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Natural Hazards and Earth System Sciences
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Discussions

Review article: Sea-level rise in Venice: historic and future trends

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Abstract. The City of Venice and the surrounding lagoonal ecosystem are highly vulnerable to variations in relative sea level. In the past ~150 years, this was characterized by a secular linear trend of about 2.5 mm/year resulting from the combined contributions of vertical land movement and sea-level rise. This literature review reassesses and synthesizes the progress achieved in understanding, estimating and predicting the individual contributions to local relative sea level, with focus on the most recent publications. The current best estimate of historical sea-level rise in Venice, based on tide-gauge data after removal of subsidence effects, is 1.23±0.13 mm/year (period from 1872 to 2019). Subsidence thus contributed to about half of the observed relative sea-level rise over the same period. A higher - yet more uncertain - rate of sea-level rise is observed during recent decades, estimated from tide-gauge data to be about 2.76 ±1.75 mm/year in the period 1993-2019 for the climatic component alone. An unresolved issue is the contrast between the observational capacity of tide gauges and satellite altimetry, with the latter tool not covering the Venice Lagoon. Water mass exchanges through the Gibraltar Strait currently constitute a source of substantial uncertainty for estimating future deviations of the Mediterranean mean sea-level trend from the global-mean value. Subsidence and regional atmospheric and oceanic circulation mechanisms can deviate Venetian relative sea-level trends from the global mean values for several decades. Regional processes will likely continue to determine significant interannual and interdecadal variability of Venetian sea level with magnitude comparable to that observed in the past, as well as non-negligible differential trends. Our estimate of the likely range of mean sea-level rise in Venice by 2100 due to climate changes is presently estimated between 11 and 110 centimetres. An improbable yet possible high-end scenario linked to strong ice-sheet melting yields about 170 centimetres of mean sea-level rise in Venice by 2100. Projections of natural and human induced vertical land motions are currently not available, but historical evidence demonstrates that they can produce a significant contribution to the relative sea-level rise in Venice, further increasing the hazard posed by climatically-induced sea-level changes.

1 Introduction

This paper critically reviews the current knowledge about mean Relative Sea Level (RSL) changes in the Venice Lagoon on time scales from interannual to centennial and the associated contribution from oceanic, land and atmospheric processes. The assessment includes a paleo perspective, considering the Quaternary period. It encompasses an overview of available observed estimates of historical RSL changes in Venice (Sect. 2) and quantification of the individual contributions by the major underlying processes, including vertical land motions (Sect. 3) and climatic changes (Sect. 4). Estimates are supported by a review of downscaling mechanisms of global and large-scale oceanic and atmospheric signals to the Venice Lagoon (Sect. 5), with special focus on processes in the Atlantic and Euro-Mediterranean regions. Estimates of projected long-term future RSL changes based on state-of-the-art models of vertical land motions and of sea-level rise under different scenarios of anthropogenic greenhouse gas emission are discussed, with emphasis on the associated major sources of uncertainty (Sect. 6). The review primarily focuses on papers published in the past decade and also aims at defining the overarching open research questions and possible approaches for progress (Sect. 7).

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Given the multidisciplinarity of this review, it is useful to specify the meaning of terms and concepts associated with sea-level changes that are recurrent in this paper and often used inconsistently by different scientific communities (see also Gregory et al., 2019, for a broader discussion). Unless otherwise specified in the text, the following definitions apply:

- Mean Seal Level (MSL): time-mean state whose precise definition should be specified when the term is used, and which is understood to refer to a period long enough to eliminate the effect of meteorological variations at least (Gregory et al., 2019). More precise definitions exist of MSL, e.g., the average value of levels observed each hour over a period of at least a year, and preferably over about 19 years, to average out cycles of 18.6 years in the tidal amplitudes and phases, and to average out effects on the sea levels due to weather (Pugh, 1987), that however are not strictly and consistently applied in the literature reviewed here;
- Relative Sea Level (RSL) change: change in local MSL relative to the local solid surface (Gregory et al., 2019);
- Absolute/geocentric sea-level change: change in local MSL with respect to a geocentric reference, namely a Terrestrial Reference Frame or, equivalently, a reference ellipsoid (Gregory et al., 2019);
- Subsidence: land surface sinking (UNESCO, 2020; see also: Gregory et al., 2019).

A list of acronyms recurrently used in the paper is provided in Table 1.

The Reader is referred to Lionello et al. (2020a) and Umgiesser et al. (2020) in this special issue for details about the geographical and historical setting of the Venice Lagoon, the linkage between RSL changes and the phenomenology of surges and extreme water levels affecting the lagoon, about their prediction and about broader implications for the ecosystems and the historical city.

2 Monitoring sea-level changes

The monitoring of sea-level changes in Venice relies on both in-situ data acquired by tide gauges (sect 2.1) and remote sensing observations provided by satellite radar altimetry (sect. 2.2). Tide gauges record sea-level heights with reference to a permanent benchmark on land. As a consequence, they provide measurements of RSL embedding the effects of vertical land motion (Sect. 3). Tide gauge data sets consist of local, long-term measurements acquired at high frequency and accuracy (Zerbini et al., 2017). Satellite radar altimetry measures geocentric sea-level changes (Fu and Cazenave, 2001; Stammer and Cazenave, 2017) that are therefore independent of variations of the local land level changes (Gregory et al., 2019), hence missing a potentially key component of RSL (Wöppelmann and Marcos, 2016). These measurements have a lower sampling rate (several days) and a lower accuracy than those provided by tide gauges, but they are representative of wider oceanic areas and have the potential to characterize the evolution of sea-level variability from the open ocean to the coastal zone.

2.1 Tide Gauges

Tide gauges have been providing sea-level data in Venice for about 150 years. Historically, the establishment of tide gauges was primarily dictated by navigational needs and tidal measurements, with an operational accuracy of a few centimeters. The first self-recording tide gauge in Venice was installed at Palazzo Loredan, Campo Santo Stefano, in Rio San Vidal at a distance of about 100 m from the Grand Canal (Fig. 1). Systematic measurements began on 27th November 1871. The observations were performed under the responsibility of the Civil Engineering Office (Ufficio del Genio Civile) until 27 July 1896, when the management was taken over by the Italian Military Geographic Institute (Istituto Geografico Militare), which was also in charge of land levelling. Two additional tide gauges became operational in 1888 and 1906. The first one, owned and managed by the Royal Italian Navy, was installed in the Venice Arsenal; the second one was installed in the Grand Canal, near Punta della Salute. The tide gauges at Santo Stefano and in the Arsenal were decommissioned in 1911 and 1917, respectively. In 1923, the gauge on the Grand Canal was moved to the Giudecca Canal side of Punta della Salute. This gauge is still active under the management of the "Istituto Superiore per la Protezione e la Ricerca Ambientale" (ISPRA, Venice branch, www.venezia.isprambiente.it). Since 2002, a gauge on the Grand Canal side is again operational on the site of the previous installation, thanks to the Venice municipality ("Centro Previsione e Segnalazione Maree", www.comune.venezia.it/content/centro-previsione-e-segnalazione.maree).

Further details on the tide gauges installed in the Venice Lagoon up to the early 20th century are reported by Magrini et al. (1908). Dorigo (1961) reviews the sea-level observations in Venice and summarizes the main development stages of the observational network in the Venice Lagoon, including lists of active and decommissioned tide-gauge stations. Battistin and Canestrelli (2006) provide the most recent review of tide-gauge data for Venice and collect quality-checked published and unpublished records of high and low waters since 1872.

Linking the data from the various tide gauges to provide one continuous dataset of long-term sea-level change requires an accurate knowledge of the corresponding reference levels (or datums) on land. Before the 1910s, the most common vertical reference level in Venice was the so-called 'comune alta marea' or 'comune marino' (CM). The CM represents the upper edge of the green belt formed by algae on quays and walls and corresponds to mean high water. It was often indicated by an engraved horizontal segment and/or a 'C' (Rusconi, 1983; Camuffo and Sturaro, 2004). According to Dorigo (1961), Mati established the tide gauge datum at Santo Stefano at 1.50 m below the CM of 1825. In 1910, the reference for sea-level data was changed to the mean tide level (MTL) of 1884-1909 (central year 1897), computed from the high and low waters measured at Santo Stefano. The new reference, that corresponds to the "Zero Mareografico Punta Salute" (ZMPS), was 1.2754 m above the tide gauge datum and 0.2246 m below the CM of the year 1825. Since 1910, the ZMPS has been the standard reference for RSL observations in Venice. The benchmarks of the two tide gauges at Punta della Salute were also connected to the levelling network in 1910 and 1923, respectively. The heights of the various benchmarks and vertical reference levels are shown in the inset of Figure 2. The record of high and low waters since 1872 allowed a composite 148-year MTL time series to be developed from 1872 to 2019, with very few gaps (Fig. 2). Note that, whereas MTL and MSL are different because MTL does not consider shallow water tidal effects, this difference is negligible in Venice. From observations covering the period 1940-2012, Zerbini et al. (2017) obtained MTL-MSL = -0.1±0.1 cm. The Permanent Service for Mean Sea Level provides a value of 0.0 cm, estimated according to Woodworth (2017) (www.psmsl.org/data/obtaining/stations/168.php).

Estimates of secular trends of Venetian RSL and MSL based on tide gauge data are summarized in Sect. 4.1.

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2.2 Altimetric data

Reliable altimetric data are available since the early 1990s when the launch of the TOPEX/Poseidon mission marked the beginning of the so-called 'satellite altimetry era'. Since then, satellite radar altimeters have been providing an operational global monitoring of the geocentric sea level (Cazenave et al., 2019). The spatial resolution of these data is controlled by the orbital parameters selected for each mission, as the radar altimeters acquire narrow threads of measurements along those portions of the ocean surface that are directly overflown by the satellite (along-track data). Depending on the orbital period, these tracks can be separated by hundreds of km, limiting the actual spatial coverage provided. For example, the Jason-3 mission that continues the climatic sea-level record started in 1993 with TOPEX/Poseidon has only four tracks crossing the Adriatic Sea and does not cover the Venice area. In order to improve the monitoring, it is possible to take advantage of the data collected by various radar altimeters flying at the same time. However, this requires a characterization of the inter-mission biases and the development of suitable interpolation schemes of the independent ground tracks. Multimission datasets are typically distributed over regular grids.

An additional potential limiting factor for the Venice area is the degradation of the technique performance towards the coast resulting from the contaminating presence of land in the satellite footprint and from the enhanced inhomogeneity of the local ocean surface. Limitations and possible perspectives of coastal altimetry in the Adriatic Sea have been discussed in several studies since the late 1990s (Cipollini et al., 2008; Fenoglio-Marc et al., 2012; Vignudelli, 1997; Vignudelli et al., 2011, 2019a). This has motivated further investigations (Cipollini et al., 2013; Passaro et al., 2014) based on the latest coastal altimetry datasets (e.g., CTOH, see Birol et al., 2017) and/or reprocessing initiatives (e.g., ALES, see Passaro et al., 2014). In the Northern Adriatic, these studies analyzed data around Venice and Trieste, including their validation against tide-gauge measurements. The results show that a reasonable increase in quantity and quality of data can be achieved compared to standard products up to a few kilometers from the coastline. The comparative assessments with tide gauges confirm that correlation of coastal altimetry products is always higher than standard products and that the difference in sea-level estimates provided by the two techniques is typically below 10 cm in proximity of the point of closest approach to the tide gauge. Among the most relevant reprocessing efforts of the last years, we should mention the Sea Level Climate Change Initiative (SLCCI) of the European Space Agency, that encompassed nine satellite radar-altimetry missions over the period 1993-2015 (Legeais et al., 2018). The SLCCI product, distributed over a homogenous grid of 0.25°, contains data close to the coast, e.g., 10 km near Trieste, and was used for the assessment of coastal sea-level trends (Rocco, 2015; Vignudelli et al., 2019b).

The sufficient maturity of the algorithms and processing in coastal altimetry offered the opportunity to extend the SLCCI product to the coastal zone. During the bridging phase in 2018 a new product with an along-track spacing of about 350 m for estimating sea-level trends has been developed in selected regions, including the Adriatic Sea. The experimental dataset only covered the period from July 2002 to June 2016 and the Jason-1 and Jason-2 missions. It combines the post-processing strategy of X-TRACK (Birol et al., 2017) and the advantage of the ALES re-tracker (Passaro et al., 2014). The product was tested along

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track 196 in the Gulf of Trieste. The improvement is particularly good in the entire Gulf of Trieste (ESA CCI, 2019), confirming what was found by Passaro et al. (2014).

Altimetry-based assessments of multidecadal trends of Venetian MSL are summarized in Sect. 4.2.

3 Vertical land movement

The characterization of the RSL cannot be separated from an understanding of the phenomena that control the vertical land movement. Therefore, these are presented in the following together with their relevant time scales and estimated trends. This section includes a paleo perspective on vertical land movements and considers processes whose characteristic time scales extend in some cases largely beyond the observational RSL period. We consider information on such time scales essential in the context of this review to understand ongoing processes and frame them within the correct time scale. The aim is therefore to provide the reader with an overview of the main characteristics of the local vertical land movement, of the methods that allow quantifying it over different time intervals and of the resulting uncertainties. The joint consideration of all these elements determine the constraints on our current ability to make predictions on the future evolution of the local vertical land movement.

The vertical velocity of a given area results from the sum of different velocity components due to tectonics, sediment loading, sediment compaction, Glacial Isostatic Adjustment (GIA), and anthropic activities (Carminati and Di Donato, 1999; Pirazzoli, 1996).

In the Venice area, all the components listed above induce non-negligible displacements, even though their magnitude and relative importance have changed over time. The net result is a time-dependent land lowering (subsidence) that enhances RSL. Natural and anthropogenic components are assumed to act on different time scales: millions to thousands of years and hundreds to tens of years, respectively. This assumption allows a separation of the factors controlling sea-level changes, if the estimates of vertical land movements over different time spans are available (Carminati and Di Donato, 1999).

3.1 Natural land movements

The Venice area is naturally subsiding. This process is characterized by a long-term component controlled by tectonics/geodynamics and sedimentation, active on time spans of about 10^6-10^4 yr, and a short-term component controlled by glaciation cycles and due to GIA processes acting on periods of 10^3-10^4 yr (Antonioli et al., 2017; Cuffaro et al., 2010; Stocchi et al., 2005).

