,* 118, pp. 1-15.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Martínez-Asensio, A., Tsimplis, M. N. and Calafat, F. M. (2016) 'Decadal variability of European sea level extremes in relation to the solar activity', *Geophysical Research Letters,* 43(22), pp. 11,744-11,750.

Mel, R., Carniello, L. and D'Alpaos, L. (2019) 'Dataset of wind setup in a regulated Venice lagoon', *Data in brief,* 26, pp. 104386.

Mel, R., Sterl, A. and Lionello, P. (2013) 'High resolution climate projection of storm surge at the Venetian coast', *Natural Hazards and Earth System Science,* 13(4), pp. 1135-1142.

Mentaschi, L., Vousdoukas, M., Voukouvalas, E., Sartini, L., Feyen, L., Besio, G. and Alfieri, L. (2016) 'The transformed-stationary approach: a generic and simplified methodology for non-stationary extreme value analysis', *Hydrol. Earth Syst. Sci.,* 20(9), pp. 3527-3547.

Mentaschi, L., Vousdoukas, M. I., Voukouvalas, E., Dosio, A. and Feyen, L. (2017) 'Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns', *Geophysical Research Letters,* 44(5), pp. 2416-2426.

Međugorac, I., Orlić, M., Janeković, I., Pasarić, Z. and Pasarić, M. (2018) 'Adriatic storm surges and related cross-basin sea-level slope', *Journal of Marine Systems,* 181, pp. 79-90.

Međugorac, I., Pasarić, M. and Orlić, M. (2016) 'Two recent storm-surge episodes in the Adriatic', *International Journal of Safety and Security Engineering,* 6, pp. 8.

Neu, U., Akperov, M. G., Bellenbaum, N., Benestad, R., Blender, R., Caballero, R., Cocozza, A., Dacre, H. F., Feng, Y., Fraedrich, K., Grieger, J., Gulev, S., Hanley, J., Hewson, T., Inatsu, M., Keay, K., Kew, S. F., Kindem, I., Leckebusch, G. C., Liberato, M. L. R., Lionello, P., Mokhov, I. I., Pinto, J. G., Raible, C. C., Reale, M., Rudeva, I., Schuster, M., Simmonds, I., Sinclair, M., Sprenger, M., Tilinina, N. D., Trigo, I. F., Ulbrich, S., Ulbrich, U., Wang, X. L. and Wernli, H. (2013) 'Imilast: A community effort to intercompare extratropical cyclone detection and tracking algorithms', *Bulletin of the American Meteorological Society,* 94(4), pp. 529-547.

Oppenheimer, M., Glavovic, B., Hinkel, J., Van de Wal, R., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., Deconto, R. M. and Ghosh, T. 2019. Sea level rise and implications for low-lying islands, coasts and communities IPCC Special Report on the Ocean and Cryosphere in a Changing Climate ed HO Pörtner et al.

Orlić, M. (2001) 'Anatomy of sea level variability-an example from the Adriatic', *The Ocean Engineering Handbook*: CRC Press.

Pasarić, M. and Orlić, M. (2001) 'Long-term meteorological preconditioning of the North Adriatic coastal floods', *Continental Shelf Research,* 21(3), pp. 263-278.

Pirazzoli, P. A. and Alberto, T. (2002) 'Recent Evolution of Surge-Related Events in the Northern Adriatic Area', *Journal of Coastal Research,* 18(3), pp. 537-554.

Raicich, F. (2015) 'Long-term variability of storm surge frequency in the Venice Lagoon: an update thanks to 18th century sea level observations', *Nat. Hazards Earth Syst. Sci.,* 15(3), pp. 527-535.

Reale, M., Liberato, M. L. R., Lionello, P., Pinto, J. G., Salon, S. and Ulbrich, S. (2019) 'A global climatology of explosive cyclones using a multi-tracking approach', *Tellus A: Dynamic Meteorology and Oceanography,* 71(1), pp. 1611340.

Reale, M. and Lionello, P. (2013) 'Synoptic climatology of winter intense precipitation events along the Mediterranean coasts', *Natural Hazards and Earth System Sciences,* 13(7), pp. 1707-1722.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Robinson, A. R., Tomasin, A. and Artegiani, A. (1973) 'FLOODING VENICE PHENOMENOLOGY AND PREDICTION OF THE ADRIATIC STORM SURGE', *Quarterly Journal of the Royal Meteorological Society*, 99(422 (OCTOBER, 1973)), pp. 688-692.

Roland, A., Cucco, A., Ferrarin, C., Hsu, T.-W., Liau, J.-M., Ou, S.-H., Umgiesser, G. and Zanke, U. (2009) 'On the development and verification of a 2-D coupled wave-current model on unstructured meshes', *Journal of Marine Systems,* 78, pp. S244-S254.

Šepić, J., Vilibić, I. and Belušić, D. (2009) 'Source of the 2007 Ist meteotsunami (Adriatic Sea)', *Journal of Geophysical Research: Oceans,* 114(C3).

