**Introduction to the special issue "Venice flooding and sea level: past evolution, present issues and future projections"**

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**Abstract.**

Venice is an iconic place and a paradigm of huge historical and cultural value at risk. The frequency of flooding of the city centre has dramatically increased in recent decades and this threat is expected to continue to grow and even accelerate through this century. This special issue collects three review articles addressing different and complementary aspects of the hazards causing the floods of Venice: (1) the relative sea-level rise, (2) the occurrence of extreme water heights, and (3) the prediction of extreme water heights and floods. It emerges that the effect of compound events poses critical challenges to the forecast of floods, particularly from the perspective of effectively operating the new MoSE mobile barriers and that relative sea-level rise is the key factor determining the future growth of the flood hazard, so that the present defence strategy is likely to become inadequate within this century under a high emission scenario. Two strands of research are needed in the future. Firstly, there is a need to better understand and reduce the uncertainty on the future evolution of relative sea level and its extremes at Venice. However, uncertainty might not be substantially reduced in the near future, reflecting uncertain anthropogenic emissions and structural model features. Hence, complementary adaptive planning strategies appropriate for conditions of uncertainty should be explored and developed in the future.

## 1. Motivation

The great historic, ecologic, and economic interest of the city of Venice and its lagoon and the threats at which they are exposed are known around the world. In 1987, Venice and its lagoon were recognised as a UNESCO World Heritage Site based on six criteria of outstanding cultural, environmental and landscape universal value encompassing the historical and artistic relevance of the city and the exemplarity of the ecosystem (https://whc.unesco.org/en/list/394/). In UNESCO's words, Venice symbolizes "*the people's victorious struggle against the elements as they managed to master a hostile* *nature*" and its semi-lacustral habitat" *has become vulnerable as a result of irreversible natural and climate changes"*.

The history and the very essence of Venice are tightly intertwined with the sea and the lagoon, which have represented a source of resources and wealth, and a natural defence system against enemies. However, the threat of floods has always been present (Enzi and Camuffo, 1995). This hazard has been exacerbated by the increased rate of relative sea level (RSL) rise after the 1930's (Zanchettin et al., 2021; Lionello et al., 2021, hereafter Z2021 and L2021, respectively), posing serious and growing threats to the city of Venice and its lagoon. In fact, the recurrent floods that afflict Venice, referred to as "aqua alta" in the local dialect, are the best known and debated symptom of the frailty of the Venetian lagoon system. The Venetian RSL has risen at an average rate of 2.5mm/year in the past 150 years due to mean sea-level rise and sinking of the ground by natural and anthropogenic subsidence, which accelerated the RSL rise rate up to 5mm/year in the period 1950-1970 (Z2021), leading to increased frequency of floods (L2021). The lowest part of the Venice's central St. Mark's Square is approximately 55 cm above the present mean sea level and nowadays a positive water height anomaly (see section 3) that is only a few centimetres above astronomical high tide (whose amplitude is about 50cm) can flood it.

The dramatic surge of 4 November 1966 showed unequivocally the need for counteracting an increasing hazard level. The event reached the highest ever recorded water height (194 cm) and persisted over 110 cm for 22 hours (see L2021; De Zolt et al., 2006; Cavaleri et al., 2010). Figure 1 shows the flooding of the central monumental area at a time close to the peak of the 6 November 1966 event. In 1973, the Italian government established a legal framework, the Special Law for Venice, establishing objectives, responsibilities, regulations, actions and funding allocations to safeguard Venice and its lagoon. The solution finally approved by the Italian government is a system of large mobile barriers (MoSE, Modulo Sperimentale Elettromeccanico) at the three lagoon inlets. Barriers will be raised only during severe events, closing the lagoon inlets and preventing the water height exceeding the safeguard level within the lagoon, while under normal conditions, they lay on the bottom of the lagoon inlets, allowing water exchange and ship traffic between the lagoon and the Adriatic Sea. After a long planning phase, construction started in 2003 and it is foreseen that the barriers will be fully operational at the end of 2021. The recent event on 12 November 2019 (Cavaleri et al.; 2020, Ferrarin et al.,2021), which has been the second highest water height (189 cm) ever measured in Venice by a tide gauge, has dramatically reconfirmed the need for an adequate defence system. November 2019 was the worst month since the beginning of the local tide-gauge records for excessive high waters, with 15 events exceeding 110 cm and 4 events above 140 cm. MoSE has already been operated for a few exceptional events, such as on 3 October 2020, when, for the first time, the lagoon was cut off under real hazard conditions from the Adriatic Sea. While the peak water height during the event was 130 cm in the Adriatic, it was kept at 70 cm in the lagoon and at St. Mark's Square, and flooding was avoided. Figure 2 shows an aerial view of the barriers blocking the lagoon inlets and the time series of the water height outside ("Piattaforma CNR") and inside the lagoon ("Punta Salute Canal Grande" represents the tide gauge commonly used as reference for the sea level in the city centre).