Depending on the time interval considered, different datasets are available for investigating the rate of vertical land movement. Subsidence rates up to 2 Myr ago can be inferred from the thickness of the different layers of Quaternary sediments. Over this time frame, sedimentation rates are equivalent to subsidence rates, since the entire sedimentary sequence was deposited in shallow marine to continental environments (Massari et al., 2004). Investigation further in the past is made through seismic lines, which indicate buried interfaces between materials of different acoustic impedances, and drilled cores. Deposition rates can be computed using sedimentological indicators (Antonioli et al., 2009 and references therein; Carminati and Di Donato,

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1999; Favero et al., 1973), nannofossil biostratigraphy, paleomagnetic polarity and magnetic susceptivity (Kent et al., 2002). Additional techniques are available for more recent epochs. Radiocarbon dating allows investigating organic sediments, mainly peats, up to ~50,000 years ago (Bortolami et al., 1985), while the depth of archaeological remains and historical data provide information for the last few thousand years (Flemming, 1992). Finally, information on the natural component of the contemporary land subsidence is provided by tide-gauge and leveling measurements made before the 1930s, when human activities impacting land subsidence started to develop (Gatto and Carbognin, 1981). The following sections illustrate the evolution of the natural component of subsidence using the Marine Isotope Stage (MIS) 5.5 event as a reference to separate geologically older and newer RSL changes. Due to its relevance within geophysical studies on sea-level variations, a dedicated section on GIA is also provided.

3.1.1 Pleistocene up to MIS 5.5

The natural subsidence of Venice on timescales from tens of millennia to millions of years is controlled by sedimentary and tectonic/geodynamic processes. Venice is located at the northeastern border of the Po plain (Figs. 1 and 4), which is the foreland basin of two fold-and-thrust belts: the N-NE vergent Northern Apennines and the S vergent Southern Alps (Carminati et al., 2003). Figure 4 shows the geometry of the foreland regional monocline related to the subduction of the Adriatic plate (that includes the Po plain) below the Northern Apennines from the southern Po plain to the Friuli Region, as reconstructed from seismic reflection profiles. The dip of the regional monocline gradually decreases from about 22° to close to 0°. This geometry is consistent with the southward increasing thickness of Quaternary sediments, found in borehole stratigraphies (Carminati and Di Donato, 1999). These data imply that the long-term component of subsidence in the Po Plain and in Venice is almost entirely controlled by the retreat and flexure of the Adriatic plate subducting underneath the Apennines (Carminati et al., 2003; Cuffaro et al., 2010).

Kent et al. (2002) derive a more complex evolution for the Venice area from integrated magneto-bio-cyclo-stratigraphy and palynofloral analyses on the VENEZIA-1 borehole, drilled in 1971 by the Consiglio Nazionale delle Ricerche (CNR, 1971) down to a total depth of 950 m. They concluded that the region collapsed at about 1.8 Myr ago and was characterized by slow marine sediment accumulation until around 0.8 Myr ago, shoaling rapidly in subsequent times. The initial transition to continental sediments occurred during a glacioeustatic low-stand dated at 0.43 Myr or 0.25 Myr. From the VENEZIA-1 record, Kent et al. (2002) calculated a total long-term subsidence rate of less than 0.5 mm/year, about half of that proposed earlier on less refined data, and a mean subsidence rate of 0.36 mm/year for the last 600 kyr. The latter value is considerably lower when compared with rates obtained for the Holocene and the upper MIS 5.5. The most reasonable interpretation is that the mid-Pleistocene rates are unavoidably averaged over many cycles of quiescence and rapid motion, thus they cannot be readily compared to shorter periods, which could experience phases of rapid change induced by both natural and anthropogenic factors. Concerning natural variations acting on shorter time scales (10^3-10^4 yr), several transgressive/regressive Pleistocene cycles are recorded in well-core stratigraphies consisting of alternating shallow marine and continental deposits. In the Late Quaternary, the evolution of the Venetian–Friulian plain was strongly influenced by glacial cycles and a general regressive trend is apparent

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(Massari et al., 2004). The coastal to shallow-marine deposits assigned to MIS 5.5 can be tracked in borehole logs up to 30 km west of the present shoreline. South of the Po Delta, the base of the Tyrrhenian coastal deposits lies at about 125 m b.s.l., but its depth rapidly increases toward the south along the Romagna coastal plain (Amorosi et al., 2004; Bondesan et al., 2006). This pattern may reflect the northeasterly retreat of the Adriatic slab (Cuffaro et al., 2010; Ferranti et al., 2006).

The MIS 5.5 markers allow calculating reliable rates because compaction is negligible, the basal MIS 5.5 unconformity is widely distributed and the overlying lagoonal paralic sediments in cores are fairly easy to recognize. Several sites related to sea-level position during MIS 5.5 are considered in Antonioli et al. (2009) and Lambeck et al. (2011). These have a fairly good W–E distribution along the distal sector of the Venetian plain. The stratigraphic data were obtained from boreholes mainly drilled for the Geological Map of Italy (CARG-Veneto Region) and for the mobile barriers-based protective system (so called MOSE, see Lionello et al., 2020a) project by the Venice Water Authority. An error bar of ±2 m was assigned because the sediments are lagoonal. The northwestern Adriatic coast (Friulian and Venetian plain) shows homogeneous subsidence, with rates ranging between 0.58 and 0.69 mm/yr. The MIS 5.5 data from the VENEZIA-1 core provides a rate of 0.69 mm/year (Ferranti et al., 2006).

3.1.2 Late Pleistocene and Holocene

After the Last Glacial Maximum several lagoons developed along the Adriatic Sea, formed by the rivers flowing into the sea. Only two of them, the Grado and Venice lagoons, still exist today, while the rest have been infilled by sedimentation (Tambroni and Seminara, 2006). Recent stratigraphic information about Holocene sea levels (2-6 kyr Cal BP) were obtained from lagoonal deposits found in boreholes between the Tagliamento River and the city of Venice. Other data were derived from archaeological markers reported in the abundant literature available for the Venice Lagoon and its mainland (Antonioli et al., 2009; Fontana et al., 2017; Lambeck et al., 2011). The shell base of the lagoon indicates a subsidence rate over the last 7.3 kyr of 1.6±0.3 mm/year (Antonioli et al., 2009, their Tab. 1 average of H/G values for sites 26 and 28). The higher Holocene subsidence with respect to the MIS 5.5 is possibly due to sediment compaction, which does not contribute to the long-term rate (Gatto and Carbognin, 1981; Tosi et al., 2009).

Subsidence rates up to 1.2-1.3 mm/year were calculated by radiocarbon dating on late Pleistocene and Holocene deposits of the Venice Lagoon (e.g., Bortolami et al., 1985; Gatto and Carbognin, 1981). This estimate is interpreted as the average of a time-varying trend related to periods of excess sedimentation alternating with periods without deposition or even with erosion (Bortolami et al., 1985). Indeed, over relatively short periods, different rates can be observed. For instance, the largest rate, ~5 mm/year, occurred during the Last Glacial Maximum which induced the maximum effect of isostatic lowering.

Finally, it is generally assumed that natural subsidence of Venice is continuous in time. However, abrupt catastrophic pulses of subsidence cannot be ruled out as suggested by the sudden disappearance of the island of Malamocco at the beginning of the XII century. Carminati et al. (2007) investigated the potential effects of earthquakes on the subsidence of Venice by means of numerical models. The authors concluded that, while the coseismic effects of a single event are unlikely to be detectable, *a priori* they cannot be considered as negligible given the number of seismogenic sources within a 100 km distance from the

town. These authors, however, suggest that earthquake-induced liquefaction may cause or have caused local acceleration of subsidence in Venice. For example, the destruction and sinking of ancient Malamocco is roughly coincident with a strong earthquake cycle that was associated with phenomena possibly explained by liquefaction of sandy layers.
A summary of the rates of natural subsidence discussed in this and in the previous sections is presented in Table 2. The values reported in the literature are often presented without indicating the corresponding uncertainty level. In some cases, it is even explicitly stated that the data available to the study did not allow for a quantification of uncertainty (e.g., Carminati and Di Donato, 1999). Uncertainty estimation is further complicated by the fact that subsidence does not only vary with time, but also in space, depending on the local conditions of the subsoil (Brambati et al., 2003). For what concerns uncertainties of geomorphological and historical markers, Antonioli et al. (2009, 2017) proposed a strategy based on archaeological metadata and on standard bathymetric corrections for the Holocene and late Pleistocene (Ferranti et al., 2006; Lambeck et al., 2004). The resulting median uncertainty for the Venice area is 0.2 mm/year (markers 24-30 in Antonioli et al., 2009, their Table 1).

3.1.3 Glacial Isostatic Adjustment

GIA describes the response of the Earth System to the growth and decay of continental ice sheets as a consequence of past, present or future climate variations (for recent reviews, see: Spada, 2017; Whitehouse, 2018). GIA stems from interactions between the cryosphere, the solid Earth and the oceans, involving sluggish deformations of the crust driven by surface mass redistribution, mutual gravitational attraction and rotational variations (Melini and Spada, 2019; Spada and Melini, 2019). The GIA-induced RSL variations are characterized by a strong regional imprint reflecting such interactions. They can be modeled by means of the Sea Level Equation first introduced by Farrell and Clark (1976), which is an implicit equation that accounts for variations of the Earth's topography in response to sea-level change, consistently with changes in the gravity field (Peltier, 2004). Among the processes contributing to present-day RSL change (e.g., Milne et al., 2009), GIA is the only one that is sensitive to the solid Earth rheology. Because changes in the Earth system observed by geodetic methods would be unfeasible without taking GIA properly into account (e.g., King et al., 2010), GIA modeling plays an important role in the study of the impacts of contemporary and future climate change.
Due to the widespread evidence of past RSL variations since the late Holocene across the Mediterranean Sea, much work has been done to reconcile field observations of past RSL variations with GIA modeling predictions (Antonioli et al., 2009, 2017 and references therein). In two recent contributions, attention has been paid to the history of sea level in the Northern Adriatic, also providing GIA modeling predictions for the city of Venice. The first one (Lambeck et al., 2011) is based on the ice-sheets history "K33_j1b_WS9_6"; it assumes a 65-km thick elastic lithosphere and one order of magnitude viscosity increase across the 670 km depth seismic discontinuity. The second one, proposed by Roy and Peltier (2018) and named "ICE-7G_NA(VM7)", is characterized by a 90-km thick lithosphere and by a comparatively milder viscosity increase (by a factor of ~3). The two models predict distinctly different histories for the GIA-induced RSL variations during the Holocene: the first shows ~2.2 m of RSL rise in the last 5,000 years, whereas the second indicates essentially unvaried RSL during the same period. Note that in previous work (Lambeck et al., 2004), the GIA predictions for the Northern Adriatic had a larger uncertainty, with a range

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of RSL rise between ~5 and ~2 m in the last 5,000 years. This shows that GIA models are constantly being updated due to improvements in the constraining RSL datasets and of modeling techniques.

Based on the work quoted above, the rate of long-term RSL change in Venice due to the melting of the late-Pleistocene ice sheets does not appear to be tightly constrained (Tosi et al., 2013). Further uncertainties arise from the effects of the melting of the Würm Alpine ice sheet, whose chronology remains uncertain regarding several aspects (Spada et al., 2009). Nonetheless, the long-term rate of Venetian RSL change due to GIA can be assessed in the range between -0.2 and +0.5 mm/year based on the published works cited above. Estimates by Carminati and Di Donato, (1999) and Stocchi and Spada, (2009) broadly fall within this range, although these works are more pertinent to the Po Plain scale. Note that since the GIA acts on timescales of millennia, these natural contributions to total RSL change will remain constant over the 21st century.

3.2 Anthropogenic subsidence

Anthropogenic land subsidence mainly occurs due to extraction of subsurface fluids causing compaction of unconsolidated sediments. This is a process that is widespread in susceptible areas (e.g., Gambolati et al., 2006; Galloway and Riley, 1999; Erkens et al., 2015; Galloway et al., 2016). Measurements of piezometric level and of vertical land movements are fundamental to constrain quantitatively these processes. Numerical modeling is often used to link the flow of subsurface fluids to the corresponding geomechanical response of the porous medium, although caution is needed. In fact, the paucity of geological data, the imperfect knowledge of forcing processes and the geomechanical and hydraulic properties generally require significant modeling assumptions and approximations. These techniques have been used to analyze and control the effects of human activities on subsidence in the Venice area.

Prior to 1930, subsidence rates in the Venice region were similar to Holocene rates, suggesting limited anthropogenic contribution. This is confirmed by both leveling measurements (Dorigo, 1961; ISPRA, 2012; Wöppelmann et al., 2006) and differences in RSL trends between Venice and Trieste. The post-1930 period is now considered in more detail.

3.2.1 The 1930-1970 period

In the Po and Veneto Plains, anthropogenic activities affecting natural land subsidence mainly began in the 1930s due to the overpumping of groundwater and natural gas to support intense civil and industrial development, as shown by geodetic data and reproduced by numerical models (Gambolati et al., 1974; Gambolati and Gatto, 1975; Carbognin et al., 1976). Between World War II and 1970, anthropogenic subsidence was a problem common to the whole Northern Adriatic coastline (Tosi et al., 2010). However, the nature of the withdrawn fluids varied: artesian water in the Venice area, gas-bearing water in the Po Delta and both groundwater and gas in the Ravenna region. Anthropogenically driven subsidence rates of 10 to 20 mm/year and even higher occurred in certain locations (Carminati and Di Donato, 1999; Teatini et al., 2005), dominating there the RSL change.

In the Venice area, large quantities of groundwater were pumped to develop the industrial zone of Marghera after 1930. Groundwater pumping was most intensive after World War II during the period of greatest industrial growth. The six aquifers found in the upper 350 m were progressively exploited (Fig. 5a); the most intensively used aquifer was between 200 and 250 m depth due to its productive character (Carbognin et al., 1976).

Between 1950 and 1970, human-induced subsidence reached 14 cm at Marghera and averaged 10 cm at Venice (Fig. 5d). The dramatic effects of this loss of elevation became apparent in the exceptional flood ("acqua alta") of November 1966. The ground beneath Venice is more sensitive to changes in the hydraulic head because of the occurrence of a larger amount of clay in the subsurface (Zezza, 2010): the ratio between subsidence and piezometric decline was 1/100 at Marghera and 1/50 at Venice (Gatto and Carbognin, 1981).

3.2.2 The post-1970 period

After the 1966 flood, the problem of subsidence in Venice received more attention and drastic measures were taken after 1970 to reduce both industrial and other groundwater extraction. Groundwater consumption in the Marghera area decreased from 500 l/s in 1969 to 170 l/s in 1975 (Gatto and Carbognin, 1981). A corresponding rapid piezometric rise occurred (Fig. 5a): in 1978 the hydraulic head rose to ground level, re-establishing the levels existing in 1950 (Gatto and Carbognin, 1981). Land subsidence slowed concurrently and stopped; by 1975, a surface rebound of about 2 cm was recorded (Fig. 5d), equal to 15% of the total anthropogenic subsidence experienced. This result is consistent with mathematical model results and was interpreted as the elastic response of cohesive soils after recovery.

