THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

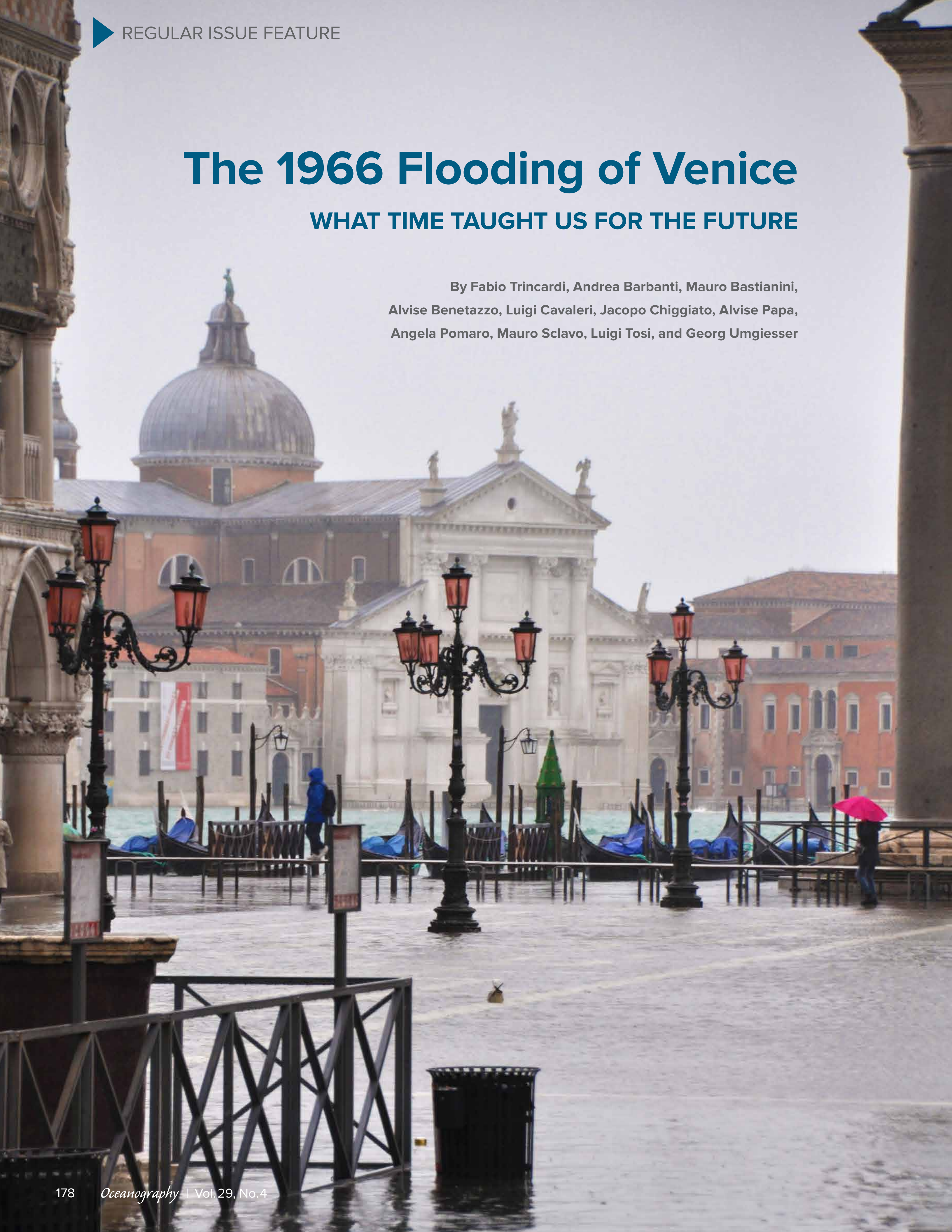
DOI

https://doi.org/10.5670/oceanog.2016.87

The 1966 Flooding of Venice

WHAT TIME TAUGHT US FOR THE FUTURE

By Fabio Trincardi, Andrea Barbanti, Mauro Bastianini, Alvise Benetazzo, Luigi Cavaleri, Jacopo Chiggiato, Alvise Papa, Angela Pomaro, Mauro Sclavo, Luigi Tosi, and Georg Umgiesser



> "In the twentieth century, Venice lost 26 cm in ground elevation with respect to mean sea level through the combination of land subsidence and global sea level rise."

ABSTRACT. Upon this fiftieth anniversary of the storm that flooded the historical Italian centers of Venice and Florence, we review the event from the perspective of today's scientific knowledge. In particular, we discuss the components of relative sea level rise in Venice that contribute to flooding, the monitoring networks and forecast capabilities that are currently in place, and the engineering actions adopted since the 1966 flood to safeguard the Venice lagoon and the city. Focusing on the meteo-oceanographic aspects, we also show how sheer luck at the time avoided a much worse disaster in Venice.

INTRODUCTION

Millions of tourists from around the world have an idea of, if not uncomfortable direct experience with, what life is like in Venice during high water events: seeing the water rise in San Marco square, walking on narrow wooden catwalks like ants along their paths, or simply looking for boots or plastic bags to wrap around their feet, if not their entire legs.

"High water" (*acqua alta,* Italian for floods) in Venice develops seasonally, reflecting a mixture of astronomical (tides) and meteorological (storm surges) forcing, as well as the consequences of human uses of this coastal region, including historical diversion of rivers, modification of inlets, and, more recently, pumping of freshwater from beneath the lagoon (reflecting a lack of awareness of how this process adds to natural subsidence).

Half a century after the big flood, *l'Acqua Granda*, of November 4, 1966, we revisit this event, detailing the background conditions and the meteo-oceanographic aspects of the storm. We then describe how society, science, and the Italian government reacted to the event and the specific actions that were undertaken to safeguard Venice. We conclude by addressing the crucial aspects of the safeguarding strategy and also look toward the future.

WHY DOES VENICE FLOOD?