A large scientific literature considers the factors leading to the flooding of Venice, predicting the timing and intensity of the events and describing changes in their frequency and intensity under future global warming scenarios. This special issue aims to critically review the current understanding of the Venice flooding phenomenon. It considers the meteorological and climatic factors producing "aqua alta", its prediction, and its historical and expected future variations under a globally changing climate. The synthesis is oriented toward clarifying consolidated knowledge, highlighting gaps in knowledge, and identifying major opportunities for progress.

This special issue comprises three review articles addressing three different and complementary aspects of the hazards causing the flood of Venice. Z2021 considers the Venetian RSL evolution on multiple time scales and the factors determining it. Umgiesser et al. (2021, hereafter U2021) describe the tools that have been developed and are currently used for the prediction of the floods and gives recommendations for further improvements. L2021 describes the factors leading to extreme water-height events, their past evolution, and expected future trends under a climate change perspective. The outcomes of these papers provide a thorough critical review of the scientific literature. It is, hence, a basis for the assessment of present and future risks and helps to define the requirements of the adaptation strategies that are appropriate for Venice over the 21st century.

This editorial provides an introduction to these three reviews. It shortly provides general background information by describing the geographical and historical setting (section 2) and the phenomenology of surges and high-water levels (section 3). Section 4 describes the overall key findings produced by the three reviews. Implications for future flooding and its management are addressed in the conclusive section 5.

## 2. Geographical and historical setting

The Venice Lagoon covers about 550 $km^2$ along about 50 km of low-lying coast within the easternmost boundary of the Po Plain, and is connected to the northern Adriatic Sea through three tidal inlets: Lido, Malamocco and Chioggia (Fig. 3). The historical city is located in the centre of the lagoon and is built at low elevation on a basis made of wooden piles reaching an underground hard layer and supporting the buildings.

The Venice Lagoon is governed by a fragile equilibrium, which has been artificially preserved over the centuries by contrasting the natural evolution of this transitional area that is driven by coastal dynamics via geomorphological (e.g., erosion and sedimentation), chemical (e.g., salinification), biological and ecological (e.g., loss of wetlands and other ecotypes) changes. Since the 15th Century, Venetians have engaged in an enduring struggle against sedimentation in the lagoon, mainly by diverting away - with variable degrees of success - the major rivers Adige, Bacchiglione, Brenta, Sile, and Piave and their sediment supply, hence altering the morphology of the alluvial plain and the coastal margins. Bondesan and Furlanetto (2012) provide a recent assessment, based on historical cartography analysis, of the artificial fluvial diversions performed during the 16th and 17th centuries. More recent works in the 19th and 20th centuries include deepening of existing channels within the lagoon, excavation of the “Canale dei Petroli” (Oils Channel) and construction of breakwaters at the lagoon’s mouths to allow modern ships to reach the ports of Giudecca and Marittima in the historic city and, more recently, Porto Marghera.

The tidal regime is a mixed semidiurnal cycle with a tidal range of more than 1 m at spring tide and only three components above 10 cm, with the semidiurnal M2 and S2, and the diurnal K1 providing the largest contributions (23, 14, 16 cm, respectively) both outside the lagoon inlets and in the city center (Polli, 1952; Ferrarin et al. , 2015)

Hydrodynamics linked to tidal exchange are critical for the great ecological variety and biodiversity of the Venice Lagoon, with habitats ranging from tidal flats, marshlands, channels and canals, inlets and tidal deltas with strong hydrodynamics and tidal renewals.

Changes in RSL may critically compromise the ecosystem functionality by inducing morphodynamic changes that alter the ecological vocation of such areas (Zanchettin et al., 2007). Several studies show that the increase of extreme floods since the mid-20th century is explained by RSL rise (Lionello et al.,2012; L2021). Further, future sea-level rise (Z2021) might dramatically increase both the frequency of high sea level events and resulting floods, as well as increasing the duration and extent of flooding (L2021). This reinforces the need to understand the historical context of sea-level change in Venice, and consider its prognosis.

## 3. Characteristics of surges and high water levels

The floods of Venice are associated with the positive anomalies of the water height, defined as the difference between the instantaneous sea level and the bottom level. The term “water height” is introduced because considering only sea level does not account for the fundamental role that the local vertical land motion (subsidence) has and will continue to have in the increased frequency of floods. The contributions leading to large water height anomalies are meteorological surges, seiches, tides, seasonal-to-decadal sea level variability and long term RSL changes. The meteorological surges result from three different contributions characterized by different time scales: surges produced by planetary atmospheric waves (PAW surges) ,with duration from 10 days to 100 days, storm surges produced by mid-latitude cyclones with time scales of a few days, meteotsunamis and surges produced by mesoscale systems (with a short duration of a few hours). The characteristics of the different contributions and the criteria for their distinction are explained in section 2.1 and 2.2 of L2021. Note that this terminology differs from Gregory et al. (2019) in that the term “water height” is introduced and the surge is distinguished by three components, reserving the term “storm surge” for the component produced by the passage of a cyclone.

