RECONSTRUCTING SEA LEVEL RISE AND STORM SURGES FLOODING VENICE, FROM WRITTEN SOURCES, VISUAL ARTS AND URBAN ARCHAEOLOGY

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Climate

e.g. climate change, atmospheric forcing, glacier melting, tide gauge, sea level rise...

Culture

e.g. history of Venice, history of art, literature written documents, visual arts, painting methodologies, local laws and traditions...

Cultural Heritage

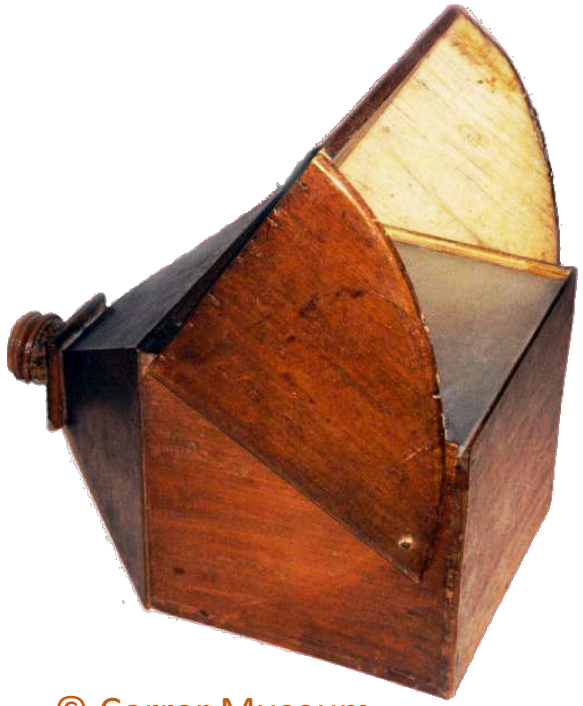
e.g. built heritage, safeguarding of the city, deterioration mechanisms...

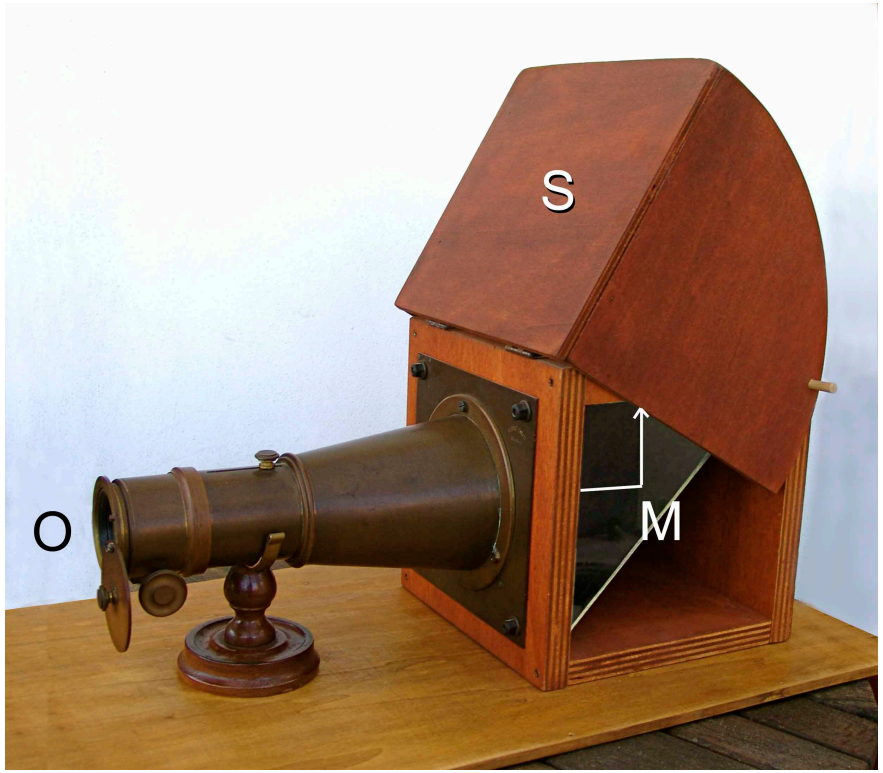
.... data analysis, forecast of future scenarios, mitigation strategies...

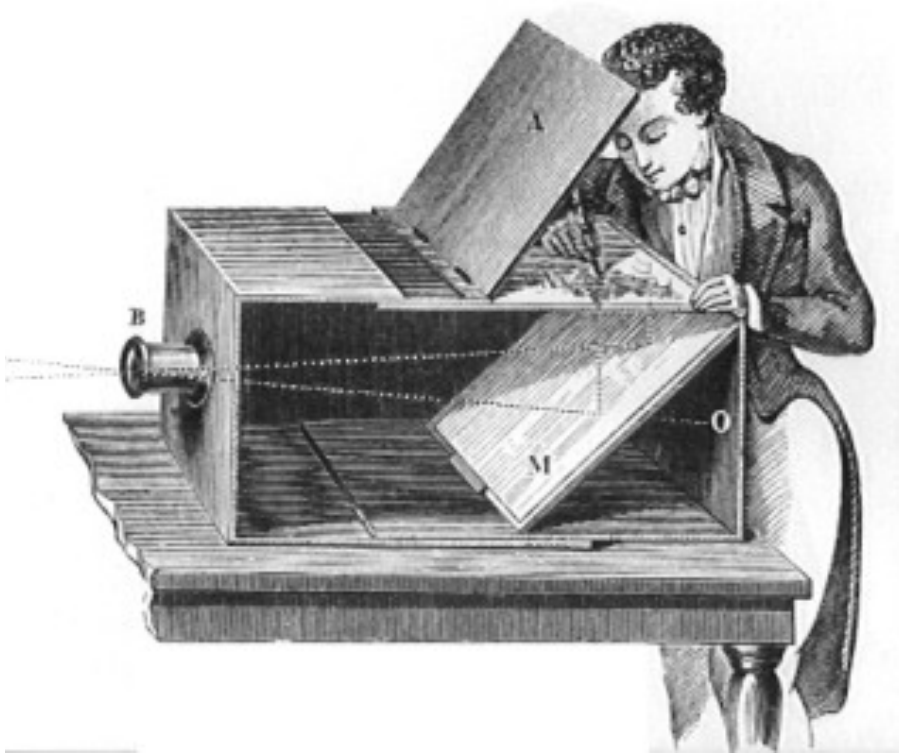
Can we see Venice, as it was in the past centuries?

Canaletto and Bellotto drew accurate paintings with the aid of a ***Camera Obscura***, a device similar to a modern **reflex camera.**

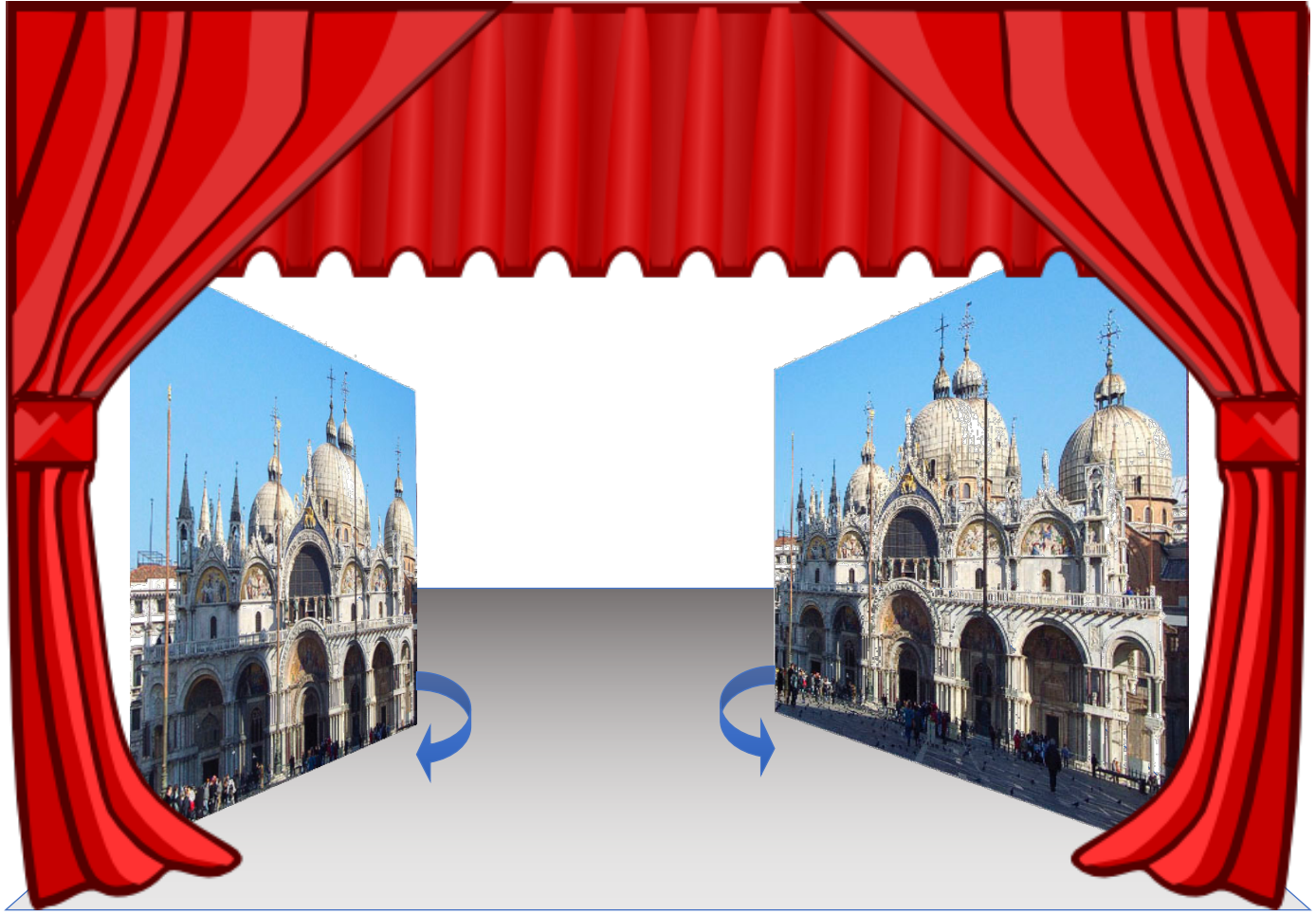
Canaletto placed a sheet of paper on the projected image and drew the contour lines.







