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LAGOONS AND COASTAL WETLANDS

Observations on future sea level changes in the Venice lagoon

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Abstract ‘Venice is sinking while the sea level is rising’ is a common statement in issues concerning the future of the Venice lagoon. The search for a reliable interpretative tool for measured sea-level changes has taken on more urgency since the sea-level rise was indexed as the consequence of global warming—with catastrophic scenarios for both the ecotone and the city, linked to increasing lagoon erosion, sudden modifications of biological equilibriums, loss of wetlands, salt aggression and an increasing frequency of exceptional high tide events. However, the peculiar hydrodynamics of the northern Adriatic Sea, made more complex by the freshwater inflow from the Po River, and the conceptual limits of existing long-term predictive systems, would suggest a more cautious approach to the scenarios yet proposed for the next century.

Keywords Sea level · Lagoon · Tidal flats · Subsidence · Climate · Venice · Po River · Northern Adriatic

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Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues

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Introduction

The Venice lagoon (Fig. 1) is situated along a low-lying coast within the easternmost boundary of the Po Plain and connected to the northern Adriatic Sea through three wide mouths (Chioggia, Malamocco and Lido). It is the largest lagoon in the Mediterranean since it extends for about 550 km^2. Given the enormous amount of (ecological, historical and economical) interest in both the ecotone and the city, the lagoon has undergone a number of anthropic interventions since the fifteenth century, in an attempt to preserve a state of unstable equilibrium by counteracting its natural evolution. These include diverting river outflows to outside the lagoon and opening and widening the tidal inlets (an historical introduction to human interventions in the Venice lagoon can be found in: Ravera, 2000). In this context, the best known and most debated symptom of the disruption of this fragile ecotone’s delicate equilibrium is the periodic ‘*acqua alta*’ phenomenon (excessive high tides with water at flood level). The city is in such a unique setting—in the centre of the lagoon and built on piles—that even storm surges with comparatively small amplitudes (of less than 1 m) can cause flooding. However, the search for a reliable tool for interpreting measured sea levels has taken on more urgency in recent decades when an increase of the city’s susceptibility to these high tides and flooding

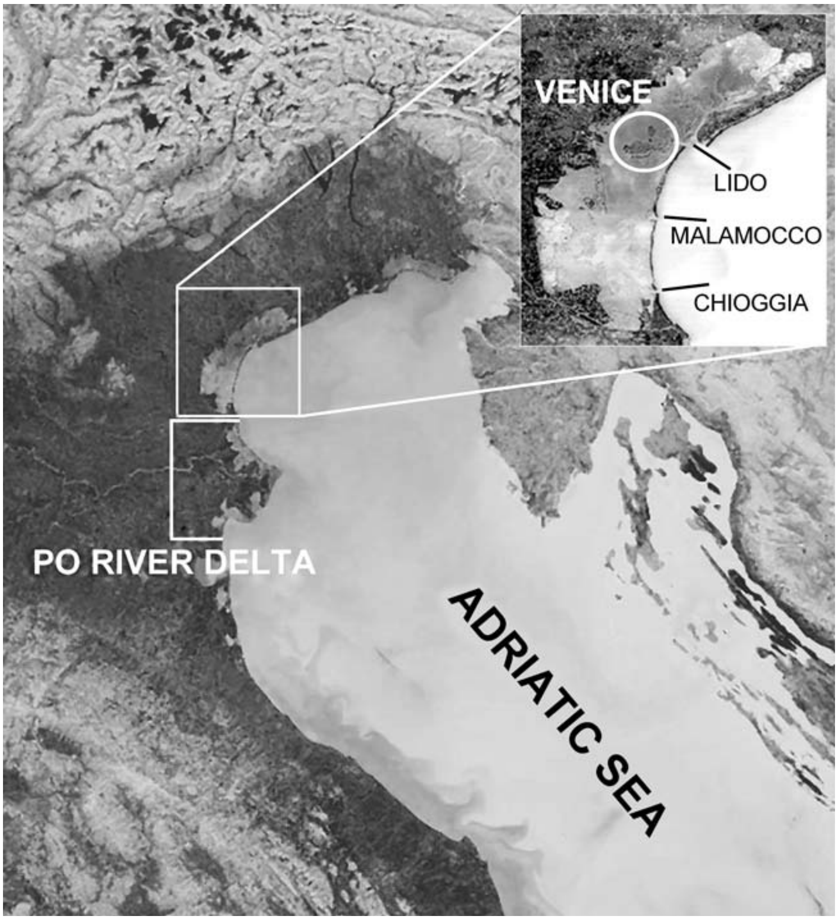


Fig. 1 Map of the northern Adriatic Sea showing the Venice lagoon and the Po River Delta

events has been observed (Canestrelli et al., 2001) and the global sea-level rise, that is expected to lead to progressively higher background water levels in the lagoon, was indexed as the consequence of global warming (Church et al., 2001).