Meteorological surges in Venice are caused by a combination of various physical processes, mainly triggered by the water level in the neighbouring Adriatic Sea. The main component of extreme events is the storm surge produced mostly by the south-easterly wind (Sirocco), pushing the water versus the north-western end of the Adriatic Sea (wind set-up), and the low atmospheric pressure that increases the mean sea level by one centimetre per millibar of pressure decrease (inverse barometer effect). The surge produced by atmospheric planetary waves and mesoscale atmospheric systems can also provide a significant contribution. To these meteorological processes, the contribution of the regular tides has to be considered, which can add about 50 cm during a spring tide (Ferrarin et al., 2015). Another flood process is seiches, i.e., free oscillations of the Adriatic Sea triggered by wind setup. The main seiches, which have a period of around 23 hours, very close to that of the diurnal tides, overlay the meteorological and tidal processes and may cause flooding even if the main meteorological conditions have calmed down (Bajo et al., 2019). These processes and their superposition leading to compound events are described in L2021.

The positive water-level anomaly in the Adriatic Sea enters the lagoon nearly undisturbed through the deep inlets (8-13 meters) and then reaches and floods the city centre of Venice (Umgiesser et al., 2004; U2021). While there might be some local water height differences due to wave setup outside the inlets and wind stress inside the lagoon, the water height in the city of Venice closely follows the level outside the lagoon. Wave run-up and infra-gravity waves are not relevant for the water height in the city centre, although they may have an effect at the sea side of the barrier islands separating the lagoon from the Sea (see L2021).

## 4. Key insights from the papers

The important potential role of compound events (resulting from the superposition of the different contributions introduced in section 3) for causing extreme sea levels emerges clearly from L2021. Many past studies concentrated on the storm surge contribution, which was the determinant contribution for the 4 November 1966 and the 19 October 2018 events, and on the need for a precise prediction of its timing in relation to the phase of the astronomical tide and pre-existing seiches. However, the presence of other factors can determine extreme sea-level events when they act constructively, namely planetary atmospheric wave surges and meteotsunamis, even if their individual magnitude is not exceptionally large (L2021), as it was apparent in the recent 12 November 2019 event (Ferrarin et al., 2021). This poses a great challenge to the prediction of extreme sea levels (U2021) and the management of MoSE. Further, historic floods show large interdecadal and interannual fluctuations, whose dynamics are not sufficiently understood (L2021), preventing reliable seasonal predictions.

The water height forecast (U2021) has paramount importance, because it is needed by civil protection for flood warnings and by the consortium that operates the mobile barriers (MoSE), which are currently in a pre-operational phase at the inlets. Considering the operativity of MoSE, a reliable forecast should be able to satisfy the requirements of the different stakeholders, especially in terms of the forecast range and error statistics (Umgiesser, 2000). The present plan is to operate the barriers and to close the lagoon on the basis of the forecast water level, wind and rain only a few hours before the event. The port authority is particularly sensitive to unnecessary closures, which produce unmotivated economic losses by limiting the port operations and to anticipate (in the range from one to two days) the decision to close in order to facilitate proper management of the ingoing and outgoing ship traffic. Residents, shopkeepers and most commercial activities in Venice would support a more conservative approach that minimizes the risk of flood damages to goods and properties. Therefore, the port authority is interested in avoiding false alarms, while other stakeholders are worried about missing closures. Tourist activities would in general be concerned by cancellations of reservations and visits that may be caused by an excessive water level forecast.

An operational forecasting system has been in place for the last 40 years, but further developments are needed to match the requests of stakeholders and the requirements for operating MoSE. Lack of accuracy in the forecast of the compound event that led to the exceptional water-height maximum on 12 November 2019, produced a severe underestimate (up to 45 cm) of the maximum event height by all available forecast systems (Ferrarin et al., 2021). The need to improve the operational forecasting system has been further demonstrated by the flooding of the city on 8 December 2020, when the MoSE was not operated, in spite of being available, because the forecast underestimated the height of the water level. Therefore, further developments are needed, particularly the use of ensemble methods, assimilation of real time data, and the exploitation of multi-model approaches (U2021). Implementing these features in the forecasting systems can (and should) be done to guarantee an improved and adequate water-level forecast in the near future.

RSL rise is the factor that has produced the past increase of the Venice flood frequency. Z2021 shows that the 2.5mm/year RSL trend in Venice has been caused in approximately equal parts by land subsidence and mean sea level (MSL) rise. L2021 shows that increased frequency of floods is attributed to such RSL rise, with no robust evidence of intensification of the meteorological conditions associated with extreme water heights. Figure 4 summarizes these results by showing the RSL rise in Venice and the corresponding increase of frequency of water-height maxima above 120 cm, which has increased from less than two events per decade (average frequency during the first half of the 20th century) to 40 events in the last decade (2010-2019). Considering a lower (110 cm) water-height threshold, the number of events has increased from 4.2/decade to 95/decade (L2021).

