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A novel proxy and the sea level rise in Venice, Italy, from 1350 to 2014

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Abstract The evolution of relative sea level (RSL) in Venice, Italy, is crucial for the safeguarding of the city and it is now possible to extend our knowledge back to 1350, including the whole Little Ice Age and modern global warming. The existing tide gauge record is extensive, going back to 1871, but it is affected by the superposition of multidecadal swings and short-term fluctuations, including both natural and manmade forcing factors. A biological proxy, i.e. the green algae belt reported on paintings made with the help of a camera obscura by the Venetian painters Canaletto and Bellotto (eighteenth century) and Veronese (sixteenth century), helps us to go back to 1571. This paper presents an exceptionally long series (i.e. 664 years) and adds a novel proxy: the submersion of water stairs of the historic palaces facing the Grand Canal. Originally, the bottom step of the water stairs was built in relation to the sea level and the slippery algae belt, while today, the water stairs are mostly submerged. An underwater survey of 78 water stairs has provided new data about the RSL since 1350. The results show that RSL in Venice was always rising at an increasingly fast rate. By subtracting local land subsidence (LLS) from RSL, absolute (eustatic) sea level (ASL) has been calculated. For both RSL and ASL, the apparent acceleration is $+0.0030 \pm 0.0004$ mm year^{-2}. This figure becomes unstable when the record length is reduced. A discussion is made about the interpolation functions, i.e. the second-order polynomial and the exponential that provide almost the same best-fit over the common period. The RSL and ASL trend lines and the possibility of turning points are also discussed and compared with other scholarly studies. A eustatic turning point is suggested for the mid fifteenth century, consistent with the literature. However, the comparison between scholarly papers is difficult due to geographic and geological differences between sites and record durations.

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1 Introduction

The need to understand the present-day sea level rise (SLR) has stimulated intensive research at various time and space scales. Most instrumental series are shorter than one century, though a few have spanned two or three centuries (e.g. Church and White 2011: Meyssignac and Cazenave 2012; Jevrejeva et al. 2014, Long et al. 2014). To extend the timescale, it was necessary to include proxies (Ammerman 2005; Lambeck et al. 2004, 2010; Gehrels et al. 2005; Miller et al. 2009; Stewart and Morhange 2009; Kemp et al. 2011; Vacchi et al. 2016) with problems related to time resolution, uncertainty band and local context. Models linking temperature to SLR over the last 1800 years, suggest that the maximum elevation was during the Mediaeval Warm Period (i.e. 12 to 21 cm higher than the 1980–1999 average), with a decrease during the Little Ice Age (LIA) with a minimum around 1730 and an accelerated rise during global warming (Grinsted et al. 2009); however, the comparison with existing records shows gaps in data and understanding.

The longest instrumental records were taken with tide gauges fixed to local structures that may be affected by vertical land movements (VLM), either local land subsidence (LLS) or uplift (LLU). Therefore, instruments could not record the so-called absolute sea level (ASL), i.e. the sea level independently from a local frame, but they only record relative sea level (RSL), i.e. RSL = ASL + VLM. This makes it difficult or even impossible to distinguish between RSL changes due to ASL or VLM component. For instance, ASL changes may be due to weather forcing, or eustatic volume expansion for global warming; VML changes to regional tectonics, isostasy or soil compaction. Satellite interferometry (Tosi et al. 2013, 2016), available since 1992, is free from the local soil influence and is very useful for assessing the subsidence of specific areas and the individual building response in the recent times.

Venice, Italy, one of UNESCO's most famous World Heritage Sites, is affected by LLS for natural and man-induced factors (UNESCO 1969); the combination of global warming and LLS constitutes a terrible challenge for it. Relative sea level rise (RSLR) caused a continuous loss in elevation with respect to the mean sea level of the city and the lagoon, which is well documented by numerous works made in the past centuries to raise the floor level to counteract the exponential increase of the frequency at which storm surges flooded the city. Today, the sea has reached the level of ground floors and is causing dramatic damage to buildings and monuments (Enzi and Camuffo 1995; Camuffo et al. 2000, 2014a). In the worst cases, some people have raised the floors and bricked up the lower parts of doors to avoid the penetration of seawater; others have built a wooden dock walkway or a floating platform in front of the door.