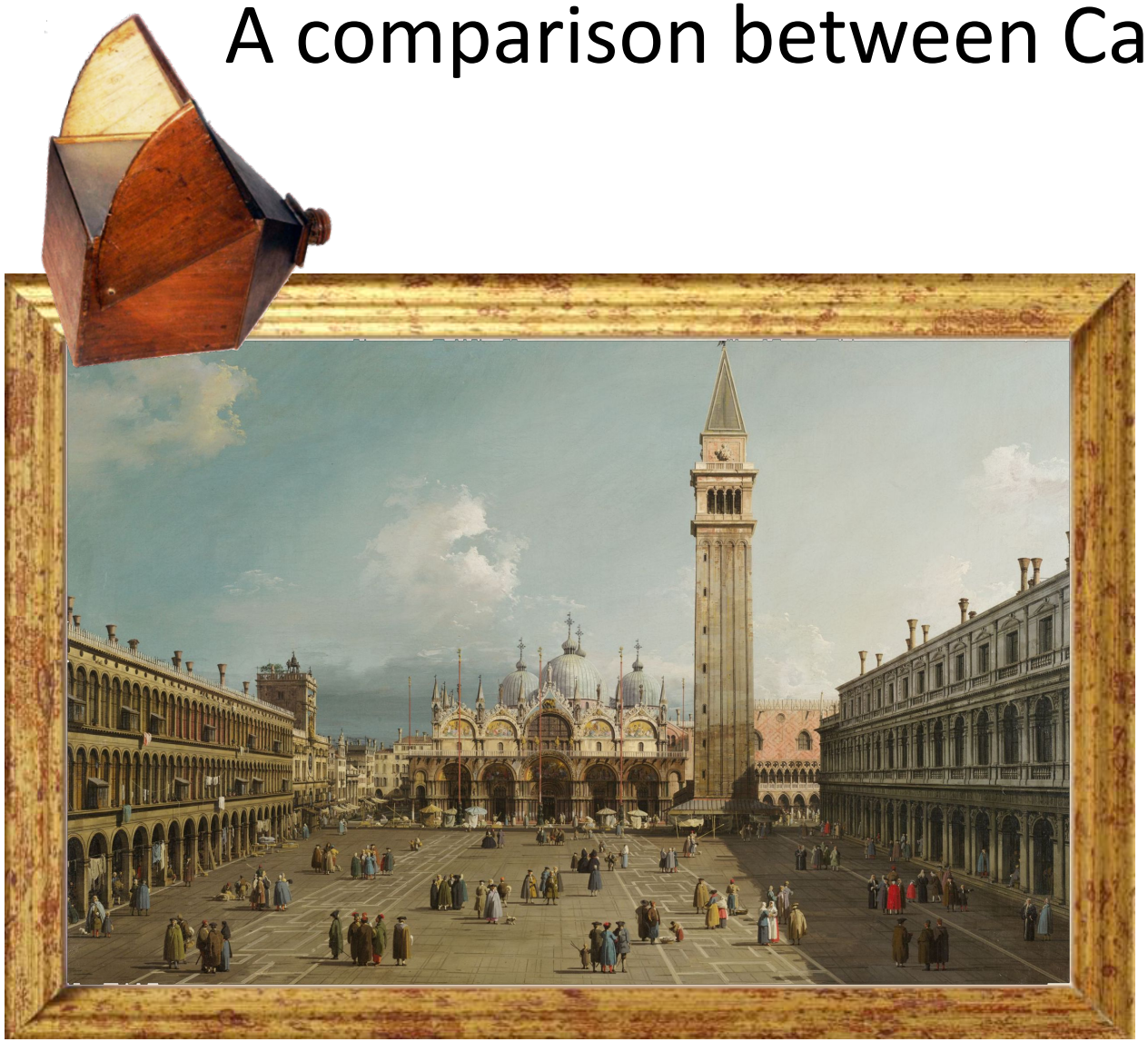
(a) *Camera Obscura* used by Canaletto; (b) a replica to show how the camera works. O: objective; M: mirror; S: light screen. (c) an example of use



Canaletto was born as a **theatre scene painter**.

He learned how to **rotate the movable lateral scenes,** expanding or shortening buildings, to stay within a selected frame or to enhance views. The effect was surprising: realistic and very accurate images, but organized in **a mosaic** of different perspectives.

A comparison between Canaletto and the real world



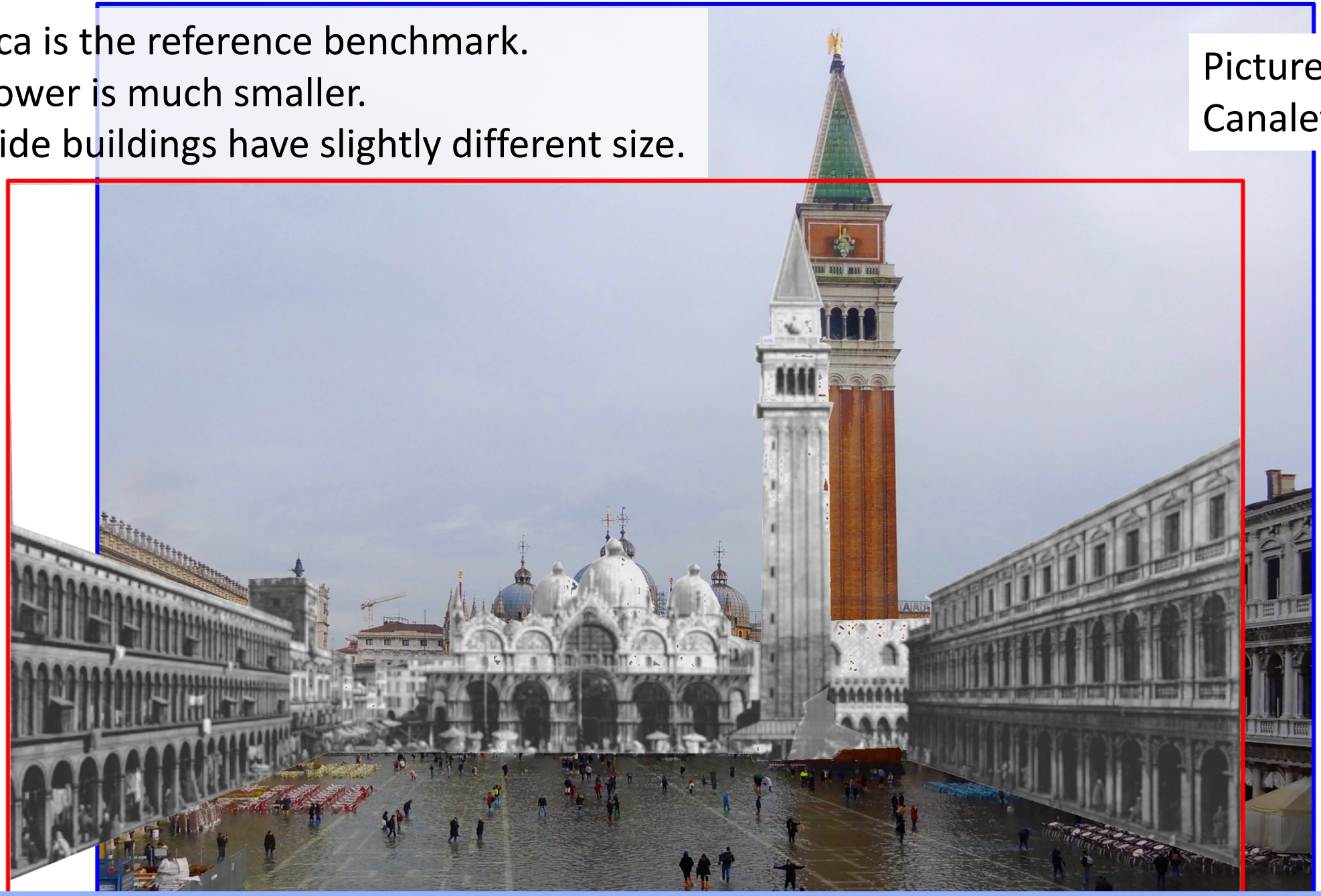
View by Canaletto, 1735-40

76 x 114,5 cm, Harvard Art Museums/Fogg Museum

The same view, picture taken from the same window of Correr Museum

The Basilica is the reference benchmark.
The bell tower is much smaller.
The two side buildings have slightly different size.

Picture: colour
Canaletto: B&W



Anatomy of a Canaletto Painting

A view must stay within a selected frame size.

The painting is a **mosaic** composed of a number of parts having different proportions to fit with the canvas size and to enhance the main subject.

1 the Basilica, in central position

2 the Bell Tower, with reduced size to stay within the frame

3-4 left & right side buildings with different proportions to be recognizable and give space to the Basilica

The 1st proxy: visual. A view of Grimani Palace through centuries

Camera Obscura

Early Camera

Observed algae shift 1735-2002: 79±12 cm

Canaletto, 1735
7 clear steps: 79±12 cm

Photograph, 1880s
5 clear steps 43±10 cm

2002: 2 clear steps

Algae are a biological proxy accurately reported in Canaletto

A Precious Bio-Indicator: The Algae Belt i.e. the Common Marine Mark (CM)

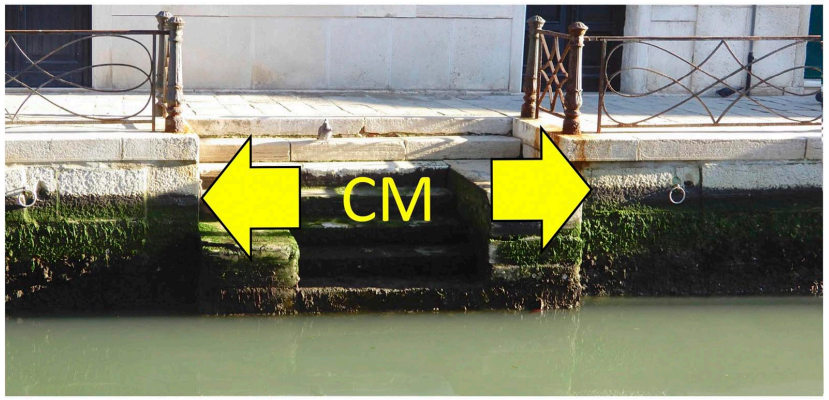
Green algae need light and periodic wetting to live.

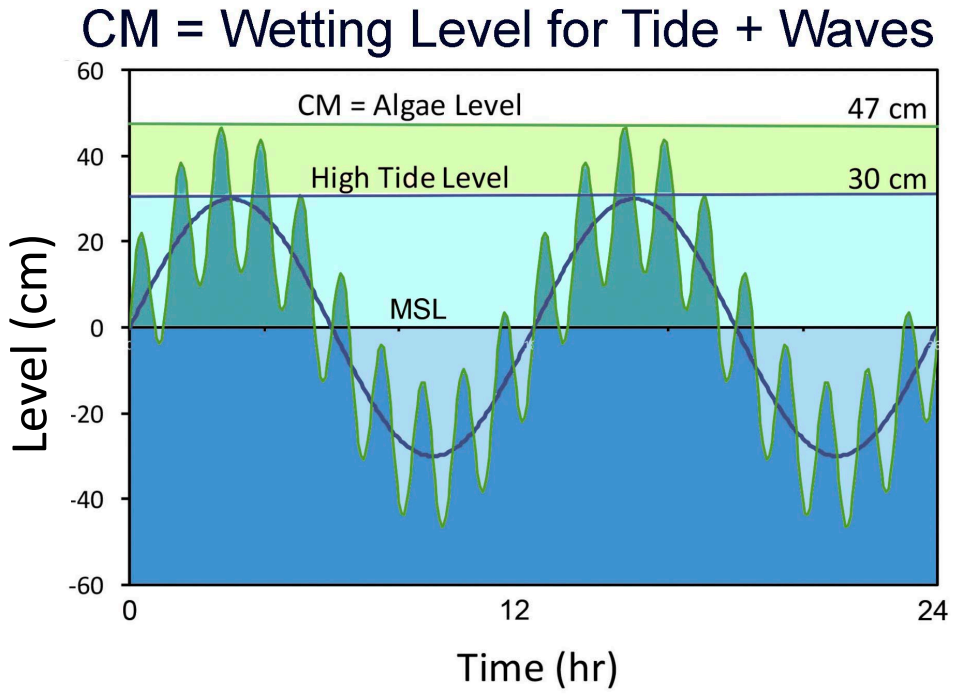
Algae colonize stone and walls up to a certain level that is determined by the **high tides plus the local waves**.

The green algae belt is a **biological indicator of the sea level**, and in the past it was used as a official reference for public works.

With motor boat traffic the algae level is 47 cm above MSL; with rowboats, 42 cm.

An upward shift of the algae belt indicates that the sea level has increased of the same amount.



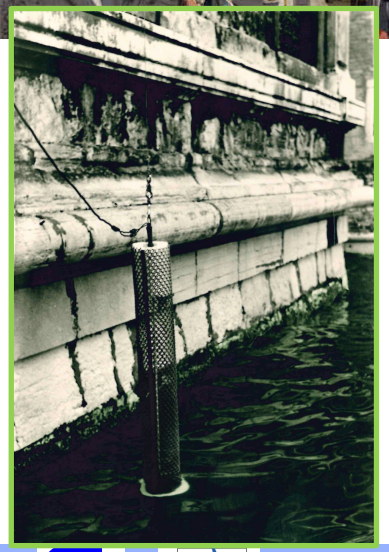


Canaletto, (1740) A Regatta on the Grand Canal,
© The National Gallery, London

What is the difference between the waves of modern motorboat traffic, and the old rowboats?