Uncertainty in future greenhouse gas emissions (largely depending on governmental and societal decisions) and structural modelling uncertainties (particularly in relation to the melting of the large Greenland and Antarctic ice sheets) lead to a wide range of possible future sea-level rise scenarios (Zanchettin et al., 2020). Figure 4 shows that the past MSL in Venice closely follows the MSL evolution of the Subpolar North Atlantic. Differences between these two time series consists of inter-annual and inter-decadal sea level fluctuations in the North Adriatic, with no sustained different trends. This and other studies indicate that future sub-regional deviations play a minor role for long term planning and add an uncertainty estimated in the order of ±10 cm to the RLS at the end of the 20th century (Z2021). Figure 5 shows a RSL rise range from about 30 to 110 cm at the end of the 21st century (with a wider 10 to 120 cm range, accounting for the uncertainty associated with sub-regional deviations). This could grow to above 180 cm if an unlikely, but plausible, high-end scenario is realised. These values are obtained considering regional analysis of future RSL (Thiéblemont et al., 2019), integrated by accounting for centennial natural vertical land movement occurring at the past rate) and adding a further 10 cm uncertainty caused by sub-regional deviations from the Subpolar North Atlantic sea level (Z2021).

Future RSL rise will be the key factor determining the future duration of extreme water heights above the safeguard thresholds, which correspond to the duration of the closures of the inlets by the MoSE mobile barriers. Figure 5 reports the RSL thresholds for the closures based on the consensus between Lionello (2012) and Umgiesser (2020) and it shows that the period of closure will grow at a rate controlled by RSL rise. Closing of the inlets for three weeks per year is unlikely before the 2040's, but virtually certain before the end of this century, even under a low-emission scenario (RCP2.6). Two-months closures per year are unlikely before the late 2050's even under a high-end emission scenario (RCP8.5). However, they become virtually certain by the late 2080's under a high-emission scenario and about as likely as not before the end of this century for a low-emission scenario. Note that a six-month closure per year (which can be used as criterion for considering the present defence strategy to be inadequate and would require new additional actions) is likely to occur before the end of this century under a high-emission scenario.

RSL rise will also be the key factor responsible for the future increase of extreme sea-level frequency and height, while the reduction of intensity of meteorological events and changes of tidal regimes will play a secondary role (L2021). In the case of a high-emission scenario the magnitude of 1-in-100 year sea-level events at the northern Adriatic coast is projected to increase by up to 65% in 2050 and 160% in 2100 with respect to the present value, continuing to increase thereafter through the 22nd Century and beyond (L2021).

## 5. Implications for future flooding and its management

The insights from the three review articles have important implications for our understanding of the future occurrence of floods in Venice and their management. They demonstrate that RSL rise has been and will continue to be the main driver of increasing extreme water heights and increasing flood potential. Projected future RSL rise is the product of local changes due to subsidence and regional and global trends linked to human-induced climate change. Natural background subsidence (up to around 1 mm/year) due to enduring long-term geological trends apparent over many centuries and longer is inevitable in Venice (Z2021). Importantly, however, most subsidence in the last 100 years was due to human actions (largely groundwater withdrawal). Since the 1970s, regulation and provision of alternative sources of water for industrial, agricultural and civil use have avoided such subsidence. It is important that these successful regulations to control human-induced subsidence continue to be enforced in the future. Efforts could even be strengthened further, as some localised subsidence can still be measured linked to construction works and related activities (Tosi et al., 2018). Costs, benefits and practicality of the required measures might be considered in the context of building regulations and permitting. Therefore, future human-induced contributions to local subsidence can be controlled based on historic experience and awareness.

In contrast, most ongoing and projected future climate-induced sea-level rise is a result of global actions concerning greenhouse gas emissions and resulting temperature rise. It is therefore of paramount importance to identify and support collective global actions to reduce such emissions, especially the Paris Agreement. It is also important for Venice, as in other coastal jurisdictions around the world, to stay aware of future expectations about sea-level rise and plan accordingly. The regular assessments of the Intergovernmental Panel on Climate Change (IPCC) are especially important in this regard, with the Sixth Assessment being expected in 2021. Currently, it is not clear whether the world is heading towards emissions more comparable to RCP4.5 or RCP6.0 (Hausfather and Peters, 2020), rather than to RCP8.5 (Schwalm et al., 2020). With further reductions, emissions close to RCP2.6 (following the Paris Agreement) is a plausible albeit challenging target to achieve. However, the recent IPCC Special Report on the Cryosphere and Oceans (Oppenheimer et al., 2019) has emphasised the fundamental point that stabilizing temperature does not stabilize sea level, but rather, the rate of sea-level rise.