The potential consequences of an increase in the mean sea level go beyond the scenario of the serious degradation of the city of Venice, as a sea level rise would impact on the entire ecosystem that surrounds the city, mainly in terms of the loss of valuable ecotope areas such as the intertidal flats (see ‘‘Sea level rise in the Venice lagoon: ecological impacts’’).

The Venice lagoon ecosystem is morphologically definable as estuarine, hence it is controlled substantially by tidal excursions (with a micro- to meso-tidal regime). The inflow of saltwater throughout the whole basin occurs by means of an intricate network of canals, through which tidal currents can propagate. In some inner areas (i.e. shoals inside the lagoon) where waves are actually more important than the tides for the hydrodynamics (for instance in terms of sediment entrainment), the ‘tidal breath’ induced by the inflow/outflow through the lagoon mouths also assumes a fundamental ecological role by controlling the emersion/submersion ratios in marshy areas (*barene*) through changes in sea-level height.

As for the potential impact of the changes in tidal flushing due to sea-level fluctuations, it is the position and height of the sea in relation to the land [Relative Sea Level (RSL)] that is important, as this determines the location of the shoreline. In addition to global fluctuations in sea levels (resulting from the growth and melting of continental glaciers and thermal expansion of oceanic waters), many physical processes may result in changes of the RSL at local-to-regional scales. These include changes in meltwater load, crustal rebound from glaciation, uplift or subsidence in coastal areas related to various tectonic processes, fluid withdrawal, and sediment deposition and compaction (see "RSL in the Venice lagoon: the role of subsidence"). Moreover, the water mass structure and the water fluxes and exchanges with adjacent seas are concurrent with long-term sea-level fluctuations. In particular, most of the Mediterranean sub-basins have an evaporative nature, resulting from strong evaporation and weak river runoff, so that in recent years their sea-level trends have been substantially different from those based on global ocean-related estimates (see "RSL in the Venice lagoon: the role of seasonal to decadal climatic fluctuations").

The tide gauges located in the Venice lagoon and inside the city provide a direct measurement of the RSL, as they incorporate landmass movements (natural and urban subsidence, the subsidence of the man-made structures on which tide gauges are mounted and changes in the seabed and coastal topography), which are read by the instruments as sea-level variations. Thus, even if gauge records are coherent and indicative, they are difficult to interpret in dynamic and evolutionary terms. In fact, although the direct measurement of the parameter "perceived" by the coast is the best value of gauge measurements, this also represents their major limitation as they cannot lead to a reliable sea-level change estimate unless independent estimations of local crustal movements are available. Hence, the necessity for estimating individual contributions to the RSL is crucial in order to provide reliable future sea-level fluctuation scenarios.

Once the possible ecological impacts of fluctuations in the RSL in the Venice lagoon have been presented (see "Sea level rise in the Venice lagoon: ecological impacts") and the contribution of local subsidence (natural and anthropogenic) in the Venice lagoon have been estimated (see "RSL in the Venice lagoon: the role of subsidence"), the fraction of the RSL fluctuations measured in the lagoon and attributable to effective sea-level changes is calculated and linked to climatic fluctuations on a regional scale, through the hydrodynamics induced in the Northern Adriatic by the freshwater inflow from the Po River (see "RSL in the Venice lagoon: the role of seasonal to decadal climatic fluctuations"). Concluding remarks follow, with some criticisms of former forecasts for next century sea-level rise in the Venice lagoon.

Sea level rise in the Venice lagoon: ecological impacts

The bed of a lagoon is the substrate upon which biodiversity is dependent. Changes in the morphology can induce a shift in the biological communities that reside in a defined area by changing the potential vocation of the area itself. Given the great variability in biomass and biodiversity which characterizes the Venice lagoon (i.e. low energy and highly confined zones with low biodiversity; marshlands and gutters; canals; protected marine environments with high biodiversity; areas near the mouths with strong hydrodynamics and tidal renewals), it is fundamental to assess the areas where the ecosystem functionality may be compromised. In fact, over recent decades the lagoon has been suffering from severe environmental degradation, which was induced also by complex morphodynamic changes caused by natural processes (geomorphologic variations have been naturally occurring in the lagoon since its formation) and by the direct and indirect impact of human activities. As early as the seventies (Montanelli et al., 1970) there were great concerns about the loss of a large proportion of tidal flat habitats in the lagoon—up to 160 km^2 on the northern, southern and inner borders of the lagoon—because of human interventions (amongst others: the construction of the Malamocco canal, which services the industrial area of Marghera, and fish farms). The ecological importance of these habitats is not only naturalistic, because of the biological communities they host, but also environmental, through their role in controlling the water quality by sequestrating the industrial and domestic pollutants that are discharged into the lagoon. This is the reason why tidal flushing is central to the well-being of the lagoon, and many scientific and technical interventions currently focus on controlling and recovering the tidal flats in an attempt to limit their natural erosion (from the effect of waves and wave resuspension).