Regatta is the key

A Regatta nowadays.
© Ve.La. S.p.A. Venice



Measuring waves in the Grand Canal:
17 cm with motor boats (nowadays)
12 cm with row boats (18th Century)

Dario Camuffo, CNR – Institute of Atmospheric Sciences and Climate, Padua, Italy

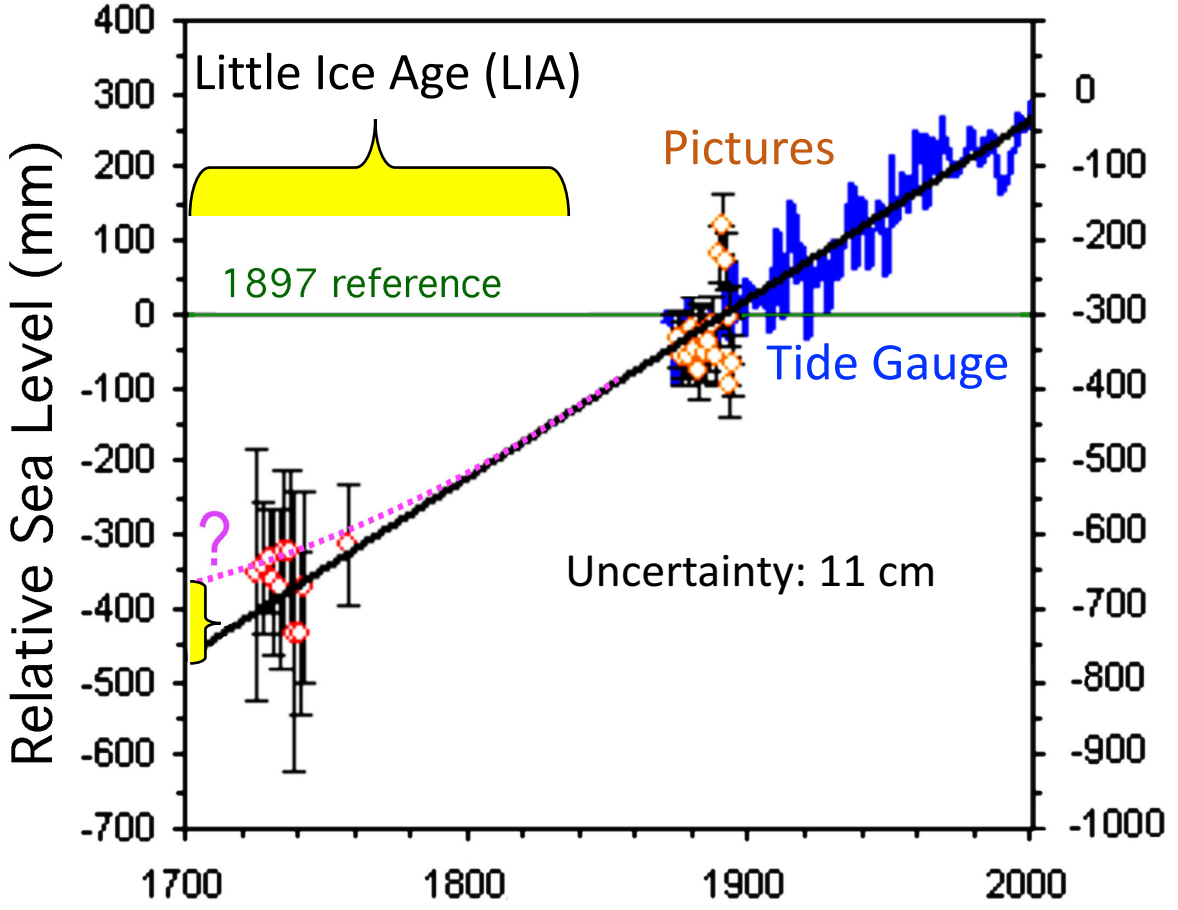
The methodology: comparing the algae band on paintings and buildings

The sea level in paintings **is not useful**, because we don't know the tidal phase (high, low?).

Therefore, another **indicator of sea level** was considered: the green band of phototropic algae that grow where the porous stones are **periodically wetted with sea water** (i.e. CM).

Determining the Relative Sea Level Rise from Canaletto and Bellotto paintings

69 ±11 cm	Average algae shift (observed)
-5±1 cm	Waves generated by motor boats: 5 cm higher than the background in the 18th century (wind and row boats)
-3±0.1 cm	Amplification of the tidal wave for dynamic effects
61±12 cm	Relative Sea Level Rise



Uncertainty: Standard Deviation of yearly sea level & algae fluctuations: 3.8 cm + Reading architectonic detail
Total = ±11 cm

Camuffo & Sturaro (2003) *Climatic Change*

Controlling Canaletto and Bellotto data

(i) our measurements have been taken on site, on the building itself, not on paintings. Therefore, the result is not affected by any distortions due to the lens of the *camera obscura*;

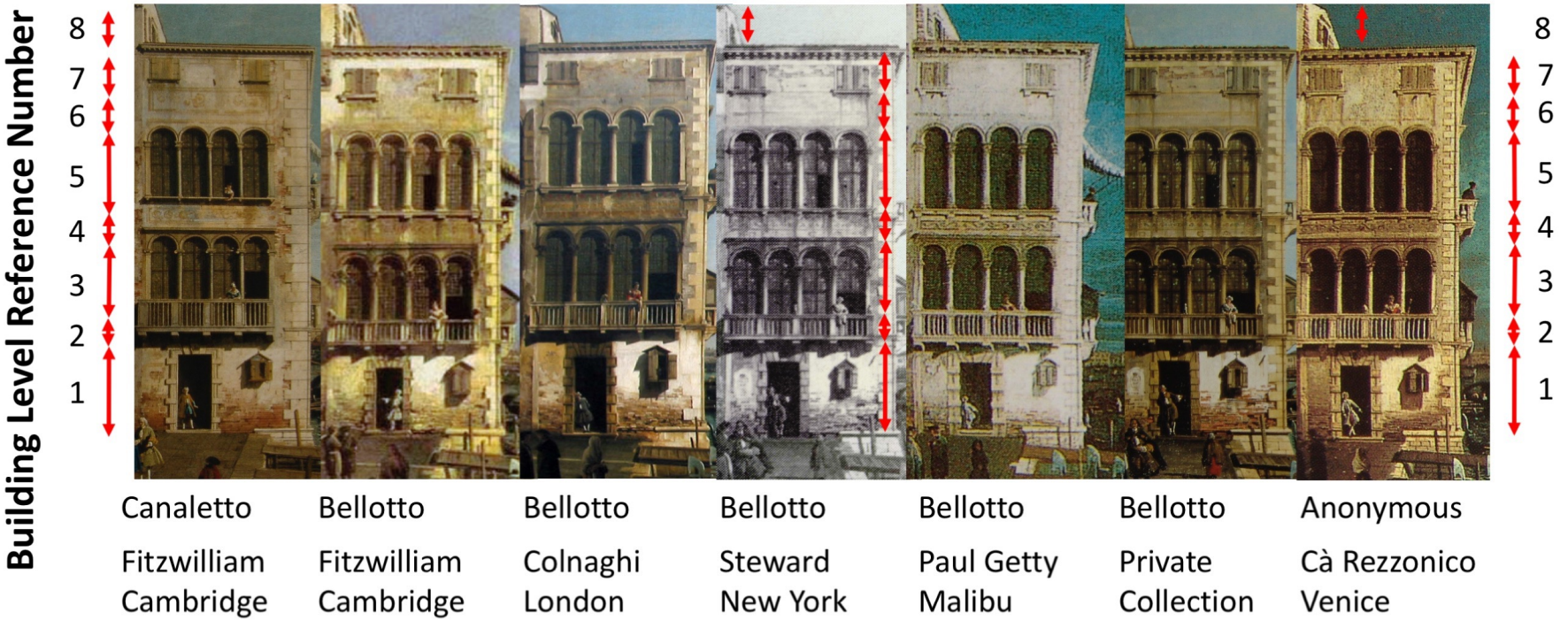
(ii) if the method was not accurate, the results would be randomly distributed, while they are all consistent within 10% uncertainty band;

(iii) when there are different paintings of the same view, we have demonstrated that paintings are all "originals" (not copies), and provide the same result.

(iv) the Canaletto and Bellotto data are consistent with the instrumental tide gauge data and other independent proxies;

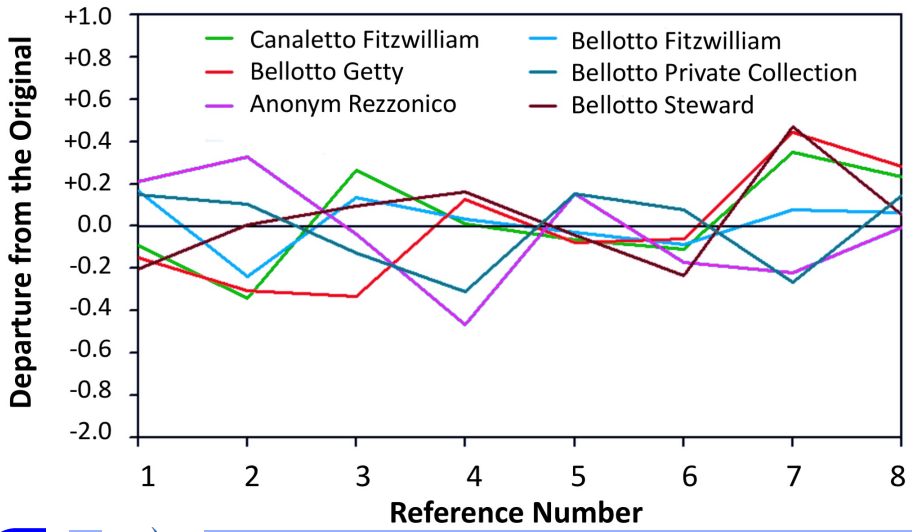
(v) the study was repeated as a field experiment by the Worcester Polytechnic Institute, which obtained the same results.

“Original” paintings or “copies”? There is a propagation of errors?



One might suppose that the earliest painting is “the original” and the following ones are “copies”, with lower accuracy.

Does the quality of details (i.e. copying errors) worsen when replicas are reproduced?



Can we establish in an objective way if a painting has been derived from another, i.e. can we reconstruct the family tree and distinguish between mother and children?
None of the tested paintings repeats the same sequence are independent works.
All paintings are **independent from each other**.
There are no copies, but Canaletto and Bellotto returned on the same site to do their accurate “original” paintings.

Veronese, 1571
(© Gemäldegalerie Alte Meister, Dresden)

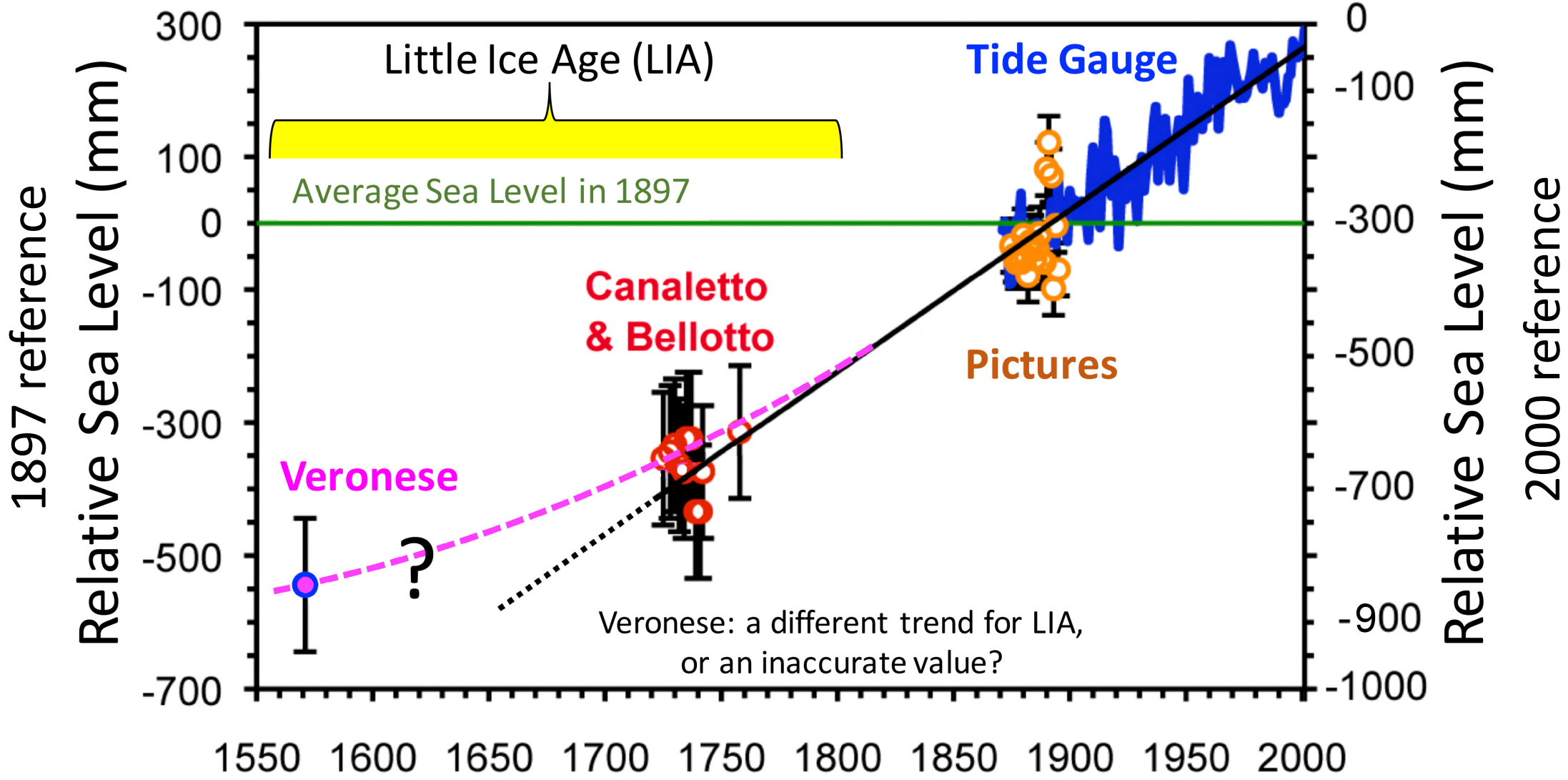
Picture by Ongania 1880-90
(attic raised in 1874/5)