In recent years, Global Navigation Satellite System (GNSS) and Synthetic Aperture Radar (SAR) measurements confirm that the city of Venice is no longer sinking due to groundwater pumping (Tosi et al., 2013). However, at the local scale, ground movements are still impacted by anthropogenic activities such as new construction and conservation works dedicated to preserve the Venetian architectural heritage. Tosi et al. (2018) estimated that about 25% of the city experienced movements attributable to anthropogenic causes. In most cases (15%) these displacements induced an increase in local subsidence, but in some areas (10%) the short-term sinking rate was found to be smaller than the natural one. The measured displacement rates range between -10 and 2 mm/year.

3.3 Monitoring land subsidence

Over the 20th Century, high-accuracy geodetic techniques became available for monitoring land subsidence with unprecedented temporal and spatial resolution. These new data were key to reveal the increasing impact of human activities on the subsidence rate.

The first direct measurements of changes in land elevation were obtained through leveling campaigns based on both local and national networks (Salvioni, 1957; Gambolati et al., 1974; Gatto and Carbognin, 1981; Arca and Beretta, 1985; Carbognin et al., 1995a, 1995b). Additional information was derived by comparing the tide-gauge records acquired in Venice with those available in neighboring areas subjected to the same absolute sea-level changes (Carbognin et al., 2004; Zerbini et al., 2017). These techniques allowed an unambiguous detection of the impact of anthropic activities on land lowering. It was possible to identify the increase in subsidence between the 1950s and the 1970s caused by severe groundwater extraction (Gambolati et al., 1974). The maximum rate was observed in Mestre in 1968-69 when the local subsidence reached 17 mm/year (Brambati et al., 2003). Leveling lines also provided information on the spatial variability of subsidence over a few tens of kilometers. The cone of land depression was found to spread from Marghera, where most of the pumping occurred, towards the Venice area (Fig. 3).

During the following decades, leveling measurements performed in 1973 and 1993 recorded the slowdown in subsidence rates, and even a small uplift, which followed the dismissal of artesian wells and the diversification of water supply (Carbognin et al., 1995b, 1995a).

The monitoring capabilities further improved during the 1990s with the development of space techniques such as GNSS and SAR (Teatini et al., 2012; Tosi et al., 2013, 2018; Zerbini et al., 2017). The latest measurements provided by the integrated use of these techniques confirmed that, in Venice, the anthropogenic subsidence due to activities characterized by large-scale and long-term effects ended a few decades ago. However, relevant trends are still observed locally. Subsidence up to 70 and 20 mm/year is found around the inlets where the MOSE is being constructed and in artificial salt marshes, respectively (Tosi et al., 2018). In addition, spatial patterns in subsidence have been identified at different scales. The average ranges of subsidence rates observed over the lagoon are 3-4, 1-2 and 2-3 mm/year for the northern, central and southern parts respectively (Tosi et al., 2018). This reflects both the increase in the thickness of Holocene deposits from the Venice mainland to the lagoon extremes and residual groundwater pumping in the northeastern sector (Tosi et al., 2013). In the historic center of Venice, the ancient areas are more stable than those urbanized over the last centuries. This is consistent with the older settlements being developed on well-consolidated sand layers, while recent land claims occurred over areas where consolidation processes are still ongoing. Thanks to the high spatial resolution of SAR images, Tosi et al. (2018) were able to detect the impact of restoration work and new construction down to the single-building scale. This variability in displacement correlates with the nature of the shallow subsoil, the different phases of growth of the city, and the load and foundation depth of the buildings.

Table 3 presents the evolution of subsidence rates in the historical center of Venice, as measured by geodetic instruments over the last century. Assessments of uncertainty associated with the estimates of each technique are available in the literature. Precise leveling allows measuring height differences with a mean error ranging from 0.3 to 1 mm in a line of 1 km (Torge and Müller, 1980). The average uncertainty for the vertical component of the GNSS trends is in the order of 0.3 mm/year for time series spanning a decade or more (Santamaría-Gómez et al., 2017). This estimate increases to 0.4 mm/year when reference frame uncertainties are considered in the error budget (Santamaría-Gómez et al., 2017). Finally, Tosi et al. (2013) propose to present the results of the SAR technique over a selected area in terms of average rate and standard deviation of the spatial variability. By doing so, the technique provides insights on the representativeness of the estimated trend at the investigated spatial scale.

4 Estimation of sea-level changes

This section reviews the estimates of secular and recent multidecadal trends, and interannual-to-interdecadal variations identified in historical sea-level records for the Venice lagoon and its surroundings and puts them in the context of observed sea-level changes in the Mediterranean Sea and the global ocean.

4.1 Secular trend

One of the first estimates of the long-term relative MSL trend at Venice Punta della Salute was made by Polli (1953), who obtained 2.3±0.2 mm/year performing a least-square fit of the annual means from 1872 to 1941. Since then, several authors have proposed updated estimates by progressively considering newly acquired data and different approaches. A summary of the long-term RSL trends from tide-gauge data proposed during the last 15 years is presented in Table 4; analogous MSL estimates are presented in Table 5. The available estimates can be distinguished depending on whether the analyzed period starts before or in 1993, when satellite altimetry became available. Marcos and Tsimplis (2008), Wöppelmann and Marcos, (2012) and Vecchio et al. (2019) used a linear fit to analyze the RSL data from about 1910 to 2000, obtaining trends between 2.4 and 2.5 mm/year. Vecchio et al. (2019) also modelled the time series by means of the superposition of a straight line and three Empirical Mode Decomposition components, suggesting a slightly larger trend of 2.78 mm/year. Zerbini et al. (2017) isolated the effect of subsidence on the Venetian RSL time series by deriving an empirical curve from levelling data of benchmarks close to the tide gauge, GPS and InSAR heights (Fig. 5c). After removing the estimated subsidence from the tide-gauge data, the secular trend of the corrected time series was 1.23±0.15 mm/year for the period 1872-2012 (see Table 5). It should be stressed that the trend analysis has little meaning without the correction of subsidence effects because the linear model is otherwise inadequate to represent the Venice time series. The application of the same procedure to the neighboring tide gauge of Marina di Ravenna, also located in a rapidly subsiding area, provided a consistent estimate of 1.22±0.32 mm/year (period 1896-2012).

These corrections allow for a proper comparison with other secular tide-gauge records in the Mediterranean Sea that are not affected by significant vertical land motions, namely Trieste in the Adriatic and Marseille and Genoa in the northwestern Mediterranean (Carbognin et al., 2009; Wöppelmann et al., 2014; Zerbini et al., 2017; Sánchez et al., 2018) (Fig. 1). The RSL time series of Trieste, Marseille and Genoa exhibit centennial trends between 1.2 and 1.3 mm/year (Marcos and Tsimplis, 2008; Wöppelmann and Marcos, 2012; Zerbini et al., 2017). The estimates agree with the 20th century trend of sea-level rise of 1.2±0.1 mm/year reported for the same stations by Marcos et al. (2016). The 1-sigma errors are around 0.1 mm/year according to Marcos and Tsimplis, (2008) and Wöppelmann and Marcos, (2012), and between 0.10 and 0.24 mm/year (90% confidence) in Vecchio et al. (2019). Zerbini et al. (2017) obtained uncertainty values between 0.13 and 0.22 mm/year at 95% confidence level considering a reduced number of degrees of freedom due to time autocorrelation. Therefore, the 20th century secular trends in Venice are consistent within uncertainty with those of Marseille, Genoa and Trieste. Accordingly, EOF analysis on annual means from 1901 to 2012 of the corrected time series of Venice and Marina di Ravenna, and those of

Marseille, Genoa and Trieste yields a leading mode explaining 62% of variance and corresponding to coherent sea-level variability of the long time series from Mediterranean tide gauges (Zerbini et al., 2017). Scarascia and Lionello (2013) estimated a trend of 1.3 mm/year for the period 1905-2005 for the Adriatic Sea using a combination of Adriatic tide gauges and manually removing the land subsidence in Venice.

Tables 4 and 5 include an update on the RSL trend calculation to the period 1872-2019 including a comparison between estimates with and without the subsidence contribution following Zerbini et al. (2017). The subsidence curve by Zerbini et al. (2017) was updated to 2019 by applying a 1 mm/year trend since 2013 based on the SAR estimate by Tosi et al. (2013) and on the trend exhibited by the PSAL GPS from 2014 onward (Table 3). Our estimates confirm previous results concerning the magnitude of the full-period trends in both, RSL (2.53 ± 0.14 mm/year) and MSL (1.23 ± 0.13 mm/year). Subsidence therefore contributed to about half of the total RSL rise in the period 1872-2019 and explains discrepancies between published Venetian RSL trends.

These regionally coherent estimates are lower than those for the global-mean sea-level (GMSL) rise during the 20th Century reported in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC-AR5), quantified as 1.7 [1.5 to 1.9] mm/year (likelihood >90%, period from 1901 to 2010, see: Church et al., 2013). They are, however, consistent with revisited estimates of historical GMSL rise that include significantly slower rates than reported by the IPCC-AR5 for the pre-altimetry period, e.g., 1.2±0.2 mm/year (90% confidence interval, Hay et al., 2015), 1.1 ± 0.3 mm/year (99% confidence interval, Dangendorf et al., 2017) and 1.56 ± 0.33 mm/year (90% confidence interval, Frederikse et al., 2020).

Figure 6 revisits the connection between Venetian and GMSL trends on time scales ranging from interannual to centennial. Clearly, the significant difference between secular trends in Venetian RSL and GMSL is strongly damped when the Venetian MSL is considered, confirming the critical role of subsidence in determining local RSL variations. Nonetheless, the Venetian MSL appears to rise at a lower rate than the GMSL, in particular over the second half of the 20th century (Fig. 6a). This is consistent with the lesser contributions of glaciers and Greenland ice-sheet melting in the Subpolar North Atlantic basin - to which the Mediterranean Sea is connected – as reported in Frederikse et al. (2020). Note that the GMSL-Venetian MSL discrepancy observed in the first portion of the record is resolved when uncertainty in GMSL estimate is taken into account (not shown).

4.2 Recent multidecadal trends

Sea level measurements acquired with satellite radar altimetry are available since 1993, allowing, together with tide gauges, to estimate recent multidecadal trends from two independent sources. While an overall GMSL trend of about 3 mm/year during the satellite altimetry period is consistently reported by several studies (Hay et al., 2015; Chen et al., 2016; Dangendorf et al., 2017; Quartly et al., 2017), the regional departures from this GMSL are more poorly described and explained (Scharroo et al., 2013; Legeais et al., 2018; Cazenave et al., 2019). This is also the case of the Mediterranean Sea that is subject to pronounced spatial and temporal variability (Figure 7a), with the entire area of the Adriatic Sea exhibiting positive MSL trends that peak in the northern part of the basin.

Several altimetric datasets have been used to estimate sea-level trends in the Venice area. Fenoglio-Marc et al. (2012a) estimated a trend of 5.9±1.4 mm/year over the period 1993-2008 for an along-track point about 80 km away from Venice (see their Table 2). Rocco (2015) obtained trends of 4.18±0.92 mm/year (period 1993-2014) and 3.40±0.99 mm/year (period 1993-2013) for the closest grid point to the Venice tide gauge in the AVISO and SLCCI V1 products, respectively, with both estimates consistent with each other within errors. A reprocessing of the SLCCI V2 data set over the period 1993-2015 yielded a trend of 4.25±1.25 mm/year (Vignudelli et al., 2019b), further reduced to 4.03±1.27 mm/year after removing the seasonal signal (ESA CCI 2019). Explanations for the differences between trend estimates in these studies include the different time spans, especially for Fenoglio-Marc et al. (2012), different methodological aspects in the spatial characterization of the study area (e.g., closest point vs. area with a certain radius), and the recurrent reprocessing and continuous improvement of the satellite radar altimetry products.

The altimetric trends derived for Venice are typically consistent with those estimated around Trieste over corresponding time spans (Fenoglio-Marc et al., 2012). This evidence is supportive of a rather uniform sea-level trend in the Northern Adriatic (Fig. 7a, see also Bonaduce et al., 2016).

A thorough comparison between tide-gauge and altimetric data in Venice is made possible by the availability of independent information on the evolution of the vertical land motion (Fenoglio-Marc et al., 2012; Wöppelmann and Marcos, 2016). For consistency with altimetry, the tide-gauge time series need to be corrected for seasonality and atmospheric forcing (see Sect. 5.1.1). The most recent trend estimates by Vignudelli et al. (2019b) provide values of 6.17±1.50 mm/year from in situ data at the Acqua Alta Platform (AAPTF), 14 km offshore the Venice coast, and +5.81±1.47 mm/year at Punta della Salute (inside the city center) during the overlapping altimetry period. After subtracting altimetry and AAPTF tide-gauge time series, the residual time series shows a trend of -2.14±0.65 mm/year. This estimate agrees with the trend of 2.17 mm/year extrapolated from Figure 3 in Zerbini et al. (2017) that represents a best fitting of the benchmarks, GPS and PS InSAR normalized heights. Table 4 and Figure 6 also provide updated RSL trend estimates for the period 1993-2019 based on the Punta della Salute tide-gauge data. Our estimates confirm that for the satellite altimetry period the total RSL trend from the tide gauge (5.01 ±1.75 mm/year, including subsidence) is consistent with uncertainties with some satellite estimates and the tide-gauge estimate by Vignudelli et al. (2019b) over similar periods. Our estimate for the MSL trend for the same period is 2.76±1.75 mm/year, again confirming the results by Vignudelli et al. (2019b).

4.3 Interannual-to-interdecadal variability

In addition to the long-term trend, the tide-gauge time series of Venetian RSL is characterized by a number of significant interannual-to-interdecadal periodicities. Hereafter, we indicate periodicities as $O_{XXyears}$, where O means order of magnitude and the pedix indicates the period in years. Based on detrended seasonal Venetian RSL for the period 1872-2003, Zanchettin et al. (2009) report spectral peaks in the autumn time series at $O_{22years}$ and at larger multidecadal periodicities, at around $O_{2.4years}$ and at around $O_{3.4years}$, with secondary peaks at around O_{5years} and O_{8years}. In the winter time series, they report significant multidecadal periodicities at $O_{50years}$ and larger, at $O_{3.4years}$, O_{8years} and, less apparent, O_{5years}. Carbognin et al. (2010) also identify

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an O_{8years} component in Venetian RSL variability. An updated spectral analysis based on the Fourier transform applied on autumn (OND) and winter (JFM) raw detrended (second order polynomial fit) Venetian RSL indicates that the dominant periodicities contained in the Venetian RSL time series over the time interval 1872-2019 are the interannual components at $O_{2.4years}$ and O_{5years}, for both autumn and winter series (95% confidence level) and they account for about 20% of the total variance of the records. Moreover, the winter time series features the O_{8years} (~6% of the total variance) and $O_{50years}$ (~9% of the total variance) periodicities as highly significant. A secondary peak at $O_{16years}$ is detected at 90% confidence level in the autumn series (~7% of the total variance). Removal of subsidence does not change the spectral features of the series, except for the $O_{50years}$ component in the winter series, whose significance then only reaches the 90% confidence level.