In conclusion, long-term series are of uppermost importance for verifying models and tuning the time response of a number of forcing factors. The aim of this paper is to extend our knowledge about RSL in Venice back to 1350 using a novel proxy: the bottom step of water stairs.

2 Evidence of past sea level changes in Venice

2.1 Tide gauge record (1871–2014)

In Venice, regular instrumental records started in 1871, taken with a mechanical tide gauge, Thomson float type, placed in a stilling well (Online Resource 1). In 1908, the

network of monitoring stations located in the city, the lagoon and the local coastal area was composed of 18 stations; in 1970, another station was added on an offshore platform. In the 1970s, the uncertainty of the ink pen recording instrument (e.g. gear backlash, pulley friction, inertia, thermal elongation of the wire connected to the float) was estimated to be ±9 mm with a 10-cm-diameter float (i.e. before 1970) and ±4 mm with a 20 cm float (after 1970). The uncertainty for the stilling well was ±25 mm for temperature and salinity layering; the bias may increase in the case of waves, marine currents around the well or growth of biofouling on the orifice (Camuffo et al. 1972; Parker 1991). The total uncertainty is mostly due to the well; it might have been around ±50 mm in the early period, ±35 mm from 1923 to 1970 and ±29 mm after 1970. This bias is often disregarded in the literature.

Over the instrumental period, from 1871 to 2014, the observed RSL was swinging but generally rising at 2.5 ± 0.2 mm year^{-1} average rate, calculated by determining the least squares best-fit regression line (Fig. 1). LLS was due to geological factors and human interference. In the far past, LLS may be considered to have been almost constant, and we have assumed 1.15 ± 0.2 mm year^{-1} as the average value (Gambolati 1998; Bondesan et al. 2001, 2008; Carbognin et al. 2004; Lambeck et al. 2004; Carminati et al. 2005; Tosi et al. 2016). The situation changed from 1920 to 1970 when underground water was extracted for industrial purposes, causing 10-cm depression at 2.0 ± 0.2 mm year^{-1} mean rate (Carbognin and Taroni 1996; Online Resource 1). This was followed by a modest rebounding of the water table: satellite remote sensing from 1992 to 2011 has shown 0.9 ± 0.7 mm year^{-1} average value, although with some local departures (Tosi et al. 2013). The average LLS over the instrumental period was 1.5 ± 0.3 mm year^{-1}.

Subtracting year-by-year LLS from RSL, one obtains ASL due to the eustatic component. The least squares best-fit regression line shows that ASL was rising at 1.0 ± 0.3 mm year^{-1} (Fig. 1). This is not far from the evaluation of 1.1–1.5 mm year^{-1} found for the Mediterranean over the past century (Tsimplis and Baker 2000); however, any comparison is difficult due to the uncertainty concerning LLS that might affect any station.
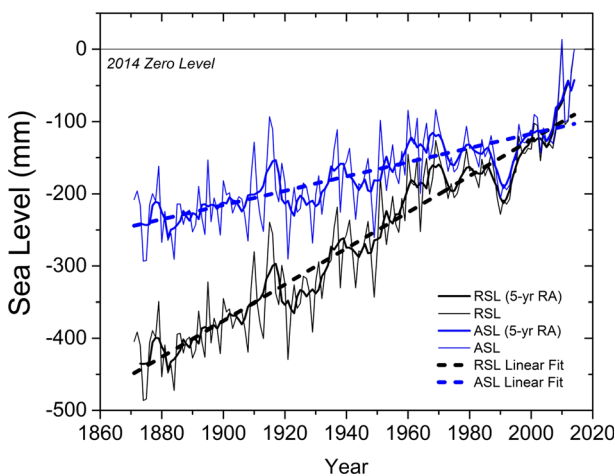

Fig. 1 The sea level in Venice after the 1871–2014 tide gauge record. *Black lines* observed RSL, *blue lines* calculated ASL after having subtracted LLS from RSL. *Thin lines* annual average, *thick lines* 5-year running average, *dashed lines* linear interpolation