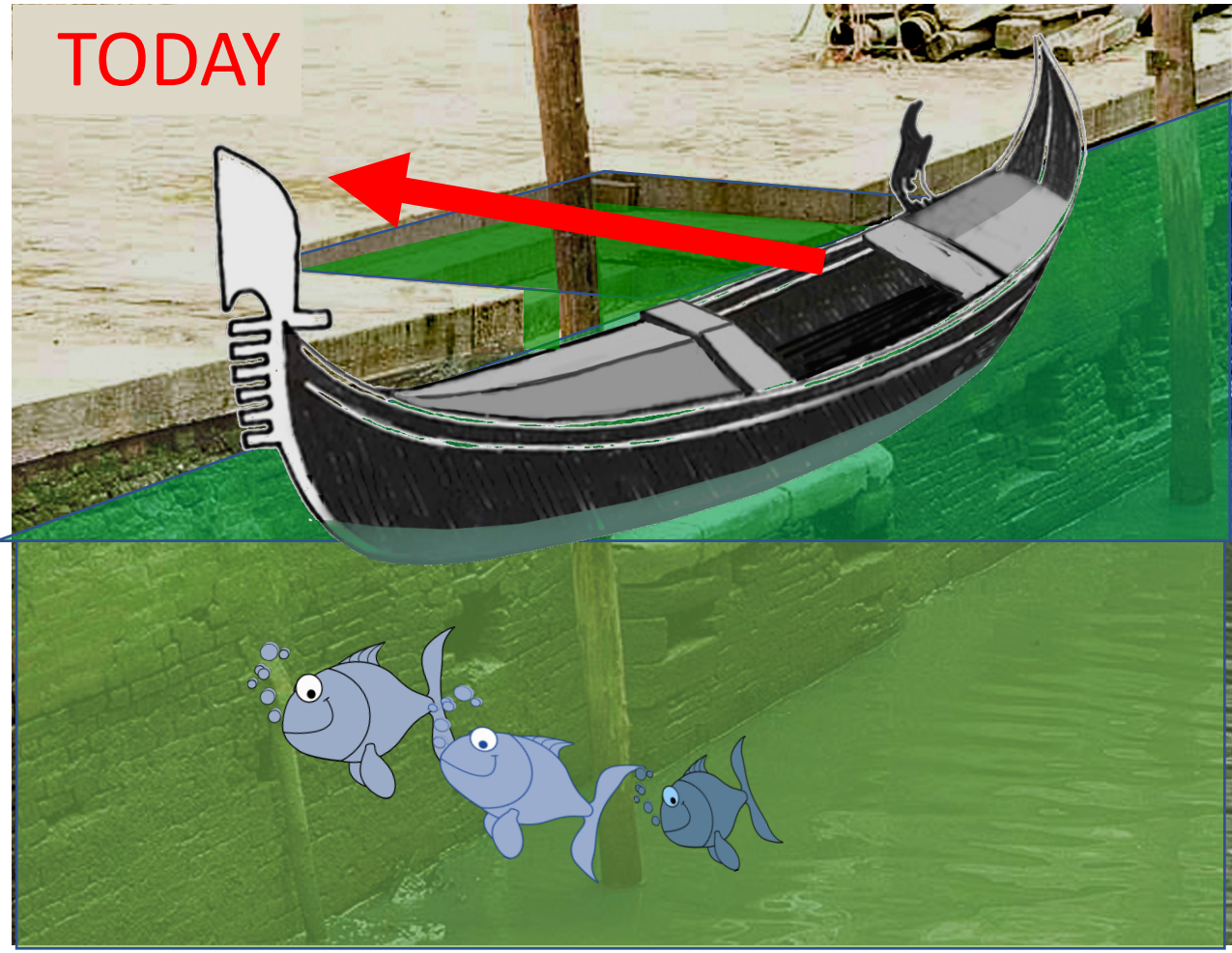
Veronese too used a *camera obscura*

In 1571, five external steps clear from algae i.e. -5x18 = -90 cm; after correction = -80 cm making reference to the MSL in 2010

Camuffo (2010) *Rév Hist Mod Contemp*

The Sea Level in Venice after 1571: Veronese departs from the linear interpolation



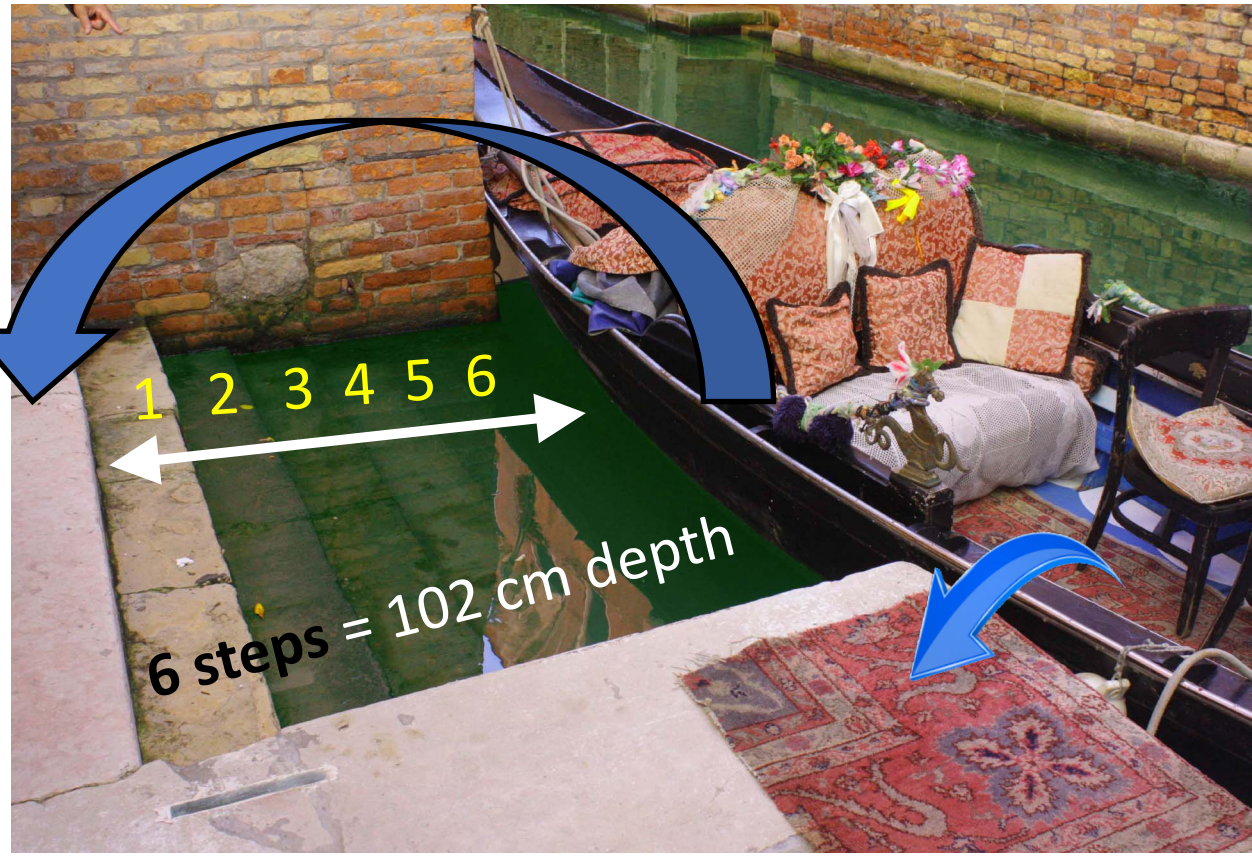


The past sea level, when the stair was built. The lowest step was at gunwale level, i.e. 1 Venice foot above CM. (The canal has been emptied for maintenance works)

Today, after the sea level rise, the stair cannot be used and the landing is too far from the boat

In the past, quay stairs were necessary. Today, they are not longer usable

A quay stair in a painting by Canaletto. Originally, the quay was at shoulder level of a man standing in the boat



Nowadays, the gondola remains 1 m far from the landing platform, and stairs are no longer usable

With sea level rise, it will be impossible to pass under bridges

Gondole "mutilate" per passare sotto i ponti. A Venezia c'è chi sega la poppa per togliere il ferro

Il Mattino 29/10/2021

In 1560, Alvise Cornaro wrote: "The sea level has always been rising, so it was necessary to raise quays and paving, demolish and rebuild bridges, which had become too low to allow the passage of boats". Nowadays, we are facing a similar situation.

Evidence that sea level continued to rise since previous centuries.

In this door, the sea level rose 120 cm above the original threshold level, that was placed at safe distance above the high-tide level.