Focusing on autumn Venetian surge events for the period 1948-2008, Lionello (2005), Barriopedro et al. (2010), Troccoli et al. (2012) and Martínez-Asensio et al. (2016) consistently identify significant decadal variability, in good correspondence with the 11-year sunspot cycle of solar activity. However, an updated analysis (see Lionello et al., 2020b, in this special issue) suggests that this correlation is not stable in time. Continuous wavelet transform analysis on updated and detrended seasonal time series of the Punta della Salute tide-gauge record confirms the presence of statistically significant interdecadal fluctuations in autumn ($O_{20years}$, period 1960-2000) and interannual (O_{5years} and O_{8years}, periods 1930-1950 and 1970-1990, respectively) and multidecadal ($O_{50years}$, since 1950) fluctuations in winter (Figure 8). Such fluctuations, however, appear only over limited periods, typically for a few decades or even less. This intermittent recurrent interdecadal variability can significantly impact on sub-centennial trend estimates and contribute to explaining associated spatial features. For instance, in the period between the mid-1960s and the early 1990s, the RSL time series of Venice and Trieste appear almost stationary (Figs. 2 and 6). Marcos and Tsimplis (2008) estimated RSL trends to be zero (within the errors) in the 1960-2000 period at the tide-gauge stations of Trieste, Genoa and Marseille. So, stationary sea level characterized the whole Mediterranean Sea during this period but not the Atlantic Ocean, and proposed explanations include an atmospheric contribution mainly consisting of persistent high pressure and an oceanic contribution due to steric changes in deep water masses (Tsimplis and Baker, 2000; Tsimplis et al., 2005; Gomis et al., 2008). Figure 6c confirms that often bidecadal trends, but occasionally also longer ones, in annual-mean Venetian MSL are negative and can differ in sign from the GMSL trend. Accordingly, the integral of the absolute trend differences for bidecadal and shorter periods often yields values of about 10 cm (but up to about 20 cm occasionally), and rather small (generally <5 cm) for interdecadal and longer periods (not shown).

5 Climate forcing of Venetian sea-level variations

5.1 Mechanisms of Venetian RSL variability

Variations of Venetian RSL closely depend on sea-level variations in the Adriatic Sea, which in turn closely depend on sea level variations in the Mediterranean Sea. The latter can be summarized as being driven by three major processes: steric effects, which can affect both basin-average and local variability; water-mass exchange with the Atlantic, whose sea-level signal

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propagates from the midlatitude eastern North Atlantic into the Mediterranean as a basin-scale barotropic signal, and other ocean circulation processes; atmospheric forcing, which provides spatial heterogeneity to Mediterranean sea-level variations and is therefore critical to determine Venetian RSL variability. Attribution of Mediterranean sea-level variability is often separated on the basis of the timescale: intraseasonal and interannual variability is associated to atmospheric mechanical forcing (e.g., Jordà et al., 2012a, 2012b), whereas multidecadal and longer time-scale variability is associated with oceanic lateral forcing from the eastern North Atlantic (e.g., Marcos et al., 2016).

5.1.1 Atmospheric forcing

The paradigm of modes of large-scale atmospheric and oceanic variability is widely used to characterize internal climate variability, to describe responses to natural forcing and to assess the skills of decadal forecast systems Zanchettin (2017). Han et al. (2019) provide a recent review on the connection between variability of dominant climate modes and coastal sea level in the three major ocean basins. Statistical analysis of atmospheric pressure demonstrates coherent large-scale patterns covering the North Atlantic, Europe and the Mediterranean Sea, which explain significant parts of the atmospheric signal variability at interannual and interdecadal scales, particularly during winter. The large-scale coherency of the atmospheric pressure fields means that several of the local atmospheric parameters as well as the oceanic circulation driven by this forcing becomes correlated. Such linkage drives coherent sea-level changes within the whole Mediterranean basin and, ultimately, in the Venice Lagoon. Despite being studied so far mainly within the framework of interannual to multidecadal climate variability, the same connections can be relevant for longer-term trends as well, and we therefore include them in this review.

The most important local atmospheric parameters are pressure anomalies, associated with the so-called Inverse Barometer Effect (IBE), and the geostrophic wind, a descriptor for large-scale surface wind forcing. Accordingly, numerous studies consistently attribute to the climate mode known as North Atlantic Oscillation, or NAO, the IBE and the large-scale wind forcing determining winter variability of coastal RSL in the Mediterranean Sea (e.g., Tsimplis et al., 2006; Gomis et al., 2008; Tsimplis and Shaw, 2008; Calafat et al., 2012; Tsimplis et al., 2013; Martínez-Asensio et al., 2014; Ezer et al., 2016). Mass exchange with the Atlantic Ocean can occasionally dominate the above-mentioned atmospheric forcing factors during some years such as 2010 (e.g. Fukumori et al., 2007; Menemenlis et al., 2007; Gomis et al., 2008; Calafat et al., 2012; Landerer and Volkov, 2013; Tsimplis et al., 2013; Volkov et al., 2019). Nonetheless, the imprint of the NAO on Mediterranean coastal sea-level variability in 2010 remains clear from tide-gauge data (Rubino et al., 2018).

Zanchettin et al. (2009) estimate that about half of the variability of detrended winter Venetian RSL can be explained linearly by the NAO. They identify significant spectral components in the autumn series of the Scandinavian (SCA) and East Atlantic Western Russia (EAWR) patterns at the relevant O_{8year} periodicity, the former accounting for 20% of the total variance of autumn detrended Venetian RSL in the period 1872-2003, and a significant O_{5year} component in winter EAWR. An updated analysis between seasonal time series of NAO (Jones et al., 1997) and detrended (second order polynomial fit) raw Venetian RSL for the period 1872-2019 confirms large values of the correlation statistics (r_{JFM}=-0.68, p~0 accounting for autocorrelation

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in the series; $r_{OND}=-0.50$, $p<0.0001$). Results on MSL, i.e., after removal of subsidence, confirm the strong connection between NAO and detrended Venetian RSL during the cold semester.

Barriopedro et al. (2010) link changes in the frequency of fall Venetian storm surges with variations in solar activity during the period 1948-2008 and associate them with two anomalous spatial patterns of the large-scale atmospheric circulation: a large-scale wave train pattern linked to storm track paths over northern Europe (not directly linked to the classical NAO pattern) under solar maxima, and a meridionally oriented dipole with a preferential southward shift of storm track activity under solar minima. We update previous results about the statistical connection between NAO and Venetian RSL by performing a wavelet analysis on the 1872-2019 autumn and winter time series of the NAO index and Venetian RSL. The wavelet coherence spectra (Grinsted et al., 2004) in Figure 8 confirm the strong link between NAO and Venetian RSL fluctuations in autumn and winter, robustly in rough antiphase over a broad range of timescales, from interannual to multidecadal. In autumn the connection becomes more significant in the recent portion of the series after removal of subsidence from the RSL data, confirming the importance to account for it in studies on MSL, i.e., the climatic component of RSL variability.

Contribution of IBE to Northern Adriatic sea-level variability has been quantified by Zanchettin et al. (2009) and Calafat et al. (2012). The former study reports a contribution of IBE to the total variance of detrended Venetian RSL for the period 1872-2003 of 32% in autumn (with a strong link with NAO(-), EAWR and SCA) and about 41.5% in winter (with a strong link with NAO(-)).The latter study quantifies in 25% the IBE contribution to detrended and smoothed (4-year running mean) winter sea-level variability in Trieste for the period 1950-2009.

Zanchettin et al. (2009) indicate three dominant factors that concur to strengthen the impact of large-scale atmospheric forcing along the northern coast of the Adriatic Sea and especially in the Venice Lagoon: (i) the peculiar morphology of the basin displaying a NW–SE elongation and a shallow northern portion; (ii) the remarkable strength and frequency of the meridional Sirocco wind; (iii) the conspicuous and noticeably time-varying inflow of freshwaters from the Italian Po River, whose delta is located only 90 km south of the Venice Lagoon (Fig. 1). Note that, at the basin scale, riverine input to the Mediterranean Sea and other freshwater fluxes resulting in net loss of freshwater are regarded as negligible for sea-level variability, as they are quickly compensated by changes in the mass transport through the Strait of Gibraltar (Adloff et al., 2018). A strengthened northeastward flow in the Central Mediterranean (i.e., prevailing Scirocco-favorable conditions) favors the piling of Ionian surface waters toward the northern Adriatic, resulting in an increase of Venetian RSL. Such meteorological conditions are strongly linked with NAO(-) in winter, and with SCA and EAWR in autumn, when these modes are identified as among the primary large-scale precursors of the interannual-to-decadal variability of meridional atmospheric flow over the Adriatic Sea (Zanchettin et al., 2009). Calafat et al. (2012) used ocean models to separate the barotropic and baroclinic components to decadal sea-level variability in the Mediterranean Sea, and identified the main mechanism of decadal sea-level variability along the northern coast of the Adriatic Sea. The mechanism primarily entails longshore wind and wave propagation forcing a coherent sea-level signal on the western boundary of the basin that narrows and strengthens northward. Minor contributions are from the barotropic response to local wind forcing, quantified in only 15% for (detrended and smoothed) winter sea level

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variability in Trieste. Calafat et al. (2014) reported that the barotropic model employed in Calafat et al. (2012) tends to underestimate positive extreme events of Mediterranean sea-level variability, but can also significantly overestimate them in the Northern Adriatic.

Sea-level pressure variability in the Euro-Mediterranean region is known to be modulated by the so-called Atlantic Multidecadal Oscillation or AMO (Mariotti and Dell'Aquila, 2012) describing multidecadal fluctuations in North Atlantic sea-surface temperature. Accordingly, an atmospheric bridge may also constitute a potential precursor to multidecadal ($O_{50\text{-}60years}$) Venetian RSL variability. During warm AMO phases the frequency of cyclones increases over the Tyrrhenian and Ionic Seas between November to March (Maslova et al., 2017). This could contribute to explaining the statistical connection between bidecadal variability of Venetian RSL and the Atlantic Multidecadal Oscillation identified by Scafetta (2014) via multi-scale acceleration analysis.

Scarascia and Lionello (2013) have shown that interannual MSL variability in the period 1940-2005 is very well explained by the mechanical action of the atmosphere, changes of upper ocean (uppermost 500 m) temperature and surface layer salinity. However, these drivers have no trend that can explain the sea-level trend observed in the same period (the authors estimated an absolute sea-level rise of 1.3 mm/year). Their conclusion is that the mean sea-level rise in the Adriatic since 1940 has been caused by a remote effect, namely ice cap melting.

5.1.2 Ocean processes

The Mediterranean basin circulation is driven by an excess evaporation which is balanced by net inflow of Atlantic Water through the Strait of Gibraltar. Thus, water mass exchange through the Strait of Gibraltar critically contributes to determining how sea-level changes in the World Ocean propagate within the Mediterranean basin (Brandt et al., 2004).

The exchange at Gibraltar consists of a strong surface current of relatively fresh and warm water from the ocean and a deep-water current of salt and cold Mediterranean water, outflowing into the ocean and sinking in the North Atlantic in the form of gravity current. The two-way water exchange regime within the Strait critically depends on the number and location of its hydraulic controls, being sub-maximal if subject to only one control in the western part, or maximal if the flow is also controlled in the eastern part, with different implications for the characteristics of the circulation. Local dynamics are strongly influenced by tides, which are responsible for the amplitude modulation of water transport and for the substantial vertical mixing that has been observed (Garcìa-Lafuente et al., 2013), as well as for the migration of the eastern hydraulic control (Armi and Farmer, 1988).

Sea-level variability in the eastern North Atlantic is among the dominant drivers of interannual-to-interdecadal Mediterranean variability (e.g., Adloff et al., 2018). Fluctuations of surface fluxes linked to the large-scale atmospheric forcing drive variations in thermal and haline oceanic properties, ultimately affect processes such as the intermediate or deep water formation and transformation (e.g., Calafat et al., 2012; Cusinato et al., 2018). Hence the large-scale atmospheric forcing has a pronounced effect on sea-level variability. Associated ocean circulation changes lead to the negative MSL trends observed in the Ionian Sea and south-east of Crete shown in Fig. 7a (Bonaduce et al., 2016).

5.2 Numerical modelling of Mediterranean and coastal sea level changes

Over recent years, considerable efforts have been invested into developing and applying regional climate and ocean circulation models approaching the issue of dynamical downscaling from different perspectives (e.g., Somot et al., 2008; Sannino et al., 2009; Artale et al., 2010; Naranjo et al., 2014; Sein et al., 2015; Turuncoglu and Sannino, 2017; Androsov et al., 2019; Palma et al., 2020).

Sannino et al. (2015) demonstrated that the inclusion of explicit tidal forcing in an eddy resolving Mediterranean model has important effects on the simulated circulation, in addition to the expected intensification of local mixing processes. The signal induced in the Atlantic water crossing the Strait in fact propagates into the basin interior and concurs to determine the dispersal paths of the main water masses, with consequences on critical processes such as deep water formation in the Gulf of Lion and Levantine intermediate water recirculation. Since the Mediterranean ocean state and variability critically depend on the lateral boundary forcing from the eastern North Atlantic, recent progress on the simulation of water mass exchange through the Strait of Gibraltar led to a major improvement in the simulation of Mediterranean circulation. Marcos et al. (2016) decompose the Mediterranean sea-level signal into two components: first, variations in the eastern North Atlantic sea level, estimated through global coupled climate models, second, relative variations in the Mediterranean sea level with respect to the eastern North Atlantic, estimated through regional climate models. More recently, Adloff et al. (2018) provide an overview of current methods to implement Atlantic sea-level forcing at the lateral boundary of state-of-the-art regional ocean models for the Mediterranean Sea, concluding that the quality of such forcing is essential for appropriate modelling of Mediterranean sea level.

6 Prediction and projection

Projections of RSL change at Venice require that all the different components described in the previous sections are considered over the coming decades and combined (Nicholls et al., 2020). It is useful to distinguish GMSL changes which can be derived from the SROCC ("Special Report on Ocean and Cryosphere in a changing climate", Oppenheimer et al., 2019), regional sea-level changes in the Mediterranean and Northern Adriatic, and local vertical land movement contributions.

