The Future of Venice

and its Lagoon in the Context of Global Change

2.

Workshop Report

The Ecological Implications of Climate Change on the Lagoon of Venice

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The Ecological Implications of Climate Change on the Lagoon of Venice

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26-27 May 2011, Venice (Italy)

Contents

Foreword

The urban ecosystem of Venice and its Lagoon is among the most studied urban and environmental systems in the world. Acting as neutral broker and facilitator, UNESCO Venice Office has mobilized expertise in the interdisciplinary fields of science and culture to identify and discuss the scientific, environmental, cultural and socio-economic challenges faced by the World Heritage site of Venice and its Lagoon in the context of global change.

This document in your hands presents a summary of the results and discussions from the second of four thematic workshops that were held to gather the necessary expert inputs needed to evaluate the current situation of Venice and its Lagoon and to contribute to a shared sustainable vision for its future. The Workshop on *The Ecological Implications of Climate Change on the Venice Lagoon* was held 26-27 May 2011 at Palazzo Zorzi in Venice, Italy and was organized in partnership with ISMAR-CNR. The results from this international workshop will form a basis for a better understanding of the vulnerability of the Venice Lagoon, in relation to the climate change scenarios at local level as well as the ecosystem response to global change mechanisms, and may contribute to better define the limits and opportunities of the development of Venice and of the proposed plan for a Regional City.

The results of the thematic workshops will be used by UNESCO to facilitate the vision, strategy and management plan for Venice and its Lagoon, and to prepare in collaboration with the local authorities a follow-up report to the one already elaborated by UNESCO in 1969 after the devastating *aqua alta* of 1966. This new report is intended to help guide sound decision-making and further enable sustainable management of not just the World Heritage Site of Venice and its Lagoon, but of urban coastal and lagoon systems worldwide that are facing challenges stemming from global change phenomena, and in particular those in the South-East European and the Mediterranean regions.

Prepared by the participants of the workshop, this report provides a shared overview of the main challenges that are being faced by the World Heritage site of Venice and its Lagoon and significantly contributes to the growing body of knowledge on the effects of climate change on coastal and lagoon cities.

Engelbert Ruoss
Director, UNESCO Venice Office

Introduction

In spring 2011, under the auspices and organization of the UNESCO Venice Office, the Institute of Marine Sciences of the Italian National Research Council gathered an International group of experts on lagoons and estuaries to discuss the major ecological implications of Climate Changes on the Lagoon of Venice for the end of this century. The discussion was based on the available climate change scenarios and on the outputs of a previous UNESCO workshop on Sea Level Rise held in November 2010 (Umgiesser et al., 2011).

Climate Change (CC) has both site-specific and global ecological effects that are common to all lagoon and estuaries, from the nearby lagoons of Marano-Grado and Po river delta to the Jamaica Bay, regardless their geographical position (Kjerfve, 1994; Valiela, 2005; Aliaume et al., 2007; Anthony et al., 2009). Site-specific effects are generated by the interplay between 1) environmental changes appropriately downscaled from global to local dimensions, focusing on climatic factors, relative sea level rise and geomorphological processes, including subsidence; 2) the geophysical context of the lagoon and its watershed, and 3) the human use of the territory. Increases in temperature, changes in precipitation patterns and sea level rises (SLR) are globally expected to occur (IPCC, 2007). Locally, site-specific effects of climatic factors, such as air and water temperature, wet depositions, and sea level rise can be amplified by land uses and human activities. Contrasting factors like resource exploitation with a 'business as usual' approach and the perception of the value of ecosystem good

© Godromil - View on Torcello island

services supplied by the lagoon and its watershed are of paramount importance in determining the local impact of CC. The propagation of CC effects is often characterized by non-linear responses of lagoon ecosystems, which in turn are mediated by complex and interlinked processes among biological components of the ecosystem. These responses involve direct and indirect alterations of physiological and behavioural processes encompassing many scales and levels of organization spanning genome, populations, communities, ecosystem and biomes, and ultimately the human society.

Global responses to CC include:

- alterations of the physical structure of the water column, e.g. with the establishment of a stronger termo-haline stratification, which in turn can affect water oxygenation;
- modification in runoff and river hydrology due to changes in timing and quantity of wet deposition, with effects on freshwater and nutrient delivery to coastal lagoons, and nutrient stoichiometry within lagoons;
- increased primary productivity and overall metabolic rates, especially at the microbial level, which influence organic matter processing, oxygen consumption and biogeochemical processes
- increase in the spatial and temporal extent of hypoxic or even anoxic events;
- decrease of seawater pH as a result of increasing CO2 concentrations, with consequent stress on organisms (e.g. calcification);
- northwards shift of bioclimatic regions, with effects on species distribution and community composition;
- effects of CC on phenology and reproductive cycles as a consequence of earlier warming and later cooling;
- possible asynchrony in biological and ecological cycles, viz in the prey-predator interactions;
- successful invasion of alien species which adapt to the climatic settings imposed by CC;
- increased impact of pathogens and parasites species which benefit from increased temperature;
- loss of pristine habitats and gain of new habitats.