Hence, some RSL rise is inevitable for Venice and extreme water heights and flood potential will grow: uncertainty concerns only the rate of this increase. Significant aspects of this uncertainty relate to future emissions, the response of the Greenland and Antarctic ice sheets to global temperature rise and future subsidence of the Venice Lagoon. It is important to remember that Venice has adapted to RSL rise through its more than 1,000 year history. Hence, the adaptation actions since the 1966 floods, comprising both local adaptation (by raising parts of the historical center), and large-scale adaptation for the whole lagoon (the construction of the MoSE barriers) continue this tradition. With the MoSE barriers being fully commissioned in 2021 the risks of flooding in Venice will be greatly reduced. However, as RSL is still rising and is projected to rise beyond the 21st Century even with the Paris Agreement being fully implemented, ultimately even this new world-class adaptation system will be challenged. The critical question is when a new adaptation strategy will be required, being aware that, considering the uncertainty of future RSL scenarios, it might happen in the worst case within a few decades, or maybe much later during the 22$^{nd}$ century. This suggests that experience from the long-term planning for sea-level rise under uncertainty that is carried in locations such as London (Ranger et al., 2013) and drawing on adaptation pathways more widely (Haasnoot et al., 2019) should be considered also in the Venetian context.

Lastly, the recognition of the possible role of compound flood events due to superimposed extreme water heights drivers shows the potential for improved flood forecasts in Venice, which in turn will allow for better control of the MOSE barriers. Thus, improved understanding and forecasting of short-term events will contribute to better long-term adaptation at Venice. With such improved forecasts and greater confidence in those forecasts, this has the potential to extend the operational range of the MoSE barriers and its life as an adaptation tool for Venice. This needs to be more fully explored.

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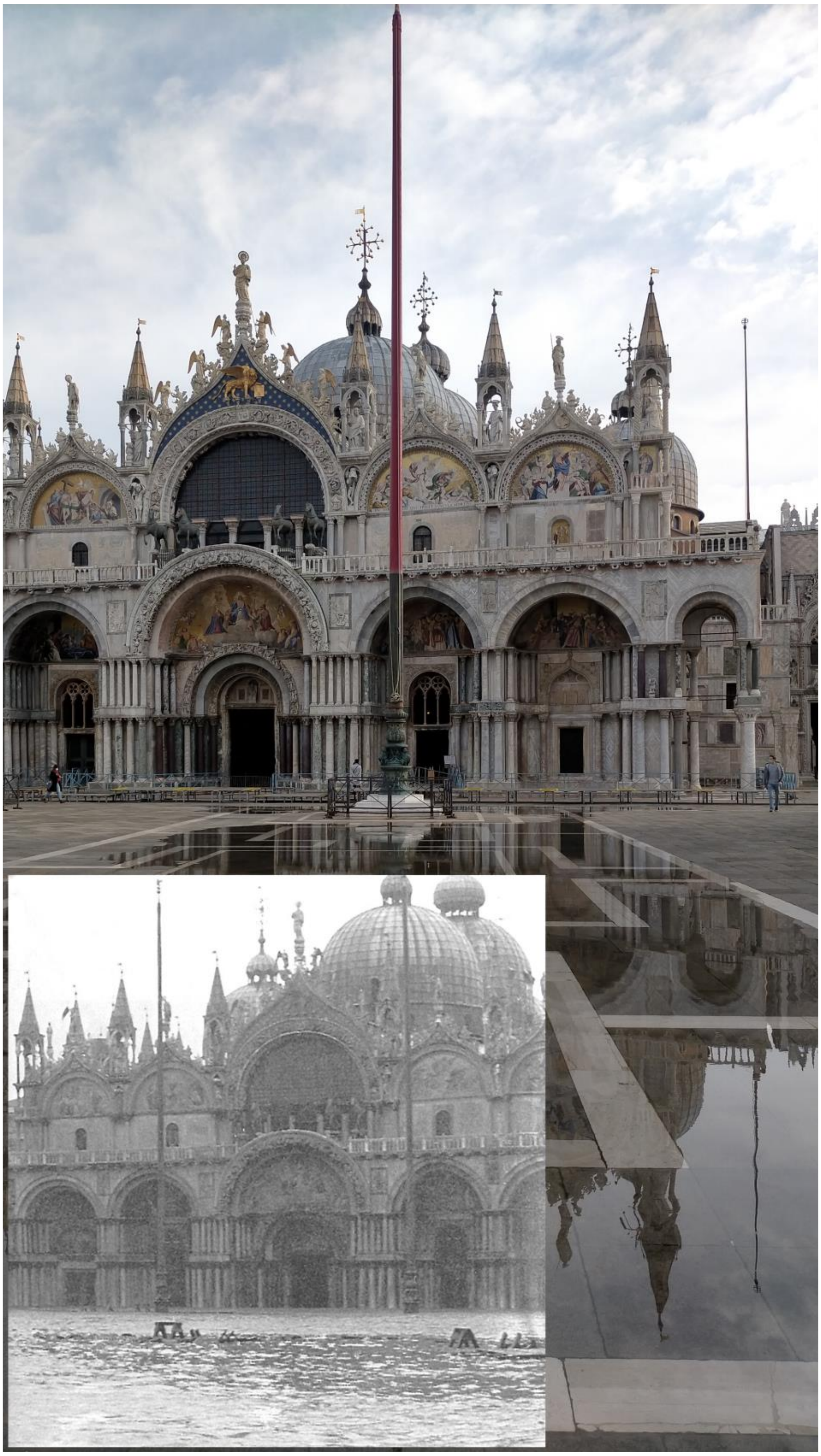