Thiéblemont, R., Matthes, K., Omrani, N.-E., Kodera, K. and Hansen, F. (2015) 'Solar forcing synchronizes decadal North Atlantic climate variability', *Nature Communications,* 6(1), pp. 8268.

Tomasin, A. (2002) *The frequency of Adriatic surges and solar activity.*: Istituto Studio Dinamica Grandi Masse (ISDGM-CNR).

Toreti, A., Xoplaki, E., Maraun, D., Kuglitsch, F.-G., Wanner, H. and Luterbacher, J. (2010) 'Characterisation of extreme winter precipitation in Mediterranean coastal sites and associated anomalous atmospheric circulation patterns', *Natural Hazards and Earth System Sciences,* 10(5), pp. 1037-1050.

Trigo, I. F., Bigg, G. R. and Davies, T. D. (2002) 'Climatology of Cyclogenesis Mechanisms in the Mediterranean', *Monthly Weather Review,* 130(3), pp. 549-569.

Trigo, I. F. and Davies, T. D. (2002) 'Meteorological conditions associated with sea surges in Venice: a 40 year climatology', *International Journal of Climatology,* 22(7), pp. 787-803.

Trigo, I. F., Davies, T. D. and Bigg, G. R. (1999) 'Objective climatology of cyclones in the Mediterranean region', *Journal of climate,* 12(6), pp. 1685-1696.

Troccoli, A., Zambon, F., Hodges, K. I. and Marani, M. (2012) 'Storm surge frequency reduction in Venice under climate change', *Climatic change,* 113(3-4), pp. 1065-1079.

Ulbrich, U., Leckebusch, G. C., Grieger, J., Schuster, M., Akperov, M., Bardin, M. Y., Feng, Y., Gulev, S., Inatsu, M., Keay, K., Kew, S. F., Liberato, M. L. R., Lionello, P., Mokhov, I. I., Neu, U., Pinto, J. G., Raible, C. C., Reale, M., Rudeva, I., Simmonds, I., Tilinina, N. D., Trigo, I. F., Ulbrich, S., Wang, X. L. and Wernli, H. (2013) 'Are Greenhouse Gas Signals of Northern Hemisphere winter extra-tropical cyclone activity dependent on the identification and tracking algorithm?', *Meteorologische Zeitschrift,* 22(1), pp. 61-68.

Ulbrich, U., Leckebusch, G. C. and Pinto, J. G. (2009) 'Extra-tropical cyclones in the present and future climate: a review', *Theoretical and Applied Climatology,* 96(1-2), pp. 117-131.

Ulbrich, U., Lionello, P., Belušić, D., Jacobeit, J., Knippertz, P., Kuglitsch, F. G., Leckebusch, G. C., Luterbacher, J., Maugeri, M., Maheras, P., Nissen, K. M., Pavan, V., Pinto, J. G., Saaroni, H., Seubert, S., Toreti, A., Xoplaki, E. and Ziv, B. (2012) 'Climate of the mediterranean: Synoptic patterns, temperature, precipitation, winds, and their extremes', *The Climate of the Mediterranean Region,* pp. 301-346.

Umgiesser, G., Canu, D. M., Cucco, A. and Solidoro, C. (2004) 'A finite element model for the Venice Lagoon. Development, set up, calibration and validation', *Journal of Marine Systems,* 51(1-4), pp. 123-145.

Umgiesser, G. et al. (2020) The prediction of floods in Venice: methods, models and uncertainty", *Natural Hazards and Earth System Sciences (submitted)*

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Vilibić, I. and Šepić, J. (2009) 'Destructive meteotsunamis along the eastern Adriatic coast: Overview', *Physics and Chemistry of the Earth, Parts A/B/C,* 34(17), pp. 904-917.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M. and Feyen, L. (2017) 'Extreme sea levels on the rise along Europe's coasts', *Earth's Future,* 5(3), pp. 304-323.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P. and Feyen, L. (2018) 'Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard', *Nature Communications,* 9(1), pp. 2360.

Vousdoukas, M. I., Voukouvalas, E., Annunziato, A., Giardino, A. and Feyen, L. (2016) 'Projections of extreme storm surge levels along Europe', *Climate Dynamics,* 47(9), pp. 3171-3190.

Zanchettin, D., Rubino, A., Traverso, P. and Tomasino, M. (2009) 'Teleconnections force interannual-to-decadal tidal variability in the Lagoon of Venice (northern Adriatic)', *Journal of Geophysical Research Atmospheres,* 114(7).