6.1 Vertical land movements

Projections of future contribution of vertical land motion are available only for the GIA component, which, in the Mediterranean Sea, is expected to provide a small (order of 5-10 cm/century) and spatially rather uniform positive contribution to RSL (Galassi and Spada, 2014). For the other components of vertical land movements, it is only possible to consider their historical variations in order to contemplate their potential to affect future RSL changes.

Estimates of subsidence at sub-regional scale can be constrained on the basis of observations of past evolution. The sum of sediment compaction, tectonics and GIA is estimated about 0.6 and 1.0 mm/year (Antonioli et al., 2017; Tosi et al., 2013) with a constant rate on centennial time scale. At local scale, trends of a few cm/year are still observed in restricted areas such as at

the lagoon inlets interested in the construction of mobile barriers against high-tides (Tosi et al., 2018). Controls on groundwater extraction should prevent returning to the large subsidence rate that occurred between 1930 and 1970, but shallow natural processes, notably consolidation, and anthropogenic activities are observed to continue contributing at rates spatially varying from 10 to -2 mm/year (Tosi et al., 2013). Hence, human activities can contribute significantly to RSL rise, but relevant scenarios are currently not available in the literature and this is a generic problem (Nicholls et al., 2014). All these natural and anthropogenic contributions have the potential to increase RSL in Venice, further worsening the negative impact of MSL rise, with contribution of order of 10 centimeters at sub-regional scale, and potentially much larger locally.
Melting of ice sheets and glaciers induced can affect vertical land motions. Adopting the “mid range” and “high end” climate change scenarios defined by Spada et al. (2013), Galassi and Spada (2014) have evaluated the effect of terrestrial ice melting on future regional RSL evolution across the Mediterranean Sea by solving the Sea Level Equation including the contribution of glaciers, ice caps and of the Greenland and Antarctic ice sheets. They found that GIA from the terrestrial ice melting will be responsible for a sea-level rise in the Northern Adriatic of ~8 and ~17 cm to 2040–2050 relative to 1990–2000, in the two considered scenarios, respectively. Since the sources of terrestrial ice melting are mostly located in the far-field of the Mediterranean Sea, these contributions shall be largely uniform across the whole Adriatic Sea.

6.2 Sea level projections for the Northern Adriatic

Sea-level anomalies linked to GMSL rise propagate from the mid-latitudes of the eastern North Atlantic to the Venice Lagoon through the Gibraltar and Otranto straits. MSL variations along this path is further determined by the mechanical action of the atmosphere and by steric effects associated with changes of temperature and salinity of the water masses. Therefore, beyond local effects on RSL, the projection of sea-level evolution in the Venice Lagoon depends crucially on processes acting on GMSL, sea-level variations across the World Ocean and regional patterns of MSL change inside the Mediterranean basin.
The recent SROCC report summarizes projected GMSL rise estimates suggesting a likely range from +29 cm to +110 cm for the year 2100 with respect the 1986-2005 average depending on the future climate scenario, with the low RCP2.6 and the high RCP8.5 providing the lower and the upper limit, respectively. Here “likely” corresponds to the IPCC uncertainty language, meaning that the probability of future sea-level change within this range is estimated from ≥66% to 100%, and therefore not actually excluding values outside this range. The contribution of ice sheets, in particular the Antarctic one, and the underlying dynamical processes that have been intensively discussed lately (e.g., DeConto and Pollard, 2016; Edwards et al., 2019), provide the main source of uncertainty - or deep uncertainty - in future sea-level change projections (Bakker et al., 2017; Oppenheimer et al., 2019). Therefore, although high-end GMSL rises (up to 2 m at the end of the 21st century) are unlikely, they cannot be ruled out (e.g., Nicholls et al., 2014; Kopp et al., 2017) and are particularly useful for decision-making applications and adaptation planning, especially in decision contexts with low tolerance to uncertainty (Hinkel et al., 2019). Results in Slangen et al. (2017) suggest that sea-level rise at the subtropical and mid-latitudes of the eastern North Atlantic (and the Mediterranean Sea itself) will only have small deviations (less than 10%) from the global-mean value.

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Analysis of the possible deviations of future mean sea level in the Mediterranean basin from the GMSL has been attempted using dynamical and statistical models. Dynamical models of the circulation inside the Mediterranean Sea allow to estimate directly the mechanical effect of the atmosphere on the circulation (wind stress and IBE). There is a general consensus that this is a small contribution with changes generally less than 10 cm (Tsimplis and Shaw, 2008; Tsimplis et al., 2008; Jordà et al., 2012b; Jordà, 2014; Adloff et al., 2018). The steric effects are computed from temperature and salinity changes using a diagnostic offline computation. This computation obviously depends on the water depth and vanishes at the coastline. In fact, the spatial variations of the resulting sea-level change follow the bathymetry of the Mediterranean Sea and are rather small (< 5 cm) over shallow water areas such as the northern Adriatic Sea (e.g., Tsimplis et al., 2008). The overall steric sea-level change is the consequence of two contrasting effects: thermosteric expansion (associated to warming of water masses) and halosteric contraction (associated to increasing salinity of the water masses). Most studies agree that the former is larger, also because of the freshening effect of the Atlantic inflow across the Gibraltar strait, whose magnitude is poorly constrained. Several studies contributed to an assessment of the overall steric effects at Mediterranean scale, with differences depending on periods, models, scenarios and the representation of water exchange between Mediterranean Sea and Atlantic Ocean (Adloff et al., 2018). Various basin-wide Mediterranean steric MSL projections are found in the literature. For instance, a range of 2 to 7 cm for the mid-century sea-level anomaly (2050 with respect to 2001) under the SRES-A1B scenario was reported (Carillo et al., 2012). By the end of the 21st century (i.e. 2070-2099), Tsimplis et al. (2008) found a 13 cm sea-level anomaly (with respect to 1960-1990) under the A2 scenario, while Adloff et al. (2015) reported sea-level anomalies over the same periods that range between 34 cm and 49 cm considering a 6-member ensemble and the A1, A1B and B1 scenarios (see Fig. 7b).

Estimates of future sea-level rise in the Northern Adriatic Sea from a statistical model are provided by Scarascia and Lionello (2013). The computation is based on a linear regression linking the deviation of the sub-regional sea level to changes of MSL pressure, water temperature and salinity, meant to represent the mechanical atmospheric forcing, steric effects and also the redistribution of mass inside the basin (Jordà and Gomis, 2013), which is ignored in computation of pure steric effect. Scarascia and Lionello (2013) concluded that regional effects, at the end of the 21st century for the A1B scenario, result in a deviation in the range from 2 to 14 cm from the sea level of the Eastern Atlantic outside the Strait of Gibraltar and concluded that the main contribution to local sea-level rise is caused by remote effects, such as mass inflow across the Gibraltar strait caused by polar ice melting. The melting was conservatively estimated without accounting for a likely future acceleration and information from climate projections.

Northern Adriatic RSL projections informed by climate projections can be obtained by summing up the future regional contributions of sterodynamic effects - which corresponds to changes in ocean density and circulation corrected from the IBE -, melting of mountain glaciers and ice sheets, land water and vertical land motions (Slangen et al., 2014; Gregory et al., 2019). Figure 7c shows probabilistic projections of Northern Adriatic RSL for two climate scenarios (RCP2.6 and RCP8.5) and one high-end scenario (Thiéblemont et al., 2019). The sterodynamic component is derived from the outputs of the coupled climate-model simulations performed within the 5th phase of the Coupled Model Intercomparison Project. The rather coarse resolution of coupled climate models prevents an accurate representation of small-scale processes (e.g., water exchange at Gibraltar),

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which in turn affects regional sea-level estimates (Marcos and Tsimplis, 2008; Slangen et al., 2017). The Mediterranean sterodynamic sea-level projections are therefore estimated by relying on those of the Atlantic area near Gibraltar. Other mass contributions to sea level (i.e., glaciers, ice sheets, land water) have a global effect due to the addition of water mass to the ocean (barystatic sea-level rise) and a regional effect through instantaneous changes in the geoid (GRD-induced RSL change). Both contributions are combined into a geographical pattern called barystatic-GRD fingerprint (Mitrovica et al., 2009; Gregory et al., 2019) and are proportional to the land water mass change. Considering an annual subsidence rate of 1 mm/year, Northern Adriatic RSL is projected to rise by 47 cm (likely range 32-62 cm) for the RCP2.6 scenario and by 81 cm (likely range 58 cm-110 cm) for the RCP8.5 scenario by the end of the 21st century with respect to the reference period 1986-2005. These projections start to diverge after 2050 and yield a range of MSL rise by 2100 between 21 and 100 centimeters, i.e., ~10% lower than GMSL rise. The high-end scenario – obtained by selecting, for each sea-level component, the highest physical-based estimate found in the literature (see Thiéblemont et al., 2019 for details) – shows that, by 2100, Northern Adriatic MSL could unlikely but possibly rise by more than 1.8 m. Note that for this high-end scenario, the Antarctic component contributes to nearly half of the MSL change in 2100. This estimate agrees with the value by Scarascia and Lionello (2013).

In conclusion, while our understanding of past RSL change in Venice has improved, the large uncertainty in the magnitude of future GMSL rise remains a major scientific challenge (Oppenheimer et al., 2019). Hence, science and public policy need to recognize this uncertainty and monitor sea-level change as part of the management of this uncertainty, including drawing on relevant experience from elsewhere (e.g., Ranger et al., 2013). Regional effects can determine differences in the order of 10 cm between the mean Mediterranean sea level and the GMSL and within different parts of the Mediterranean basin itself. Changes over interdecadal periods can also distort the detection of forced trends over rather long periods of time (e.g., Jordà, 2014). However, no regional mechanism has been identified that can sustain a deviation from the GMSL rise of the future, atmospherically corrected MSL at the Venetian coastline that is larger than the abovementioned order of magnitude. RSL can differ by more as land movements and regional atmospheric patterns could provide additional and important contributions.

7 Gaps of knowledge and opportunities for progress

This literature review brings several outstanding issues into light, including improving and integrating satellite observations of sea-level change with tide-gauge measurements, improving monitoring and prediction of vertical land motions, determining the shape of the historical RSL trend, i.e., best statistical model to estimate it, improving the simulation of Mediterranean oceanic circulation, and reducing uncertainty on estimates of regional effects on future climate-induced sea-level rise.

Concerning observations, satellite data refer to the open sea and therefore do not capture coastal variations, especially the vertical land-movement component of RSL. Altimeter data are nonetheless fundamental for providing a regional perspective and reaching robust conclusions on observed MSL and RSL rise, as they provide an independent source of information from the local tide-gauge data. The contribution of coastal altimetry is considered essential to within 0–10 km to link the sea-level

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changes derived from satellites with those measured at tide-gauge locations (Ponte et al., 2019). The extension of the satellite-based sea-level record toward the coast with measurement quality comparable to the open ocean is also important to assess the coastal impacts due to hazards (Ablain et al., 2016; Benveniste et al., 2019). It has been shown that by improving processing, it is possible to make more accurate sea-level measurements in coastal zones (Cipollini et al., 2017). Progress has been made in fitting the radar signal (the so-called re-tracking) in order to extract a robust estimate of the distance between satellite and sea surface. The ALES retracker, with a proper threshold on error, recovers significantly more data in the 10 km near the coast (Passaro et al., 2014). A number of satellite radar altimetry operational products (along-track and gridded) dedicated to the monitoring of open-ocean sea level exists, whose quality is constantly improved. Various experimental coastal altimetry products are also now available and validated in some regions, thus being used for sea-level research in the coastal zone (Gómez-Enri et al., 2019). An updated table is accessible at www.coastalt.eu/datasets. Importantly, merging altimeter data from different missions requires homogenous re-processing and minimization of drifts and systematic biases between missions. For the Northern Adriatic, an opportunity for progress is provided by the ESA SLCCI extension (CCI+), which will process along-track data from additional satellite missions using re-tracked data, dedicated coastal geophysical corrections and improved editing that will then be combined in a global grid with higher resolution near the coast (Anny Cazenave, personal communication). Also, the novel GNSS-derived Path Delay Plus (GPD+) correction now provides accurate wet tropospheric delays (Fernandes and Lázaro, 2016). The Wide-swath interferometry will be boarded for the first time on the Surface Water Ocean Topography mission to provide for the first time sea-level imaging (Vignudelli et al., 2019a).

Concerning the monitoring of vertical land motions, integrated systems have been shown to offer the best approach to the study of subsidence (Wöppelmann and Marcos, 2016; Zerbini et al., 2017; Tosi et al., 2009): GNSS provides point-wise continuous positioning with respect to a global reference frame; SAR offers spatially dense measurements of surface displacements relative to a ground target selected as reference point. However, if these techniques can support the investigation of present subsidence patterns with unprecedented detail (i.e., at the single building scale), future scenarios are still difficult to construct, with the anthropogenic component of vertical land movements being the most difficult to assess. Historical observations showing the potential of anthropogenic subsidence to be in the order of tens of cm per decade demonstrate the need of continued careful regulation of land and groundwater use, and monitoring of local subsidence. This might be used to develop high and low subsidence scenarios, respectively.

Concerning the simulation of Mediterranean oceanic circulation, despite recent progress in the representation of lateral boundary forcing at the Strait of Gibraltar, there are several aspects that remain poorly understood or worth deeper investigation. For example, small changes in the salinity difference between Mediterranean and Atlantic waters around a threshold of 2 psu can determine shifts in the simulated hydraulic regime within the Gibraltar Strait, from sub-maximal to maximal (e.g., Artale et al., 2006). Accordingly, a climate change scenario involving a positive trend in the salinity difference can result in a partial isolation of the Mediterranean Sea from the rest of the World Ocean (Tsimplis and Baker, 2000). How non-linear interaction between large-scale ocean variations and local strait phenomena may sustain an abrupt change in the salt/freshwater transport between the Mediterranean and the Atlantic, and a shift in the Mediterranean mean circulation, remains to be investigated in a comprehensive modelling framework. Other Mediterranean Straits are also relevant: for instance, water-mass exchanges through Turkish Straits remain idealized in current simulations, and their effect underrepresented in future projections. Water mass exchange between shelf and ocean is performed through cascading processes, which are hardly reproduced by both regional and global solutions (e.g., Polyakov et al., 2012; Holt et al., 2017). In this context, promising is the unstructured approach adopted by Ferrarin et al. (2018), in which the system of inter-connected basins formed by the Mediterranean, the Marmara, the Black and the Azov seas was numerically investigated through the use of a unique computational mesh allowing for a seamless transition between different spatial scales, from narrow straits to open sea (see also Umgiesser et al., 2020, in this special issue).