**Figure 1** - Present condition of St.Mark square during partial flooding of its lowest areas (estimated water height: 80cm) and historical picture close to the time of highest level of the 4 November 1966 flood (black and white photo courtesy of Gianfranco Tagliapietra)

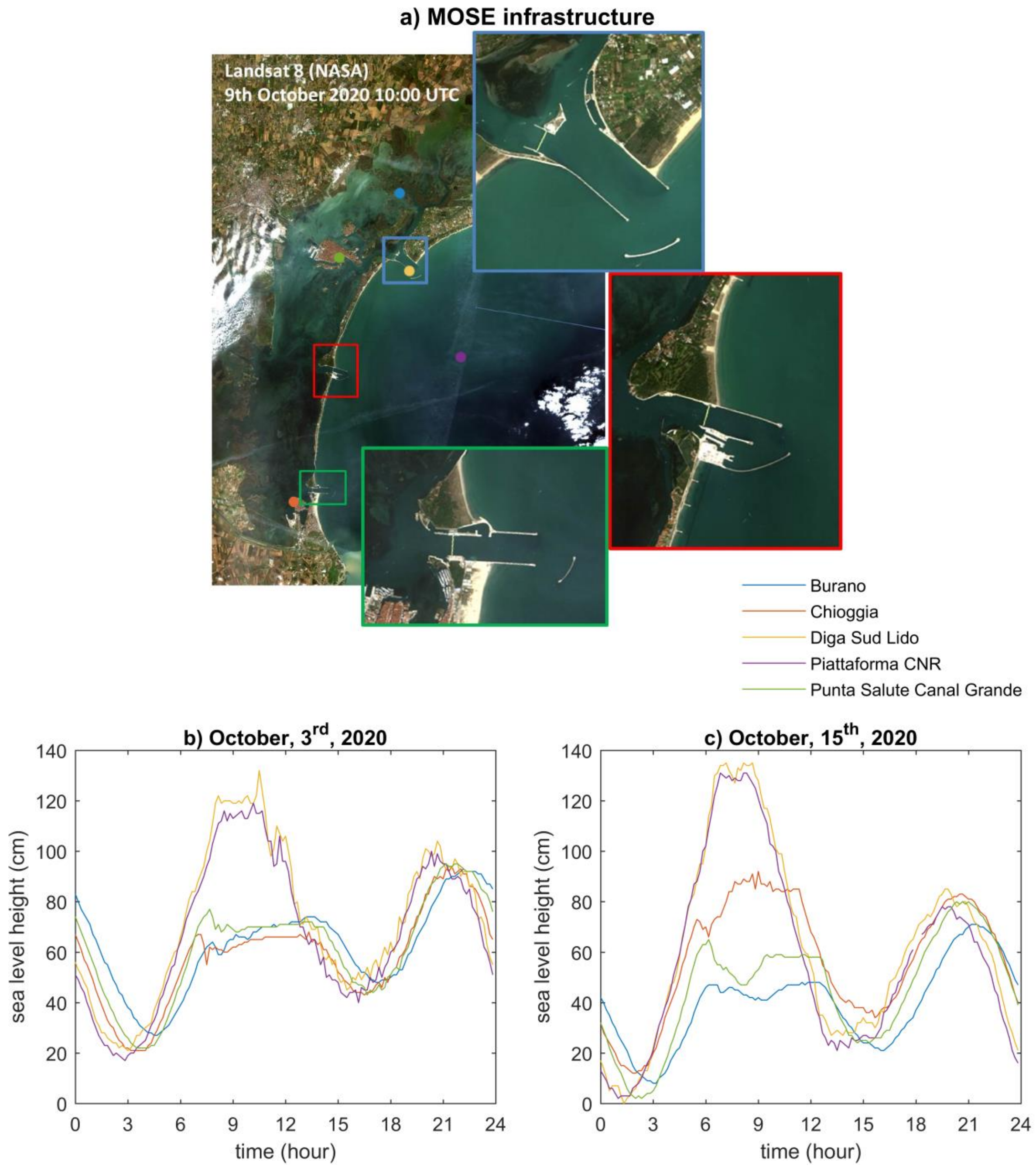


**Figure 2** - Pre-operational closures of the MoSE in October 2020. a) Pseudo-true-colour pan sharpened Landsat 8 OLI imagery acquired on 9 October 2020 showing the Venice Lagoon inlets during a test closure of the MoSE. Landsat 8 image is available from the U.S. Geological Survey and processed by CNR-ISMAR. b) water height anomalies measured on 3 October 2020 by tide gauges located within the Venice lagoon (Burano, Chioggia, Punta della Salute-Canal Grande) and in the open Adriatic Sea (Diga Sud Lido, Piattaforma CNR), showing the effect of the MOSE closure on the water-height level inside the lagoon. Panel c) is the same as b) but for the MoSE Closure on 15 October 2020.