Zanchettin, D. et al. (2020) "Sea-level rise in Venice: historic and future trends", *Natural Hazards and Earth System Sciences (submitted)*

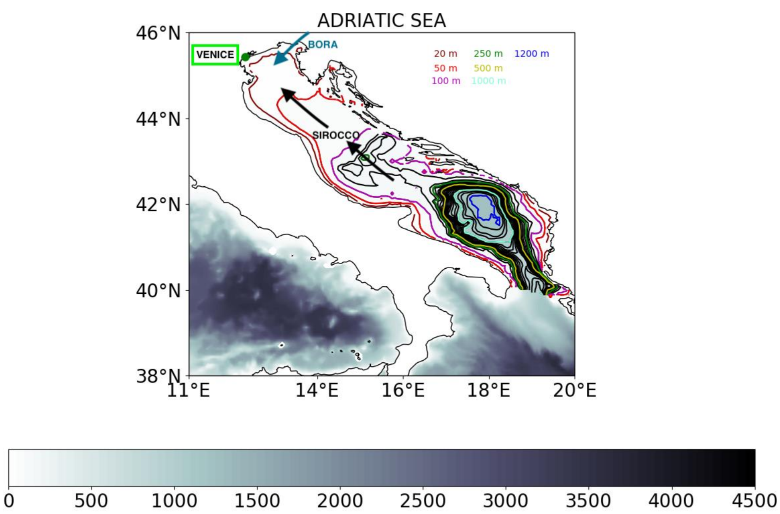


Figure 1: Bathymetry of the Adriatic Sea with the position of Venice and arrows denoting the directions of the two main wind regimes affecting the North Adriatic

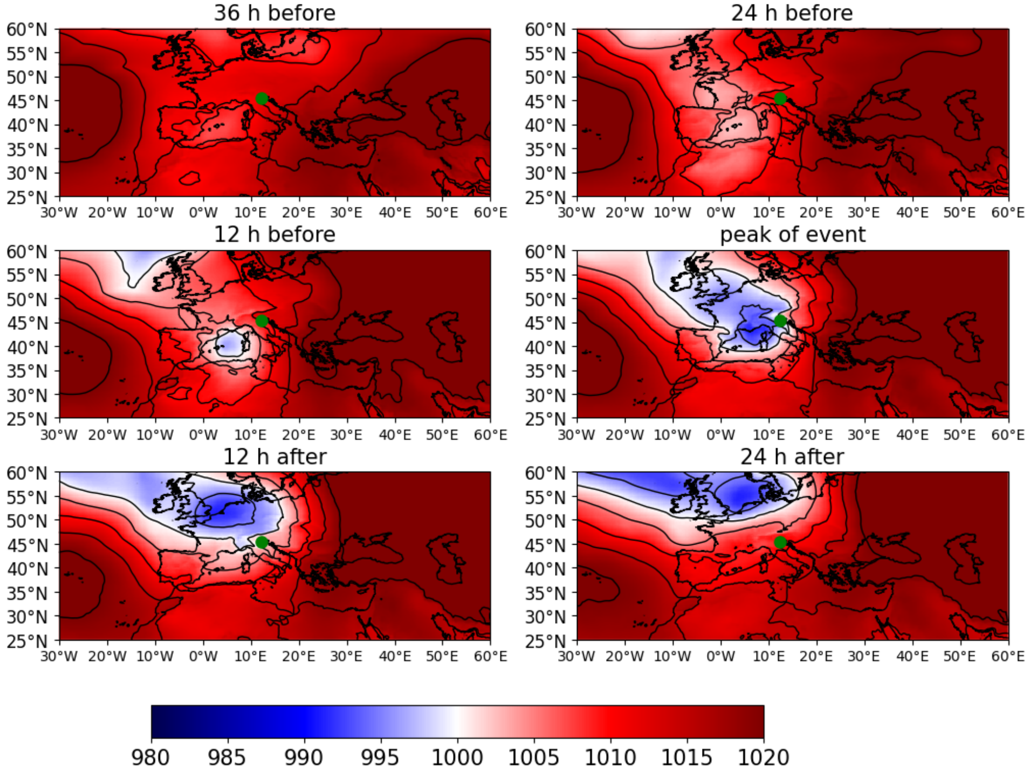


Figure 2 Composite of SLP fields based on ERA5 (in hPa) datasets associated with storm surges higher than 50 cm in Venice (see table 1). The time lags chosen for the composites is 36, 24 , 12 hours before and 12, 24 hours after the peak of the event. Green dot shows the location of the city of Venice