Poorly simulated internal ocean variability also provides potential weakness to projected circulation changes in the Mediterranean Sea, which calls for a stronger focus on the validation of regional ocean models regarding interior and abyssal dynamics linked to fundamental oceanographic processes. In fact, the Adriatic Sea is the only Mediterranean sub-basin in which the evaporation-precipitation-runoff budget is negative: the buoyancy flow at the Otranto Strait is either positive or negative depending from the predominance of production of dense water within the Adriatic or of the inflow of the Levantine Intermediate Water, respectively. Numerical simulations indicate that a nonlinear convection-mixing feedback can favor hysteresis in the Adriatic Sea with multiple equilibria encompassing estuarine and anti-estuarine circulation (Pisacane et al., 2006; Amitai et al., 2017). Such behavior could have important implications for future sea-level variability in the Venice Lagoon. Overall, even under accurate representation of global steric and mass addition from the Atlantic, projections of Mediterranean sea-level change from current regional ocean models would be reliable only in the basin mean tendencies. Further, comparison of the regional simulations with satellite-derived data highlights local biases in the historical sea-surface height patterns and trends, as well as large inter-model heterogeneity in projected changes at the local scale driven by differences in simulated circulation changes. Improved assessment and progress is hoped in this direction as well.

The higher rate of RSL rise observed in recent decades compared to the longer-term estimate (Table 4) brings the practical question of the most appropriate statistical model to extract the trend for time series analysis. We have evaluated the performance of a linear and a quadratic regression model on the RSL times series, including the raw series and the climatic component alone, and for the periods 1872-2019 and 1993-2019. According to a number of skill metrics including R^2, AIC and FPE (Alessio, 2015 and references therein) (Table 6) the quadratic model only slightly outperforms the linear model for both periods and both series. Further research is therefore needed to determine the shape of the local RSL rise in Venice and to capture the higher RSL trends observed in recent decades, as the simple acceleration expressed statistically in terms of quadratic fitting seems to be insufficient.

Concerning the exploration of future evolution of Venetian RSL, we identify two critical gaps of knowledge. First, the energetic variability observed in Venetian MSL on timescales from interannual to multidecadal requires studies (presently missing) addressing the viability of its near- and mid-term prediction. Then, on the long term, there has been no exploration of the implications of high-end GMSL rise for RSL in Venice, which has been only outlined here for the first time. Research on both

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aspects could contribute to improved understanding of forcing mechanisms of Venetian sea-level changes, risk assessment and management, and to more effective scientific communication.

Finally, this literature review represents a first attempt to combine uncertainty ranges of future projections for the individual processes contributing to Venetian RSL change. Further approaches to objectively combine such uncertain estimates are hoped to be tested, based on qualitative criteria (e.g., considered process, statistical and numerical framework) or quantitative metrics, such as relative or absolute model skills in representing relevant physical features (e.g., boundary forcing at the Gibraltar Strait).

8 Conclusions

The City of Venice and the surrounding lagoon ecosystem are critically affected by variations in RSL height driven by a host of diverse processes. These encompass oceanic processes driving RSL variations from diurnal astronomical oscillations to climatic interannual-to-multi-centennial fluctuations, and vertical land movements causing RSL variations on time scales ranging from a few decades due to, e.g., anthropic activities, to multi-millennial trends due to tectonic activity. This review has summarized and reassessed recent progress in the estimation, understanding and prediction of the individual contributions to RSL by exploiting new observational datasets, improved statistical methods and more realistic numerical simulations of ocean and Earth system components achieved in the past decade. Our estimate of the historical long-term linear trend of Venetian MSL is 1.23±0.13 mm/year (from 1872 to 2019, with subsidence removed). Looking to the future, the effects of both subsidence and climate-induced sea-level rise will have profound implications for Venice, making this scientific evidence even more relevant. By the end of the 21st century natural local subsidence is expected to result in a RSL rise from 6 to 10 cm relative to the present. Projected climatically-induced Venetian MSL rise from estimates for the GMSL corrected for further uncertainty associated with the regional redistribution of different mass contribution components such as glacier, ice-sheet and groundwater is in the range from 21 to 100 centimeters by 2100. This estimate neglects the effect of atmospheric forcing of local MSL, which potentially contributes to uncertainty estimated here in the range of about 10 centimeters. The total uncertainty range of the RSL rise in Venice obtained by combining the estimates above is thus very large: from +17 to +120 centimeters by 2100. An additional contribution could be produced by anthropogenically-driven subsidence. While, in general, the resulting effect of regional climatic processes could either attenuate or increase regional RSL with respect to GMSL, local subsidence will necessarily aggravate it. Further, because of the differential rates of subsidence observed in the Venice area, the land movement estimates at the tide gauges may underestimate the risk for other parts of the city. Ice-sheet melting provides a highly uncertain contribution: no mechanism has been identified capable of contrasting the impact on Venetian MSL of a large GMSL rise caused by the melting of Greenland and Antarctica; therefore, a high-end change, with RSL rise possibly exceeding 180 cm by 2100 is an unlikely but potential high-end change.

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Among the important advances highlighted in the review are: Centennial RSL variations are now known to be spatially heterogeneous within the lagoon and the city due to different vertical ground movements, hence local trend estimates are not expected to be representative for the city or lagoon as a whole; due to the non-linear variations caused by ground subsidence, a linear detrending of Venetian RSL time series is unsuitable unless data are preliminarily corrected for the effect of vertical land motion; remote climate forcing from the Atlantic sector via atmospheric and oceanic processes critically contributes to interannual-to-multidecadal Venetian RSL variability; Atlantic hydrographic boundary conditions are a major source of uncertainty for future projection of Mediterranean Sea sea-level rise: uncertainty in water mass flows at the Strait of Gibraltar yields an ensemble spread between simulations comparable to that determined by uncertainty in greenhouse gas emissions. We confirm the existence of a strong link between interannual and interdecadal variability observed in Venetian sea levels and in the large-scale atmospheric circulation over the North Atlantic during the winter semester, particularly with the North Atlantic Oscillation (about 46% of shared variability for January-March average time series in the period 1872-2019).

The review has highlighted a number of major gaps of knowledge as well. Among these: altimetry data are recorded rather far from Venice and may not represent the lagoon RSL variability; uncertainties in geologic trends remain difficult to assess; a reliable framework is lacking to combine uncertain future estimates of RSL change due to individual contributions, which provides for a major opportunity for progress to better constrained ranges of future projections; historical evidence demonstrates that subsidence can be temporarily dominated by the anthropic component. This shows the importance of sustaining the management regime that brought this anthropogenic component under control across the lagoon, and possibly strengthen it to bring the small-scale ongoing anthropic subsidence under control. Finally, whereas several studies explored scenarios of RSL changes in Venice at the end of the 21st century under global climate change, near-term predictions have not been attempted yet and high-end scenarios have not been subject of explicit focus.

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Author contribution

DZ and SB coordinated the paper with help from FR. Specific contributions to the sections are as follows (LA = leading author, CA = contributing author). Section 1: LA: DZ; CA: SB. Section 2: LA: FR; CA: MT, SV, GW, SZ. Subsect. 2.1: LA: FR; CA: GW, SZ. Subsect. 2.2: LA: SV. Subsect. 2.3: LA: SZ; CA: FR, MT, SV, GW. Section 3: LA: SB; CA: FA, EC, GS, GW, SZ. Section 4: LA: DZ, FR. CA: PL. Section 5: LA: DZ, PL; CA: MT, GS, FA, AA, VF, AR, CF. Section 6: LA: DZ, PL; CA: RT, FR, SB, RJN. Section 7: LA: DZ; CA: SB, PL, RJN, CF. Section 8: LA: DZ, PL, RJN; CA: all authors. SR created figure 1. DZ created figures 2,4,6,7,8. SB created figure 5. SV created figure 3.

Competing Interest

The authors declare that they have no conflict of interest.

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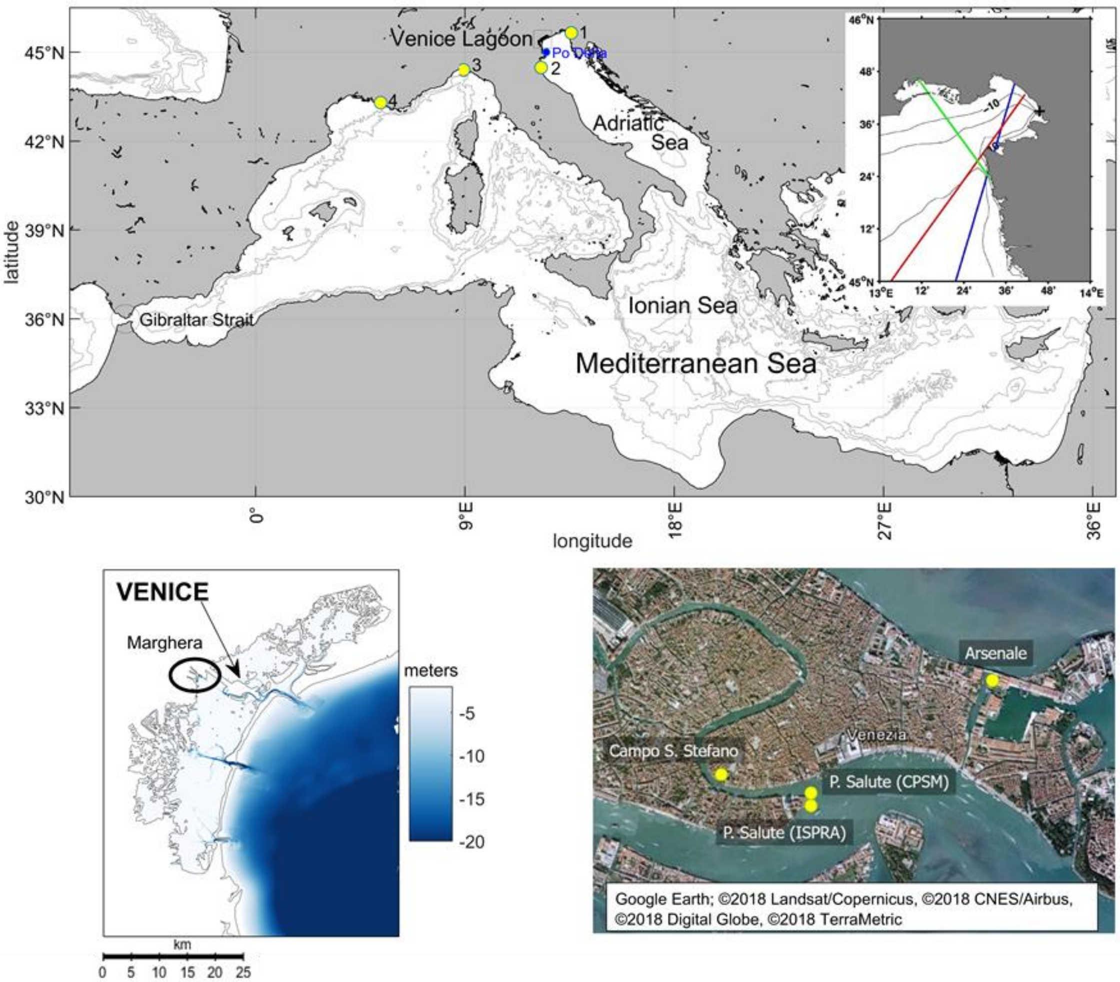

Figure 1: Maps of the study area and major locations and geographical features mentioned in the paper. Top: the Mediterranean Sea (main panel) and satellite altimetry tracks over the northern Adriatic Sea (blue: Envisat 416; red: Jason1-151; green: Jason2-196) (inset); bottom left: the Venice Lagoon; bottom right: the historical city of Venice. Tide gauge stations are indicated with yellow dots (1-Trieste, 2-Marina di Ravenna, 3-Genoa, 4-Marseille). Map for bottom right panel extracted from Google Earth; ©2018 Landsat/Copernicus, ©2018 CNES/Airbus, ©2018 Digital Globe, ©2018 TerraMetric.

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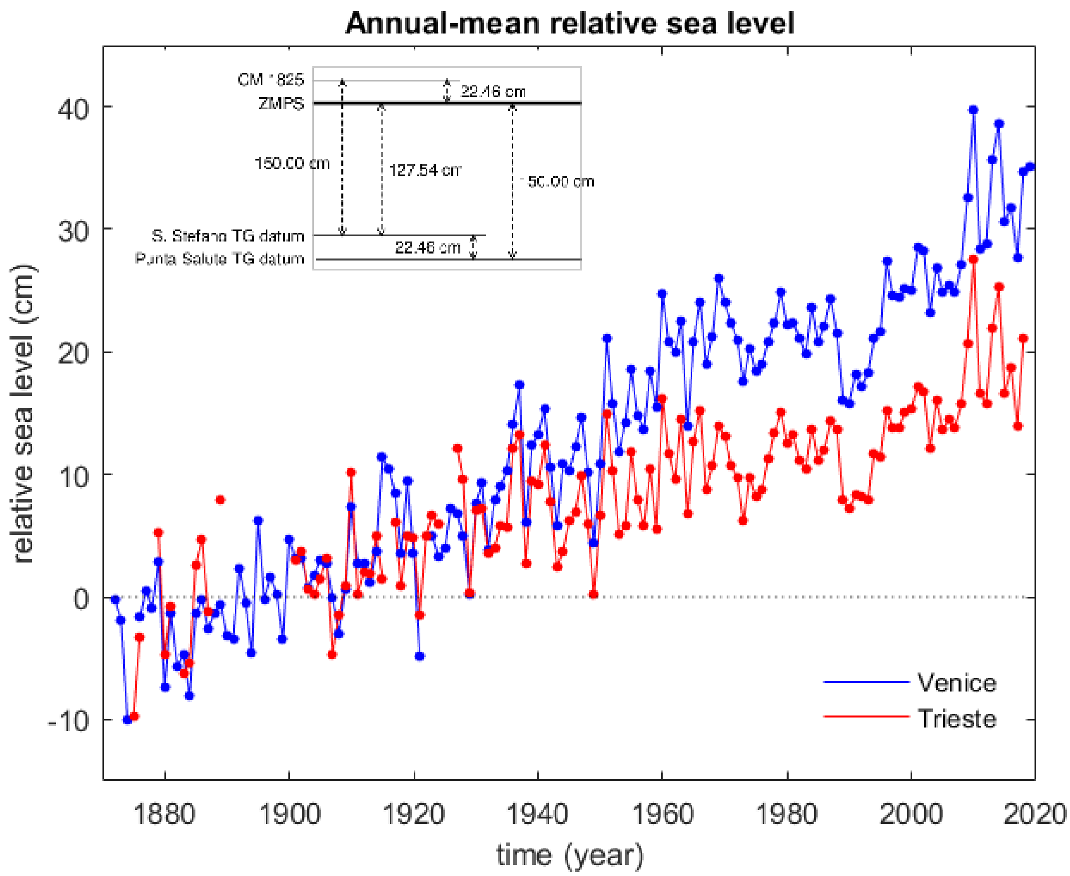