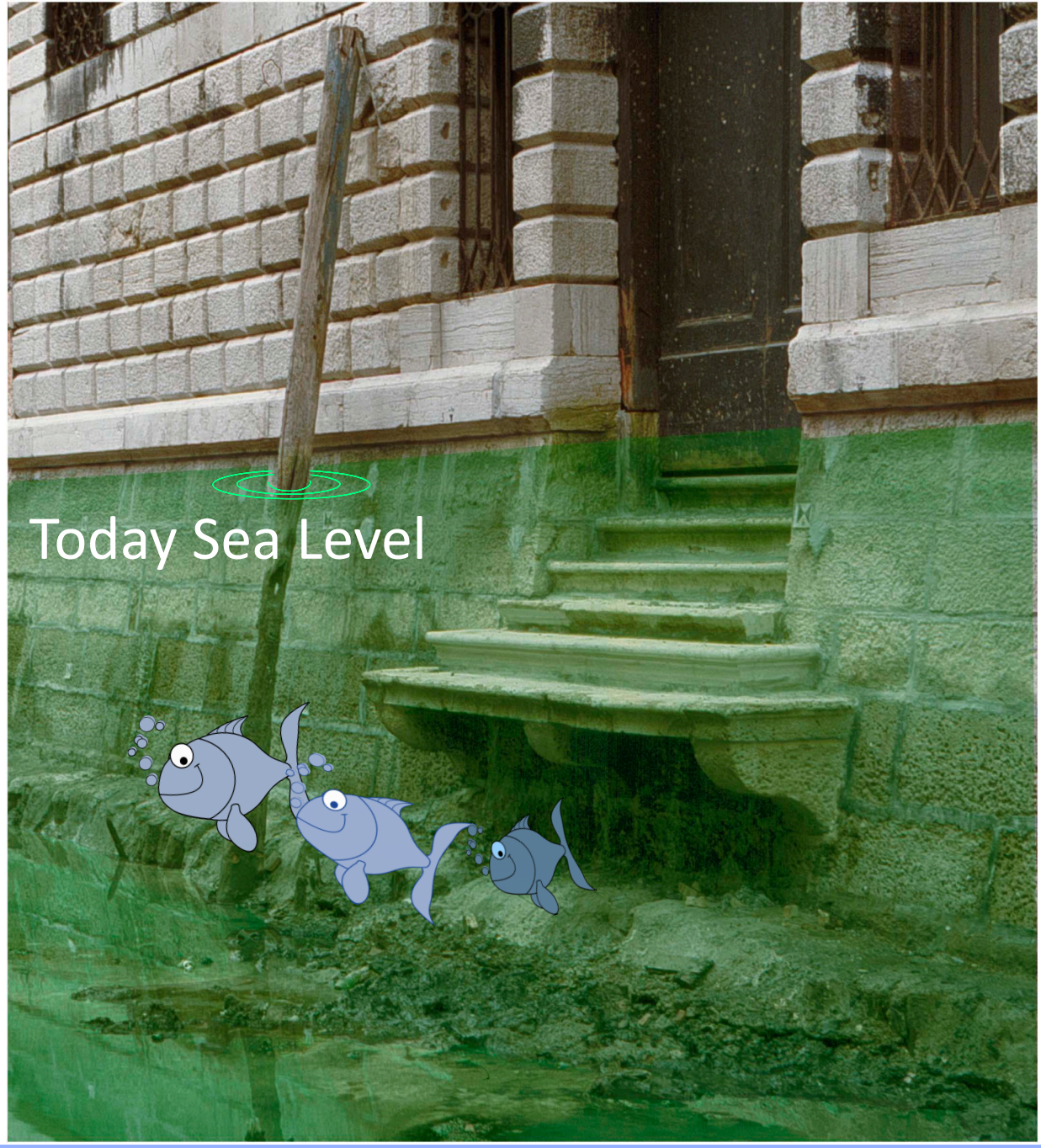
This involved raising the ground floor and resurfacing the drainage sewer.

Original threshold level

Photo: D. Resini
Insula Spa, Venice

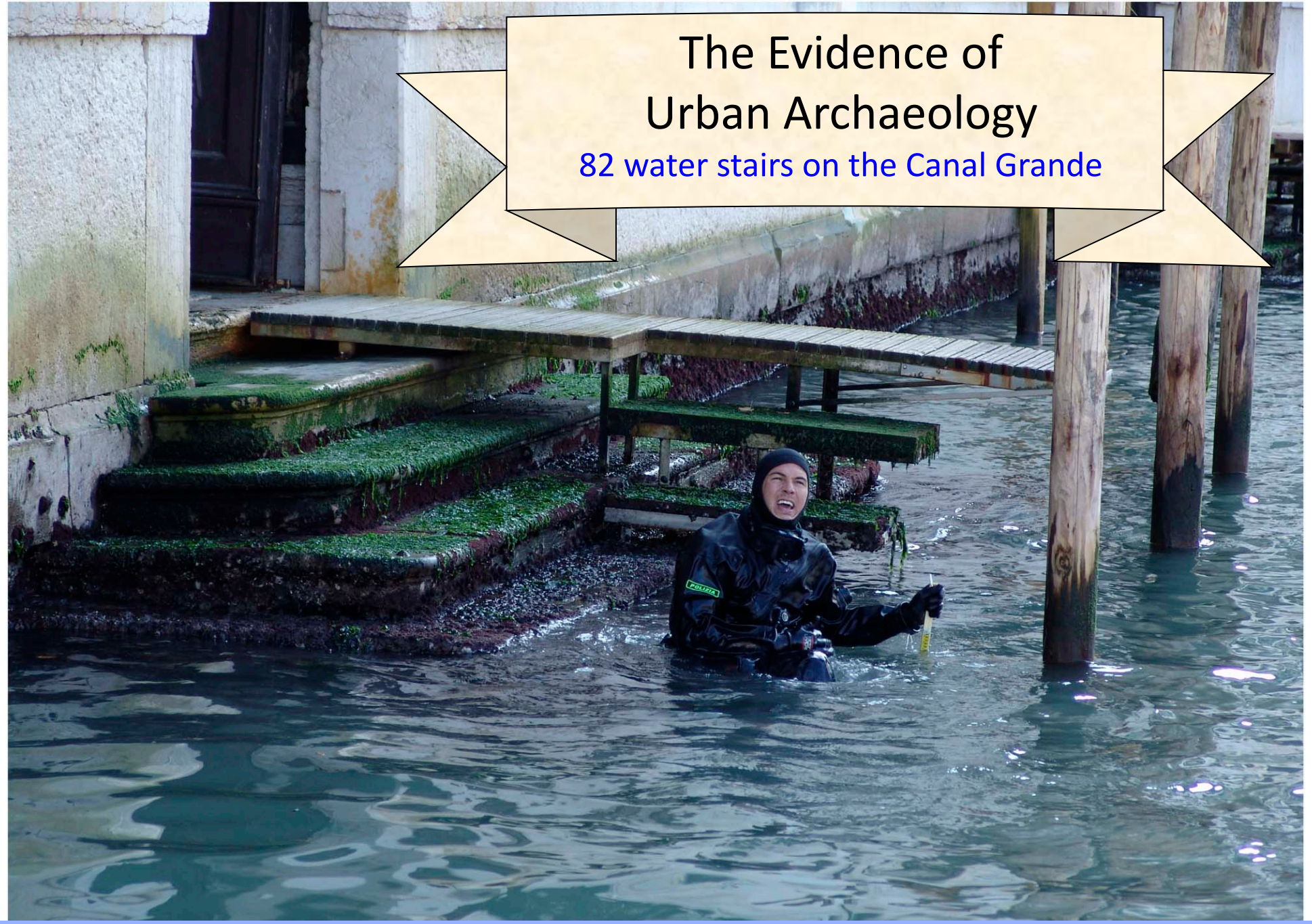

CM
1 m
Photo: D. Resini, Insula Spa, Venice


Original Sea Level (1530 ca)
(the canal was emptied for
maintenance works)


Today Sea Level

The Evidence of Urban Archaeology

82 water stairs on the Canal Grande



Study made with the Frogmen Team of the State Police, Venice

Dario Camuffo, CNR – Institute of Atmospheric Sciences and Climate, Padua, Italy

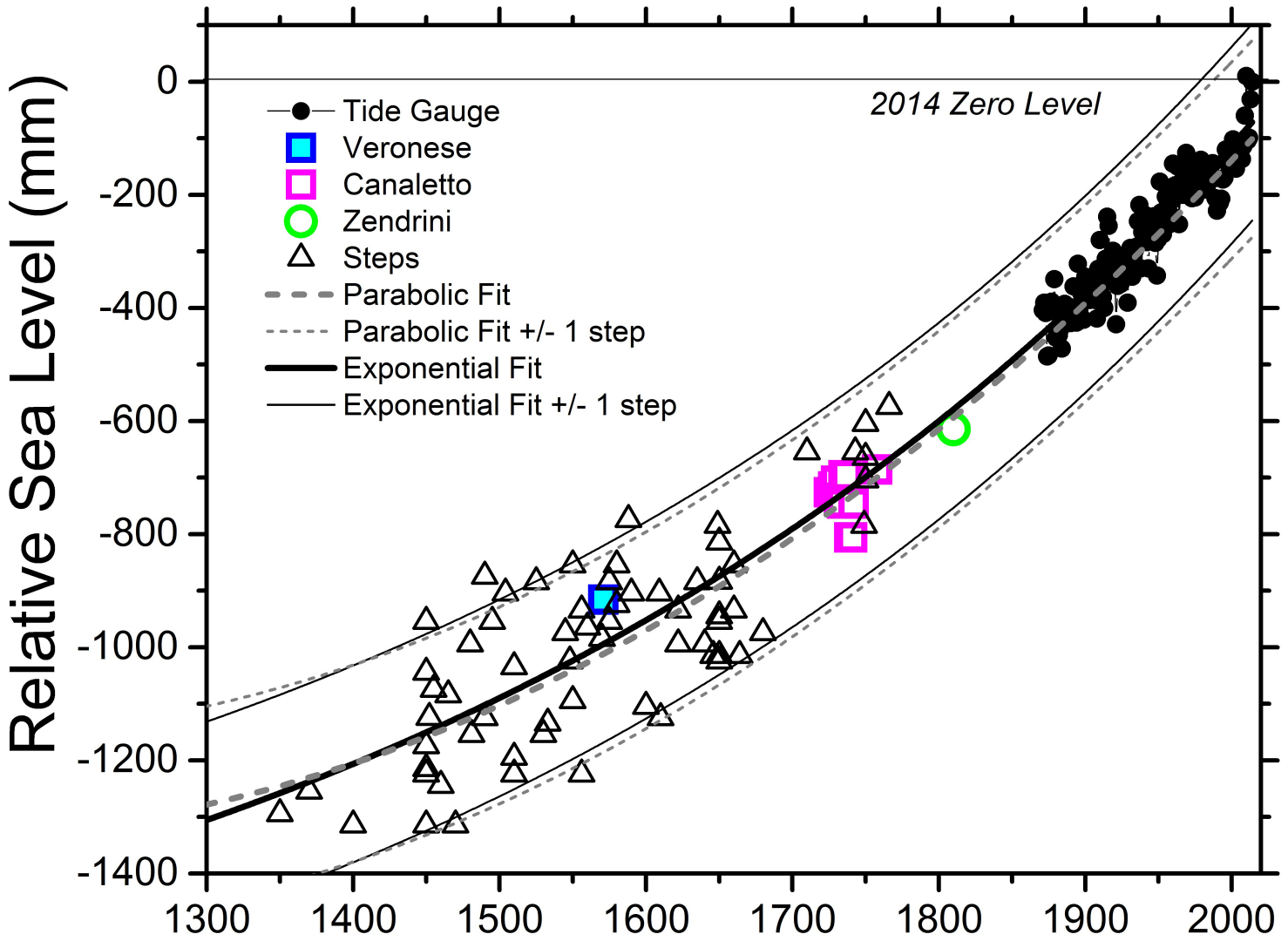
The lowest step as a proxy of the past sea level.

Field surveys have been made with the Frogman Team of the Italian State Police.

The lowest step of the most ancient 82 sea stairs was measured.

This has permitted to reconstruct the sea level rise since 1350.

Relative Sea Level Rise in Venice



Over these past centuries, **the sea level rise** is equally represented by a **parabola** or an **exponential trend** i.e.

$$RSL = a\,t^2 + b\,t + c$$

$$RSL = k_1\,(\exp\,k_2\,t)$$

Camuffo, Bertolin & Schenal (2017) *Climatic Change*

Sea Level forecast with the Trend Extrapolation Method (TEM)