2.2 Pictorial proxies (1500–1758)

Pictorial proxies document the situation of several buildings during the eighteenth century and of one in 1571. From 1727 to 1758, Antonio Canal, nicknamed Canaletto, and his nephew, Bernardo Bellotto, painted views of the city with extremely accurate details. Not only did they use a camera obscura, but they also reproduced all particulars, including the algae belt which is the biological tracer of the common marine (CM) level (Online Resource 2). Making a comparison between the algae level in the paintings and today, it was possible to measure 61 ± 12 cm uplift of the CM, with 2.3 ± 0.4 mm year^{-1} average rate (Camuffo and Sturaro 2003, 2004).

It was later found that in 1571, Paolo Caliari, nicknamed Veronese, had accurately reproduced, with the aid of a camera obscura, the image of the Coccina Palace facing the Grand Canal: *The Adoration of the Virgin by the Coccina Family*. The comparison between the level of the algae belt on the 1571 painting and today gave 92 ± 9 cm RSLR (Camuffo 2010). However, this finding was based on only one proxy value and needed confirmation. An early part of our research aimed to assess its reliability. As the painting by Veronese had a man standing on the bottom step of a water stair, we investigated the depth of the bottom step of the stairs of palaces built in the same period of time. The best-fit interpolation calculated from the paintings and tide gauge observations passed through the observed stair depths and confirmed the painting accuracy (Camuffo et al. 2014b). This also inspired the use of sea stairs as a novel proxy as we will discuss later.

The pictorial proxies suggest that RSLR and the rate in the period between Veronese (i.e. 1571) and Canaletto (i.e. 1727–1758) was 1.2 ± 0.4 mm year^{-1} (Camuffo 2010). This figure is close to LLS rate and suggests a poor eustatic rise over the seventeenth century or even the possibility of being in proximity of a turning point of the eustatic changes.

2.3 Written and archaeological documentary sources (millennial scale)

Making an archival research on books and documents from the sixteenth to the nineteenth century, written in Latin, Italian and Venetian languages, it was clear that Venetians were aware that the sea level increased at a fast rate since the Roman and the early Medieval times. They also reported that island coastlines were receding and the sea level was increasing. The historian Gallicciolli (1795) discussed the problem quoting several sources, including authoritative engineers and officers, e.g. Sabbadino (1545, 1550 ca), Cornaro (1560) and Temanza (1761). Gallicciolli reported an interesting list of buried archaeological remains, roads, floors and foundations of Roman, Byzantine and early mediaeval buildings found in Venice, the lagoon and the hinterland, including their construction date and depth. On this ground, Sabbadino (1545) estimated that the sea level was increasing by three fourth of a Venice foot per century (i.e. 26 cm century^{-1}) and Gallicciolli (1795) one Venice foot per century (i.e. 34.7 cm century^{-1}).

The above rates were derived from observations of the coastline recession or the depth of some archaeological remains and are very likely overestimated. There was no consensus about the reason why the sea level changed. Most people believed that the cause was SLR; the minority that buildings were sinking due to their own weight or other effects related to rivers discharging into the lagoons. Others misinterpreted the coastal erosion or the bottom uplift as sedimentation. To stop SLR and avoid mud transport and sedimentation, from 1324 to 1683, Venetians diverted all rivers outside of the lagoon. Old Venetians were unable to assess precise

quantitative evaluations, except Zendrini (1811) who gave a precise indication of SLR and the algae front at his time. In particular, he compiled a list of archaeological evidence that inspired modern research.

Ammerman (2005) investigated buried floors and other archaeological remains since Roman times in the lagoon area. He considered nine sites, each characterized by a series of superposed archaeological levels. Dating was performed using stratigraphy, pottery recognition and radiocarbon. In this record, RSL appears to be rising at accelerated rate, and reached some 230 cm over 2000 years. This series is important for the exceptional length, but has low resolution as it is composed of a limited number of sites, with large uncertainty bands in dating and in evaluating the height above the sea level. To increase time and level resolution, further research is needed.