Despite the great morphodynamic complexity of the tidal flats (currently the northern part of the lagoon is witnessing a tendency for the growth of tidal flats while the southern and central parts have been scoured and deepened—see Amos et al., 2002), which includes a link between marsh elevation, sea-level changes and sediment deposition/resuspension (Reed, 1995), the flows through the three mouths and the materials carried by the main tidal channels are likely to be key factors in balancing the sediment budget, and in turn the geomorphological evolution of marshes.

Thus, particular emphasis should be placed on comparing sedimentation rates and contemporary RSL estimates. With a scenario of rising sea-levels and given the micro- to meso-tidal nature of the subsiding lagoon (see "RSL in the Venice lagoon: the role of subsidence"), a sedimentation deficit is a likely consequence of increased erosion due to higher energy waves (Stevenson et al., 1986). Because of the inadequate sediment supply, the elevations of marsh systems may not adjust to even a moderate rate of sea-level rise, which could lead to a substantial reduction of the tidal flats. The ecological effects are likely to be significant for the benthic assemblages of tidal flats (for a review see Raffaelli and Hawkins, 1996) and for the consumers they support, especially fish, shrimps and shorebirds, through complex and not easily predictable biological mechanisms. In addition to the loss of intertidal or shallow sublittoral areas, a rise in sea level would provide more habitats for salt tolerant flora and fauna, and fewer habitats for freshwater marsh grasses, thus changing nutrient and phytoplankton distributions in the lagoon.

Therefore, an understanding of both (a) the hydrodynamics in the Venice lagoon and of the erosion-transport-sedimentation processes, as well as their interrelations, and (b) soil subsidence and sea-level rise, are fundamental for preserving the delicate lagoon ecosystems. Great effort has already been put into understanding the phenomena of subsidence, sediment erosion, re-suspension, transport and sedimentation, sea-lagoon balance and hydrodynamics, as well as to the planning and management of interventions and protection works: several investigations have been conducted, including geomorphological and sedimentological studies (Ciavola et al., 2002; Rizzetto et al., 2003, respectively), profiles (Cola & Simonini, 2002), and mapping (Strozzi et al., 2002); a number of mathematical models have also been developed, focussing on hydrodynamics and morphology (Umgiesser, 2000; Bergamasco et al., 2001; Amos et al., 2002; Umgiesser et al., 2002; Bonardi et al., 2003). In this connection, once reliable estimates of interannual to decadal RSL fluctuations have been defined, these models may become optimal tools for evaluating how the distribution of the biologic communities in the lagoon would change in relation to sea-level changes, through distribution gradients related to hydro-morphological and chemical-physical conditions.

RSL in the Venice lagoon: the role of subsidence

The Venice lagoon's increased vulnerability to sea-level fluctuations is partly due to its location in an active area that is naturally subject to both tectonic and sedimentological processes, and partly to the consequences of human activities (i.e. urbanism, artesian withdrawals and modifications to the lagoon morphology).

The Po Plain encompasses an area of about 38,000 km^2 south of the Alps mountain range and its geodynamic features are related to long-term processes (plates subduction and Quaternary sediments compaction), and to short-term processes [PostGlacial Rebound (PGR) and differential compaction]. The PGR, which is the slow readjustment and rebalancing of the lithosphere and mantle during deglaciation after the downflexure caused by the Alpine ice cap during the last Ice Age, controls approximately 50% of the subsidence rates in the Po Plain (which range between 0 and 5 mm/yr) (Carminati et al., 2003b). It has been inducing temporal and spatial variability in the landmass movements since the Late Quaternary (different subsidence rates in the areas close to and far from the Alps) and they are still likely to be active (Mitrovica & Davis, 1995). Moreover, the Venice lagoon is located on a segment of the active southwest dipping monocline that is related to subduction in the northern Apennines, so that a significant part of the natural component of lagoon subsidence could be related to this downflexure (Carminati et al., 2003a). The solid material that is transported by rivers flowing into the Adriatic sea is distributed along the coast by the currents and this counterbalances the coastal lowering rate, while the subsidence effect in the Venice lagoon is not offset by sediment accumulation since its most important tributaries have been artificially diverted away from the lagoon since the XV century.

Subsidence rates within the Venice lagoon are spatially differentiated (the levelling campaigns of 1973 and 1993 showed rates ranging between 1.4 and –0.5 mm/yr: Teatini et al., 1995). In the second half of the 20th century, this variability was mainly affected by human activity, particularly urban subsidence and groundwater extraction. A comparative analysis of artesian exploitation and subsidence identified three distinct periods (Carbognin et al., 1977): the first before 1952, when artesian exploitation was not very intensive and subsidence was only due to natural causes; the second from 1952 to 1969, when artesian water extraction was very active, causing a local average subsidence rate in the city of over 9 cm, with local maxima of 10 cm; the last period, after water extraction had been stopped, was characterized by a period of stability and a subsequent ground-surface rebound (more than +2 cm in the historic centre in 1975 compared to 1969). At present, land subsidence maps of the lagoon (Strozzi et al., 2002) and the consistence between tidal records in Venice, Trieste, Rovinj and Bakar indicate that subsidence triggered by human activity is no longer an issue for Venice (apart from recently urbanized areas such as the isle of St. Elena, where sediment compaction is active), and that the ground level in the historical centre of Venice is almost stable and only subject to natural subsidence.