Site-specific effects for the Lagoon of Venice (LoVe) are expected to be driven mainly by the Relative Sea Level Rise (RSLR) and by the human responses addressed to the protection of the historical City and the other islands from flooding. The Venetian society is faced with the dilemma of how to re-establish an average sea level that allows full, urban and social functions without disturbing the physical structure of the City, world-renowned as an irreplaceable socio-cultural ecosystem service. The townscape of Venice including the lagoon, encompassing its art, culture and history, represents a global-wide resource satisfying aesthetic and recreational needs. This is testified by the large number of tourists that visit Venice daily and by the inclusion of the City in 1987 in the list of the UNESCO's World Heritage Sites of outstanding universal value to all of humankind. The recent scientific UNESCO workshop on Sea Level Rise (SLR) (Umgiesser et al., 2011) concluded that the sea level will continue to rise during this century to levels that cannot be tolerated by the historical City of Venice and will dramatically impact the hydraulics of the lagoon. The mobile gates currently under construction will allow to reduce the incidence of extreme events in the coming decades, but at the cost of increasing the number and frequency of closure events, with the consequent risk of a worsening of the environmental conditions. The key question is thus when the infraction of the safety levels will become unavoidable, as pointed out by the conclusive statement of the previous workshop: "The question is not if this will happen, but only when it will happen." Therefore, it is now essential to understand the time horizon within which we must prepare for the event. It is difficult to say what solutions will be proposed and applied to resolve the problem of sea level rise, e.g., closure of the entire lagoon or possibly enucleation of Venice and the islands, leaving the lagoon to its fate. This is not the direct aim of this workshop, but is of fundamental importance in determining ecological scenarios.

Present geographic and climatic setting

© NASA - Satellite photo of the Venice Lagoon (taken by Aster - EOS)

The Venetian area is in transition between Mediterranean and continental climates being influenced by the mitigating action of the sea, the orographic effect of the Alps, and the continental influence of Central Europe. Dry summers that characterize the Mediterranean climate are lacking because of the frequency of storm convections. The mitigating action of the Adriatic Sea is limited: winters are therefore not mild, the average temperature of January in LoVe being 2-4 °C (Spiro et al., 2006; Spiro and Guerzoni, 2006).

The Veneto region is characterized by strong geographic and physiographic gradients, with elevations ranging from the sea to a mountain chain reaching more than 3000 m (Marmolada mount) in a range of less than 200 km. This configuration generates intense precipitations especially when humid air masses are transported on the plain and the hills by south-easterly "Scirocco" winds. The Veneto can be divided into 2 main climatic zones: 1) the alpine zone; and 2) the Venetian Plain, characterized by a continental climate. The latter zone can, in turn, be further subdivided into 2 belts: the inland plain; and the coastal region which is more influenced by the Adriatic Sea (Brunetti, 2004; Salon et al., 2008). On the watershed, the climate is more continental, with precipitation distributed quite evenly over the year. Winter is the driest season. In all seasons, the average temperature of the LoVe is higher than on the watershed, and rainfall is significantly lower. There is a significant temperature gradient between the LoVe and its watershed area of about 1 to ~14.5 °C at the lagoon and 13.5° at the watershed (Spiro et al., 2006; Spiro and Guerzoni, 2006). The Venetian plain, close to the Adige Estuary, is subjected to a NW-SE gradient of decreasing precipitations from about 1000 mm y-1 to less than 700 mm y-1. The LoVe itself is less rainy than the watershed and more rainy in its north-eastern part than in the southern reaches (Zuliani et al., 2005). The LoVe gets about 250 mm y-1 less rainfall than its watershed. During winter, differences in temperatures and precipitation are less marked. Winter is a fairly dry season, but the snow on the Alps constitutes a water reserve which is released later during the warm season (Spiro et al., 2006; Spiro and Guerzoni, 2006). Precipitations have two peaks, one in spring and one in autumn with a maximum in October, and minimum in winter and summer. Intense precipitations of more than 100 mm d−1 occur in autumn (Zuliani et al., 2005). The tributaries of the drainage basin of LoVe are small streams with low individual discharge of about 35 m3 s-1 on the annual basis. The maximum discharge peak from the drainage basin has been about 350 m3 s-1. (Zonta et al., 2001, 2005; Zuliani et al., 2005). From October until late spring the dominant wind is the north-eastern "Bora", that it is also the most frequent wind in the year, followed by the south-eastern wind "Scirocco", dominating during summer.

The average annual percentage of calm days is about 30%. The frequency of fall and winter fogs is favoured by calm or weak winds (Marotta and Guerzoni, 2006).


© Francesco Rossi - Typical landscape of the Venice Lagoon with the characterizing network of channels and intertidal flats

The LoVe is characterized by a complicated network of channels, intertidal flats and shoals. A few principal deep channels (maximum depth around 15 m) cross an area of very shallow water with an average depth on the order of one meter. The three inlets, called from north to south, Lido, Malamocco and Chioggia, are from about 500 to about 900 m wide and up to 15 m deep. The main driving forces for water circulation within the lagoon are tides and wind. Tides are semidiurnal, with an average tidal range of about 60 cm and about 1 m excursion during spring tides. The tide propagates into the lagoon along the deep, narrow channels onto the tidal flats and tidal marshes. Due to the high tidal energy and relatively shallow water, the water masses are generally well mixed (Umgiesser et al., 2004). The water exchanges between the lagoon and the sea that are driven mainly by the tide and the wind action, are essentially barotropic in nature. Over 90% of the total variance in the average water flux through the inlets is due to tidal forcing and the amount of marine water that flows in and out during each tidal cycle amounts to about a third of the total volume of the lagoon (Gačić et al., 2004).

On average, the LoVe can be considered eu-polyhaline with salinities ranging from 18 to 30 PSU in the innermost belt and over 30 PSU in the middle ranges of the lagoon (Ghezzo et al., 2010). The LoVe presents a salinity gradient from the bayhead estuaries to the sea inlets where the salinity is about 34 PSU, which is close to that of the Adriatic. The gradient is compressed due to the modest river flow. Salinity in the lagoon varies spatially and seasonally due to both the volume of water discharged by the rivers and to precipitation-evaporation balance, which is affected by temperature as well. Lower salinity occurs at the northern sector of the lagoon which receives the largest freshwater inflow. During summer, when river flows are minimal, the lagoon is more saline and more uniform.