3 A novel proxy: the water stairs in Venice

In Venice, canals are more important than streets, and the Grand Canal is the main canal with the most magnificent palaces on both sides; their façades face the water and are reflected in it. The palaces have service doors to reach the narrow streets; the main entrances are on the Grand Canal with water stairs, i.e. stairways, leading down to welcome guests and unload supplies arriving by boat. Nowadays, water stairs are fully or almost fully submerged and disappear underwater; sometimes, they are masked by recently built dock walkways. However, when Venetians built their palaces, they conceived the water stair for a practical use, with all steps usable. The idea is that the bottom step, in association with the building date, may provide a useful proxy to reconstruct the change of the RSL over the centuries. The advantage is that there are numerous water stairs and they may provide a very long, high-resolution series.

This novel proxy requires some preliminary stages: a precise determination of the green algae belt over the city; an underwater survey of all the water stairs on the Grand Canal to record the depth of the bottom step; dating all stairs, rejecting stairs affected by subsequent works, and interpreting depths in relation to the various architectural styles used in Venice; and, finally, data discussion and conclusions.

3.1 The algae belt in Venice

In Venice, quays, streets, palaces and bridges were initially built at a safe height above mean sea level (MSL), and reference was made to the upper border of the green algae belt, nicknamed common marine (CM) level (Online Resource 2). CM was defined as the level periodically reached by seawater, recognizable from the green algae belt on quays, buildings and canal sides (Temanza 1761). More exactly, CM is the level where the high tides and small waves regularly supply water to feed phototrophic algae that need light and water. The officers of the Water Magistrate, responsible for waters and public works, were aware of the problem and placed some white stone benchmarks with engraved CM as official reference level on the canal sides. Unfortunately, the majority of CM benchmarks were not dated and the most ancient ones were moved and inaccurately replaced during maintenance works (Rusconi 1983), making useless this extremely important proxy.

The tide gauge record shows that the normal tide range is some 60 cm (i.e. 58.6 cm mean and 60 cm median); high tide level (HTL) is 30 ± 1 cm above MSL. It is known that CM exceeds HTL as it is affected by traffic and, to a lesser extent, sun exposure, the main

wind direction that generates small waves blowing over the limited length of the internal canals, and porosity of the building materials. However, so far nobody has measured how much CM exceeds HTL and how accurate reference was for Venetians in the past centuries.

We have measured CM in some hundred locations and exposures on either side of the Grand Canal, avoiding proximity to particular corners affected by splashing waves. The result was CM = 47 ± 2 cm above MSL, i.e. 17 ± 2 cm above HTL. The band above HTL is mostly due to waves generated by motorboats. In the past few centuries, waves caused by rowboats were smaller in height. It has been possible to do a quantitative evaluation by measuring waves during normal business days and during regattas (i.e. historical parades with traditional boats and rowing boat races). The result is that rowboat waves were 5 ± 1 cm smaller than modern traffic waves, and in the past, CM was 12 ± 2 cm above HTL (Camuffo and Sturaro 2003).

3.2 The underwater survey: measuring the depth of the bottom step

The underwater depth of the bottom step of all the water stairs of historic palaces on either side of the Grand Canal was measured during extensive field surveys done in cooperation with the Frogmen Team of the Italian National Police. This highly qualified team has been essential for accurate underwater inspections and to operate under normal water traffic conditions. The field survey included the following: identifying the exact position of the bottom step that was often rotten or broken; measuring the depth of this step in relation to the water level at the inspection time; ascertaining the tide level via GSM; and monitoring the distance between the water level and CM. The bottom step depth was known with ±1 cm accuracy.

3.3 Water stairs in Venice

Literature is abundant for internal stairs but is poor for water stairs. For all stairs, the step size was standardized (Serlio 1600): the tread was 1 Venice foot (35 cm) and the riser one half foot (17.5 cm). Four steps almost corresponded to the average tide range.

Some research was devoted to the construction technology (Online Resource 3) and the individual story of each building, seeking information about the date of the water stairs because building works lasted for decades or even a century or more, or had transformation works. When a palace was planned, the first action was to build a watertight barrier to pump the water out of the canal and create the building foundations. The foundations consisted of wooden piles driven vertically into the ground, with a wooden platform put on top and then the fabric (Miozzi 1968). Water stairs were intimately connected with the basement and were built together with the basement. When the foundation works were concluded, the temporary barrier was removed; the canal waters returned to their natural bed and the water stairs were useful for unloading building materials transported by boat. Consequently, we dated water stairs with the start of the foundation works.