Hence it is now crucial to assess the natural subsidence rates in the area, their origin and variations over time. In particular, the difference between the estimates of long-term (10^6 yr) natural subsidence affected by the subduction associated with the Apennines (0.7–1.0 mm/yr, see Carminati et al., 2003a) and present-day natural subsidence in the lagoon (approximately 0.5 mm/yr, see Tosi et al., 2002) would suggest that the natural short-term component (10^3–10^4 yr) is still dominant in the Venetian area, since it is likely to be related to climatic changes such as the PGR. Thus, although the PGR effect has been diminishing, significant variations in the natural subsidence rate are not likely to occur in the Venice lagoon within the next century. This would mean that a lowering of the ground level in the order of 5 cm from present levels would seem to be a realistic estimate for the year 2100.

RSL in the Venice lagoon: the role of seasonal to decadal climatic fluctuations

The inter-relation between the mean sea level, the resulting circulation and wave climates in the Northern Adriatic may induce changes in the sea level inside the Venice lagoon, both in terms of tidal extremes and of seasonal to decadal fluctuations. In particular, the evolution of the meteorological and regional climatic parameters induce hydrostatic responses (through the ‘inverse barometer’ effect, see Anthes, 1982) and non-hydrostatic responses (thermoaline circulation and wind-driven Ekman Layer transport) in the sea levels of the Northern Adriatic. Notably, sea-level fluctuations occurring in the Mediterranean Sea and in its sub-basins on interannual to decadal scales are generally much larger than those associated with secular trends (Woolf et al., 2003), because of their evaporative nature which makes them sensitive to changes in precipitation/evaporation budgets. Changes in decadal sea-level trends in the Mediterranean are likely to be induced by transitions in the processes of deep water formation, through changes in the temperature and salinity of deep and intermediate layers (Tsimplis & Baker, 2000). Moreover, the Adriatic Sea’s shallow northern part, with an average depth of about 30 m, has strong continental characteristics so that its hydrodynamics and oceanographic parameters are highly dependent on the freshwater inflow, mainly through the induction of density currents. The plume of the River Po, whose formation and evolution are linked to the river's flow rates, seawater stratification and the wind stress from the Bora and Scirocco, adds to the complexity of the baroclinic geostrophic structure of the general circulation in the basin. Under typical winter conditions (November to March), when a cyclonic gyre north of the Po River delta—Rovinj line is present (Krajcar, 2003), the plume of the Po is confined to the western Adriatic shelf region. Nevertheless, following prolonged intense Bora events, the plume appears to be entrained into the circulation of the northern cyclonic gyre induced by the wind stress curl applied by the Bora (Paklar et al., 2001). Upwelling-favourable winds such as Scirocco reverse the western coastal current and advect Po waters towards the northern coast and offshore (Alberotanza et al., 2004).

In order to estimate the relationships between the Po River discharges and sea levels in the Venice lagoon, the monthly-mean values of the 'Punta della Salute' dataset (the gauge is sited in the historical centre of Venice) and the monthly-mean Po River discharges at Pontelagoscuro for the period 1968–2001 (after the worst flooding event ever recorded in Venice, occurred in the autumn of 1966) have been considered. The sea-level dataset was provided by the 'Ufficio Idrografico' (Hydrographic Office) of Venice and has been conventionally chosen as the reference data for the RSL in the Venice lagoon. The harmonic components of astronomical tides and the contribution of subsidence were subtracted from the observed sea-level, in order to obtain the meteorological contribution. Subsidence was estimated in accordance with the model by Carbognin et al. (1977), assuming the present-day subsidence rate to be 0.5 mm/yr.

The linear correlation ($r = 0.58$ for 34 cases, significant at $p < 0.001$) between the October–March averages of discharge and sea level (Fig. 2) would suggest the existence of a relationship; however, nothing can be deduced about the phase relationships or the causality between the two variables.