The Northern Adriatic is the northern and coldest part of the Mediterranean Sea. This distinctive characteristic is reflected in the structure of biocoenoses with reduction of the more thermophilic Mediterranean species, and the presence of some microthermal species, especially amongst vegetation taxa. The area northward of the Po River is therefore defined as "the Venetian biogeographical gap" (Marcello, 1962). Examples of more temperate species are the brown alga *Fucus virsoides* that is widely distributed along Atlantic coasts, but is the only Mediterranean species of Fucaceae which is endemic in the North Adriatic, and the cord grass *Spartina stricta* that is not found anywhere else in the Mediterranean. Both species are closely associated with intertidal environments. On the contrary, the alien crab *Percnon gibbesi*, which established in most Mediterranean coast twelve years after its introduction, is absent from the Northern Adriatic Sea, as well as the Ligurian Sea, the Corsica Island, and the Aegean Sea, possibly because of the low winter temperatures (Katsanevakis et al., 2011). Another feature of the North Adriatic lagoons similar to the Atlantic coast environment is the presence of tidal "temperate" salt-marshes that are found practically nowhere else in the Mediterranean.

Climatic projections for the lagoon of venice

Ecological considerations will be based on the available projections of CC for the LoVe.
Projections which have been generated globally, must be carefully downscaled (Gao et al., 2006; Salon et al., 2008) for LoVe because it is an end-member of a series of nested systems (global, Atlantic, Mediterranean, Northern Adriatic, Venice lagoon) in which relationships are non-linear and can generate effects far from what would seem intuitive.
Global scenarios used as a baseline for climate change projections in LoVe are A2, A1B and B2 (IPCC, 2007). Scenario A2 illustrates a planet with high population growth and slow economic and technological development. Conversely, the A1 scenario assumes a very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. B2 depicts a world with intermediate population and economic growth as a result of local solutions to social, economic, and environmental sustainability.

Air temperature, precipitations and storminess


© Armando De Bortol - Stormy weather in the Venice Lagoon

Precipitation and temperature regimes for the drainage basin of the LoVe were derived (Salon et al., 2008) from multi-decadal high-resolution simulations produced by the ICTP Regional Climatic Model (Giorgi et al., 1993a, 1993b; Gao et al., 2006). Projections comparing the reference period 1961–1990 and the simulated 2071–2100 period gave a slight increase in annual precipitation under both the A2 (4.3%) and B2 (7.2%) IPCC scenarios. The Regional Climatic Model (RCM) scenarios indicated a clear accentuation of seasonality with an increase of precipitation in winter, spring and autumn and a reduction during summer (Cossarini et al. 2008). The variability in seasonality and intensity of precipitation would cause an increase in the variability of the water characteristics in coastal lagoons. This slightly increase in precipitation is in contrast with the global tendency towards a dryer climate (IPCC, 2007). According to these simulations, temperature over the LoVe will increase from the reference period 1961-1990 to the target period 2071-2100 by 3.2 °C in winter (December-February), 3.0 °C in spring (March-May), 5.0 °C in summer (June-August) and 3.8 °C in autumn (September-November) under the A2 scenario. The RCM projections, therefore foresee a gradually rising of the temperature, with summers warmer and dry and less rainy, whereas winters, although less cold than today, will be characterized by increased precipitation.

Rainy seasons will present more intense and short-term precipitations, with the increase of flash floods and less soil infiltration into groundwater (Ramieri et al., 2010). Differences between winter and summer will become more accentuated.

This simulation is in slight contrast with 1961- 2003 observations reporting a tendency for annual precipitation to decline (Spiro et al., 2006). Milder winters will result in less snow and ice accumulation on the Alps, with a more variable flow of the alpine rivers such as Piave and Brenta, which can affect LoVe.

Storms in the Northern Adriatic are projected to be progressively mild during the second half of this century, intense storms are suggested to be more frequent under the B2 scenario but not under the A2. Extreme storm sea surges and waves should not change substantially during this century (Umgiesser et al., 2011). The IPCC – Intergovernmental Panel on Climate Change (1997; 2007) foresees a variability in storminess with an increase in some regions and a decrease in others.

Water temperature, salinity and water residence time

Response of different Mediterranean lagoons to global warming and sea level rise simulated by Umgiesser et al. (in press) by forcing a 3D hydrodynamic model (SHYFEM, Umgiesser et al., 2004) under the A2 scenario (IPCC, 2007) and with data from Somot et al. (2008); Tsimplis et al. (2008), results in SLR of 51 cm, decreasing wind speed (-5%), rising air temperature (from +3.0 °to +4.7 °C), rising average sea temperature (+3 °C) and average sea salinity (+ 1.0 PSU), as well as slight variations in precipitations, leaving unchanged the river input since there was no available freshwater discharge prediction. Real forcing (tide, wind, rivers, rain) of the year 2005 and modified according the predicted climate change were imposed in these simulations. The ranges of air temperature and precipitation used to force the model, are slightly different from the output of the above mentioned RCM, the main differences being in less precipitation during autumn and more in winter, as well as warmer winters and summers.
Results indicate an average water temperature rise of 3.5 °C for the LoVe and of 3.0°C for the sea, corresponding to a lagoon-sea difference of 17.7%. The projected annual average salinity was 34.2 corresponding to an increase of 1.3 PSU (+3.8%) in the lagoon, with a lagoon-sea difference of +26%. Accordingly, the modelled residence time of the LoVe increases by 1.6 days on the average corresponding to an increment of about 15%. Sea level rise leads to a major volume increase than the water exchange increment and consequently the residence time increases.