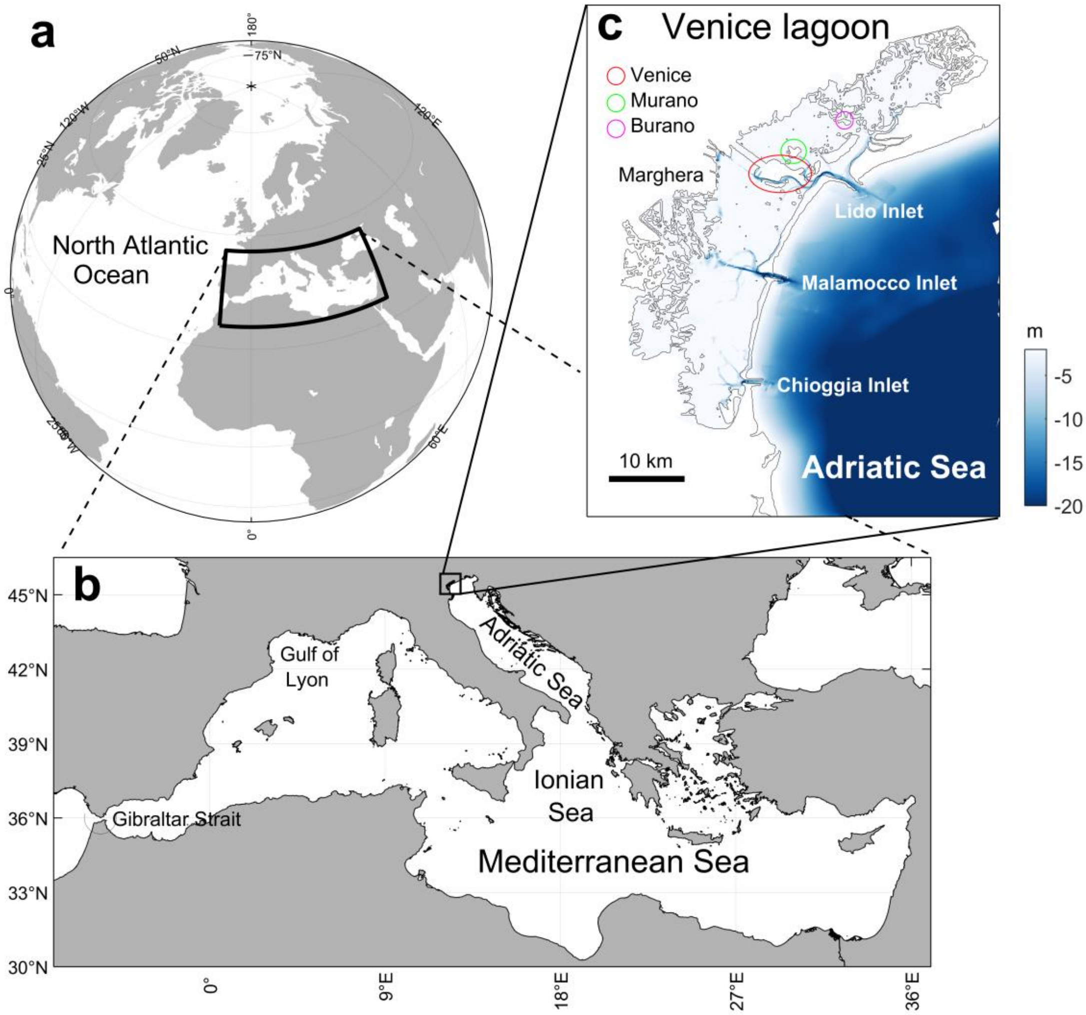


**Figure 3** - The Lagoon of Venice in the global context. (a) The Mediterranean Sea is connected with the North Atlantic Ocean through the Strait of Gibraltar. (b) The Venice Lagoon is located along the northern coast of the Adriatic Sea, a sub-basin of the Eastern Mediterranean Sea. (c) The historic centre of Venice (indicated) is located in the centre of the Venice Lagoon.