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Discussions

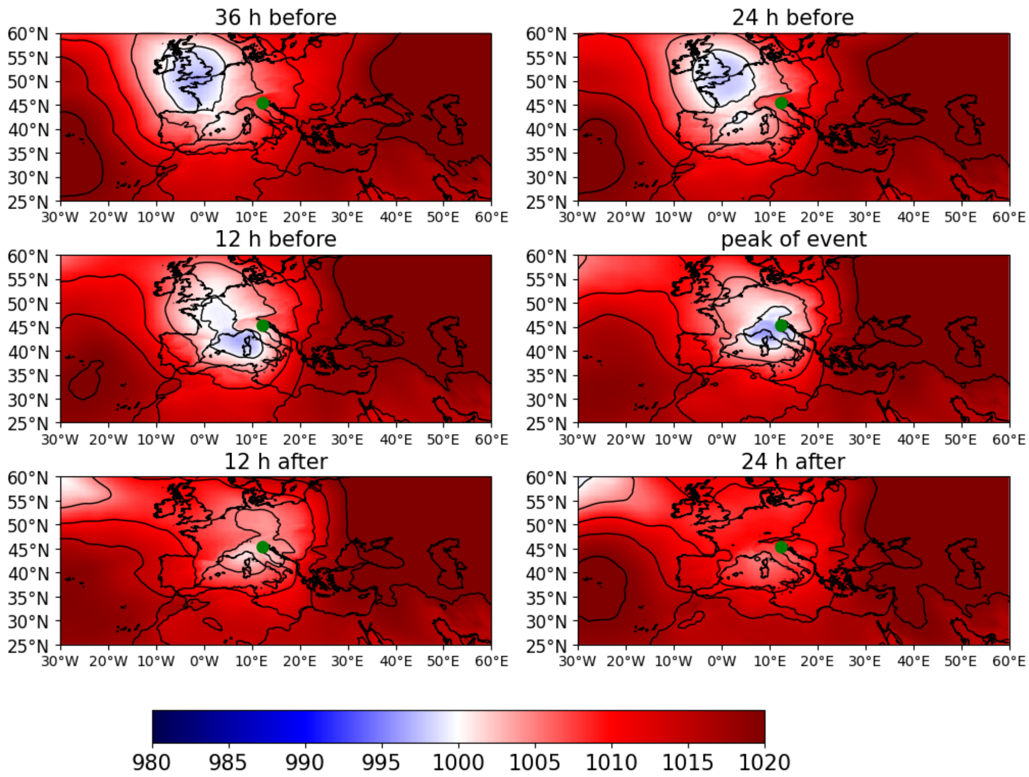


Figure 3 Same as figure 2, except it is based on the events in table 1 with storm surge height lower than 50cm

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

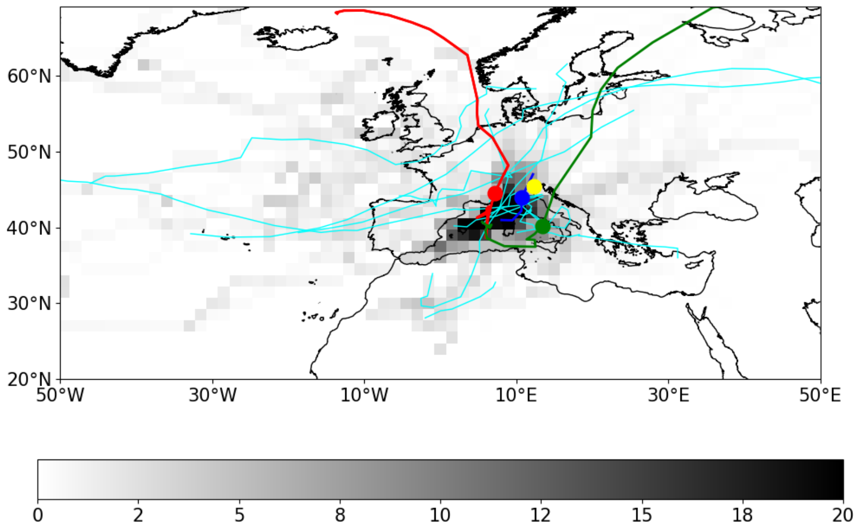


Figure 4 Density of tracks of cyclones (contour, measured as relative frequency of cyclones for each cell of 1.5 in%) based on ERA5 associated with storm surges with relative sea level higher than 110 cm . Cyan tracks represent the events reported in Table 1 with relative sea level higher than 140 cm (see Table 1), red track is the track of Storm Vaia (2018, see Table 1) , green line is the track of the event of November 2019. Blue line is the track of cyclone producing the event of 4 November 1966 (based on ERA40 field). Yellow dot represents the location of the city of Venice while the blu, red and green dot represent the location of the storm of 4 November 1996, storm Vaia (29/10/2018) and that one associated with the event of November 2019.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

