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Sinking of Venice over the last three centuries: input from Canaletto's paintings and early photographs

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ABSTRACT

The sea level is expected to rise from 10 to 80 cm by 2100 as a consequence of the global warming. In addition, Venice is affected by a local subsidence, mainly of tectonic origin. In the recent past, pumping of underground water for industrial purposes has worsened this situation. Relative sea level (RSL) rise is a combination of the two above challenges and is a crucial issue for the safeguard of Venice and its historical buildings. The phenomenon over the last three centuries has been investigated by using a proxy of mean sea level: the level of the algal front on palaces. Algae, and particularly the *Laminaria*, mark the average high sea level. This indicator was accurately reported by the Venetian painters Antonio Canaletto (1697-1768) and his pupils, mainly Bernardo Bellotto (1722-1780), in their "photographic" paintings made with an optical *camera obscura* in the first half of the 18th century. These paintings extend our knowledge about Venice submersion back in time for almost three centuries, which include the ending part of the Little Ice Age and the recent warming. Nowadays, after the relative sinking, sea water wets Venice palaces for an additional 69±11 cm. High tides and flooding waters reach brick and plaster which are rapidly destroyed by salt crystallisation cycles. The rise of the algae belt, however, has also increased by some 8 cm, as a sum of two contributions: the increased height of waves generated by motor boats, and the dynamic increase of the tidal wave after the excavation of some canals. With the above corrections the bulk submersion of Venice estimated from all the analysed paintings is 61±11 cm, which corresponds to an average sinking ratio 2.3±0.4 mm yr^{-1}.

IntroductionAbstract. Relative sea level (RSL) rise is a crucial issue for the safeguard of Venice and its historical buildings. The phenomenon over the last three centuries has been investigated by using a proxy of mean sea level: the height of the algae front on palaces. This indicator was accurately drawn by Canaletto and his pupils in their "photographic" paintings made with an optical camera obscura. The positions of the fronts in the 18th Century and the present were compared. The RSL rise is due to a combination of natural and anthropogenic factors which affected the land subsidence. An analysis was performed to establish the long-term trend and distinguish between natural and anthropogenic contributions. A prudent scenario for the future would suggest a rate between 1.9±0.4 mm yr^{-1} and 2.3±0.4 mm yr^{-1}.

Venice risks being submerged as a consequence of two problems: local land subsidence and sea level rise as a consequence of thermal expansion of sea water and land ice melting (IPCC, 2001). They both contribute to what is referred as Apparent Sea Level Rise (ASLR) where the

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term “apparent” indicates that even when the land is sinking the result from the point of view of the city is a sea level rise. In practice, the ASLR is the submersion rate of Venice. Regular tide-gauge monitoring was started in 1872 and shows an ASLR of about 30 cm. The storm surges are known from documentary sources since AD 787 and their frequency has exponentially increased in the last decades (Camuffo, 1993; Enzi and Camuffo, 1995; Camuffo and Sturaro, 2002, 2004). Ammerman *et al.* (1999) and Ammerman and McClennen (2000), on the grounds of archaeological evidence, better documented from AD 200 to 1400, suggested 1.3 mm yr^{-1} average ASL rise, with a lower rate in the early period and a greater one in the modern period. The dark period between archaeological and instrumental data should be investigated with other proxy data.

The Venice painter Antonio Canal, nicknamed Canaletto (1697-1768) and his pupil Bernardo Bellotto (1722-1780) made accurate reproductions of Venice buildings using a *camera obscura* on the site and they also reported the algal belt on buildings (Camuffo, 2001; Camuffo and Sturaro, 2002, 2003). In the *camera obscura* (Fig.1) the light beam penetrates through a lens, is reflected by a mirror or a prism, and is projected onto a glass surface, where a sheet of paper was placed. Then the painter drew in all the contours, obtaining a “photographic” painting. In a number of paintings, the brown-green front left by algae (mainly the *Laminaria* alga) is visible on some buildings. This front is a biological indicator of the average high-tide level (HTL) and is locally called *Commune Marino* (CM). In the past, the CM was in some cases also engraved on buildings with the initials CM, but this information was lost for the earliest times. The standard deviation of the yearly sea level fluctuations, and consequently of the CM, is 3.8 cm.