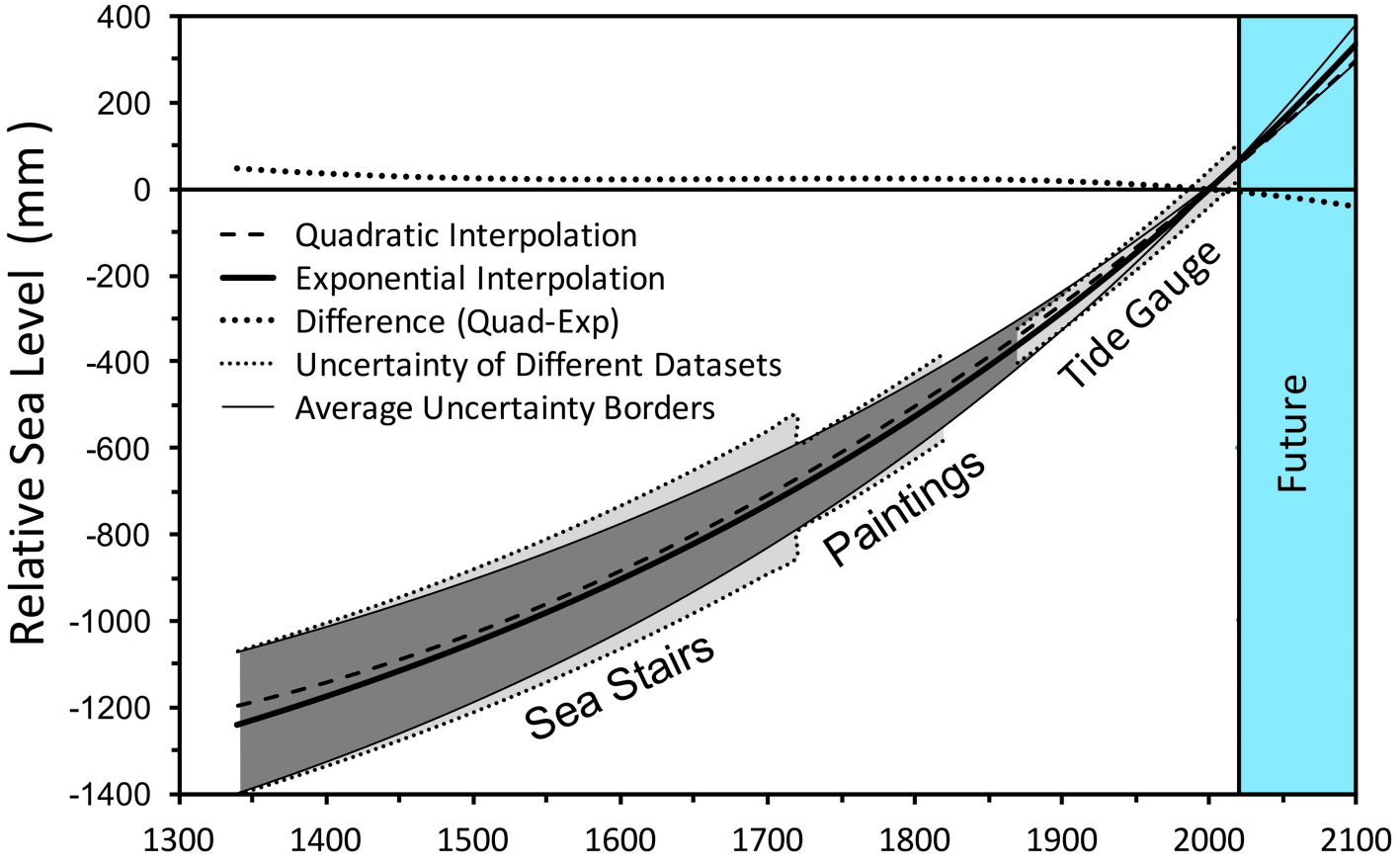
2100 projection: 33.8 ± 4 cm rise

TEM avoids physical simulation models, and assumes that, in the absence of external changes, a system will continue with the same trend.

TEM is a black box that gives prediction without need to know the processes that govern the relationships between the internal variables.

TEM may be preferable when formulae or forcing hypotheses are uncertain.

This is reasonable for short forecast periods.



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Comparison between the best-fit functions and their derivatives: two options with different physical meaning

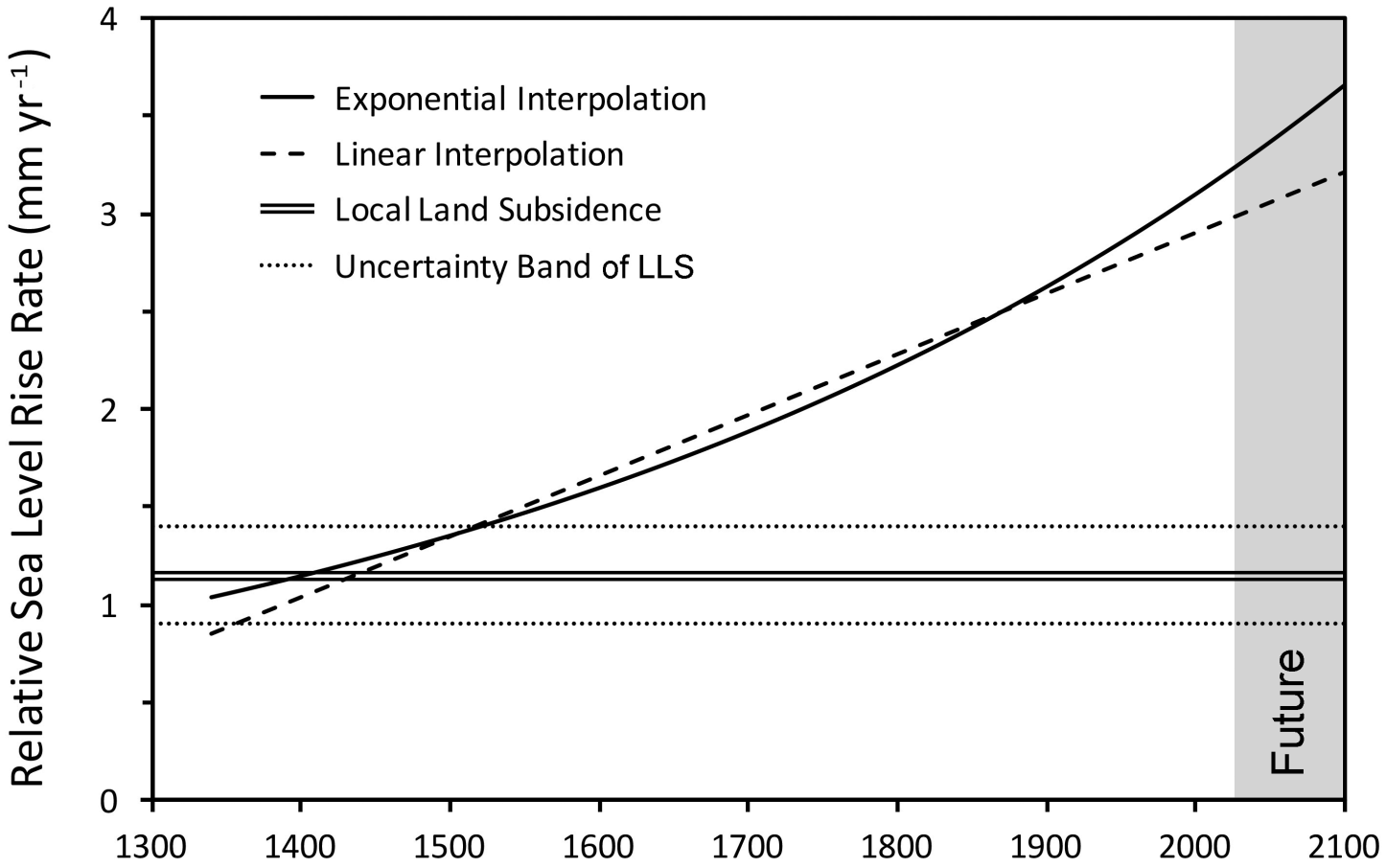
Best-fit	Exponential		Quadratic		Comment
Level SLR(t)	A exp(Bt)	exponential increase	$a\,t^2 + b\,t + c$	quadratic increase	Both functions give very similar values
Trend $\frac{dSLR(t)}{dt}$	AB exp(Bt)	exponential increase	$2a\,t + b$	linear increase	Similar increasing trend, but different curvature
Acceleration $\frac{d^2SLR(t)}{dt^2}$	AB^2 exp(Bt)	exponential increase	$2a$	constant value (=average)	Trend, curvature and values are different. Both have the same average.

Camuffo (2022) *Environmental Earth Sciences*

Relative Sea Level Rise and Trend

The derivative of the quadratic best-fit of SLR gives a linearly increasing trend. This may be a rough approximation, and requires a constant forcing mechanism (an acceleration) over 7 centuries.
This is hardly credible.

The derivative of the exponential is also an exponential. It shows a trend, and a forcing, increasing over time.
Physically, this is more realistic.



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Relative Sea Level Rise and Acceleration

The acceleration is the second time derivative of RSL i.e.

$$a_{acc} = \frac{\partial^2 RSL}{\partial^2 t}$$

The parabola gives a static answer

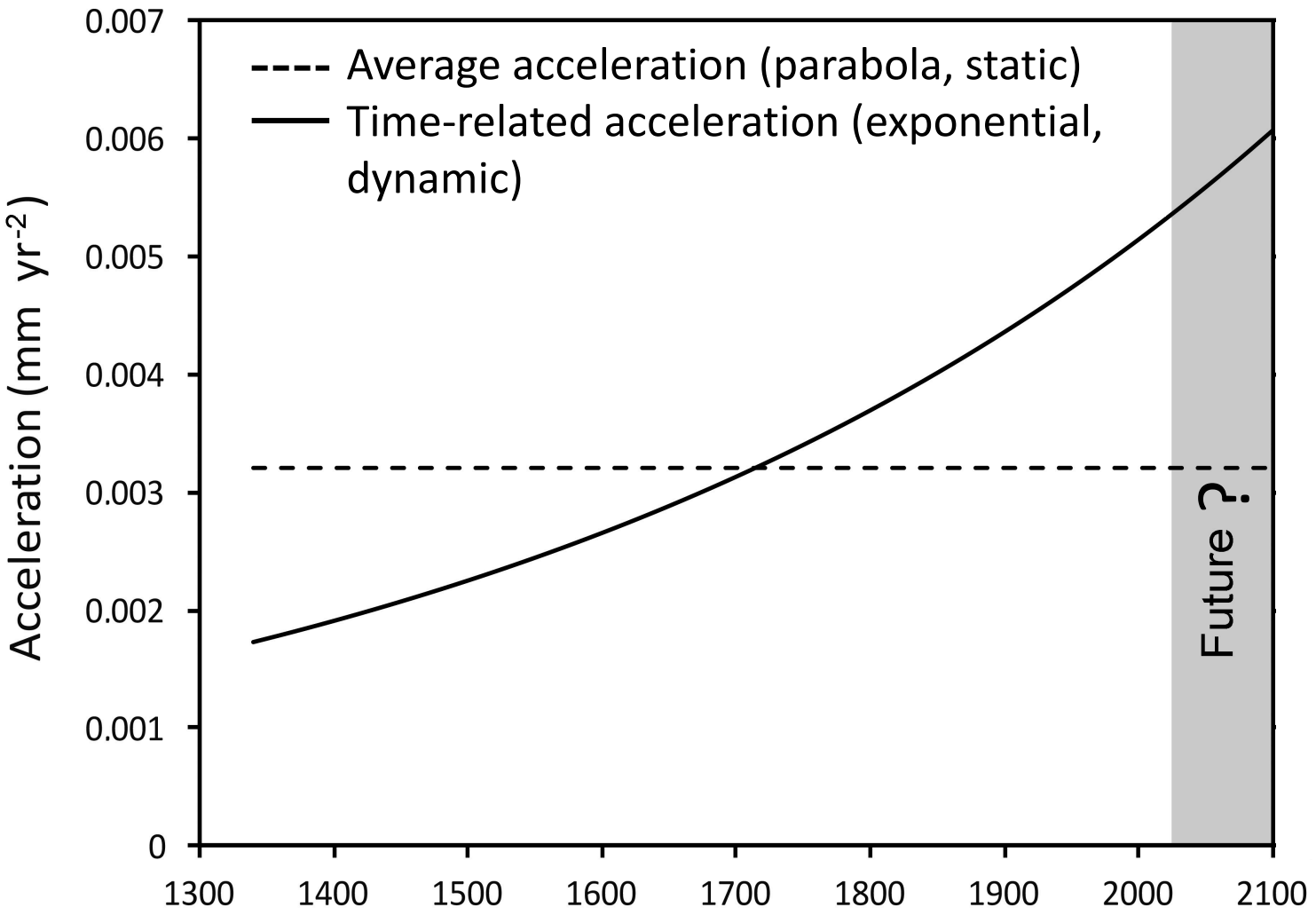
$$a_{acc} = 2\,a$$

which is constant and represents the average value over the whole period.

The exponential is a dynamic answer

$$a_{acc} = AB^2\,(\exp B\,t)$$

which is time-dependent and shows that a_{acc} too is exponentially growing.



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Physical mechanisms that may justify this Acceleration?

(1) $$F_{tot}(t) = \sum F_i(t) = \sum m_i(t)\, a_{acc,i}(t)$$

Increasing intensity of the forcing factors?

e.g. radiative forcing? How is it combined with ice melting and so on... ?

Well balanced components over 7 centuries?

m_i = inertia to respond

(2) $$a_{cc} = A\, exp(Bt)$$

Dominance of a long-term exponential relaxation? How is *B* composed?

e.g. continental glacier melting?

isostatic adjustments?

tectonic vertical movements?