In order to obtain further information, which was not readily available from the raw dataset, a Wavelet Analysis was conducted on the signals to identify time/frequency localization. Wavelet Analysis, some background of which is provided in the paper by Torrence & Compo (1998), is based on mathematical transformations that decompose a one-dimensional time series into a diffused two-dimensional time-frequency image simultaneously, providing a means for getting information on both the amplitude (and the phase) of any 'periodic' signal in a time series, and how this amplitude varies with time. This information is obtained through the projection of a generic function (a wave function with a specific frequency and finite duration) on the data, by sliding the wavelet along the time series, and scaling it by changing its width. The generic function is called the *mother wavelet* $\phi(x)$ (in this study the Morlet function was used), defined as:

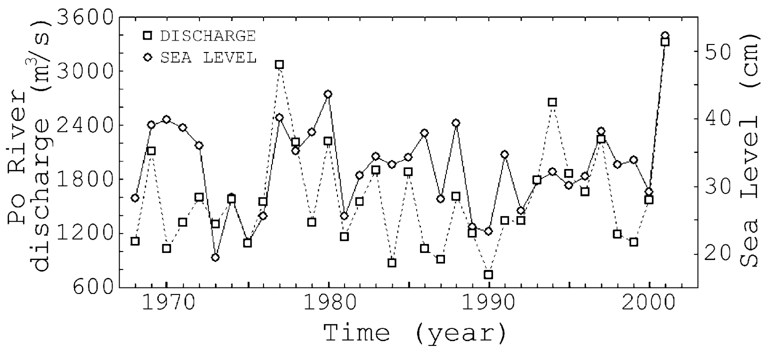
$$\phi(x) = \sum_{k \in Z} c_k \phi(2x - k) \tag{1}$$

where c_k is a set of real coefficients that verify regularity, orthogonality and normalization requirements. All the elementary basis functions are obtained by translating and scaling the mother wavelet through a *scaling function* $\Psi(x)$, defined as:

$$\Psi(x) = \sum_{k \in Z} (-1)^k c_{1-k} \phi(2x - k) \tag{2}$$

The scaling is the main advantage of the Wavelet Analysis over a Windowed Fourier Transform, whose basic elements are sines and cosines, which solves the frequency localization problem but is dependent on the window size used, so that different frequencies are treated inconsistently. The Wavelet Power Spectrum (WPS), defined as the power (absolute value squared) of the wavelet transform of the original series, provides information on the oscillations within the signal at a certain scale and a certain time. Significance levels are established by comparing the wavelet spectrum of the variable under study with background theoretical spectra of a red-noise (univariate lag-1 autoregressive) process.

Fig. 2 October–March averages of Po River discharges and of sea-levels measured in the Venice lagoon



The WPS of discharges and sea levels shown in Fig. 3 and 4 respectively, indicate that there is a greater concentration of significant power in bands below the 16-month period. The significant peaks within the 4–8-month band in Fig. 3 (around 1968, 1977, 1983–1984, 1994 and 2000–2001), which are indices of high-power seasonal signals, are concurrent to high discharges from the Po River, and not necessarily linked to longer wet periods. Interestingly, groups of peaks at these frequencies are separated by periods of low power with a mean length of about 8 years. It is worth noting that the largest significant peaks in the 4–8 months band in the WPS of sea-levels appear in periods when the seasonal signal of the discharge is low (around 1991–1993 and 1997). Within the 8–16-month band (annual), significant peaks in sea levels (around 1970–1971, 1976–1982, 1992–1994 and 1997) are much larger than in shorter frequencies; the opposite behaviour emerges from the spectrum of the discharges (around 1972, 1977–1978, 1986). It is also worth pointing out that in the annual band the significant peaks of the two time series alternate, with the exception of the concurrent peaks around 1977–1978.

The characteristics of a WPS are reflected in the Global Wavelet Spectrum (GWS), which is obtained by averaging in time the WPS over all the local wavelet spectra and provides a measure of the variation of energies across scales. The GWS in Fig. 5 shows the dominating frequencies to have period of 6 months (discharges and sea levels) and 12 months (discharges). Notably, despite the GWS of discharges and sea levels not being significant at low frequencies, both present an important peak around the 8-year period (8.25 and 7.35 years, respectively). Significance levels were derived assuming red-noise spectra with lag-1 autocorrelation parameters $\alpha = 0.49$ for discharges and $\alpha = 0.34$ for sea levels.

The normalized Wavelet Coherence (Maraun & Kurths, 2004) is a bivariate extension of the Wavelet Analysis, defined as the expectation value of the product of the two corresponding wavelet transforms (which defines the Wavelet Cross Spectrum), normalized to the two single WPS. It individuates regions with large common power in the time-frequency domain of two time series and further reveals information about their phase relationship: if two series are physically related (which may be suggestive of causality) a consistent or slowly varying phase lag is expected and the circular mean of the phase angles can be used to quantify the phase relationship. The Wavelet Coherence spectrum of discharges and sea levels is reported in Fig. 6. Although the 5% significance level is not a reliable indication of causality, the significant region of the spectrum is so extensive that it seems very unlikely that this is simply a chance occurrence, at least on seasonal (around the 6-month period) and interannual (periods of 16 to 32 months) wavelengths.