In the early period (Byzantine and early Gothic style, tenth to fourteenth centuries) water stairs (Fig. 2a) were essentially focused on practical use and were built inside the quay: either along the edge of the quay or perpendicular to it. At high tides, the bottom step was at gunwale level, about one foot above CM, for two reasons: to make it easier to land and to avoid treads getting infested with algae, especially because they are extremely slippery.
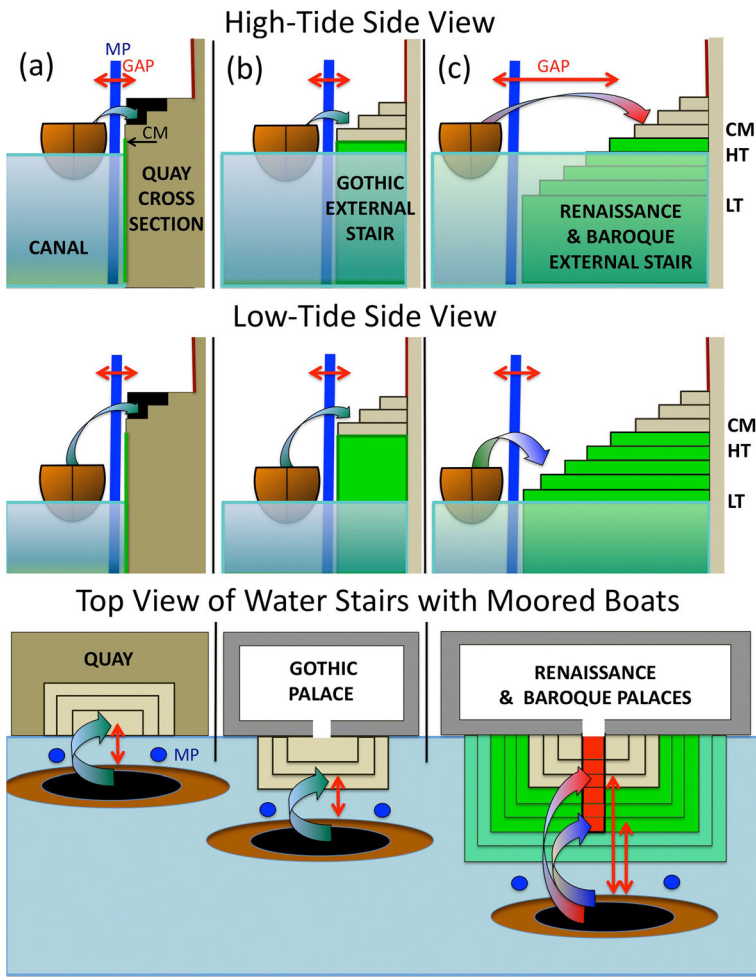
Fig. 2 Water stairs in Venice with moored boats, side view (*first row* high tide and *second row* low tide) and aerial view (*bottom row*). **a** Cross-section of a stair internal to the quay; the bottom step was built above CM. **b** External view of a water stair in the early Gothic period: stairs were external, protruding out into the canal; the bottom step was built above CM. **c** External view of a water stair in the Renaissance and Baroque periods. Stairs were external but bigger, with the bottom step at low tide level. A red carpet runner was unrolled to cover the steps infested by algae. *Arrows* indicate the gap between boats and the closest step free from algae. *CM* common marine level, *HT* high-tide level, *LT* low tide level, *MP* mooring piles in front of stairs. *Green areas* are colonized by algae

In the Gothic period (fourteenth to sixteenth centuries), buildings were light, made of brick and refined with plaster or thin marble slabs; water stairs (Fig. 2b) were external to the façade, with a few steps protruding out into the canal. Stairs were practical and safe, limited to the strictly necessary extent because the underwater structure was expensive and potentially dangerous to boat traffic. At high tide, the bottom step was at gunwale level, and it was easy to jump from the boat to the treads, all clear of algae. At low tide, the steps appeared truncated.