Note: the product or the ratio between exponentials is still an exponential;
the sum of two exponentials is a gamma function; it might be roughly approximated with an exponential.

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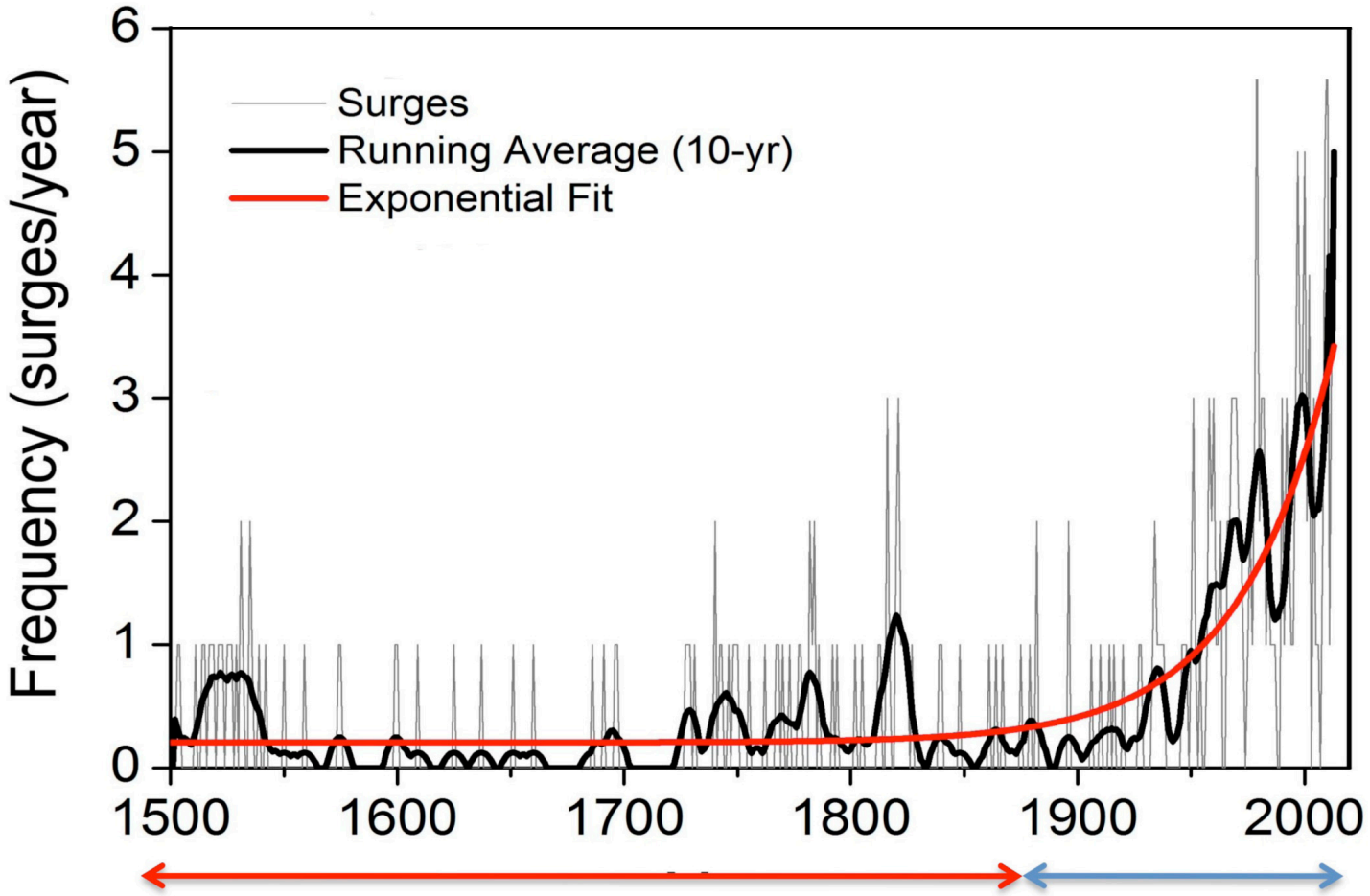
Part 2: Reconstructing flooding surges '*Acqua Alta*' from tide gauge record (1871-today), documents and proxies (1300-1870)



1500-1870: Written Documentary Proxy; 1871 – today: Tide Gauge Record

The Venice Lagoon in the 16th century

Cristofaro Sabbadino 1543

Benedetto Bordone 1534

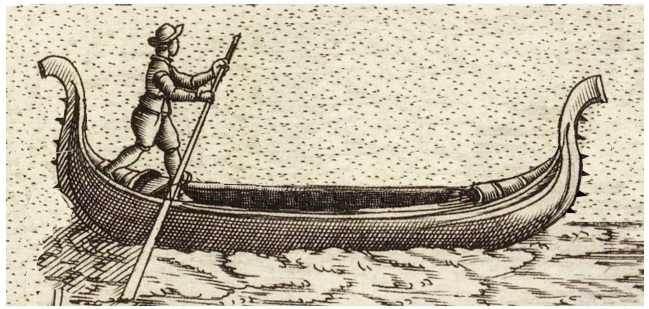
Dario Camuffo, CNR – Institute of Atmospheric Sciences and Climate, Padua, Italy

At the deepest floods, gondolas could ride in S. Marco Square

When the highest flooding depths were reached, gondolas could ride in S. Marco. Can we assess this flooding depth with reference to the MSL? The Gondola changed size and shape over time. What about its drought?

The early Roman *cymbula* (13th century Mosaics, St. Mark Basilica)

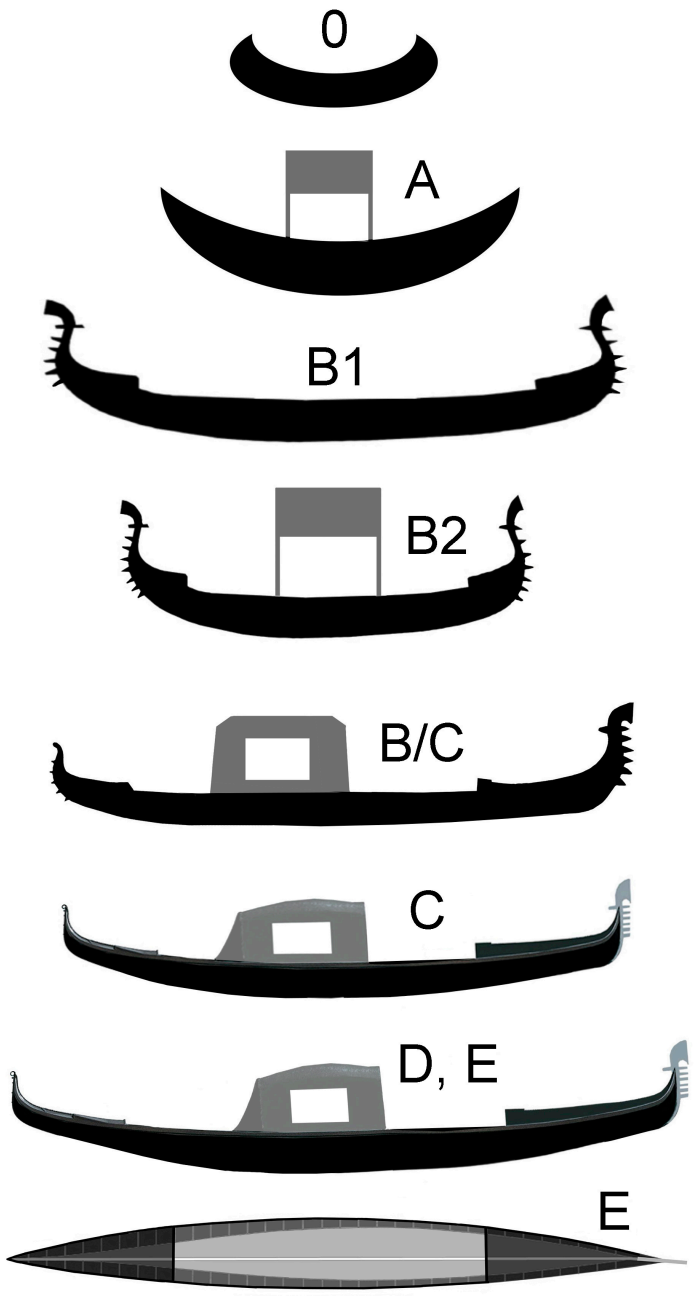
Arched Gondola, 2nd half of the 15th century (Braidembach 1486)



Military Gondola after 1509 (Franco1610) inspired by Norman-Viking vessels (Bayeux Tapestry, 11th Century)

Baroque gondola (Guardi 18th Century)

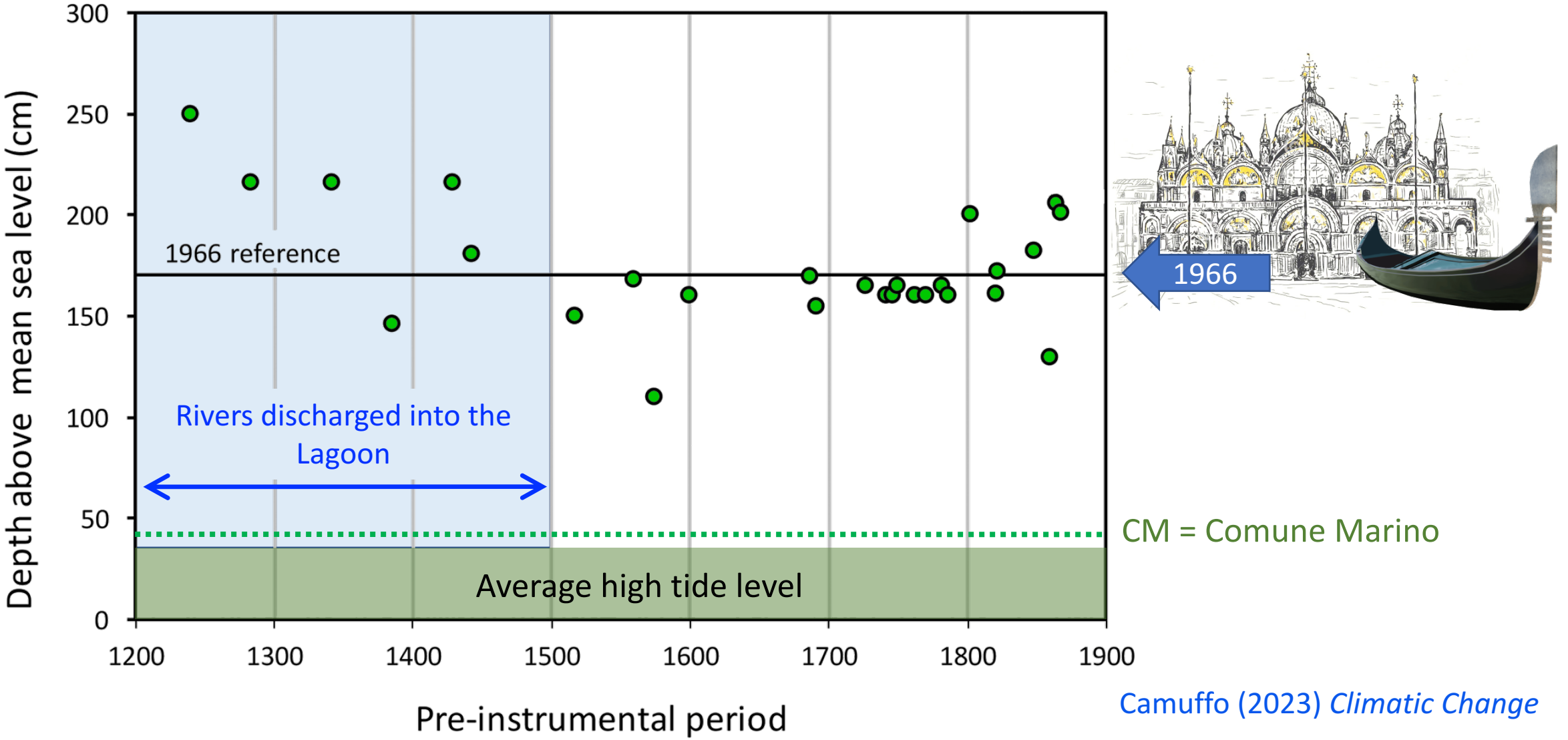
Camuffo (2023) *Méditerranée*



Type	From	Comments
O	1100	Roman *cymbula* for marshes. Small, without cabin.
A	1460	Crescent Moon (5-6 m). Stern and prow used to reach the quay. 1 or 2 rowers. U-shaped mobile cabin named *felze*
B1	1509	Symmetrical, with rostrums on prow and stern, like a Viking corsair vessel for commandos (10 m).
B2	1509	Shorter than B1 (i.e. 5.5 m), for civil use, *felze* cabin. 1 or 2 rowers
B/C	1690	Transition type (8-10 m). Mobile *caponera* cabin. 1 or more rowers
C	1700	Baroque elegant, similar to nowadays, but shorter (8 m). *Caponera* cabin. 2 or more rowers.
D	1800	Similar to the baroque type C, but longer (11 m).
E	1900	Like D, but with skew horizontal cross section to balance the path with 1 rower