Discussion

Long-term cyclic variations in sea level in the Mediterranean Sea are partly due to the interannual/decadal variability of the upper ocean circulation (Cazenave et al., 2001). Nevertheless, sea-level fluctuations induced by changes in deep water formation processes and by hydrostatic and non-hydrostatic responses to the climate variabil-

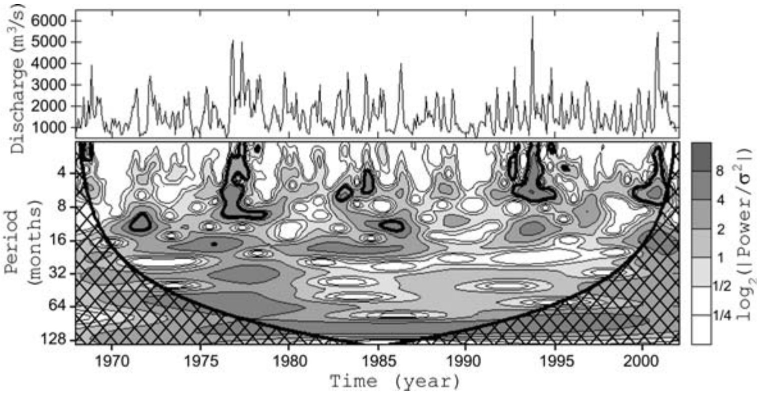


Fig. 3 Time series of monthly discharges of the Po River for the period 1968–2001 (top) and corresponding Wavelet Power Spectrum (bottom). The power is normalized by $1/\sigma^2$. The black thick contour is the 5% significance level for a red-noise AR(1) process with lag-1 of 0.49. The cross-hatched region is the cone of influence, where edge effects occur

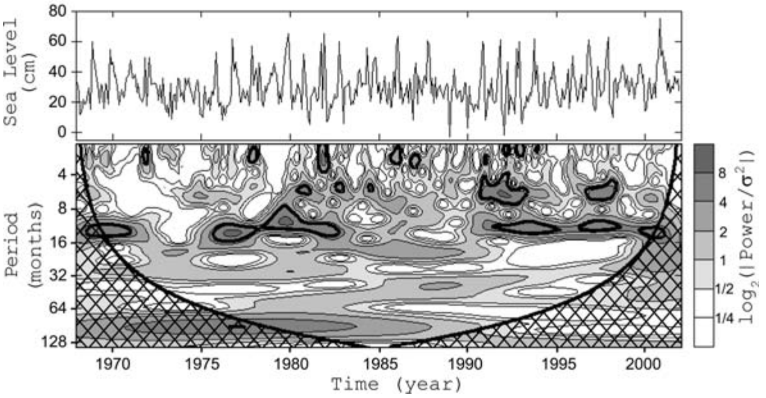


Fig. 4 Time series of monthly sea levels in the Venice lagoon for the period 1968–2001 (top) and corresponding Wavelet Power Spectrum (bottom). The power is normalized by $1/\sigma^2$. The black thick contour is the 5% significance level for a red-noise AR(1) process with lag-1 of 0.34. The cross-hatched region is the cone of influence, where edge effects occur

ity of the region, make it impossible to attain forecasts based on estimates of the global sea-level rise alone. The sea-level increase throughout the Eastern Mediterranean area during the 1990s, which was comparable to the rise in global sea-level rates recorded by the Intergovernmental Panel on Climate Change (IPCC), was concomitant to a prolonged positive phase of the North Atlantic Oscillation (NAO) (Tsimplis & Baker, 2000), which is the foremost mode of climate variability in the North Atlantic region (Hurrell, 1995) as it controls the synoptic weather over the entire Euro-Mediterranean area. Remarkably, satellite altimeter measurements (Topex/Poseidon, 1992–2001) indicate the Northern Adriatic basin as one of the areas that is most sensitive to fluctuations in the NAO, despite its influence in the Mediterranean Sea being quite homogeneous (Woolf et al., 2003).

Thus, coastal zone management would benefit by the coupling of long-term future projections of sea levels (as those based on global sea-level rise rates) with indications of the expected local interannual-to-decadal fluctuations (as those driven by the NAO). All the more so because in the Mediteranean decadal sea-level fluctuations are