The Venice lagoon lies at the upper end of the 700 km long Adriatic Sea (Italy, Figure 1). The shallowness of the northern Adriatic results from sediment deposited there by rivers (Massari et al., 2004; Amorosi et al., 2016). The lagoon itself is 50 km long and 10 km wide (Figure 1a), a dynamic and (in geological time) ephemeral system that includes a cluster of islands with Venice at its center. Three inlets connect the lagoon to the Adriatic Sea and allow continuous flushing of its water with the tidal cycle (Figure 1).

Over time, sea level rise combined with soil subsidence has lowered the level of Venetian pedestrian sidewalks such that, at present, their lowest parts are only 70 cm above mean sea level. With the spring tide excursion at 1 m, any small perturbation of this delicate situation means that water invades Venice's narrow streets. In the following sections, we describe the natural and anthropogenic factors that led to the present situation and to the great flooding event of November 4, 1966.

Meteorological Forcing

Although meteorological forcing is only one of the components that affect water levels in the lagoon, 70% of acqua alta events occur in autumn when eastward-moving low-pressure systems pass over the northern Adriatic Sea (Camuffo, 1993). Pressure eventually increases from west to east, with associated occurrence of southeasterlies (Sirocco winds). The inverted barometer effect (i.e., low atmospheric pressure favors local sea level increase) and the long-fetch Sirocco that piles up water mass in the northern Adriatic raise water levels. These low-pressure systems are frequently generated by baroclinic instability in the Western Mediterranean (e.g., Buzzi and Tibaldi, 1978), especially in autumn when the season's first northerly cold storms propagate over the still-warm Mediterranean seawater. Sometimes, depending on the track of the low-pressure center, northeasterlies (Bora winds) can blow over the Venice lagoon and the very northern Adriatic, causing a local, but intense, piling up of waters toward the southern sector of the lagoon, a configuration that is dangerous for the city of Chioggia (Figure 1a).

Tides

In addition to meteorological forcing, water levels in the Mediterranean Sea, and in the Adriatic in particular, depend on the astronomical tide. The northern Adriatic tidal range is among the highest in the Mediterranean, up to 1 m in spring conditions. The semidiurnal tidal dynamics is well known, thus tidal evolution can be forecast very precisely for years ahead.

Similar to the seasonal winds, when a storm blows from the sea toward land, a combination of wind stress at the sea surface and breaking of wind-forced waves pushes water onto shore, increasing local sea levels. This effect is more intense in shallow water, so the maximum flood level occurs along the seaward edge of the Venice lagoon, where water enters via the three inlets (Figure 1a). When the storm abates, and in most cases it does so very rapidly, the larger than usual volume of water in the northern part of the lagoon leads to a series of oscillations (seiches) that progressively dampen over the course of several days. The main seiche in the Adriatic Sea has a period of 22 hours (Tomasin and Pirazzoli, 1999). This combination of tides and seiches leads to the possibility of a flood in the Venice lagoon the day after a storm, even in fair weather conditions.

Global Sea Level Rise

When Venice was founded, its inhabitants had to combat the slow, but inexorable, increase in seawater level around their islands, even if they had no understanding of the cause. Dealing with this problem, based on the knowledge of the time, led to various actions: active ones, such as deviations of the rivers out of the lagoon, and passive ones, such as raising, where possible, the city's pavement. We now know that the apparent sea level increase is a combination of two independent components: the increase in global sea level over time and the progressive sinking of the Venetian islands.

During the twentieth century, global sea level rose on average 1.4 mm yr^{-1}, with a possible acceleration during recent decades (Church and White, 2006; Kopp et al., 2016). For the twenty-first century, taking into consideration several models, the Intergovernmental Panel on Climate Change projects a median global sea level rise of more than 30 cm (IPCC, 2015). Individual projections have a wide range of uncertainty, depending on the models used and the underlying assumptions (largely those concerning the CO_2 emission hypothesis). In addition, due to their coarse resolution, these model results are not very reliable for coastal and inner seas (see Marcos and Tsimplis, 2008; Galassi and Spada, 2014), and they are particularly inaccurate for the Mediterranean where the narrow Strait of Gibraltar modulates water exchange with the Atlantic Ocean. Combining the best available estimates of the local isostatic, temperature, salinity, and dynamical effects, Galassi and Spada (2014) project that by 2040–2050 sea level will rise in the Mediterranean between +5 cm and +26 cm, with the specific value depending on climatic assumptions and the dynamics of the basin. For Venice, the estimated rise ranges between +12 cm and +23 cm, much larger, of course, at the end of this century. And the reality for Venice is that this sea level increase will combine with simultaneous lowering of the city by subsidence, which we discuss next.

Land Subsidence

Land subsidence is the lowering of the ground surface in response to natural and human-induced processes. In the Venice region, natural subsidence is mainly driven by tectonics and sediment compaction. Anthropogenic subsidence derives from processes such as subsurface water withdrawal, building and infrastructures loads, and land reclamation. Natural and anthropogenic components of subsidence act on time scales of millions to thousands of years and hundreds to a few years, respectively. Human activity began to enhance land subsidence in the sixteenth century when, to avoid sedimentation in the lagoon, the Venetians diverted the rivers out of the lagoon. This caused the salinization of the clay

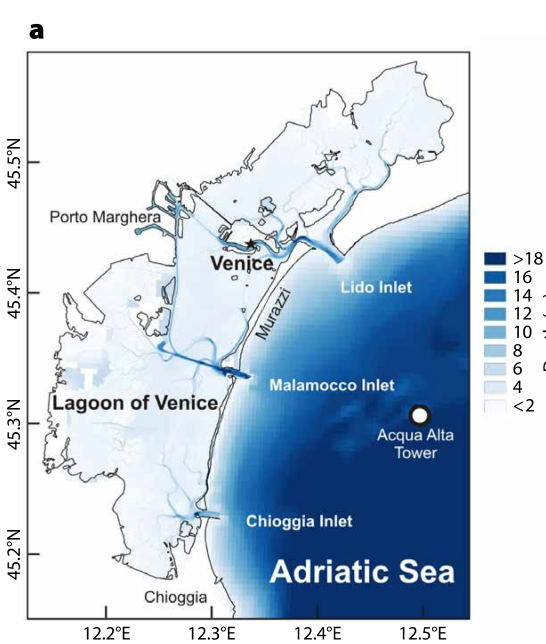


FIGURE 1. (a) The Lagoon of Venice, with the little archipelago on which Venice is built at its center. Note the locations of the inlets and of the industrial (water-demanding) district of Marghera. The star inside the city of Venice depicts the location of the historical "Punta della Salute" tide gauge. (b) The Mediterranean and Adriatic Seas, with the black square indicating the location of the Venice lagoon.