Camuffo (2023) *Méditerranée*

Flooding depth (related to the contemporary MSL) of historical *Acqua Alta*, referred to the 1966 benchmark



CM = Comune Marino

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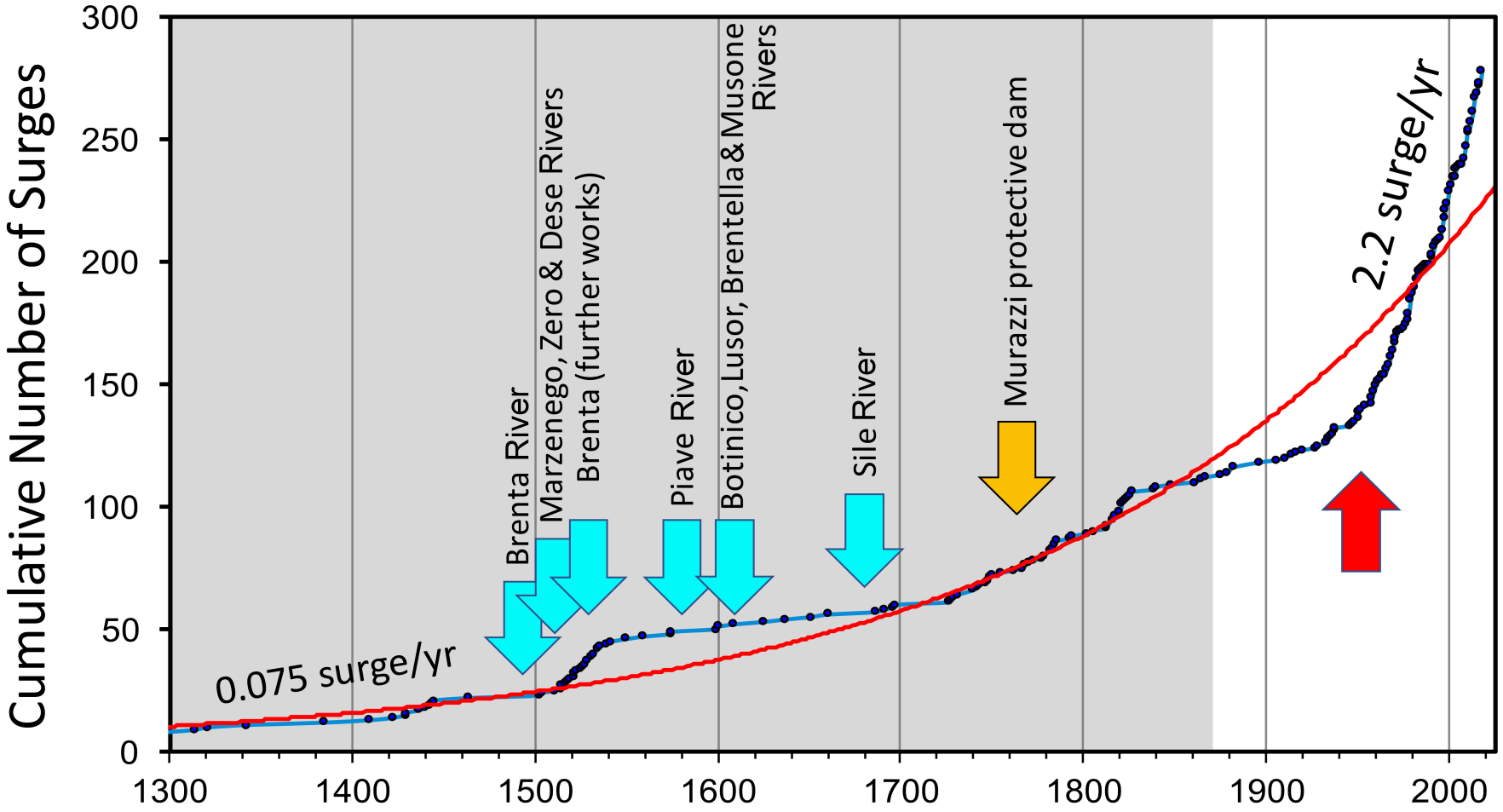
Occurrence of *Acqua Alta* and hydraulic works over the past 7 centuries



Hydraulic works changed the flooding trend, which departs from an exponential

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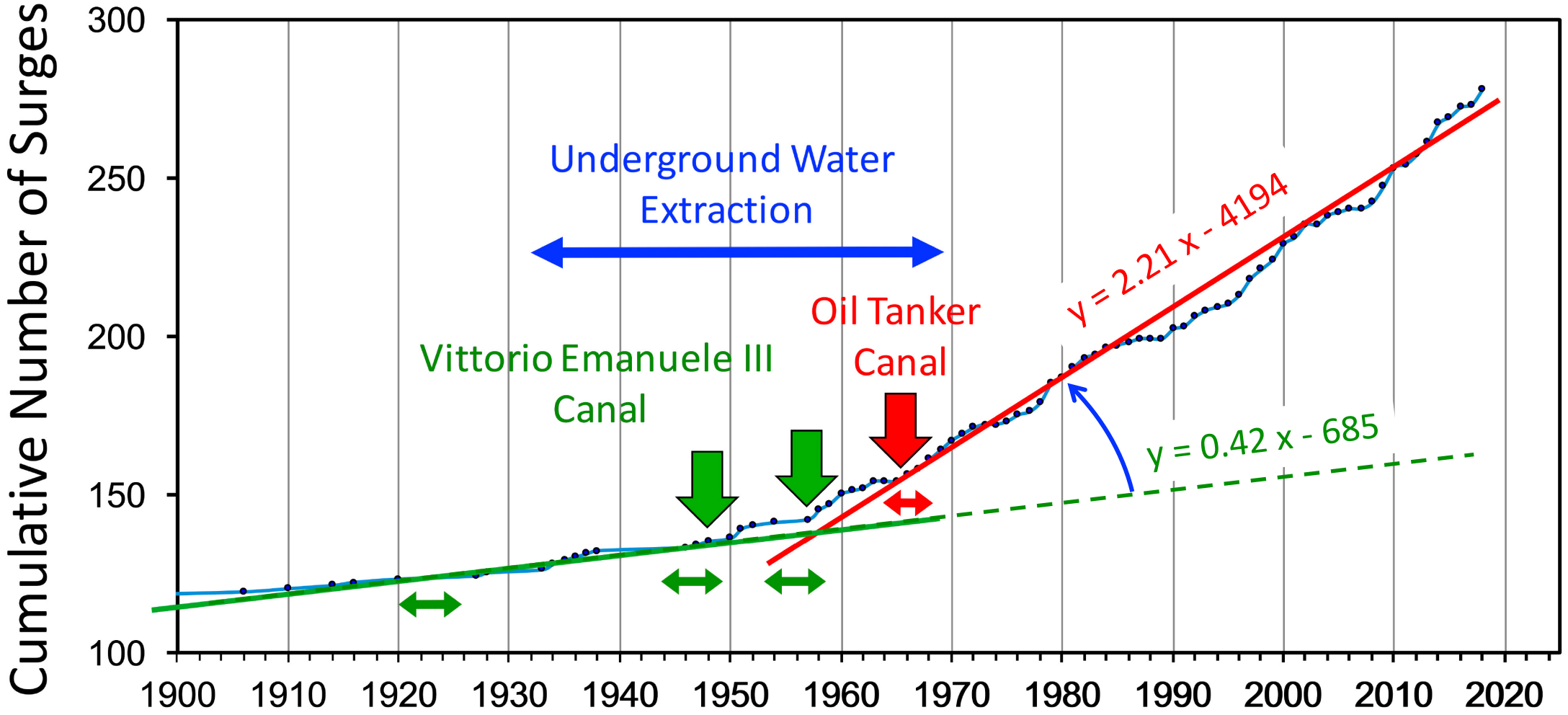
Occurrence of *Acqua Alta* in the 20th century. The hydraulic works done around the middle of the century generated a turning point



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Conclusions

The long-term response of the sea to the past forcing factors is an **exponential** SLR acceleration.

The situation **may worsen** in the future, depending on the IPCC emission scenario.

The exponential SLR implies that the flooding *Acqua Alta* will **increase in depth and frequency.**

The 1966 level of the flooding depth (referred to the MSL) is not unparalleled. In the past centuries, it **was normal**.

Deeper depths where reached in 1300-1500, when rivers outflowed into the lagoon, **adding their waters** to the water dragged by the storm surge.

Around the 1960s, the frequency of *Acqua Alta* had a **turning point** when the **water exchange** between the sea and the lagoon was increased.

After the MOSE: what long-term scenario for Venice?

- Venice will be fully submersed, and will attract **underwater tourism.**
- Venice will be fully submersed, but kept within a **glass bell**, like an overturned **aquarium**.
- Venice will be protected by **permanent dams**. How lagoon waters can be renewed?
- **Land will be rebounded and uplifted** with deep injections of water or sand. How much is it realistic?
- Venice will be **dismantled** piece by piece, **moved** and **rebuilt as a city** elsewhere.
- It is too expensive to rebuild the entire city. Only **a few palaces** will be saved, **moved away**, and rebuilt in different countries, bought by the most rich people in the world.
- Is there anyone thinking about **the next step**, i.e. the post-MOSE scenario?

Related papers

- Camuffo, D., Sturaro, G. 2003: Sixty-cm submersion of Venice discovered thanks to Canaletto's paintings. *Climatic Change*, 58, 333-343. DOI: 10.1023/A:1023902120717
- Camuffo, D., Sturaro, G. 2004: Use of proxy-documentary and instrumental data to assess the risk factors leading to sea flooding in Venice*, Global and Planetary Change*, 40, 93-103. DOI: 10.1016/S0921-8181(03)00100-0
- Camuffo, D., 2010: Le niveau de la mer à Venise d'après l'œuvre picturale de Véronèse, Canaletto et Bellotto. *Révue d'Histoire Moderne et Contemporaine*, 57(3), 92-110. DOI: 10.3917/rhmc.573.0092
- Camuffo, D., Bertolin, C., Schenal, P., 2017: A novel Proxy and the Sea Level Rise in Venice, Italy, from 1350 to 2014 *Climatic Change* 143(1), 73-86. DOI 10.1007/s10584-017-1991-3.
- Camuffo, D., 2021. Four centuries of documentary sources concerning the sea level rise in Venice. *Climatic Change* 167, 54 DOI: 10.1007/s10584-021-03196-9
- Camuffo, D., 2022: Historical documents as proxy data in Venice and its marine environment, in *Oxford Research Encyclopedia of Climate Science*. Oxford University Press, Oxford DOI: 10.1093/acrefore/9780190228620.013.875
- Camuffo, D., 2022. A discussion on sea level rise, rate ad acceleration. Venice as a case study. *Environmental Earth Sciences* 81:349 DOI: 10.21203/rs.3.rs-1073418/v1
- Camuffo, D. 2023. The Gondola: a boat to respond to the history and the morpho-dynamics of the Venice Lagoon. *Méditerranée*. DOI: 10.4000/mediterranee.14364
- Camuffo, D. 2023. The Treatise on Waters by Cornaro (1560) and a quantitative assessment of the historical sea surges 'Acqua Alta' in Venice. *Climatic Change*, 176:18 DOI: 10.1007/s10584-023-03492-6

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