In the Renaissance (late fifteenth century to seventeenth century) and Baroque (early seventeenth century to mid eighteenth century) periods, buildings reflected social and

wealth differences: the middle class built elegant light buildings following the local tradition; the noble and richest people built outlier palaces that were magnificent and massive with the façade fully made of thick stones. Stairs of the "normal" buildings were in the tidal range; by contrast, stairs of the magnificent palaces (Fig. 2c) emerged from the water at all tidal phases, the bottom step being at the average level of the low tide. In the tidal range, steps were infested with algae. Boats could not approach too easily, making landing difficult. At high tide, a plank was used to bridge the boat to the stair. At low tide, a carpet runner was unrolled on the slippery steps to enable people to walk on them more easily.

In the Classic Revival and Gothic Revival (mid eighteenth century to mid nineteenth century) periods, buildings became lighter again and stairs were visible during all tidal phases.

Water stairs were part of the basement structure, a complex frame based on a series of poles driven into the muddy clay. Venetians were aware that the subsoil was plastic and compactable with the load, and they made a lot of effort to build very resistant foundations to support massive stone buildings. Cristoforo Sabbadino, one of the leading officers of the Water Authority, wrote: "after buildings have been built, the soil has sunk and compacted, to a different extent from point to point, depending on the local resistance of the clay soil and the building foundations, that may be more or less strong to support the load" (Sabbadino 1550 ca). As a consequence of uneven sinking, the buildings could lean or crack. Satellite measurements of the historical city centre and the surrounding area have revealed a micro-level heterogeneous situation (Tosi et al. 2013) determined by local soil characteristics, depth of foundation and load of the palaces (Cavaggioni and Lionello 2009). Palaces changed size and load over time. The monumental palaces in the Classic Renaissance and Baroque periods have sunk more than lightweight buildings. This explains the spread of the observed bottom step depths, and why the depth increases with the building load.

4 Data analysis and discussion

A list of the monitored palaces, 78 in total, divided per century according to the year during which the building's construction started, is reported in Online Resource 4. All stairs (15% of the total) that had uncertain documentation or underwent transformation works have been disregarded. Unfortunately, this meant that the rare stairs from the earliest period, i.e. prior to 1350, had to be eliminated from this analysis.

The transformation of the observed depth into a proxy, i.e. the difference between MSL when the stair was built and today, has required preliminary analysis of each building. Depending on the stair type, reference was made to the high or low tide. In addition, building load and local soil compactness determined individual sinking departures. To achieve homogeneity, the following corrections were made. Five early stairs built before 1450 with the bottom step built above CM needed −42 cm correction, i.e. −30 cm for the high tide and −12 cm for the wave contribution. Ten buildings with the bottom step built at low tide level were corrected by adding two steps, i.e. +35 cm. For the majority of buildings, i.e. normal buildings made of light brickwork walls and stairs with the bottom step at intermediate tidal levels; it was impossible to establish a precise correction and their depths were left unchanged. This explains the observed scatter of

data. The estimated accuracy is ±1 step riser. The three largest Baroque palaces have been excluded from the analysis because they had an anomalous sinking for the huge load of the stone wall fabric and had monumental stairs intended to be visible even at unusually low tides.

Regression analysis has been used to obtain the best-fit equations (Online Resource 5) of the observed RSL. The result was a second-order polynomial (i.e. parabola) and an exponential fit with the same Pearson determination coefficient ($R^2 = 0.96$ for both). The parabola $y = at^2 + bt + c$ (where y is the sea level and t the time and in this case study $a = 0.0015 \pm 0.0002$ mm year^{-2}, $b = -3.3 \pm 0.6$ mm year^{-1} and $c = 506$ mm) is popularly used in oceanography (Church and White 2006, 2011; Jevrejeva et al. 2008, 2014; Woodworth et al. 2009; Kemp et al. 2011; Olivieri and Spada 2013; Long et al. 2014). In physical dynamics, the parabola represents the trajectory of a point subject to constant acceleration: $a_{cc} = 2a$. The initial velocity is given by the coefficient b of the linear term. The last coefficient c is the initial position. In oceanography, the acceleration cannot be constant over long periods due to various synergisms and the different time responses of each of them, e.g. ocean warming is relatively fast compared to isostasy or ice melting. Consequently, $2a$ is named "apparent acceleration" a_{cc} (Douglas 1992). In the case study of Venice, from 1350 to 2014, $a_{cc} = +0.0030 \pm 0.0004$ mm year^{-2}. This value might be considered consistent with the best-fit value $a_{acc} = +0.0054 \pm 0.0027$ mm year^{-2} calculated by Spada et al. (2015) as an average from scholarly papers. However, if one considers a long time series and selects given intervals in it, the coefficient a will be conditioned by the particular choice and it might be misleading to compare series with different starting or ending points.