Sea Level Rise

Regional conditions can substantially affect the SLR. A minimum SLR value of only 12-13 cm can be obtained from secular linear trend projections, but evidences suggest a divergence from the past pattern (Carbognin et al., 2010). International experts gathered at the UNESCO workshop in November 2010 suggested an end-of-century scenario of more than 60 cm, not excluding the chance of a 100 cm increase (Umgiesser et al., 2011). To obtain the "Relative SLR" (RSLR) land subsidence, in the historical centre of Venice, about 5 cm in a century should be added to sea level rise (Carbognin et al., 2010). Even if emissions of greenhouse gases will be reduced during this century, the sea level will continue to grow for centuries (IPCC, 2007). Various sources give a range of 1.5-3.5 m for 2200, and 2.5-5.1 m for 2300 (Umgiesser et al., 2011). *Figure 1* depicts the relationships among the main factors affecting climate change on lagoons (from ICES 2008, adapted for lagoons).

However, in these simulations no consideration is given to possible feedbacks which can counteract SLR, e.g. the combined effect of salinity and temperature increases (Tsimplis et al., 2008).

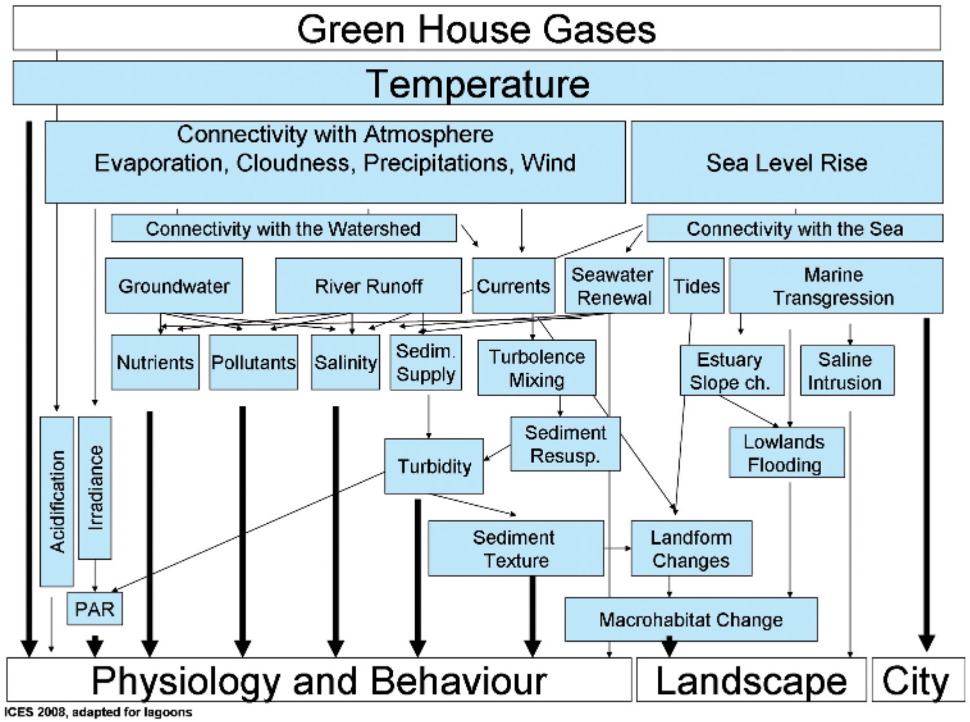

Figure 1:
Relationships among the main Climate Change Agents acting on lagoons (from ICES 2008, adapted for lagoons)

Climate change and lagoon functioning

Complex interactions between air temperature, seasonal precipitation patterns, wind, cloudiness, and geological settings make it difficult to foresee trends in important components of the hydrological cycle such as timing and volume of river flows, extent of evapotranspiration and groundwater storage. A good balance is fundamental for a healthy lagoon to determine allowable nutrient and toxic substance loads. Temperature, precipitation and seawater renewal are fundamental factors in the ecological balance of lagoons. Water flows largely control inputs and outputs of the system, modulate fluxes and ensure the connectivity with rivers and sea. Temperatures determining rates of chemical and biochemical processes influence the lagoon metabolism. Acting upon these factors, CC would influence the ecological balance of the lagoon. One of the major points which is debated today is ecological stoichiometry, especially the relative concentrations of N, P and Si which can deeply affect food wed structure and ecosystem metabolism (Howarth et al., 2011).

Sediment-water exchanges and flows

The LoVe is approximately 50 km long and 10 wide, its average depth is about one meter. A physical model of the lagoon at a 1:10000 scale would result in a sheet of paper of about 5 meters to 1, in which the depth of the water is represented by the thickness of the paper (about 0.1 mm). This simple analogy helps us to figure out how close and important the relationships are between the sediment and the water volume. Here, exchanges between water and sediments involve nutrients, organic matter and biological components (the so called benthic-pelagic coupling). Pollutants are often linked to the flow of organic matter. The diagram reported in Figure 2, represents the major exchanges between pelagic and benthic ecosystems in lagoons and coastal wetlands (from Lasserre, 2005, modified):

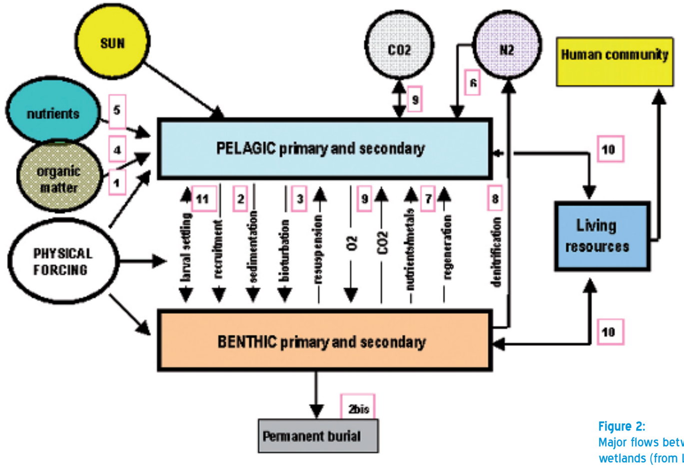

Figure 2:
Major flows between pelagic and benthic ecosystems in lagoons and coastal wetlands (from Lasserre, 2005, modified)

(i) **Organic flows.** Allochtonous organic input from land, *indicated by (1) in Figure 2*, can constitute an important energy source, complementing indigenous primary production. In eutrophic lagoons, sedimentation of organic matter *(2)* is the primary source that fuels the benthic system. This flow is primarily directed downwards, from the water to the benthos, but an upward flux, by resuspension *(3)*, may be important, especially in very shallow ecosystems. The permanent burial of refractory organic matter in the sediments *(2bis)* represents a permanent sink.