interparticle water in the subsoil, enhancing local subsidence. A strong enhancement of subsidence occurred soon after World War II following the intensive exploitation of local aquifers for civil, industrial, agricultural, and tourist use. The most intensive pumping occurred in Venice between 1950 and 1970, resulting in 10 cm land subsidence (Gatto and Carbognin, 1981). In 1970, measures were taken to curtail aquifer overexploitation. With the recovery of aquifer pressure, land subsidence rates slowed and began to return to earlier natural values. However, most of the soil compaction was permanent and irreversible.

In the twentieth century, Venice lost 26 cm in ground elevation with respect to mean sea level through the combination of land subsidence and global sea level rise. This loss has clear implications for the possible flooding of the city (Figure 2, updated from Gatto and Carbognin, 1981; Tosi et al., 2013).

The Acqua Granda Event of November 4, 1966

The great Venice flood of 1966 started in an apparently innocuous way, with a tropospheric trough positioned over Spain. On November 3, the trough had deepened and started moving eastward, reinforced by a local low-pressure system and a secondary, small-scale depression coming from North Africa. The depression in itself was not particularly pronounced; however, the zonal gradient was greatly reinforced by an intensifying anticyclone over southeastern Europe, on the eastern side of the Adriatic Sea. This convergence led to a very strong and humid meridional flow in the atmosphere, which was channeled into the Adriatic region by bordering orography (Apennines and Dinaric Alps on its west and east sides, respectively; see Figure 1). As a result, rain was locally very intense in Central and Northeast Italy (Figure 3). In the northeast, the highest recorded amount of rain was more than 750 mm over two days, causing landslides, destroying villages, and leaving several casualties.

In the Adriatic Sea, the Sirocco winds blew intensely and persistently from the southeast over the whole basin, resulting in large waves in its northern sector. It was a perfect storm, with high pile up of water in the area facing the Venice lagoon due to the combined action of winds, surge, and waves, water that then propagated through the inlets into the lagoon, flooding the city and the adjacent islands.

During the Acqua Granda event, the largest high water (1.94 m, Figure 4) recorded since tidal records were initiated in 1872 (Raicich, 2015), wind fields remained aligned from southeast to northwest, along the main axis of the Adriatic basin, for more than 24 hours. Wind speeds with a persistent and

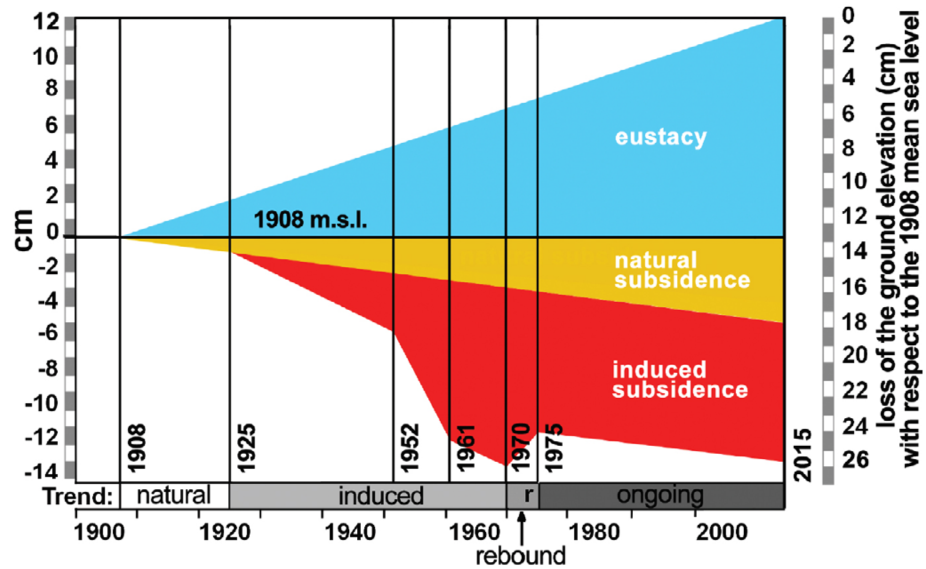


FIGURE 2. Subsidence of Venice in the twentieth century: natural in yellow, anthropogenic in red, sea level rise (eustacy) in blue. Subsidence and sea level rise combine to a total loss of about 26 cm (updated after Gatto and Carbognin, 1981).