The exponential is another, but controversial, candidate to describe the RSL in times of global warming (Parker et al. 2013; Hunter 2014), possibly related to the ice mass loss from the most vulnerable ice (Hansen et al. 2016). The equation $y = h_o + C$ exp. (λt) is determined by a starting level that for Venice is $h_o = -1866 \pm 146$ mm, an amplification coefficient $C = 67 \pm 32$ mm, and the growth rate $\lambda = 0.00163 \pm 0.0002$ year^{-1}. The characteristic time $\lambda^{-1} = 613$ years is close to the record duration.

It is not surprising to find that these two equations fit the observed data with the same strength because, within certain time intervals, the plot of an exponential may be approximated with a Taylor series of powers. By equalling the above equations, one obtains the key relation between the acceleration and the growing rate, i.e. $a_{cc} = C\lambda^2$, as well as between the other parabolic and exponential coefficients. The accuracy of the above finding depends on how closely the exponential is represented by its second-order approximation, and this only depends on the actual distribution of the readings and the selected time interval.

If one excludes a specific physical reason (i.e. cause–effect relationship) to prefer one equation to another, but only considers how closely the observed data are represented, the main difference is that, going back in time, the parabola is U-shaped and suggests a turning point (TP) at $t_o = -b/2a$, after which the trend is inverted. By contrast, the exponential has a continuous asymptotic behaviour with decreasing rate.

Almost all RSL data in Venice (Fig. 3a) fall within the band determined by the parabolic or exponential interpolation ±1 step riser around the best-fit line. The two interpolations are equivalent over the common period of this record. The main difference is that a back extrapolation of the parabola might suggest a TP around 1100 ± 250 years (possibly related to the mooring docks out of water visible in de' Barbari's view), while
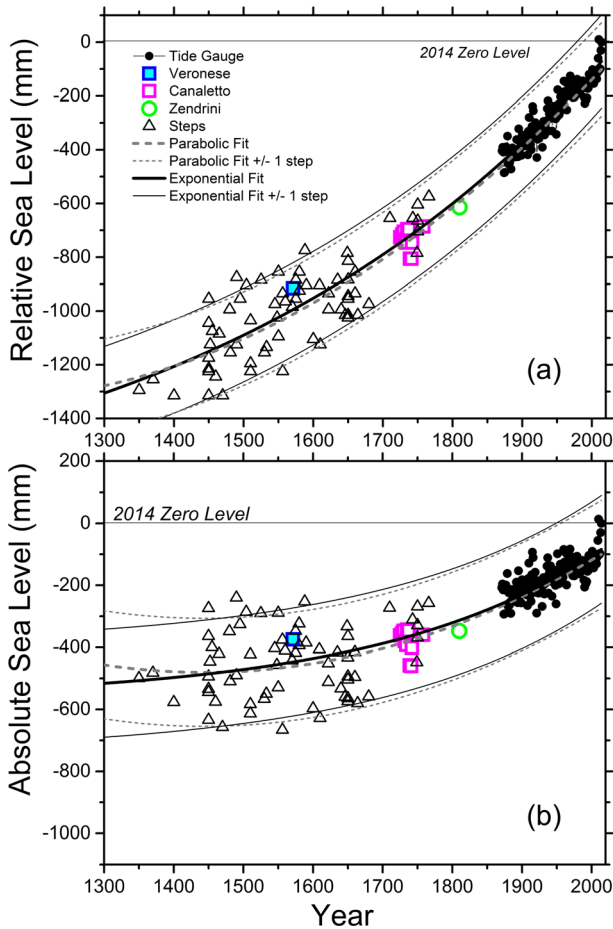
Fig. 3 a Relative sea level at Venice after instrumental readings and proxies. **b** The same but for the absolute sea level. *Dashed lines* parabolic best-fit interpolation (*thick line*) and borders of the ±1 step band (*thin lines*); *continuous lines* as above, but for the exponential interpolation

the exponential does not. However, being outside the documented record, the above dating and even the existence of a TP are only speculative.