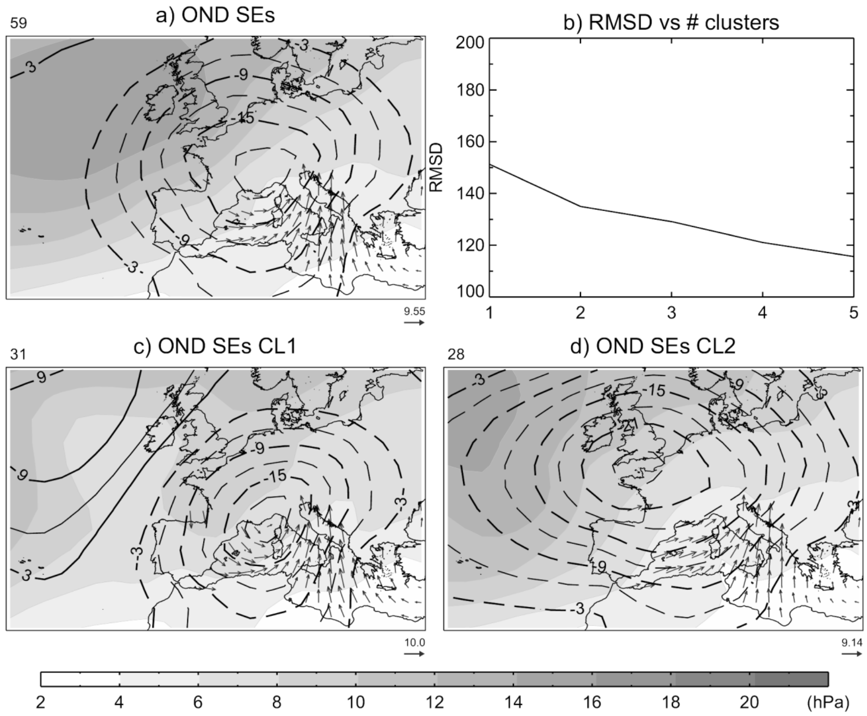


Figure 5a) Composite of daily anomalies of sea level pressure (SLP) over [30,60]°N, [30°W,30°E] (contours, hPa) and 10 m wind vector over the Mediterranean sea (arrows, m s-1) for autumn surge events in Venice with surge height above the 99.5th percentile of the 1948-2018 distribution. Shading shows the standard deviation of the composited SLP fields. The number of cases is shown in the top left corner. The modulus of a reference wind speed vector is shown in the bottom right; b) Root mean squared difference (RMSD) of the daily standardized anomalies of SLP and 10 m wind vector as a function of the number of clusters. RMSDs are computed with respect to the centroid of the respective cluster; c, d) As a) but when surge events are split in two groups, referred to as cluster one (CL1) and two (CL2), which correspond to the choice of two clusters in b). Note that a) is equivalent to considering one cluster with all events. Data sources: NCEP/NCAR reanalysis (Kalnay et al. 1996) and Fabio Raicich (Raicich 2015)

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

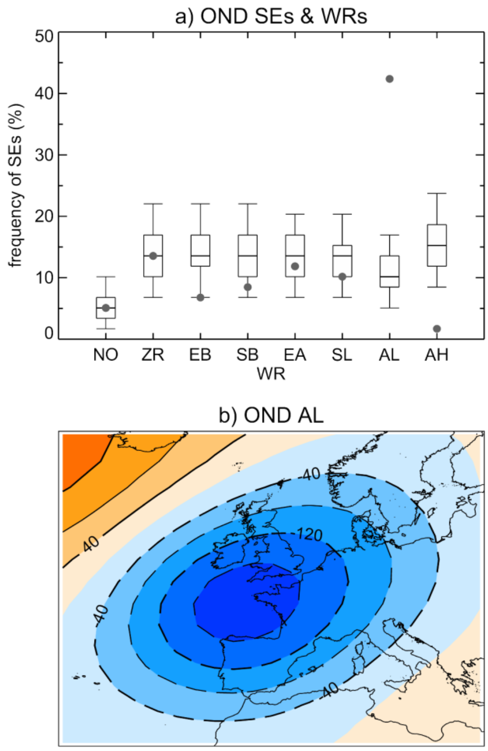


Figure 6 . Top panel: Relative frequency of autumn extreme surge events in Venice for 1948-2018 (in % with respect to the total number of events) occurring under the given Weather Regime (WR). Whiskers denote the random distributions obtained from a bootstrap of 5000 trials, each one containing the same number of autumn days of the 1948-2018 period as surge events. Boxes denote the inter-quartile distribution, with the median in between, and bars extend from the 5th to the 95th percentile of the random distributions. Surge events are defined as those with surge height above the 99.5th percentile of the 1948-2018 distribution.WRs are defined from daily fields of geopotential height at 500 hPa of the NCEP/NCAR reanalysis over the Euro-Atlantic sector [30, 65]ºN, [30°W, 25°E]. Acronyms stand for: NO: No (i.e. undefined) WR; ZR: Zonal Regime; EB: European Blocking; SB: Scandinavian Blocking; EA: East Atlantic; SL: Scandinavian Low; AL: Atlantic Low; AH: Atlantic High. See Garrido-Pérez et al. (2019) for further details. Bottom panel: The ALpattern which is associated to the occurrence of more than 40% of extreme surges. Data sources: NCEP/NCAR reanalysis (Kalnay et al. 1996) and Fabio Raicich (Raicich 2015).