In pristine clear-water lagoons, primary production depends on benthic phanerogams or perennial macroalgae that supply oxygen to the water column and refractory organic matter to the sediment, thus providing healthy conditions at the lagoon scale. Increased nutrient and organic matter loadings from the watershed can shift the primary production towards phytoplankton and ephemeral and floating macroalgae, thus enhancing the pathway *(2)*.

(ii) **Nutrient flows.** Primary production in the water column by phytoplankton and macroalgae is limited by light availability and by nutrient inputs from land *(4)* and from the atmosphere *(5)*, by nitrogen fixation *(6)* and by the upward flux of nutrient rematerialized through organic matter decomposition in the sediment *(7)*.
To date, primary production by nitrophilous species has been assumed to be predominantly nitrogen-limited, due for example to denitrification of NO3- to N2 in the sediment (8). This point is however controversial, and processes greatly depend on trophic status (Teichberg et al., 2009). At present primary production is assumed to become P-limited and often Si-limited (Howarth et al., 2011).

Under anthropogenic pressures processes of N cycling become altered, especially in eutrophic ecosystems where denitrification to N_2 decreases whilst dissimilative nitrate reduction to ammonium (DNRA) increases (Seitzinger et al., 2006). New findings are now challenging biogeochemists, viz the ANNAMOX (anaerobic oxidation of ammonium) and the shortage of Si with respct to N, due to management of freshwater in heavily exploited watershed.

The vegetal community structure is of paramount importance for oxygen production and delivery into the water mass (Middelburg and Levin, 2009). Benthic phanerogams provide better conditions than macroalgae and phytoplankton, because oxygen is delivered from the bottom upwards. Moreover, balanced respiration to photosynthesis ratios usually avoid hypoxia to occur at both diel and seasonal scales (Viaroli et al., 2010). Macroalgae and phytoplankton, especially in eutrophic waters, undergo a "boom and bust" behaviour causing supersaturation in the daylight and anoxia in the night and even prolonged anoxia when the bloom collapses (McGlatery et al., 2007; Viaroli and Christian, 2003; Viaroli et al., 2010). Benthic macrofauna play an important role in nitrogen cycling in sediments. Svensson et al. (2000) found that in some sites of the LoVe about 30% of the denitrification in sediment was explained by the presence of benthic infauna. The oxygen supply to the bottom waters and sediment *(9)* plays a key role, since it controls redox conditions, nutrient cycling and faunal community structure in the benthos.

(iii) **Biological flows.** Biomass produced within the ecosystem can be exported by species migrating between feeding and spawning areas, or as an exchange, mediated by feeding, between pelagic and benthic species *(10)*. Fish populations (possibly invasive species) entering the lagoon will not only affect community structure and internal recycling rates, but may also generate inputs of materials through spawning, defecation and excretion.

A major impact is due to aquaculture of few commercial species of mollusks, shrimps and fishes. Under the farming conditions, often with artificial food supply, the harvested and exported biomass is only a small part of the organic matter and nutrients that are released into the sediment (Nizzoli et al., 2011).

Many benthic organisms have pelagic larvae, and some planktonic organisms have benthic resting stages. These flows between the pelagos and the benthos *(11)* are critical for recruitment, larval settling, dispersal and survival.
In eutrophic lagoons the main export from the system is due to the transport of macroalgae, seston and even phytoplankton (Flindt et al., 1997). In Venice, and other lagoons exploited for shellfish farming, resuspension and loss of the pelitic fraction can also contribute favor transport and losses of both detritus and benthic organisms.


© 2011 - Consorzio di Promozione Turistica: Jesolo - Fish farm in the Venice Lagoon

In the global change context, one of the most urgent requirements is to quantify nutrients and energy fluxes, when subjected to different levels of organic and inorganic inputs: a) as properties of microbial processes in the sediment, and b) as the seasonally variable benthic metabolism that is mainly stimulated by macroalgal (*Ulva* complex) and phytoplankton blooms. Pelagic nitrogen fluxes in the Venice lagoon were estimated using 15N tracer methodology. The major ammonium sources were river inputs in spring and probably in autumn and in situ regeneration in summer. Recent studies conducted in the *Palude della Rosa* (LoVe) found a heavy ^{15}N signature linked to high DIN concentrations suggesting that N loads have a strong wastewater component (Teichberg et al., 2009). It would be worthwhile in future studies to quantify in all parts of the lagoon the N regeneration rates using ^{15}N tracer methodology, in order to better quantify the relative importance of external (river inputs, wastewater) and internal inputs (regeneration) and dissipation pathways in the LoVe. Furthermore, climate change may induce a larger role of microbial metabolism, as the organic and inorganic inputs increase. This is amenable to measurements using experimental manipulation, e.g. with benthic chambers and core incubations. A special effort should be made to use modern technologies for direct measurement of particle size (e.g. flow cytometry), oxygen micro-probes, direct calorimetry etc. so as to provide data which can then be related to changes in the balance between various microbial, vegetation and faunal components within the benthos and the water mass. Seasonal features, particularly the balance between organic input, temperature and metabolic demand, are paramount for differentiating the component processes which result in observed system level nutrients and energy flux.