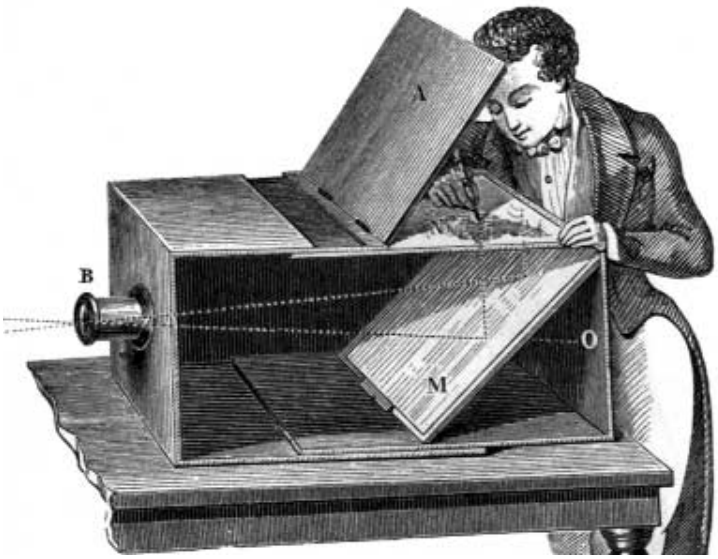


Fig. 1. Principle of operation of the *Camera obscura* in a compact box model (after Ganot, 1860).

The use of this indicator applied to 18th century paintings is justified because the overall uncertainty is small compared to the expected ASLR on the long term. In the short term and with real photographs, the ASLR is relatively modest and the uncertainty too large. In such a case, the method is acceptable only after 1872 (i.e. when the tide level is known) and if the date of the picture is known so that the reference is made to the estimated algal level and the uncertainty disappears. The method has been tested on early photographs taken in the period 1880-1890 but without indication of the precise date, and in this case the uncertainty for the algal belt fluctuations and other errors is 1/4 of the observed ASLR. The test performed with early photographs gave results coherent between them, and falling within the expected interval documented by the tide gauge observations, as we will see later. This confirms the reliability of this approach and suggesting that the uncertainty assumed is probably too large. More interesting results are expected from early pictures precisely dated in 1840s, when available.

Canaletto painted photographic views on the site, and also made duplicates in his studio. As replicas are suspected to be less reliable, in this study the earliest version of each view was pre-

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ferred. In the absence of dating, the accuracy of the paintings having the same view was tested after comparison with the actual building. The test was performed by taking a quantitative evaluation of some architectonic details on the paintings, making comparison with the actual building and then computing the standard deviation of the error. The lower the standard deviation, the better the accuracy.

The CM level in the paintings was compared to the present-day situation with site inspections and measurements. A quantitative evaluation of CM displacement was possible by making reference to certain architectural features that constituted a useful frame within which to take and compare measurements (Fig. 2). The cases where building restoration has altered these architectonic features were discarded. Although Canaletto painted some 200 views of Venice, most of them cannot be utilized due to the absence of a view on a canal or because there is no clear indication of the algal belt, or because the old buildings have since been demolished or transformed. After a search in catalogues and collections, we found 17 potentially useful views, either in the original, or in a good reproduction. After inspection in Venice of the present-day conditions, the number of paintings available to us was reduced to 12, i.e. the only ones that reproduce buildings which have remained unaltered since the 18th century.



Fig. 2. Apparent Sea Level Rise (ASLR) in Venice from Canaletto and Bellotto paintings. Bellotto, S. Giovanni e Paolo (1741), detail (right). The two arrows give the level of the algal belt in 1741 (lower) and today (upper) as derived from on-site observations. The painting shows that there were two front steps above the green belt. The displacement is 77±10 cm. (left) The same door today. The picture was taken during low tide and the top step of the old front stairs is just visible (red arrow). The door was walled up with bricks in the first 70 cm above the front step to avoid water penetration (after Camuffo and Sturaro, 2003).

An analysis of the paintings (Camuffo and Sturaro, 2003, 2004) showed that the CM has risen on average by ΔCM_{obs} = 69±11 cm since the first half of the 18th century (Fig. 3). The largest errors occurred when the green line was superimposed on a local frame and did not allow a fine resolution (e.g. uncertainty over the height of a step or a brick row). In this case, the uncertainty was resolved by the actual height of the step or row. In other circumstances, where the position of the algae was measured as a distance from an architectonic reference, e.g. a floor or a window, the uncertainty derived from the errors made in measuring these distances both on the site and in the paintings.