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

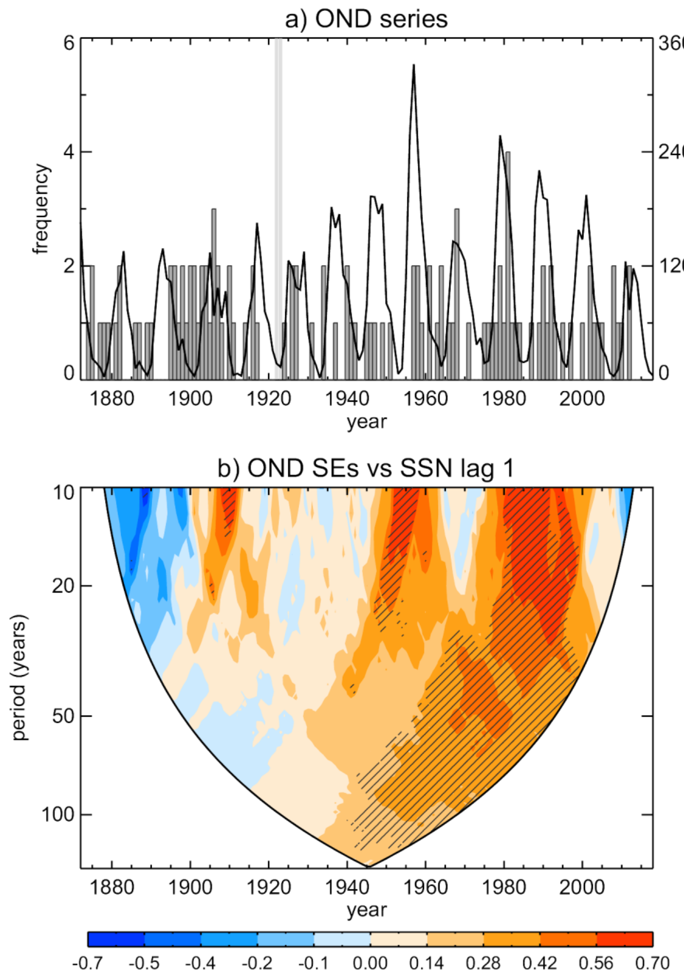
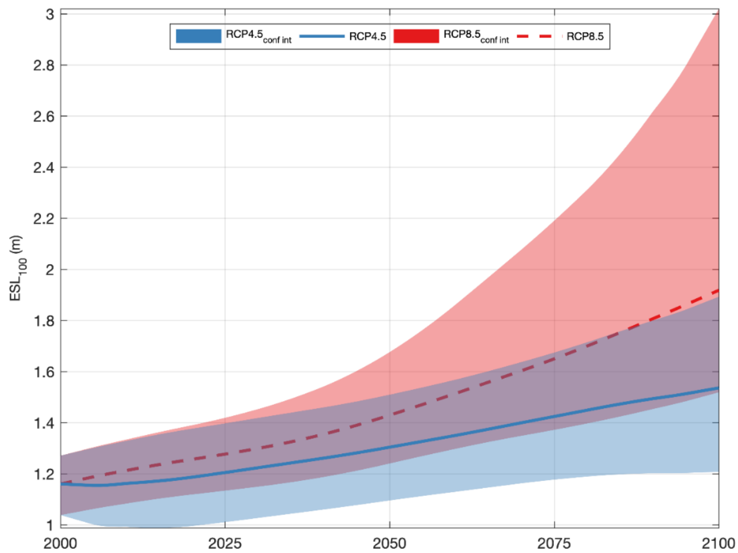


Figure 7 top panel: Time series of the autumn frequency of independent RSL extremes (SEs) for 1924-2018, defined as daily peaks above the 99.5th percentile (35.0 cm) of the distribution formed by the RSL values of all-year days of 1924-2018 Daily peaks are required to be separated by more than 72h. Black line shows the autumn mean time series of the SunSpot Number (SSN). Bottom panel: Rank Spearman's (rho) correlations between the autumn frequency of surge events in Venice and the recently revised Sunspot Number (SSN) for running windows of different width (y-axis) centered at each year of the 1872-2018 period (x-axis). Hatching denotes statistically significant correlations (p<0.05). Correlations are only computed when the sample size is equal or larger than 10 and it exceeds the half size of the window. The correlation pattern maximizes for SSN leading by 1-yr. Data sources: WDC-SILSO, Royal Observatory of Belgium, Brussels (see Clette et al. 2014) and Raicich 2015)

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020



895

896 **Figure 8 Time evolution of the 100y-ESL: Time series of the 100y-ESL under RCP4.5 (blue) and RCP8.5 (red).**
897 **Heavy: median, patches express the 5th-95th percentiles (very likely range).**