Nitrogen pathways and fate have been studied in coastal lagoons through several projects funded by the European Commission since 1992 (see for example the Project "NICE: nitrogen cycling in estuaries" at http://www.nice.org and Nielsen et al., 2004). Among other lagoons, nitrogen budget, pathways and fate have been studied in the Po delta lagoons highlighting that benthic vegetation and microphytobenthos (MPB) play a major role, with a possible competition with the microbial communities of nitrifiers and denitrifiers (Risgard-Petersen, 2003; Bartoli et al., 2008).

The intensity and direction of water-sediment fluxes depends on a myriad of interactions among primary production, microbial processes and geochemical buffers including interactions among oxygen, nitrogen, sulphide, iron and phosphate cycles (de Wit et al., 2001; Viaroli et al., 2010). Oxygen is supplied to sediments directly from the bottom waters as well as by the activity of benthic photosynthesis: seagrasses excrete oxygen through their roots, microphytobenthos oxygenates the sediment. In turn, oxygen availability controls redox conditions, nutrient cycling and ultimately, the composition of benthic communities. Responses to nutrients and organic matter are controlled by microbial processes and benthic communities. Sedimentation of particulate organic matter is the primary source that fuels the detritus food web, stimulating bacterial

degradation and increasing oxygen demand. As organic matter accumulate in sediments, anaerobic processes increase and the concentration of oxygen decreases. This is accompanied by an increase in the concentrations of toxic by-products of anaerobic metabolism. These products diffuse in the water column and produce negative effects on aquatic organisms, relative to their chemical makeup, e.g., ammonium, reduced maganese and hydrogen sulphide are particularly toxic compounds (Wilson et al., 1986; Day et al., 1989; Sanz-Lázaro and Marín, 2011) as well as species-specific tolerance. The burial of refractory organic matter in the sediments represents a sink. The plankton captured by filter feeders represents a flow of living organic matter, finally accumulating at the bottom surface as faeces and pseudofaeces. Natural benthic fauna and farmed species (e.g. Ruditapes philippinarum, Mytilus galloprovincialis) enhance fluxes through biosedimentation, bioturbation and bioirrigation (Bartoli et al., 2001; Nizzoli et al., 2007; Bartoli et al., 2009). Bartoli et al. (2001) and Nizzoli et al. (2011) recently demonstrated the creation of lagoonal 'hotspots' of nutrient fluxes by farmed mussels and clams, which are characterized by high N and P regeneration rates, questioning the proposal that suspension-feeding bivalves act as a eutrophication buffers. Many pelagic fishes can feed on benthic organisms but return their biomass to the bottom after death in the biomass/energy exchange between pelagic and benthic systems.

Hydrology and connectivity

Lagoons are characterized by progressive changes in environmental variables that generate concentration gradients. The structure of the gradients depends on the hydrodynamics of the system (Phleger, 1981). In lagoons with limited river input, such as the LoVe, the component that mainly influences the concentration of nutrient, suspended solids and salinity gradient is seawater renewal driven essentially by tidal currents. Tidal exchange is today the largest component of LoVe water balance (Solidoro et al., 2004; Bellafiore et al., 2008). Freshwater flow, also contributes to the gradient by diluting seawater and supplying suspended solids, dissolved nutrients as well as pollutants. The hydrological gradient is reflected in the distribution and texture of sediments and organic matter settling where hydraulic energy is low (Molinaroli et al., 2009). Hydrological influences interact with water-sediment exchanges and pelagic-benthic coupling modulating the budgets across habitats. Tidal flow transports oxygenated water to the system and dilutes nutrients and catabolites. The sustainable load of nutrients and organic matter, and hence, the degree of eutrophication and saprobity, in different areas of the lagoon depends largely on water renewal. As a consequence, flushing has a strong effect on the structure of biological communities and biodiversity, influencing the number of species, the density of individuals and the biomass (Pearson and Rosenberg, 1978; Guelorget and Perthuisot, 1983). Reduced flushing combined with warming temperatures are expected to increase water stratification, especially in the deeper canals, during the summer and in other windless periods. Stratification confines hypoxic waters at the bottom thereby affecting the aerobic metabolism of bacteria, invertebrates and fishes. Inputs of freshwater would also contribute to stratification. The connectivity between the sea, the lagoon and the rivers allow the movement of organisms, especially during larval stages between different habitats inside the lagoon, between the lagoon and sea, and between different lagoons. The flow of organisms and genes is necessary for the maintenance of viable populations and metapopulations. Connectivity is important for migratory species, such as marine species spawning at sea and utilizing the lagoon as a nursery as well as seasonal migrants that use the lagoon as feeding ground. Anadromous species cross the lagoon migrating up rivers from the sea to breed or spawn, catadromous migrants go to the sea from rivers (Malavasi et al. 2004; Franco et al., 2006). Biomass produced within the lagoon can be exported by species migrating between feeding and spawning areas.

Overall, the sensitivity of a given lagoon to undergo unhealthy conditions (e.g. macroalgal blooms) can be viewed as a function of water depth, water residence time (or water flushing time) and stressors, e.g. nutrient loadings (Dahlgren and Kautsky, 2004; Hauxwell and Valiela, 2004; Viaroli et al., 2010).

General effects of climate change

The primary impact of CC is due to the increased CO2 itself, which can cause water acidification. But, very subtile and chronic stress can also impair mainly the biological components of lagoons. One of the major points to be considered when assessing the CC effects is the migration northwards (polewards) and upwards of bioclimatic regions and their species (Parmesan, 2006). Range-restricted species (e.g. butterfly, amphybians, corals) are highly sensitive to changes of temperature. The reasons are lag time in life cycles (spawning, drifting etc.), shifts in grass-grazers and prey-predators cycles, different resistance to parasite/infections, over-competition by aline species.