1350 **Figure 2: Time series of annual-mean RSL measured by tide gauges in Venice and Trieste. Venice data are referred to ZMPS, Trieste data are offset for illustrative purposes. The top-left inset defines the reference planes of the tide gauges at Santo Stefano and Punta della Salute (redrawn from Battistin and Canestrelli, 2006).**

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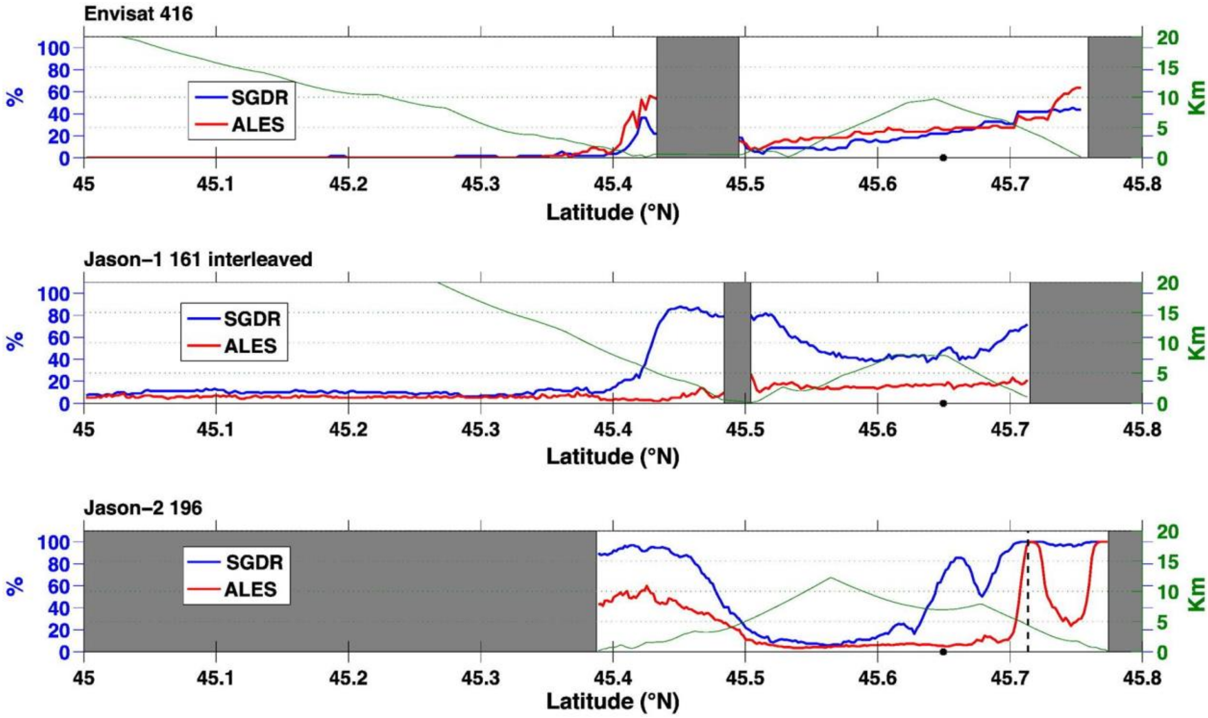

1355 **Figure 3: Percentage of outliers along track for Envisat track 416 (top right panel), Jason-1 track 161 (mid right panel) and Jason-2 track 196 (bottom right panel) from SGDR (blue line) and ALES (red line) products. Land is shaded in grey. The green line represents the distance from the closest coast (adapted from Passaro et al., 2014).**

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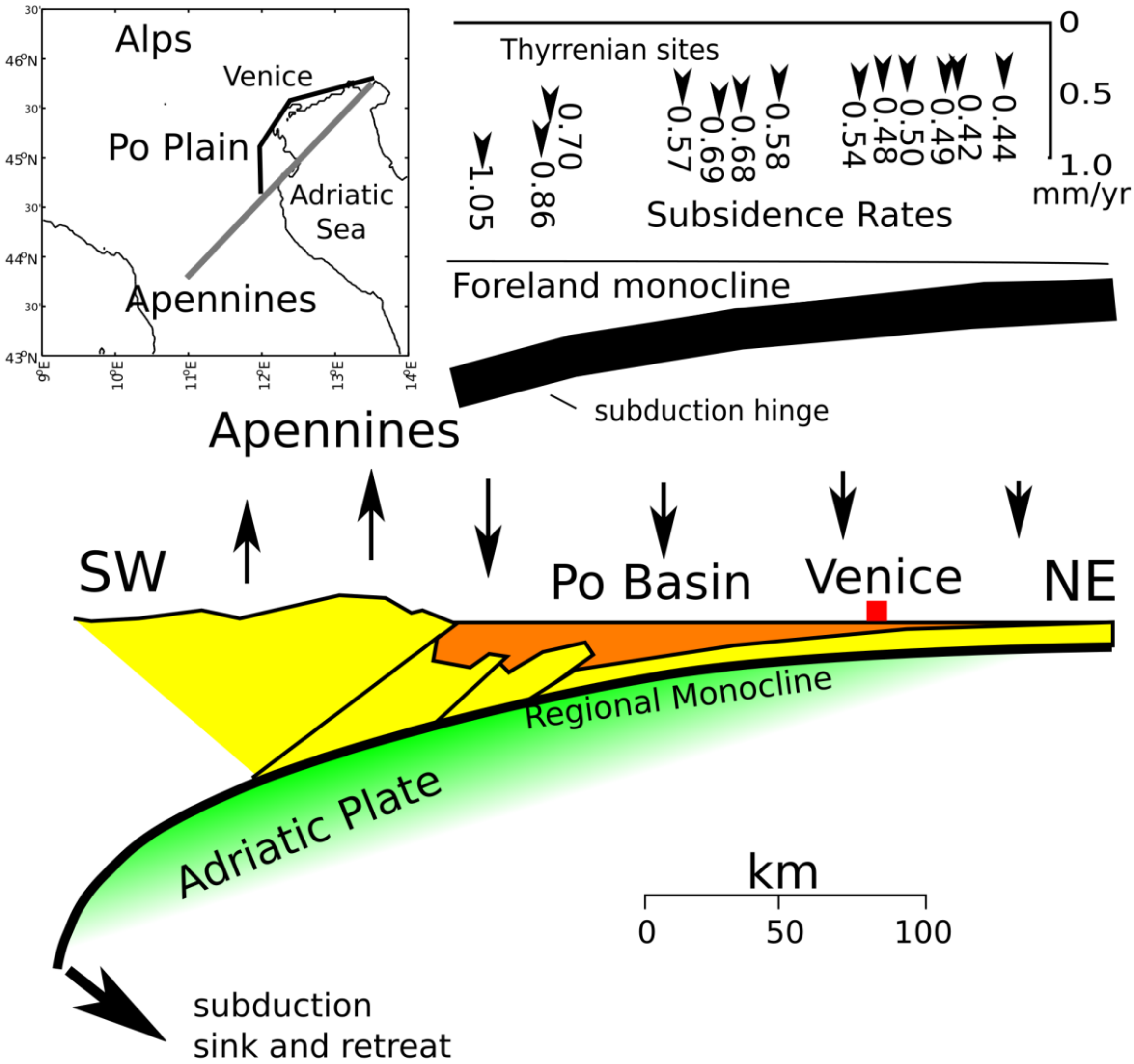

Figure 4: Geological setting of the Po plain area with dominant tectonic features (adapted from Cuffaro et al., 2010).

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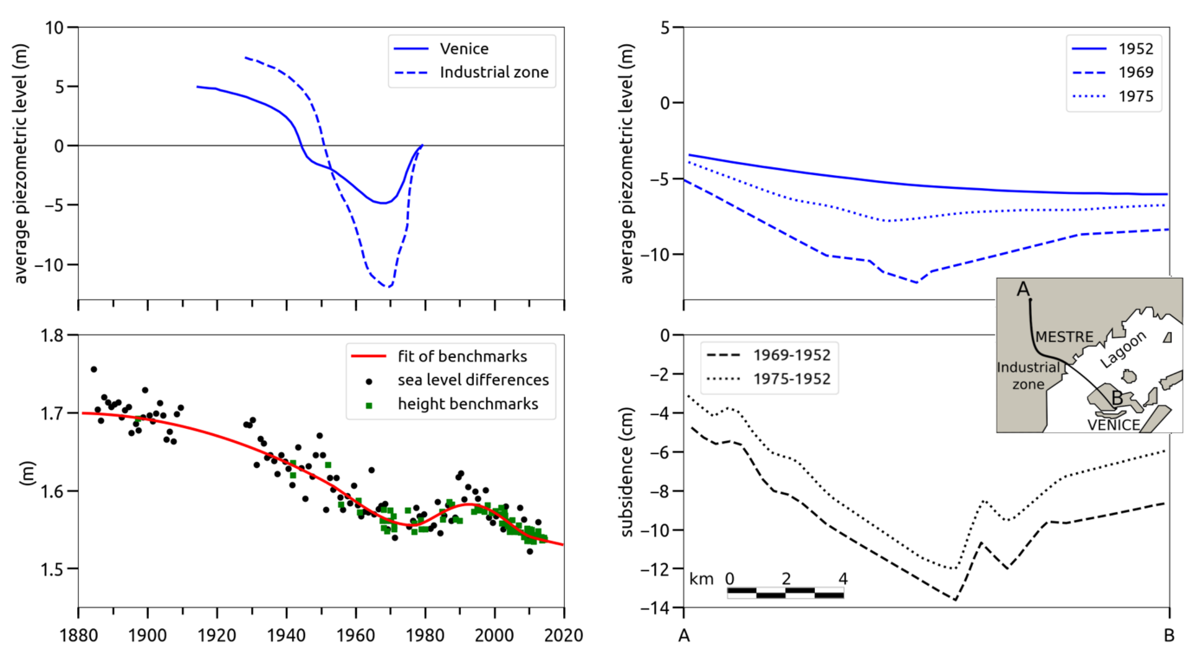

1360 **Figure 5: (a) Comparison of the piezometric level in the Marghera industrial area and in Venice from 1910 to 1980. Redrawn after Gatto and Carbognin (1981); (b) Average piezometric level between 1952 and 1975 along a levelling line from the mainland to Venice: recovery and rebound (redrawn after Carbognin et al., 1976). (c) Empirical curve (red line) accounting for subsidence in Venice (updated from Zerbini et al., 2017; from 2013 onward, the subsidence trend shown in the figure is the one derived from the GPS data of the station PSAL, see Table 3). Black dots represent the annual sea level difference between Genoa and Venice. Other**
1365 **symbols represent the height of various benchmarks; (d) same as (b) but for land subsidence.**

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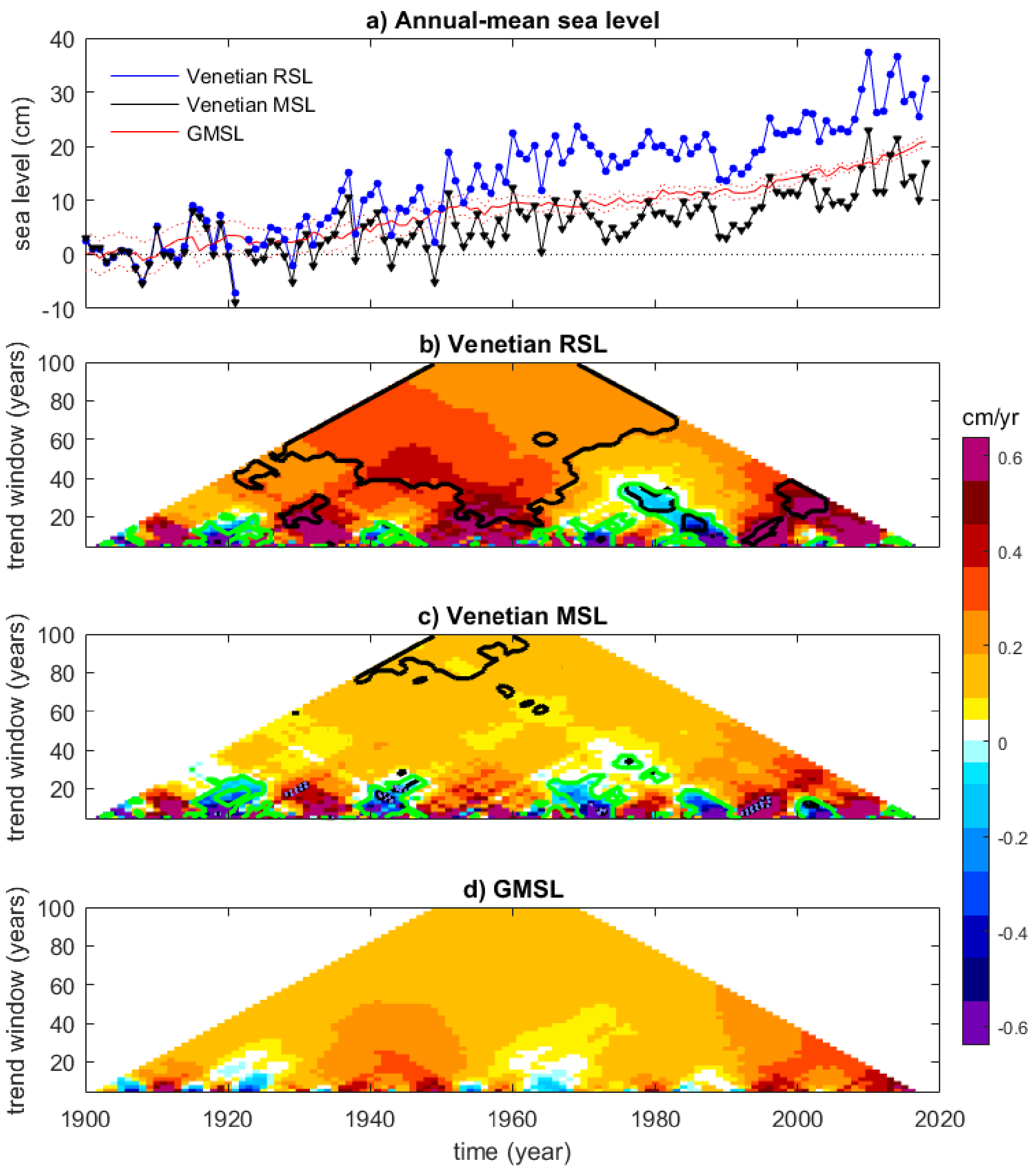