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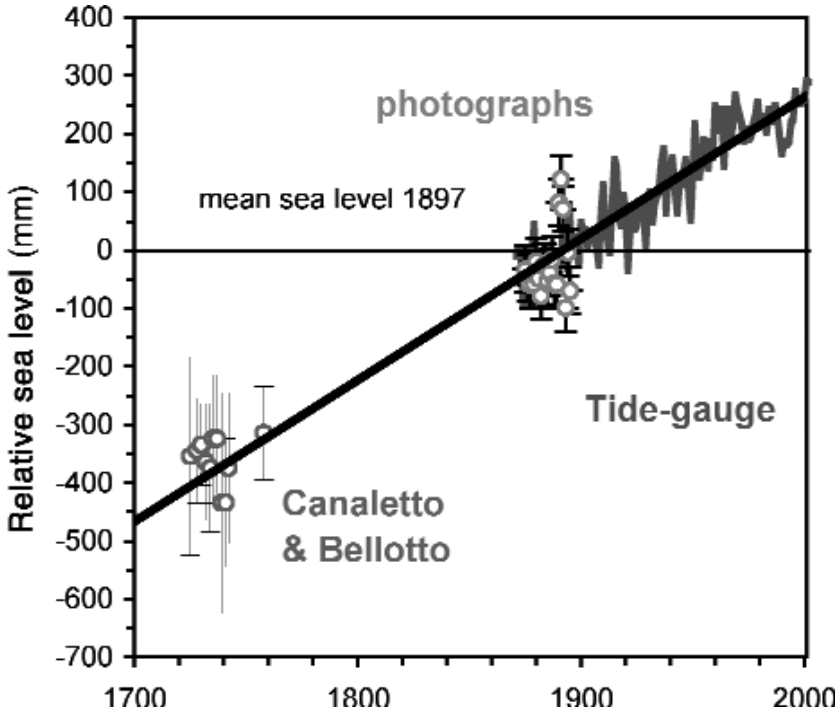


Fig. 3. Apparent Sea Level Rise (ASLR) in Venice from tide gauges (continuous blue line, period 1872-2002), from Canaletto's and Bellotto's paintings (red dots with error bars, period 1727-1758) and from early photographs (range dots, period 1880-1890). ASLR from paintings (and photographs) was estimated from the difference in level of the algae belt as it was in the paintings and as it is today.

One question was whether Canaletto and Bellotto were accurate in drawing the exact position of the algal front. The answer is given by the scatter of all the data: the better their accuracy, the smaller the scatter. The scattering of the data is limited to 12 cm, part of this being explained by the uncertainty in reading certain details, part by the yearly fluctuations of the CM, and possibly the individual response of building foundations. This confirms the reliability of the paintings and the consistency of the method.

The paintings were first analysed to check their accuracy in reproducing all details. Two kinds of details can be controlled: the architectural and decorative features of buildings making a cross comparison with the present day situation. When the algal belt falls in correspondence of a recognisable detail, it is possible to measure on the site how much the present day level is above that detail. This kind of measurement is of course independent from any distortion of the image. If the algae belt falls in the mid of a recognizable stone in the painting, the limit of uncertainty is connected with the precise evaluation of the proportion of stone covered with algae in comparison with the part free. Once this has been established, it is possible to measure the algae displacement on the site. In this case the uncertainty is a fraction of the brick or stone size, and depends on the size of the detail in the painting. For instance, in the case of algae apparently covering half of a typical brick row, 8 cm width, the maximum error is ± 4 cm.

Another test is based on the cross-comparison between the size of the architectonic features as they appear in the painting and in a picture of the actual building today. This is obtained from the ratio of the size of the corresponding items and then calculating the standard deviation of each series, as follows. For each painting, the building is divided into a number of strips corresponding to natural partitions of the facade, and the width of each strip is normalised expressing it as a fraction of the total building height. The same is made with a picture of the building today. Then the ratio is computed between each normalised size in the painting and the corresponding size in the picture of the building today, obtaining values close to, but slightly different from 1. It is finally possible to calculate the standard deviation of these ratios for each painting. The smaller the standard deviation, the better the accuracy (Camuffo and Suraro, 2003; Camuffo *et al.*, 2004).