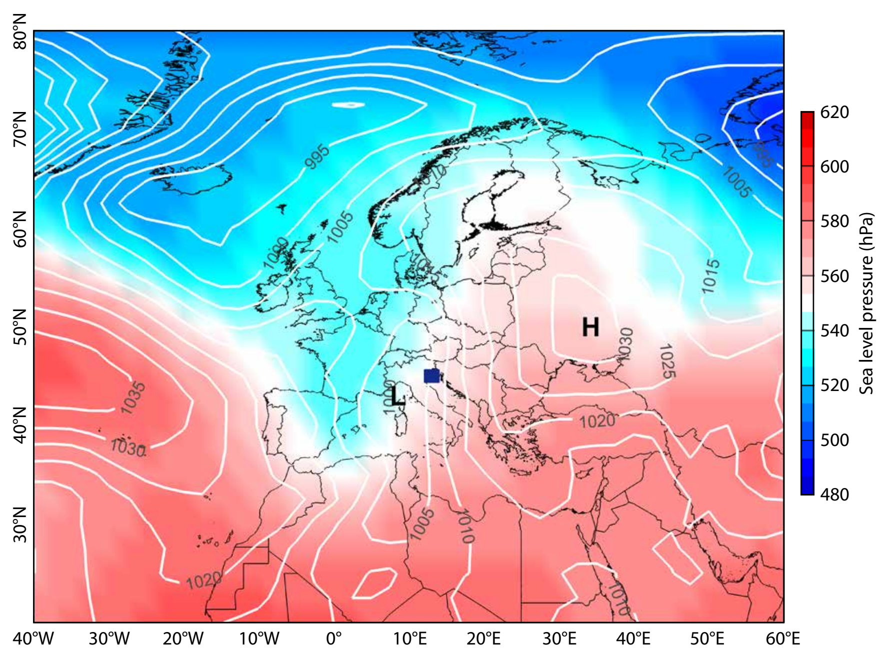


FIGURE 3. Synoptic conditions on November 4, 1966, 00 UTC. The blue square depicts the study area. Data courtesy of the National Center for Environmental Prediction/National Weather Service/NOAA/US Department of Commerce, NCEP/NCAR Global Reanalysis Products, 1948-continuing, http://rda.ucar.edu/datasets/ds090.0.

diffused value of 24 m s^{-1} were recorded seaward of Venice, with an estimated peak value of 28 m s^{-1}. The images of flooding in Venice and Florence went around the world. The historical photo of Venice displayed in Figure 4a is one example, showing San Marco square and the Doge's palace under attack by water and waves. Figure 4b plots measurements of water levels observed in Venice and the astronomical tide, highlighting the overwhelming meteorological component of the flood. It is frightening and instructive for the future that the peak of the storm occurred during low tide. Had the storm hit a few hours before, the combined meteorological and astronomical components would have led to an overall water level more than 30 cm higher. The rain was intense, and waves were very high, estimated at 10 m significant wave height well offshore the Venice coastline (Cavaleri et al., 2010), where the sea is deep enough to allow the formation of higher waves. Wave height decreased progressively toward the coast through depth-induced breaking, and was estimated to be about 6 m at the seaward edge of the three inlets to the lagoon. The higher than usual waves, possibly resulting from the storm-induced higher local water depth, also caused tremendous damage to the *Murazzi* walls, the sea walls built by the Venetian Republic in the eighteenth century to protect the two long, thin sandy islands that separate the lagoon from the Adriatic Sea (Figure 1a).

THE RESPONSE

Venice has always been a symbol of fragile beauty, a miracle of history that placed an architectural and artistic marvel in the middle of a coastal lagoon. It is not surprising then that, in the aftermath of the 1966 flood, Italy and the world reacted quickly and emotionally. Some immediate physical and economic actions were taken, the latter by both institutions and private citizens, and there were longer-term efforts to repair the damage, to protect the various aspects of the city's daily life from other acqua alta episodes, and to protect the Venice monuments from deterioration. Useful as they were, it was clear that a more organized effort was required. This was left to the scientific and political communities, whose responses we describe in the following sections.

Special Legislation for the Safeguard of Venice

Following the flooding event of November 1966 and recognizing the safeguarding of Venice and its lagoon as a national priority, the Italian Government decided to establish a Special Legislation for the Safeguarding of Venice (Law no. 171/73, Law no. 798/84, Law no. 139/92). This Special Legislation is aimed at integrated and organic management of the physical, environmental, socioeconomic, and urban/architectural aspects of the lagoon. The law and the corresponding General Plan of Interventions not only devote special attention to flood protection, but also cover all the main issues that influence the lagoon environment and ecosystems. Considering the time when it was conceived, such an integrated approach was quite innovative—it even anticipated the formalization of the Integrated Coastal Zone Management approach and commitment (Agenda 21, Rio, 1992).

The law established a governance scheme that involves several central (ministries) and local (Veneto Region and several municipalities) administrations, coordinated by the President of the Council of Ministers. The Ministry for Infrastructure and Transport, through the Venice Water Authority (MAV), is responsible for most of the interventions related to the physical maintenance and defense of the city and of the lagoon. This ministry has been in operation since 1985 and oversees studies, projects, and works

a

b

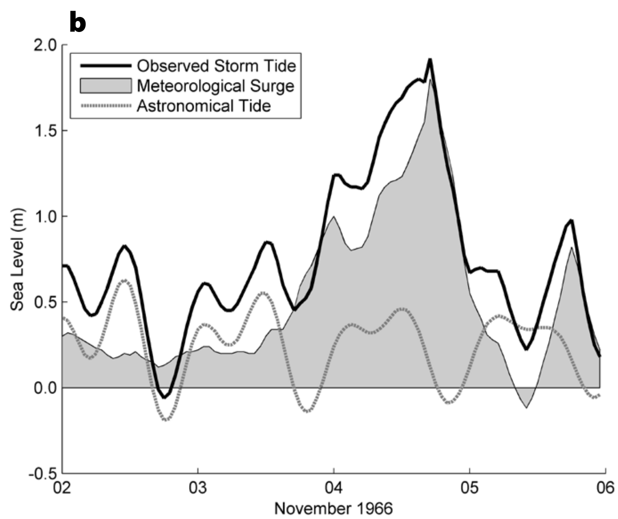


FIGURE 4. (a) The Doge's Palace in San Marco square partially underwater during the November 4, 1966, Venice flood. *Credit: Cameraphoto Epoche, Archivio Storico Comunale - Celestia* (b) The sea level progression in Venice at the time of the flood (Punta della Salute reference level). Note the differences in the contributions of the meteorological and astronomical tides.

through the *Consorzio Venezia Nuova*, a consortium of private engineering and construction companies. During the period 1984–2012, about 13 billion euros were assigned by the Italian government to fund interventions under the Special Legislation for Venice, 46% of which have been used toward flood protection and physical restoration. Since the early 1970s, the Venice Municipality established a dedicated office (now *Protezione Civile – Centro Previsioni e Segnalazioni Maree*, PC-CPSM, literally Civil Protection – Center) to collect data and run a tidal early warning system for the city.