1370 **Figure 6: Comparison between trend estimates of GMSL and Venetian sea levels (RSL and MSL). (a) Temporal evolution of annual-mean sea levels, including GMSL (from Frederikse et al., 2020; dashed lines are upper and lower estimates) and Venetian RSL and MSL (i.e., RSL with subsidence removed). All anomalies with respect to the 1900-1910 mean. (b-d) Maps illustrating linear sea-level trends, estimated via linear regression, for running windows of variable width along the observation period. In panels b and c Black contours illustrate where the GMSL and Venetian RSL/MSL trend estimates do not overlap within 95% confidence intervals, while green contours indicate where they differ in the sign.**

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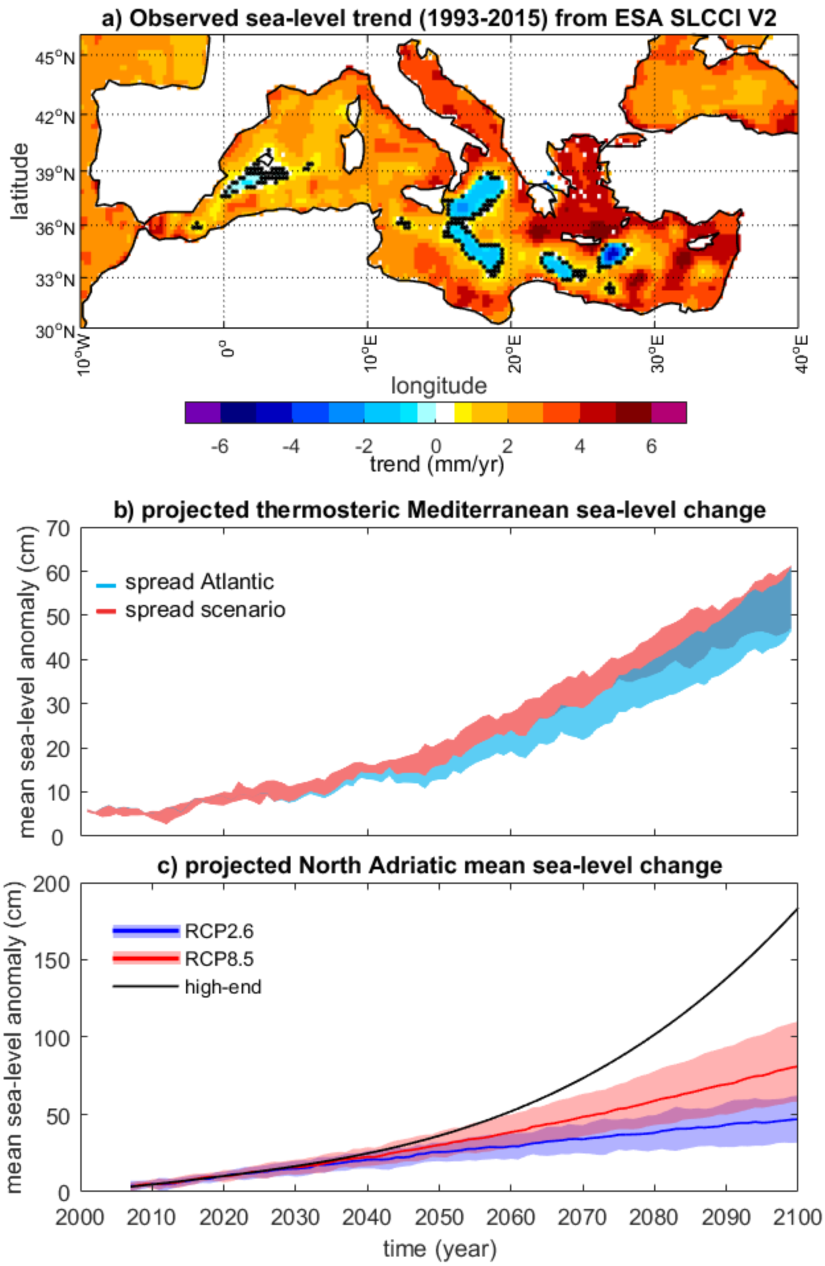

Figure 7: Observed and projected trends of Mediterranean sea level variations. (a) Sea-level trends in the Mediterranean Sea obtained using the ESA SLCCI V2 product over the period 1993-2015. Dots indicate grid points where the trend is not different from zero within the associated error range. (b) Projected thermosteric basin-average sea-level anomalies for the Mediterranean Sea and associated uncertainties related to the Atlantic hydrographic boundary conditions (blue) and to the socio-economic scenarios based on the Special Report on Emissions Scenarios (red) with the regional ocean model NEMOMED8, for the 2000-2100 period (vs. 1961-1990). Adapted from (Slangen et al., 2016). (c) Projected Northern Adriatic RSL anomalies and associated uncertainties related to socio-economic scenarios (shading: 5-95 percentile range, line: median). Adapted from Thiéblemont et al. (2019).

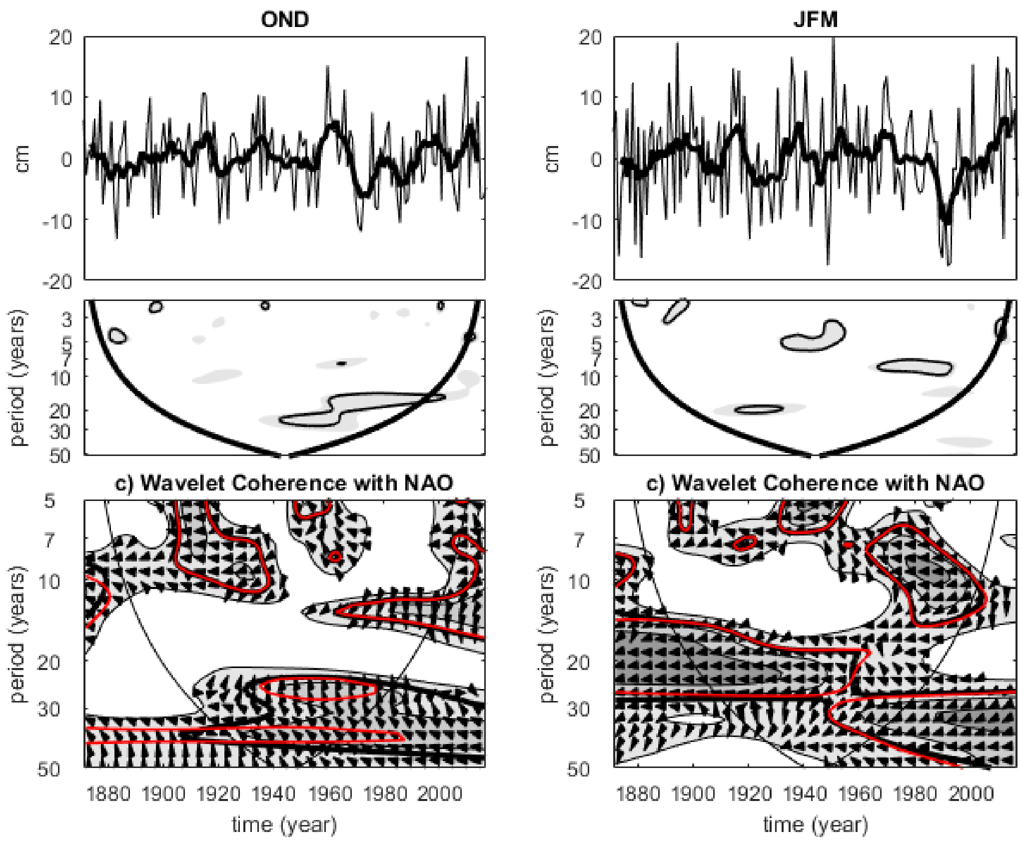

Figure 8: Interannual to interdecadal winter (left) and autumn (right) Venetian relative sea level variability since 1872 and its link with the NAO. Top: detrended (second order polynomial fit) time series of Punta della Salute gauge record, after removal of subsidence (estimated from Zerbini et al. (2017); Mid: Continuous Wavelet Spectrum (shading: 90% confidence; black contour 95% confidence; black lines: cone of influence where edge effects occur); Bottom: wavelet coherence spectrum between Punta della Salute data and the Jones NAO index (arrows indicate the phase, with co-phase pointing to the right; thick black contour: 95% confidence, in red for Punta della Salute data without removal of subsidence, detrended as in the main analysis, black lines: cone of influence).

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Table 1 - List of acronyms used in the paper.

BP	Before Present
O	Order of
NAO	North Atlantic Oscillation
RSL/MSL	Relative/Mean Sea Level
EAWR	East Atlantic Western Russia pattern
SCA	Scandinavian pattern
GIA	Glacial Isostatic Adjustment
CM	Comune Marino/Comune Alta Marea
MTL	Mean Tide Level
ZMPS	Zero Mareografico Punta Salute
ALES	Adaptive Leading Edge Subwaveform
RMS	Root Mean Square
RADS	Radar Altimeter Database System
ESA - SLCCI	European Space Agency - Sea Level Climate Change Initiative
CTOH	Centre of Topography of the Oceans and the Hydrosphere
SHYFEM	Shallow water HYdrodynamic Finite Element Model
AIC	Akaike Information Criterion
FPE	Final Prediction Error

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Table 2 Time evolution of the natural component of land subsidence in the Venetian region over geological time scales

Period	Subsidence rate [mm/yr]	Data source	Reference(s)
Last 2 Myr	~0.5	Nannofossil biostratigraphy, paleomagnetic polarity, magnetic susceptivity and sedimentologic facies of a drilled core	Kent et al., 2002
Last 1.43 Myr	0.7-1.0	Thickness of Pleistocene sediments from seismic lines and boreholes	Carminati et al., 2003
Last 125 kyr	0.58-0.69	MIS 5.5 paralic deposits in drilled cores	Antonioli et al., 2009
Last 40 kyr	1.2-1.3	Radiocarbon dating on organic remains, mainly peats and shells	Bortolami et al., 1985
4-5 kyr	1	Same as previous line	Bortolami et al., 1985
	1.1±0.3	Geomorphological and archaeological markers	Antonioli et al., 2009 (From their Table 1: average of H/G values for sites 17, 27 and 30). Original data from Antonioli et al. (2009); Lezziero (2002); Serandrei Barbero et al. (2001);

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Table 3 - Recent evolution of land subsidence in the historical city center of Venice as measured using geodetic techniques. Tosi et al. (2013) point out that the uncertainties associated with their SAR estimates represent the ground motion variability at the city scale and are not related to the measurement accuracy.

Period	Subsidence rate [mm/yr]	Data source	Reference(s)
At the turn of the 19th and 20th Century	0.9	Long-term interpolation of height benchmarks	Zerbini et al., 2017
1931-1970	2.3	Difference of tide gauge records (with reference to Trieste)	Carbognin et al., 2004
	2.3	Long-term interpolation of height benchmarks	Zerbini et al., 2017
1953-1973	5	leveling	Gatto and Carbognin, 1981
1973-1993	-0.02 (uplift)	leveling	Carbognin et al., 1995a, 1995b
1992-2002	0.8±0.7	SAR	Tosi et al., 2013
2003-2010	1.0±0.7	SAR	Tosi et al., 2013
2008-2020	1.7±0.5	GPS station VEN1 (Riva dei Sette Mari)	daily solutions provided by NGL (Blewitt et al., 2018); velocity estimated assuming a white + power-law noise model of a priori unknown spectral index (CATS Software, Williams, 2008) (consistent with Santamaría-Gómez et al., 2017)

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2014-2020	0.9±0.6	GPS station PSAL (Punta della Salute)	daily solutions provided by NGL (Blewitt et al., 2018); velocity estimated assuming a white + power-law noise model of a priori unknown spectral index (CATS Software, Williams, 2008)

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Table 4 - Linear trends of Venice RSL from tide gauge measurements estimated by various authors in the last 15 years. Errors are STD (68% confidence) except where noted in the Confidence column. The linear fit of observed sea level is used except where annotated. Estimates are grouped based on the period of analysis: long-term and satellite altimetry period.

Period	**Source**	**Trend (mm yr^{-1})**	**Confidence**	**Notes**
Long-term				
1909-2000	Marcos and Tsimplis, (2008)	2.5±0.1		
	Wöppelmann and Marcos, (2012)	2.45±0.09		
1914-2000	Vecchio et al., 2019	2.43±0.23	90%	
		2.78±0.04		trend derived from fit using straight line plus Empirical Mode Decomposition components
1872-2019	this study	2.53 ± 0.14	95%	deseasoned data
Altimetry period				
1993-2015	Vignudelli et al. (2019b)	6.29±1.53	99%	Punta della Salute tide gauge data
		5.29±1.27	99%	Punta della Salute tide gauge data with IBE correction
1993-2019	this study	5.01±1.75	95%	deseasoned data

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Table 5 - Linear trends of Venice MSL from tide gauge data after removal of subsidence and from satellite altimetry estimated by various authors in the last 15 years. Errors are STD (68% confidence) except where noted in the Confidence column. The linear fit of observed sea level is used except.

Period	Source	Trend (mm/yr)	Confidence	Notes
Long-term				
1890-2007	Carbognin et al. (2010)	1.20 ± 0.01		deseasoned data
1872-2012	Zerbini et al. (2017)	1.23±0.15	95%	deseasoned data
1934-2012		1.20±0.35	95%	deseasoned data
1905-2005	Scarascia and Lionello (2013)	1.3	N.A.	comparison among adriatic tide gauges
1872-2019	this study: (raw data, subsidence removed - Zerbini estimate updated)	1.23 ± 0.13	95%	deseasoned data
Altimetry period				
1993-2008	Fenoglio-Marc et al., 2012a	5.9±1.4	95%	altimetry data with dynamic atmospheric correction
		5.6±1.6	95%	tide gauge data with dynamic atmospheric correction
1993-2015	Vignudelli et al. (2019b)	4.25±1.25	99%	altimetry point near Venice, IBE removal
1993-2019	this study	2.76 ±1.75	95%	deseasoned data

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1425 **Table 6 - Performance of the linear and quadratic regression models applied on the raw annual time series of Venetian RSL and the corresponding climatic component alone (i.e., subsidence removed) for the periods 1872-2019 and 1993-2019. R^2 is the coefficient of determination, AIC is the Akaike Information Criterion, and FPE is the Final Prediction Error.**

	Raw series		**Climatic component**	
	Linear	**Quadratic**	**Linear**	**Quadratic**
1872-2019				
R^2	0.89	0.89	0.67	0.69
AIC	400	398	570	570
FPE	15	15	48	47
1993-2019				
R^2	0.58	0.59	0.30	0.30
AIC	70	69	76	76
FPE	14	14	18	18