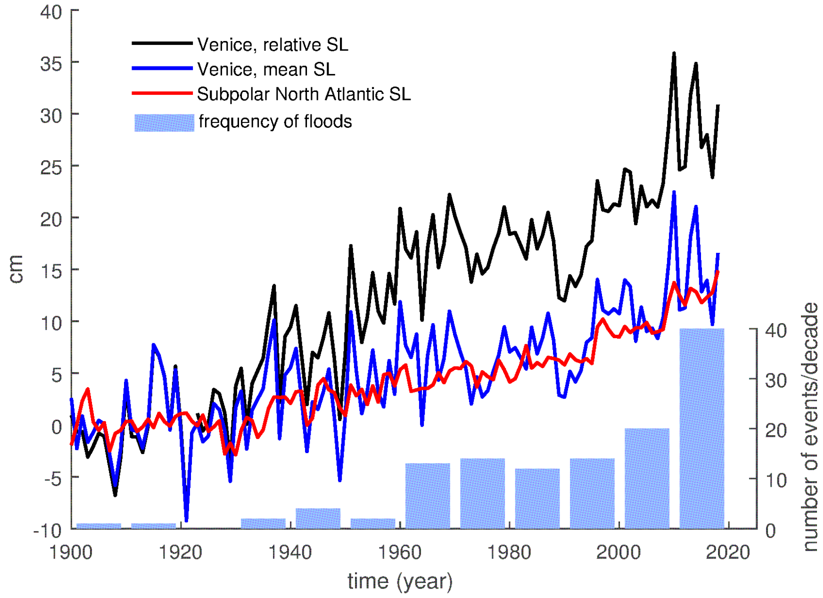


**Figure 4 -** Comparison between historical evolution of average sea level and flooding events in Venice, and the link with larger-scale changes in sea level. Venetian sea level is reported as annual-average relative sea level obtained from measurements by the Punta della Salute tide gauge (black line) and as annual-average mean sea

level obtained by removing the local subsidence estimate from the tide gauge data (blue line, Zanchettin et al., 2020). The red line illustrates the evolution of the basin-average sea level for the subpolar North Atlantic estimated by Frederikse et al. (2020). Blue bars show the number of floods exceeding the threshold of 120 cm within each decade.

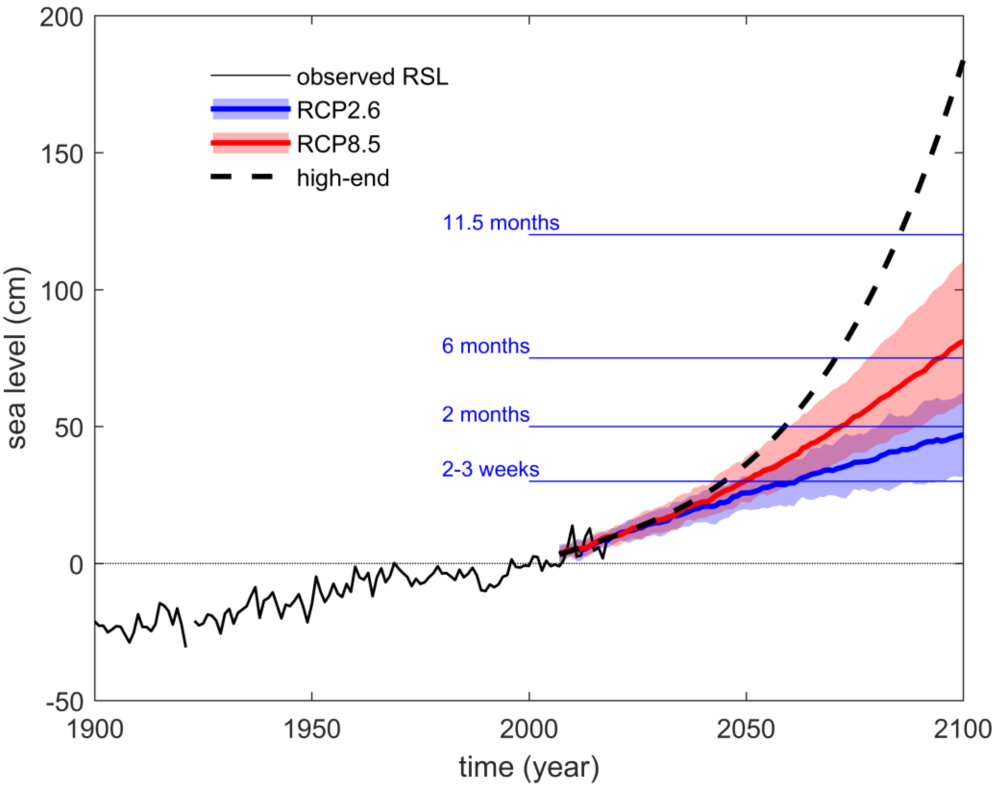


**Figure 5 -** Projected relative sea level change in Venice in the context of historical observations. Observations are annual-mean tide gauge relative sea-level height anomalies with respect to the 2000-2007 average. Projections are based on two reference scenarios of anthropogenic greenhouse gas emission, namely RCP2.6 (low emission scenario) and RCIP8.5 (strong emission scenario), and a high-end scenario illustrating a plausible evolution obtained by combining the highest estimates of all individual contributions to relative sea level rise (shading: 5-95 percentile range, line: median). The horizontal blue lines shows the relative mean sea level thresholds for annual persistence of the relative sea level above the present safeguard level (persistence durations of 2-3 weeks, 2, 6,11.5 months have been considered). These time intervals approximately correspond to the annual duration of the expected closures of MoSE.