Founding of the CNR Oceanographic Institute

In the aftermath of the November 4 Acqua Granda, having witnessed what the sea had done and could do again, it was clear that better knowledge of the lagoon and of the marine environment was required. The tidal level reached in the 1966 event was beyond any expectation, hence the lack of preparation in the city.

The *Consiglio Nazionale delle Ricerche* (National Research Council, or CNR), the main national research organization in Italy, reacted quickly and, in 1969, launched the *Istituto per lo Studio della Dinamica delle Grandi Masse* (Institute for the Study of the Dynamics of Large Masses, now part of the Institute of Marine Sciences) with two main research focuses. For geology, the immediate task was to develop a long-term framework for addressing the lagoon flooding, but the more immediate necessity was to identify why Venice and the surrounding area were rapidly sinking (see Figure 2). The second research focus addressed the urgent need to determine the dynamics of the floods, until then practically unknown, with the implicit aim of developing a forecast system.

Great results were rapidly achieved. The drilling of a 700 m continuous recovery borehole in the lagoon clarified the local stratigraphy of Pleistocene beds and the related distribution of the aquifers. Together with accurate, repeated measurements of the levels of the whole surrounding area, artesian water extraction was identified as the main factor in the rapid sinking of the city. Interaction of CNR scientists with the global oceanographic community helped to frame the physics of the floods, as did the development of the first numerical models for operational forecasts (Robinson et al., 1973).

Building the Oceanographic Tower

In March 1970, CNR acquired an oceanographic tower that immediately became the iconic symbol of research and the will of Venice to study the sea. The tower, aptly named Acqua Alta, is located in the northern Adriatic Sea, 15 km offshore the Venetian littoral in water that is 16 m deep (Figure 1a). The structure has three $5 \times 7\ m^2$ floors and extends 12.5 m above sea level. As soon as it was constructed, researchers began collecting observations of sea level (tide and surge) and wind conditions, and they soon added other physical and biogeochemical capabilities (Cavaleri, 2000). The onboard remotely operated system is now part of a larger CNR observing system. The tower boasts a long record of directional sea-wave data, continuous since 1979. A spectacular result was obtained in December 1979 following another extreme storm (the resulting acqua alta ranks second in the records since 1872). A comparison between Acqua Alta tower and coastal tidal data provided the first evidence of coastal wave setup—the piling up of water close to the coast, and hence an increase in mean water level, as a result of breaking waves. This result helped to explain the underestimate of tidal model water levels during the worst storms, and it is now incorporated into operational forecast models for Venice. Today, data collected at the Acqua Alta tower are integrated in sea level forecasting and flood early warning services provided by the PC-CPSM of the Municipality of Venice.

The Present Forecast Capability

Storm surge forecasting has advanced dramatically when compared with what was available in 1966. The key question is: should the 1966 event happen today, how good would we be in predicting it? Cavaleri et al. (2010) explored this question by applying present-day methodology to the data available at the time. The result, surprising a posteriori but positive for the future, was that the storm, and the associated flood, could have been forecast as much as six days before November 4, with a nearly perfect model fit five days prior, and a slight underestimate of flood levels (~20 cm) with the model input data starting earlier, on October 29.

In addition to this deterministic forecast, and following a well-established technique (Buizza et al., 2008), an estimate a priori of the possible errors, hence of the probability of the event, was obtained using an ensemble of N = 50 simulations (red line in Figure 5). These ensemble simulations were not available in 1966, but they are now, and can be used to better

> "Today, an event such as the 1966 flood would not appear out of the blue. Weather forecasts are now accurate for several, sometimes up to 10, days into the future."

frame the situation for a storm surge and determine the uncertainty of the forecast.

These results are very promising for present forecast capability, should another 1966, or worse, event happen today. The forecast of any serious storm a few days in advance is now standard (e.g., see the statistics by Bertotti et al., 2011). With respect to the successful a posteriori forecast for 1966, it is made possible by the enormous increase in meteorological and oceanographic data presently available in near-real time.

Subsidence Monitoring

During the last 15 years, the monitoring of land subsidence around Venice has continued. Development of satellite-based interferometric synthetic aperture radar (InSAR) has brought significant advancement over the last decade. Relying today on hundreds of thousands of ground reflectors (measured points) in the Venice region (Tosi et al., 2016), this technique has revealed large variability in local subsidence rates along the northern Adriatic coast, within the Venice lagoon, and in its historic center. Focusing on the latter, this approach has led to a new interpretation of the local subsidence. The variable pattern reflects how urbanization evolved from the primeval well-consolidated island of Venice in the year 900 and extended progressively via land reclamation to the surrounding, less favorable areas still subjected to compaction. Recently, the combination of different interferometric products made it possible to distinguish natural and anthropogenic subsidence. This technique revealed the occurrence of short-term (one to two years) very localized sinking (e.g., a single palace), up to 6 mm yr^{-1}, linked to building restoration and city maintenance activities (Tosi et al., 2013).

The MOSE Gates

The *Consorzio Venezia Nuova* was established to design and construct a system of gates aimed at abating the maximum tide level within the Venice lagoon. The project, called MOSE for *MOdulo Sperimentale Elettromeccanico* (Experimental Electromechanical Module), takes its name from the 1:1 scale prototype of a rigid gate that was tested between 1988 and 1992. MOSE consists of 78 mobile gates (20 m high, 18.5–29.0 m long, and 3.6–5.0 m thick) clustered into four barriers for the three inlets: from north to south, two at the Lido inlet (separated by an artificial island) and one each at the Malamocco and Chioggia inlets (see Figure 1). While most of the MOSE system has been built, it is not yet operational. Completion of this barrage system is expected in 2018, followed by three years of trials to refine the system. Each gate will operate independently; when a high tide is forecast, air will be pumped into the gates in order to empty them of water, and this will cause them to rotate upward around hinges located close to the inlet bottom until they emerge above sea level and separate the lagoon from the Adriatic Sea. Once the surge is over, air will be let out, the barriers will fill with water, and they will return to their normal positions inside concrete housing on the bottom of the inlet.