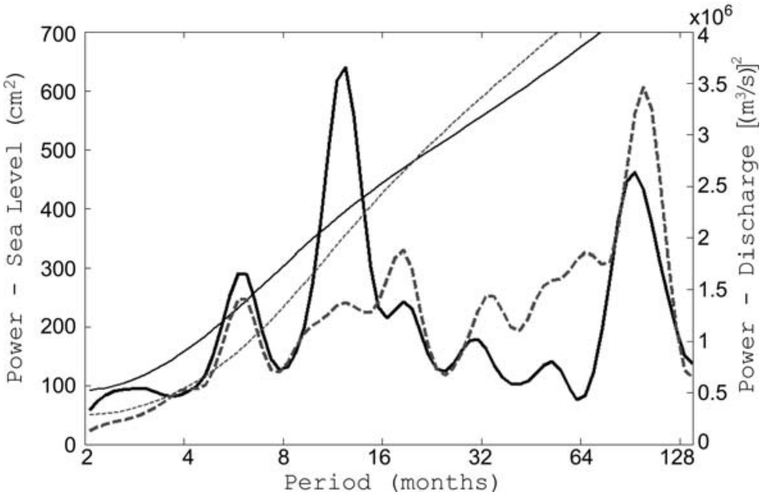


Fig. 5 Global wavelet spectra of monthly Po River discharges (black line) and sea levels in the Venice lagoon (dotted line) for the period 1968–2001, with the 5% significance levels calculated from backward red-noise spectra

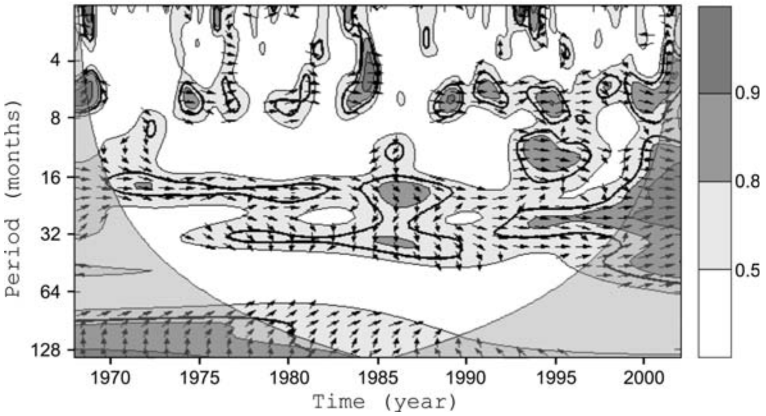


Fig. 6 Wavelet coherence between monthly Po River discharges and sea levels in the Venice lagoon for the period 1968–2001. The 5% significance level against red noise, tested with a Monte Carlo method (10,000 surrogate datasets), is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left and discharge leading sea levels by 90° pointing straight down). The shaded region is the cone of influence, where edge effects occur

far more important than secular trends (Woolf et al., 2003). In fact, the estimates for the future sea-level rise in the Venice lagoon in the year 2100 obtained from former studies from the IPCC (47 ± 39 cm/cy, see Church et al., 2001) and from the Consortium for Research in the Venice lagoon (CO.RI.LA., 1999) (a ‘most probable’ scenario of +16.4 cm/cy, of which 12.3 cm/cy due to sea-level changes) cannot really provide an effective picture of the nearest ‘most probable’ future.

In this context, the individuation of phase-locked fluctuations on interannual to decadal scales between sea levels and predictable climatic parameters may suggest sea-level patterns over the next decades. In particular, discharges are a function of the spatial integration of precipitation over the river’s catchment. Besides the hydrological processes linking rainfalls to discharge are affected by non-linear processes (such as infiltration, evapotranspiration and snow melt) and various human interventions (such as channel and catchment changes, and management of water reservoirs), the analysis of discharge records provides an immediate insight into climatic conditions. In the case of the Po River, the discharges measured at Pontelagoscuro (the closing section of the river, located about 90 km upstream the Po Delta) are indicative of the precipitation variability over the whole Po catchment, which has an extension of about 70,000 km^2, hence providing indications of the regional climate. As discussed in ''RSL in the Venice lagoon: the role of seasonal to decadal climatic fluctuations'', monthly Po River discharges and sea levels in the Venice lagoon show wavelet spectra with peculiar but related characteristics, above all on seasonal to interannual scales: (a) periods with significant peaks alternate with low power periods; (b) opposite behaviour of high-frequency power signals emerges from the two spectra; (c) global power spectra has peaks at similar periods; (d) phase relationships emerge between the two time series.

Further observations can be drawn from these results.

(1) Interestingly, peaks in the WPS of the Po River discharges seem to occur within active phases of the NAO, which are not necessarily positive as in the case of 2000–2001. The patterns of the scale averaged wavelet power (defined as the weighted sum of the WPS over a defined interval of scales) over the 8–16 month band for the Po River discharges, and of the smoothed absolute values of the NAO index in Fig. 7, are likely to confirm the existence of a link between dominant zonal or meridional atmospheric circulation (controlled by the NAO) and seasonal to interannual precipitation in regions south of the Alps, an observation which has already been suggested by Quadrelli et al. (2001).