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The observed algal shift is primarily determined by ASLR and, secondarily, by wave height change. Waves generated by motor boats have a typical height of some 10 cm that is about twice the value of those generated by an 18th-century row-boat, as estimated from wave observations in the Grand Canal under differing conditions, motor traffic being either allowed or forbidden (Canestrelli and Cossutta, 2000). This is equivalent to an apparent 5-cm CM rise. Another factor is the amplitude of the tidal wave. After the excavation of two deep channels, the ingress of sea water into the Lagoon was facilitated, slightly amplifying the tidal wave in Venice. Analysis of tide gauge observations demonstrated that this dynamic effect contributes to the yearly average tidal amplitude raising the CM by another 3 cm. The combination of both the above factors gives an ASLR contribution equal to DASLRwave = 8±1 cm.

After this correction, the estimated relative sea level change since the Canaletto's time is 61±12 cm with average trend 2.3±0.4 mm yr^{-1}. This trend is close to that computed for the instrumental period 1872-2000, which was 2.4±0.1 mm yr^{-1}.

CONCLUSIONS

The apparent sea level is substantially raised with the same rate in the last three centuries, as confirmed by Canaletto's and Bellotto's paintings. The bulk estimate from the paintings is 2.3±0.1 mm yr-1 which is very close to 2.4±0.1 mm yr-1 found after the tide gauge records from 1872.

Venice submersion is explained in terms of three main causes. The first is the natural subsidence due to tectonic movements in the deep layers. This is worsened by the compaction of clay and peat sediments, although over the past centuries attempts have been made to reduce lagoon sediments and compaction by diverting rivers. During the Holocene, the tectonic subsidence in this area was estimated to be around 1 mm yr^{-1} i.e. from 0.7 to 1.2 mm yr^{-1} (Bondesan *et al.*, 2001; Carminati *et al.*, 2003). The second cause is the local anthropogenic land subsidence. The main factor was pumping of ground water from the upper aquifers for industrial purposes. In the period 1930-1970, highly affected by water pumping, subsidence was estimated to be 10-12 cm in comparison with sea level in Trieste (Teatini *et al.*, 1995; Carbognin and Taroni, 1996; Pirazzoli and Tomasin, 1999). If the intensive sinking 1930-1970 is removed, the estimate of the natural ASLR is 1.9±0.5 mm yr^{-1} in agreement with instrumental data for the early period 1872-1930. However, the apparent sea level always fluctuated around the main trend. An acceleration is evident in the period 1930-1970, followed by a deceleration. An apparent immediate benefit was due to a number of factors. One is a small aquifer rebound after 1970, estimated 1-2 cm. Other factors are connected with the eustatism, as follows. The third cause of submersion is the sea-level change (eustatism) in the Mediterranean which has been estimated to be 1.1-1.5 mm yr^{-1} in the last century, with a negative trend after 1960 (Tsimplis and Baker, 2000). This rate is smaller than that known on the global scale for three reasons that have characterized the last decades. First, the precipitation in the Mediterranean catchment area has decreased and the evaporation increased (Piervitali *et al.*, 1998). Second, the balance with the Black Sea has changed after the water of its tributaries has been substracted for irrigation purposes. Third, the atmospheric pressure over the Northern Adriatic has increased by 1 hPa, which is equivalent to 1 cm sea level depression.

The result of this study suggests that in Venice natural land subsidence, which is substantially constant (Teatini *et al.*, 1995; Bondesan *et al.*, 2001; Carminati *et al.*, 2003) and the eustatism in the Mediterranean (Tsimplis and Baker, 2000) had the same order of magnitude during the last three centuries.

The Venetian palaces, either on canals or streets, were originally protected against groundwater rise by a belt of non-permeable Istrian stone Now, after the city has sunk, the protective belt is too low and the flooding waters reach brick and plaster which are destroyed by salt crystallisation cycles. The municipality has introduced mobile footbridges (Fig.4) to make possible walking on flooded streets. This has partially solved the problem of pedestrian traffic. The main problem, i.e. to save buildings, is still open although a project to install mobile gates and to undertake other mitigative measures is underway.

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Fig. 4. Mobile footbridges near Frari church to make possible walking on flooded streets during acqua alta.

Acknowledgements. The idea arose under researches funded by the European Commission, DGXII (Environment and Climate Programme) and was developed with funding by CORILA, Venice. Special thanks are due to Dr. Luigi Alberotanza, Director of CNR-ISDGM, Venice, Dr. Giovanni Cecconi, Consorzio Venezia Nuova and Mrs Caroline Fletcher, Churchill College, Cambridge, for their precious help.