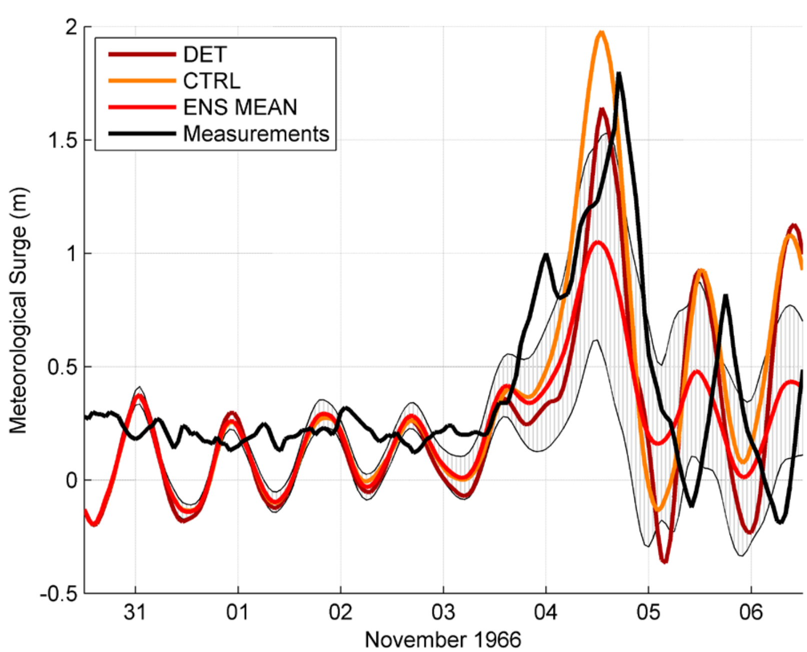


FIGURE 5. Deterministic (DET) and ensemble (ENS MEAN) simulation of the November 4, 1966, event initialized at October 30, 12:00 UTC. The black line represents the actual (de-tided) sea level measurements. DET is a high-resolution (with ECMWF T511 forcing) deterministic run. The ensemble is based on low-resolution ECMWF T399 forcing. CTRL is the deterministic (or control) run. ENS MEAN is the ensemble mean, and the shaded area shows the ensemble spread, a measure of the uncertainty of the ensemble.

According to the present management scenario, the MOSE barriers would temporarily isolate the Venice lagoon from the Adriatic Sea during tides greater than 110 cm above the *Punta della Salute* reference level (located where the Grand Canal enters the San Marco basin in Venice; see black star in Figure 1a). This level is 26 cm below current mean sea level. The 110 cm figure was selected as a compromise between the need to protect the city, to avoid disruption of commercial traffic through the inlets (the harbor, one of the most important in the Mediterranean, is located far inside the lagoon, between Venice and the mainland; Figure 1a), and to limit the impact on the lagoon ecosystems that significantly depend on water exchanges between the lagoon and the sea.

Because of its importance, the construction of MOSE has been a matter of debate for 20 years. Discussions have spanned from technical questions (e.g., overall approach and possible alternatives; analysis of gate engineering solutions; what is the best solution for constructing the hinges; and time required to activate the gates, that is, how far in advance should a high water event be forecast), to "scenario" questions (how does the lagoon ecosystem respond to prolonged MOSE closure times?), to economic questions (what are the initial and presently estimated final costs), and, ultimately, to political aspects. Notwithstanding these issues, from an engineering standpoint, MOSE is no doubt an impressive system. Key questions concern the suitability of the system and its maintenance costs in the face of likely increasingly frequent demand for its use in the future. From an environmental standpoint, however, a potentially more serious issue concerns the impact of frequent use of the MOSE system on the Venice lagoon's ecosystem.

OUTLOOK

The millennial history of Venice and our responsibility to maintain this unique marvel of human heritage forces us to look to the future, at both short and long term, to know how best to act. The range of problems that Venice faces is great and includes many technical and scientific as well as several political issues. Among the challenges is the enormous number of visitors (estimated at 25 million) who flock to Venice every year. Below, we consider four main scientific/technical questions concerning Venice and its environment.

1. Will new models be able to better predict the water events?

Today, an event such as the 1966 flood would not appear out of the blue. Weather forecasts are now accurate for several, sometimes up to 10, days into the future. An ensemble approach to predicting the weather situation, and in particular the flooding in Venice (Figure 5), also provides useful information about the accuracy, probability, and reliability of a forecast, allowing the best possible response. Ongoing attempts at seasonal forecasting are still tentative, but may in the future provide useful information on the next season.

2. With global sea levels rising and the parallel local subsidence in Venice, will high water episodes become more frequent?

The obvious response is "yes." Long-term residents of Venice know once-dry places that are now frequently wet or covered with algae. Architectural elements originally built above the waterline are now permanently under water; witness now immersed steps of the palaces bordering the Grand Canal. Figure 6 shows the number and extent of floods (vertical lines) in Venice from 1910 to the present. The red line shows how the overall mean level of the city has varied in time. We anticipate continued relative sea level rise affecting the city, not at the rate (see also Figure 2) of the 1950–1970 period, but still fast enough to induce a significant increase of the number of potential floods.

3. How might global climate change work to dampen or intensify meteorological events like the one of November 1966?

The slowly but significantly increasing global temperature is accompanied by a progressive shift of storm belts toward the poles. The climate in the Mediterranean region seems to be getting drier and warmer (Lionello and Giorgi, 2007), with fewer storms (e.g., Marcos et al., 2011; Benetazzo et al., 2012; Lionello et al., 2012; Conte and Lionello, 2013). However, individual storms may be more severe as a result of the increased temperature and humidity, and hence energy of the atmosphere (Trenberth et al., 2003). Is there any evidence to suggest fewer, but more severe storms in the future in the Venice region? Some possible insight comes from the CNR Acqua Alta tower (Figure 1). By analyzing the 37-year-long time series of wind and wave data, it has been found that from 1979 to 2015, the number of Bora storms has progressively decreased, while the number of Sirocco storms has remained substantially constant, suggesting that the Sirocco, with its associated floods, will continue to be a dominant feature in the future (recent work of authors Pomaro and Cavaleri).