898

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

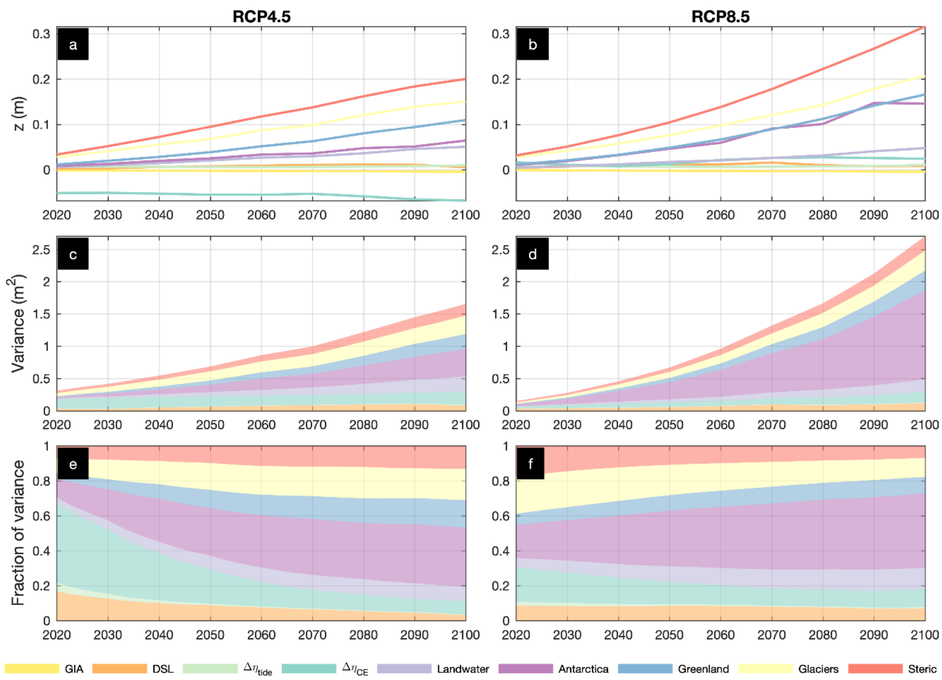


Figure 9 Break-down of projected 100y-ESL contributions and of their uncertainty, under RCP4.5 (a, c, e) and RCP8.5 (b, d, f). Projected increase of the 100y-ESL from changes in climate extremes, the high tide water level, as well as from SLR contributions from Antarctica, land-water, Greenland, glaciers, dynamic sea level (DSL), glacial isostatic adjustment (GIA), and steric-effects (a, b); variance (in m2) in components (c, d) and fraction of components' variance in global 100y-ESL change. Colors represent different components as in the legend and values express the global mean of the median.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

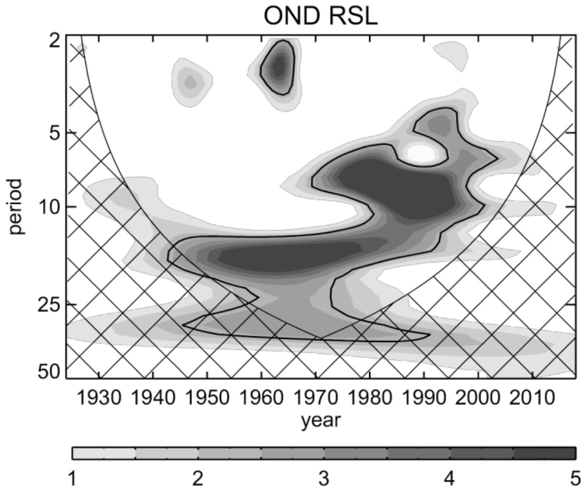


Figure A.1 Wavelet of the autumn mean time series of Relative Sea Level (RSL) for 1924-2018, expressed as power values normalized by the variance. Seasonal values are obtained from monthly means of the daily series. All months of this period have less than 10% missing days. Significant power density at 90% confidence level is highlighted by contours

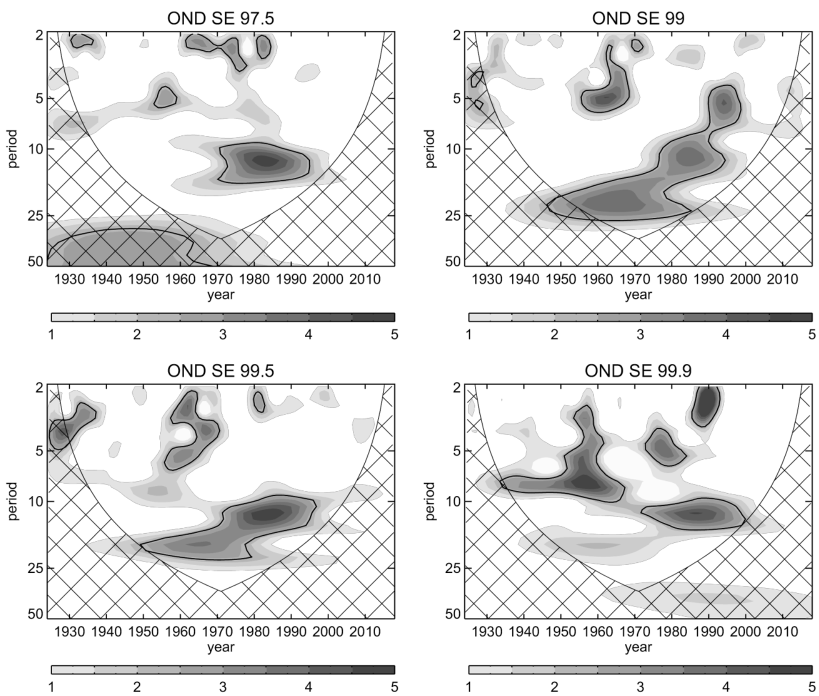


Figure A.2 As figure III.1 but for the autumn frequency series of independent SEs above the 97.5th, 99th , 99.5th and 99.9th percentiles.