(2) Phase relationships shown in the Wavelet Coherence spectrum (Fig. 6) indicate that the oscillatory patterns of discharges and sea levels are dynamically synchronized across a wide region of temporal and frequency domains: they are in-phase in the 4–8 month band, as a consequence of their similar seasonal patterns, and discharges generally lead sea-level fluctuations on an interannual scale. Non-phase-locked periods, such as the 1980s, are a consequence of the non-linear responses of regional climatic parameters to the sources of their variability. In this context, it is worth remembering that the 1980s were a particularly active period for the climate on a global scale: they followed the 'climate shift' of 1977 (Hare & Mantua, 2000), were affected by the atmospheric effects of the 1982 volcanic eruption of the El Chichon (Mexico) and by two El Niño events (a strong one in 1982–1983 and a weaker one in 1986–1987), as well as a strong La Niña event in 1988–1989 (Philander, 1990). Further discussions about the response of Po River discharges and derived indices of drought to climatic fluctuations and extreme events occurring on a regional scale can be found in Tomasino et al. (2004b).

(3) Finally, the presence of peaks around the 8-year period in the GWS of both time series (Fig. 5), although not significant, may be related to the climatic variability induced by solar forcing, whose frequency spectrum is linked to the solar wind and has one of its strongest peaks at the 8.6-year period (Landscheidt, 2000). In this connection, a study on the feasibility of long-term forecasting of seasonal discharges of the Po River based on calculable solar is available in Tomasino et al. (2004a).

Conclusions

Variations in sea-level height, from the diurnal oscillations to the decadal and secular fluctuations forced by climate changes, are the dominant forces in the dynamics of the Venice lagoon ecosystems. An understanding of sea level variability within the lagoon and in the adjacent basin (the Northern Adriatic) and of the forces that induce their fluctuations, is therefore necessary in order to gain a clearer understanding of how the delicate natural equilibriums of the ecotone can be preserved in the future. Short-term phenom-

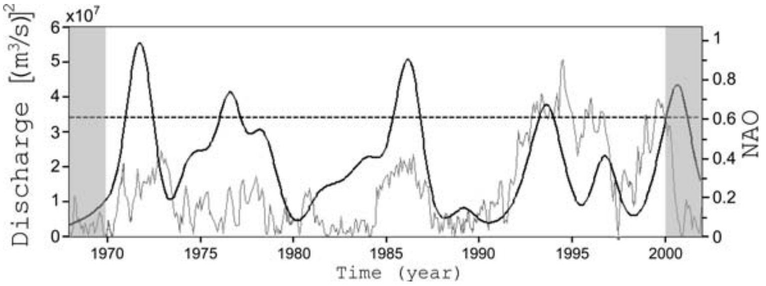


Fig. 7 Time averaged wavelet spectrum of the monthly Po River discharges for the 8–16-month scales (black line) with 5% significance level (dotted line), and absolute values of the 3-year centred smoothing of the monthly NAO index (grey line). Shaded area indicates where edge effects occur

ena such as storm surges, which are a consequence of peculiar meteorological conditions coupled with unfavourable astronomical phases, can seriously jeopardize the whole lagoon ecosystem. Nevertheless, sea-level fluctuations on longer time scales (interannual to decadal) may be as destructive for the ecotone as high-energy events can be, since they slowly alter the hydrodynamics, and in turn modify the active/passive areas of the lagoon, the distribution of nutrients and biological communities, may favour or prevent sediment deposition/resuspension and eutrophization, as well as alter the actual vocation of special areas such as tidal flats.

Assuming that the interannual and decadal variability of sea levels in the Adriatic Sea is inextricably linked to the Atlantic Sector response, the dominant influence of the NAO, coupled with the peculiar nature of the Northern Adriatic basin, are key factors for gaining an accurate understanding of the long-term dynamics of sea levels in the Venice lagoon. In fact, the main limitation of former projections of sea-level changes in the Venice lagoon for the next century was that they neglected the latter in favour of estimating rises in global sea-level rates (by IPCC and CO.RI.LA.). Moreover a secular rate is used in these projections to predict the sea-level height in the year 2100, while the interannual to decadal variability is much larger than the secular trend and may in fact obscure it, at least in the upcoming decades.

In this preliminary study, the seasonal to interannual sea-level variability in the Venice lagoon, its hydrological connections with the Northern Adriatic and specifically with the Po River, which is the major contributor of freshwater runoff in the basin, were analyzed through Wavelet Analysis techniques. In particular, this study focussed on the phase relationships between sea levels in the Venice lagoon and Po River discharges, assessing that oscillatory patterns appear to be dynamically synchronized across a wide region of the temporal and frequency domains, i.e. on seasonal to interannual scales. The coupled dynamics of discharges and sea levels would suggest a response by the regional climate system of Northern Italy/Northern Adriatic to large scale climatic patterns, i.e. the North Atlantic sector whose variability is dominated by the North Atlantic Oscillation, and also to global climate shifts and hazardous events, such as El Niño events or explosive volcanic eruptions.

The results presented, which contribute to mitigate some daring statements about what the Venice lagoon is facing, may be used as basic indications for further studies, included the development of predictive tools at the seasonal to interannual scales, that could provide a reliable means for finding an answer to some difficult questions about the future of Venice

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