Direct effects of CO2, acidification

An increase in atmospheric CO_2 partial pressure will be translated by on average higher dissolved CO_2 concentrations as predicted by equilibrium conditions. Conversely, an increase in water temperature would decrease the amount of physically dissolved CO_2. However, coastal waters can be over or undersaturated with respect to CO_2. If the increase in temperature would result as predicted in faster respiration rates that are not compensated by photosynthesis, then dissolved CO_2 concentrations would even further increase in many places. Increased CO_2 can stimulate primary production, but also leads to acidification.

© Chris 73 - Aerial view of Porto di Lido (with construction of the MOSE barrier system), one of the three inlets ensuring the connection of the Venice Lagoon with the Adriatic Sea

During the workshop it emerged that acidification could be a significant risk for the lagoon, especially in the case of increased isolation from the sea, and the consequent reduced buffering power provided by seawater. The buffer capacity of the lagoon also depends on the mineralogical composition of sediment carbonates acting as buffers since their dissolution contributes to counterbalance the pH decrease. Dolomite and silicates have opposite effects in the sediments of the LoVe. Dolomite is derived from the contribution of the Piave and Tagliamento rivers flowing from the Dolomite Mountain Chain and diminishes from North to South and landwards, whereas silicates are supplied from the Brenta, Bacchiglione and Adige rivers flowing from more metamorphic and volcanic rocks and diminish from South to North and seaward. At sea inlets organogenic marine sand contributes to carbonates. Therefore the sediments from the northern and the seaward parts of the lagoon have a higher potential to buffer acidity (Molinaroli and Bonardi, 2006). Acidity may affect the physiology and structure of organisms, especially those producing calcareous testes, tubes or shells. Specifically reef building species can be impacted with cascading effects on the organisms associated with them. Nevertheless, many estuarine species may be already adapted to higher acidity and other extreme conditions.

Some infaunal species such as the nereid polychaetes Hediste diversicolor and Neanthes succinea and some bivalves such as Scrobilcularia plana, already live in organically rich, acidic habitats which are often hypoxic and brackish. Hence these organisms are naturally able to tolerate a low pH.

Effects of temperature

With the foreseen dryer summer and milder winter the LoVe will probably align itself more closely with a characteristic Mediterranean climate. The LoVe will become more similar to lagoons located at 3-5 degrees latitude to the South, such as the lagoons of Lesina and Cabras in Italy, the lagoon of the Gulf of Amvrakikos in Greece, and also the Etang de Thau in France. Nevertheless, the LoVe will maintain greater differences between the cold and hot seasons than those recorded at present in the majority of Mediterranean lagoons. This climatic "Mediterraneization" could threaten the biodiversity for the "Venetian biogeographic gap". Endemic microthermal species of Atlantic affinity could be displaced by the new climatic opportunists. Since the Gulf of Venice is the northern dead-end of the Adriatic sea, latitudinal migration of less thermophilic species is impossible and these might go extinct.

Temperature has a direct effect on all metabolic reactions, from bacteria to higher organisms. The availability of substraum and the influence of temperature drive microbial activities and the mineralization of organic matter (Westermann, 1996; Pomeroy and Wiebe, 2001). Bacterial metabolism in sediments create anoxic conditions a few millimetres on the surface. As a result the preponderance of organic matter results in mineralization taking place anaerobically. Organic matter decomposition begins with extracellular enzymatic hydrolysis which produce high-molecular weight dissolved organic matter, which in turn is hydrolyzed and fermented to labile low-molecular-weight dissolved organic matter. The resulting organic matter is available for terminal mineralization, mainly sulphate reduction. The different phases of organic matter mineralization can be influenced differentially by temperature which may change the way these pathways operate in the lagoon sediments. Experiments have shown that rates of hydrolysis/fermentation exceed those of terminal metabolism at temperatures below 25 °C. At 25 °C the two processes were balanced but at temperatures over 25 °C, terminal metabolism exceeded hydrolysis/fermentation (Weston and Joye, 2005). At high temperatures sulphate-reducing bacterial activity is limited by the production of volatile fatty acids from fermentation, which means that a large part of available low-molecular weight dissolved organic matter can be metabolized with the production of hydrogen sulphide. It is unlikely that, in the lagoon the amount of sedimentary organic matter becomes a limiting factor for fermentation. It is more likely that the increased production of organic matter due to the increase in temperature will provide additional substrate outweighing the limitations imposed by the temperature to fermentation processes.

The top oxic layer of the sediment plays an important role in reoxidizing the metabolic products of the anaerobic metabolism, thus preventing that high quantities of hydrogen sulphide diffuse into the water column. In addition, the oxidized sediment layer contributes to sequestering phosphates by binding to iron oxides and iron hydroxides. Increased temperatures may result in a critical reduction of the thickness of the oxidized sediment top layer and may thus jeopardise these important functions (de Wit et al., 2001). Higher water temperature results in a lower solubility of oxygen. When consumed by heterotrophic metabolism, soluble oxygen could reach critical hypoxic levels. Photosynthetic processes could temporarily offset the oxygen deficit during the day. The lower solubility of oxygen in the water at higher temperatures, could limit the oxidation of hydrogen sulphide, the concentration of which would increase, possibly beyond the capabilities of biogeochemical buffers, with toxic effects on the biota (Viaroli et al., 2010). The decrease of bottom water nitrate as a consequence of hypoxia would reduce the efficiency of denitrification.