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

Datetime [UTC]	RSL	Tide	Seiche	Storm surge	Meteotsunami + local setup	PAW surge	IDAS	Mean SL (10y running mean)
1966-11-04 17:00:00	194	-10	22	108	16	19	19	20
2019-11-12 21:50:00	189	36	5	43	38	20	15	32
1979-12-22 08:10:00	166	17	15	80	16	13	4	21
1986-02-01 03:00:00	159	31	23	48	4	18	13	22
2018-10-29 13:40:00	156	23	3	51	12	29	7	31
2008-12-01 09:45:00	156	39	22	43	0	18	5	29
2019-11-15 10:35:00	154	46	5	25	2	27	17	32
1951-11-12 07:05:00	151	45	1	43	2	39	5	16
2019-11-17 12:10:00	150	33	0	35	10	23	17	32
2012-11-11 08:25:00	149	50	-5	62	2	1	9	30
2018-10-29 19:25:00	148	-31	24	73	14	30	7	31
2002-11-16 08:45:00	147	40	-7	48	2	22	15	27
1936-04-16 20:35:00	147	20	15	60	7	27	7	11
2009-12-25 03:00:00	145	31	23	22	3	19	18	29
1960-10-15 06:55:00	145	33	4	63	2	11	14	18
2019-11-13 08:30:00	144	48	4	14	6	23	17	32
2010-12-24 00:40:00	144	36	1	37	4	22	14	30
2000-11-06 19:35:00	144	13	7	71	0	18	9	26
1968-11-03 06:30:00	144	43	10	43	2	18	7	21
2013-02-11 23:05:00	143	38	15	39	0	6	15	30
2012-11-01 00:40:00	143	16	3	54	3	27	10	30
2009-12-23 04:05:00	143	21	32	23	4	17	17	29
1992-12-08 09:10:00	142	43	6	31	2	35	1	24
1979-02-17 00:15:00	140	29	-3	39	10	27	17	21

Table 1 List of the extreme sea levels higher than 140 cm alongside the contributions (see section 2.1 and 2.2): astronomical tide, seiches, storm surge, meteotsunami and local set-up, PAW surge, IDAS variability, Relative Mean Sea Level. All values in cm. The Relative Mean Sea level anomaly refers to the 'Zero Mareografico Punta Salute' (ZMPS).

https://doi.org/10.5194/nhess-2020-359
Preprint. Discussion started: 13 November 2020

Natural Hazards and Earth System Sciences
Discussions

Date	RSL (cm)	Sources of RSL height
4-Nov-66	194	DO68, CA01, BC06, CPSM
12-Nov-19	189	ISPRA,CA20,CPSM
22-Dec-79	166	CA01, BC06, CPSM
1-Feb-86	159	CA01, BC06, CPSM
29 Oct 2018*	156	BC06, ISPRA, CPSM,CA19
1-Dec-08	156	BC06, ISPRA, CPSM
12-Nov-51	151	DO61, CA01, BC06, CPSM
11-Nov-12	149	BC06, ISPRA, CPSM
29 Oct 2018*	148	BC06, ISPRA, CPSM
16-Nov-02	147	BC06, CPSM
16-Apr-36	147	DO61, BC06, CPSM
25-Dec-09	145	BC06, CPSM
15-Oct-60	145	DO61, CA01, BC06, CPSM
24-Dec-10	144	BC06, ISPRA, CPSM
23-Dec-09	144	BC06, CPSM
6-Nov-00	144	CA01, BC06, CPSM
3-Nov-68	144	CA01, BC06, CPSM
12-Feb-13	143	BC06, ISPRA, CPSM
1-Nov-12	143	BC06, ISPRA
8-Dec-92	142	CA01, BC06, CPSM

Table A.1 List of the surge events higher than 100 cm alongside the respective RSL. The asterisk indicates the two RSL peaks during the same event on 29 October 2018. (AN41 = Annali, 1941; CA01 = Canestrelli et al., 2001; CA19 = Cavaleri et al., 2019, CA20 = Cavaleri et al., 2020, CPSM = CPSM, 2020; DE06 = de Zolt et al., 2006; DO61 = Dorigo, 1961b; DO68 = Dorigo, 1968; ISPRA = ISPRA, 2008-2018; ISPRA/CPSM/CNR = ISPRA et al., 2020)