4. Should the MOSE system be used more frequently in the future, are there consequences for the Venice lagoon environment?

Should the potential for Venice to flood more frequently because of increased incidence of severe storms, combined with increasing local relative sea levels, become a reality, the MOSE barrier system will need to be used more frequently, avoiding what could otherwise be an unbearable situation. However,

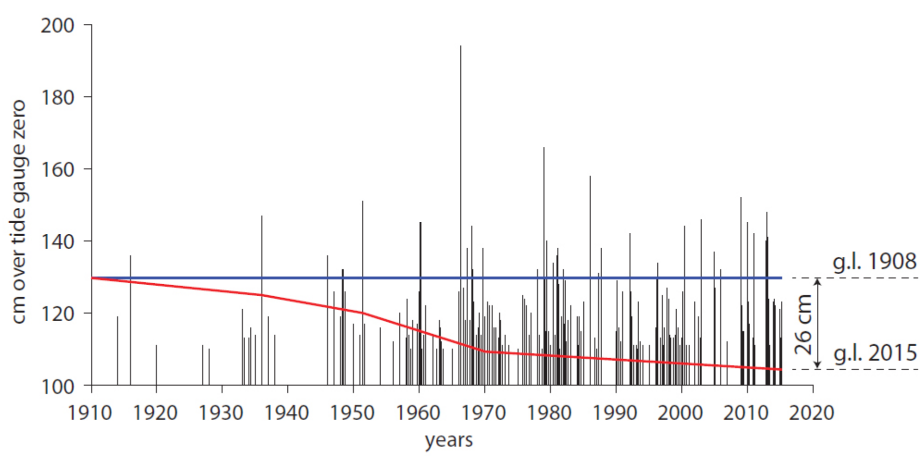


FIGURE 6. High water events (vertical lines) in Venice since 1910. The blue line represents the ground reference level (g.l.) of 1908, assuming a theoretical stable Venice, while the red line shows relative ground level loss in time resulting from the sinking of Venice and rising sea level (updated after Gatto and Carbognin, 1981). The number and intensity of floods has increased over time—an "acqua alta" flood that would have gone unnoticed in 1910 would have a significant, if not dramatic, impact a century later.

more frequent use of the barrage systems has environmental consequences. The twice-daily tidal flushing is essential for maintaining the present ecosystem of the lagoon. The lagoon is a very fragile environment in delicate equilibrium between heavy anthropic input of nutrients from the city of Venice and from runoff, and the tidal input of oxygen. Any change in this vital rhythm may negatively affect it. It is unknown how the lagoon will react if it is not allowed to flush as frequently as now.

The important new tasks for Venice's scientific community are to gain a better understanding of looming long-term problems for the lagoon and to improve the local weather forecasting system in the short term. There is an urgent need to design and implement an observing network to monitor the lagoon ecosystem before the MOSE barrier system becomes operational. On the monitoring, modeling, and engineering side, we need to better understand how the lagoon will react to the potentially more frequent floods, and hence to the corresponding closure of the barrier system. We must anticipate problems and look for possible technical/scientific solutions in order to maintain the ecosystem as much as possible. Armed with this additional knowledge, it will be up to the politicians, in cooperation with scientists, to plan what actions to take and how to regulate the interventions in order to make the best decisions for the city of Venice, its lagoon, its inhabitants, and its visitors (Suman et al., 2005).

REFERENCES

Amorosi, A., V. Maselli, and F. Trincardi. 2016. Onshore to offshore anatomy of a late Quaternary source-to-sink system (Po Plain–Adriatic Sea, Italy). *Earth Science Reviews* 153:212–237, https://doi.org/10.1016/j.earscirev.2015.10.010.

Benetazzo, A., F. Fedele, S. Carniel, A. Ricchi, E. Bucchignani, and M. Sclavo. 2012. Wave climate of the Adriatic Sea: A future scenario simulation. *Natural Hazards and Earth System Sciences* 12:2,065–2,076, https://doi.org/10.5194/nhess-12-2065-2012.

Bertotti, L., P. Canestrelli, L. Cavaleri, F. Pastore, and L. Zampato. 2011. The Henetus wave forecast system in the Adriatic Sea. *Natural Hazards and Earth System Sciences* 11:2,965–2,979, https://doi.org/10.5194/nhess-11-2965-2011.

Buizza, R., M. Leubecker, and I. Isaksen. 2008. Potential use of an ensemble of analyses in the ECMWF Ensemble Prediction System. *Quarterly Journal of the Royal Meteorological Society* 134:2,051–2,066, https://doi.org/10.1002/qj.346.

Buzzi, A., and S. Tibaldi. 1978. Cyclogenesis in the lee of the Alps: A case study. *Quarterly Journal of the Royal Meteorological Society* 104:271–287, https://doi.org/10.1002/qj.49710444004.

Camuffo, D. 1993. Analysis of the sea surges at Venice from A.D. 782 to 1990. *Theoretical and Applied Climatology* 47:1–14, https://doi.org/10.1007/BF00868891.

Cavaleri, L. 2000. The oceanographic tower Acqua Alta: Activity and prediction of sea states in Venice. *Coastal Engineering* 39:29–70, https://doi.org/10.1016/S0378-3839(99)00053-8.

Cavaleri, L., L. Bertotti, R. Buizza, A. Buzzi, V. Masato, G. Umgiesser, and M. Zampieri. 2010. Predictability of extreme meteo-oceanographic events in the Adriatic Sea. *Quarterly Journal of the Royal Meteorological Society* 136:400–413, https://doi.org/10.1002/qj.567.

Church, J.A., and N.J. White. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33, LO1602, https://doi.org/10.1029/2005GL024826.