In the scholarly literature, there is no consensus about the existence of a TP or its dating. Kopp et al. (2016) found a TP in 1400 and Grinsted et al. (2009) in 1730. We have calculated possible TP as $-b/2a$ for some of the longest records in the literature (Jevrejeva et al. 2008, 2014; Church and White 2006, 2011; see Online Resource 6); most of them fall from 1750 to 1850 and seem not to be consistent with observations. This may be justified with some reasons, for example, the parabola is not always the most convenient approximation; a and b are not constant over the whole record but are average effective values; records have different lengths, some of them not being long enough.

If LLS is removed from RSL (Fig. 3b), one obtains the eustatic component, i.e. ASL. For both interpolations, $R^2 = 0.78$. The analysis is unclear because the range (i.e. the signal) is reduced, but the scatter of data (i.e. the noise) remains unchanged. The

exponential suggests a continually increasing rate. On the other hand, the parabola keeps the above acceleration but suggests a TP around 1444, near the TP found by Kopp et al. (2016). The reconstruction of RSL in Venice made by Ammerman (2005) (Online Resource 6.2) might include a eustatic TP from 1300 to 1600, when the RSL interpolation seems to become tangent to the LLS slope; however, this cannot be precisely assessed for the large scatter and uncertainty band of the archaeological proxy.

The accurate bird's-eye view of Venice produced by de Barbari (1500) shows the city five centuries ago (Online Resource 3, Fig. 3.8). It might suggest a stationary situation, e.g. quays at man height, water stairs with the bottom step above the sea level, plants and gardens growing on the urban borders (Fig. 3.9). However, four mooring docks out of the water on the side of St. George island seem to suggest a retreat of the sea (Fig. 3.10). Briefly, a eustatic TP in Venice in the mid LIA may be likely, but it is not supported by robust confirmation.

5 Conclusions

The underwater depth of the bottom step of the water stairs constitutes a novel proxy for the long-term knowledge of RSL in Venice, in agreement with other independent proxies, e.g. the documentary paintings by Veronese, Canaletto and Bellotto. The combination of tide gauge readings and the above proxies has produced a high-resolution record covering the whole LIA and the global warming periods; the series is better documented after 1500, less so in the previous period.

This study shows a continuous SLR and corroborates the hypothesis that sea level (either RSL or ASL) was rising with apparent acceleration that has been estimated to be $a_{cc} = +0.0030 \pm 0.0004$ mm year^{-2} (i.e. $+0.30 \pm 0.04$ mm year^{-1} century^{-1}). The comparison with other scholarly series is difficult because the actual value may vary from site to site (e.g. LLS) and with the record length.

The calculated ASL shows a clear eustatic increase since the middle of the fifteenth century. In the previous period, ASL did not change much and the interpretation becomes unclear for the scattered data and the series truncation. The parabolic interpolation suggests that a eustatic TP likely occurred around the middle of the fifteenth century, as suggested by Kopp et al. (2016) and possibly in agreement with Ammerman (2005). By contrast, the exponential fit suggests a continually increasing trend. In both cases, the mid LIA had a very small eustatic rise or even a weak trend inversion.

From the mathematical point of view, our RSL record may be equally interpolated with a parabola or an exponential fit within the observed time interval. The dominant physical mechanism that may justify the choice for a parabola or an exponential needs longer records or narrower uncertainty bands to enable assessment.

The comparison between scholarly papers is difficult due to geographic and geological differences between sites and record durations; the lack of consensus means that our knowledge of the past sea level changes is far from being satisfactory. Our contribution has been to provide an exceptionally long sea level record.

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