Conte, D., and P. Lionello. 2013. Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios. *Global and Planetary Change* 111:159–173, https://doi.org/10.1016/j.gloplacha.2013.09.006.

Galassi, G., and G. Spada. 2014. Sea-level rise in the Mediterranean Sea by 2050: Roles of terrestrial ice melt, steric effects and glacial isostatic adjustment. *Global and Planetary Change* 123:55–66, https://doi.org/10.1016/j.gloplacha.2014.10.007.

Gatto, P., and L. Carbognin. 1981. The Lagoon of Venice: Natural environmental trend and man-induced modification. *Hydrological Sciences Bulletin* 26(4):379–391, https://doi.org/10.1080/02626668109490902.

IPCC (Intergovernmental Panel on Climate Change). 2015. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, R.K. Pachauri and L.A. Meyer, eds, IPCC, Geneva, Switzerland, 151 pp.

Kopp, R.E., A.C. Kemp, K. Bittermann, B.P. Horton, J.P. Donnelly, W.R. Gehrels, C.C. Hay, J.X. Mitrovica, E.D. Morrow, and S. Rahmstorf. 2016. Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences of the United States of America* 113(11):E1434–E1441, https://doi.org/10.1073/pnas.1517056113.

Lionello, P., L. Cavaleri, K.M. Nissen, C. Pino, F. Raicich, and U. Ulbrich. 2012. Severe marine storms in the Northern Adriatic: Characteristics and trends. *Physics and Chemistry of the Earth, Parts A/B/C* 40–41:93–105, https://doi.org/10.1016/j.pce.2010.10.002.

Lionello, P., and F. Giorgi. 2007. Winter precipitation and cyclones in the Mediterranean region: Future climate scenarios in a regional simulation. *Advances in Geosciences* 12:153–158, https://doi.org/10.5194/adgeo-12-153-2007.

Marcos, M., G. Jordà, D. Gomis, and B. Pérez. 2011. Changes in storm surges in southern Europe from a regional model under climate change scenarios. *Global and Planetary Change* 77(3):116–128, https://doi.org/10.1016/j.gloplacha.2011.04.002.

Marcos, M., and M. Tsimplis. 2008. Comparison and results of AOGCMs in the Mediterranean Sea during the 21st century. *Journal of Geophysical Research* 113, C12028, https://doi.org/10.1029/2008JC004820.

Massari, F., D. Rio, R. Serandrei Barbero, A. Asioli, L. Capraro, E. Fornaciari, and P.P. Vergerio. 2004. The environment of Venice area in the past two million years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 202(3–4):273–308, https://doi.org/10.1016/S0031-0182(03)00640-0.

Raicich, F. 2015. Long-term variability of storm surge frequency in the Venice Lagoon: An update thanks to the 18th Century sea level observations. *Natural Hazards and Earth System Sciences* 15:527–535, https://doi.org/10.5194/nhess-15-527-2015.

Robinson, A.R., A. Tomasin, and A. Artegiani. 1973. Flooding of Venice: Phenomenology and prediction of the Adriatic Sea storm surge. *Quarterly Journal of the Royal Meteorological Society* 99:688–692, https://doi.org/10.1002/qj.49709942210.

Suman, D., S. Guerzoni, and E. Molinaroli. 2005. Integrated coastal management in the Venice lagoon and its watershed. *Hydrobiologia* 550:251–269, https://doi.org/10.1007/s10750-005-4393-x.

Tomasin, A., and P.A. Pirazzoli. 1999. The seiches in the Adriatic Sea. Istituto Veneto di Scienze, Lettere ed Arti, CLVII:299–316.

Tosi, L., C. Da Lio, T. Strozzi, and P. Teatini. 2016. Combining L- and X-Band SAR interferometry to assess ground displacements in heterogeneous coastal environments: The Po River Delta and Venice Lagoon, Italy. *Remote Sensing* 8(4):308, https://doi.org/10.3390/rs8040308.

Tosi, L., P. Teatini, and T. Strozzi. 2013. Natural versus anthropogenic subsidence of Venice. *Scientific Reports* 3, 2710, https://doi.org/10.1038/srep02710.

Trenberth, K.E., A. Dai, R.M. Rasmussen, and D.B. Parsons. 2003. The changing character of precipitation. *Bulletin of the American Meteorological Society* 84(9):1,205–1,217, https://doi.org/10.1175/BAMS-84-9-1205.

ACKNOWLEDGMENTS

This paper was supported by the Italian Flagship project RITMARE, supported by the Ministry of Education, University and Research (MIUR). We wish to thank Andrea Rinaldo and an anonymous reviewer for their suggestions and advice. We are also grateful to Paola Malanotte-Rizzoli for helpful discussions while preparing this article. Particular thanks go to Editor Ellen Kappel for her thorough work in clarifying and improving the text.

AUTHORS

Fabio Trincardi (f.trincardi@ismar.cnr.it) is Director of the Istituto di Scienze Marine – Consiglio Nazionale delle Ricerche (ISMAR-CNR), Venice, Italy. **Andrea Barbanti**, **Mauro Bastianini**, **Alvise Benetazzo**, **Luigi Cavaleri**, and **Jacopo Chiggiato** are all researchers at ISMAR-CNR, Venice, Italy. **Alvise Papa** is Head, Operating Unit, Protezione Civile – Centro Previsioni e Segnalazioni Maree, Venice, Italy. **Angela Pomaro**, **Mauro Sclavo**, **Luigi Tosi**, and **Georg Umgiesser** are all researchers at ISMAR-CNR, Venice, Italy.

ARTICLE CITATION

Trincardi, F., A. Barbanti, M. Bastianini, A. Benetazzo, L. Cavaleri, J. Chiggiato, A. Papa, A. Pomaro, M. Sclavo, L. Tosi, and G. Umgiesser. 2016. The 1966 flooding of Venice: What time taught us for the future. *Oceanography* 29(4):178–186, https://doi.org/10.5670/oceanog.2016.87.