© Servizio Videocomunicazione della Città di Venezia - Fixed fishing nets, a traditional fishing technique widely used in the Venice lagoon

Thermal sensitivity of higher organisms varies largely within and among species. Among molluscs, arthropods, and fish, the growth rate for an increase of 10 °C (the Q10) can vary from less than 2 to more than 10 times. On this basis it would be expected that animals grow faster in warmer than in colder environments, reducing energy investment in growth and reaching adulthood earlier devoting energy to reproduction. The effect of temperature would increase growth rates, but not necessarily the body size which would be determined by other factors as life span, optimization of reproductive effort following the Bergmann's rule (i.e. individuals of the same species and age are larger in colder environments). This discrepancy is not only due to the favourable surface volume ratio of larger animals, but is also due in part to the differential influence of temperature on anabolism and catabolism and, in part, to the effect of the co-variation between temperature and other environmental factors. Temperature may vary together with food availability and predation risk. Increased predation can have, in turn, complex effects on size at maturity; an increased mortality is selective for earlier maturation but predation decreases intraspecific competition for resources that stimulate an increase in size. Hence, the way in which temperature and other environmental factors vary and interact determine, in a complex way, the selection of the optimal body size for a given temperature (Angilletta et al., 2004). Hence, after a suitable period of adaptation and selection under higher temperature we might expect ectotherms to achieve faster growth but a smaller size.

Climate change can affect larval transport by modifying the timing of recruitment. Numerical studies on larval settlement of the Manila clam, projected at 2030, suggest that CC could have a considerable impact on settlement and recruitment in the entire lagoon. The worse effect being attributable to the increase in water temperature which could be attenuated by an increased water depth resulting from the SLR (Ghezzo et al., 2010). Combinations of temperature and salinity have been known for a long time to have different effects on the physiology of estuarine organisms and their life stages, with implications for biocoenoses structure and lagoon biodiversity (e.g. Hedgpeth, 1951; Simmons, 1957; D'Ancona, 1959). The limited increase in salinity foreseen by models would not have per se a large effect on euryhaline estuarine organisms, well adapted to cope with ample salinity variations. However, salinity is among the main factors determining dissimilarities in invertebrate assemblages between Mediterranean lagoons (Basset et al., 2007), and the analyses of the factors affecting fish assemblages in Atlantic-Mediterranean coastal lagoons show that an increase in the difference in salinity between the lagoon and the sea will tend to a decrease in species richness, and that an increase in salinity can lead to a decrease in fish yields (Pérez-Ruzafa et al., 2007).

Extreme values of temperature minima and maxima have important effects on biota. Killing heat waves (as well as freezes) can compromise larval settlement and recruitment, and become a bottleneck for adult populations. The heat wave of the summer of 2003, the warmest summer in Europe since the 16th century, caused in the Comacchio Saltworks, Italy, considerable changes in the benthic community structure still persisting in 2005 (Munari, 2011). Changes in geographical distributions are more likely to happen to species living at the edge of their physiological tolerance where they are more stressed. Intertidal organisms, often sessile or sedentary, are more exposed to thermal stress and could be used as indicators of climate change. Since metabolic rates vary non-linearly with temperature, the use of mean annual temperatures can be inappropriate. Metabolic rate should be evaluated during temperature maxima (Dillon et al., 2010). It has also recently been shown that the impact of ocean warming may strongly affect the early stages of marine invertebrates rendering acidification not relevant because affecting larval development even before shell/skeleton calcification (Byrne, World Conference on Marine Biodiversity, 2011 Aberdeen). Depending on their phenotypic plasticity, resident species will undergo physiological adaptations and selection to cope with climatic changes, restructuring functional responses to new environmental conditions. Hence the genetic heterogeneity and plasticity of populations will play a fundamental role in this adaptation. Competition with alien species, diseases caused by parasites and pathogens and temporal mismatches are sources of additional stress.

Biological invasions

© Pescaturismo - "Rete a bilancia" used for fishing in the lagoon canals

This is an emerging issue likely to have impacts on ecosystems services, society and economy. As water temperature increases, a shift in the latitudinal distribution of species is expected. Species that thrive in warmer waters may possibly invade warmer lagoons. The relationship between temperature change and species distribution are made more complex by the interplay with other environmental factors such as physical barriers, vector facilitation, dispersal ability and habitat connectivity (Occhipinti-Ambrogi, 2007). The colonization of a lagoon by habitat forming or engineering species, such as various reef building organisms, can have deep implication to the structuring of the whole biocoenoses (Rilov and Crooks, 2009). Some invasive species, for example, can facilitate the invasion of other alien species in a process termed invasional meltdown . The impact of some alien species can be increased by human behavior, particularly when the new species is a valuable resource. This is the case of the Manila clam *Ruditapes philippinarum*. This species was introduced some decade ago to the LoVe, but its major impact on the ecosystem was not due to its spreading but rather to its harvesting practices. This clam has already caused major consequences for the ecosystem functioning because of its value as a goods and services provider (Facca et al., 2002; Solidoro et al. 2003; Pranovi et al., 2006, Melaku Canu et al. 2011). These consequences have been modified in recent decades, affecting the economy of some social groups.

Higher temperature can favour the diffusion of parasites and pathogens (Confalonieri et al., 2007). Change in temperatures can also modify the parasite-host interaction in native species triggering cascading effects with implications for the structure of populations and communities. In the innermost mesohaline part of the LoVe, the mud snails *Hydrobia ulvae* and the amphipod *Coropium insidiosum* occur together in high numbers. They are the intermediate hosts of trematodes. An increased incidence of the parasites linked to a temperature elevation, could impact deeply populations of both species as already described for the Wadden Sea (Mouritsen and Jensen, 1997).

Phenology

Climate change is likely to influence the timing of life cycle events and the response to seasonal and inter-annual variability (phenology) of a variety of organisms. A wide assortment of biotic and abiotic factors influence phenological processes, especially temperature. Temperature influences the reproductive cycle controlling gonad maturation, onset of spawning and embryonic development. Developmental and reproductive timing effects are already evident by early gonad maturation and spawning in some lagoon fishes associated with higher water temperatures (Malavasi et al., 2010). Alien species could take advantage of weather and phenological timing of the new environment as well. Another important aspect of phenology is the match or mismatch of the seasonal activities of different biological and abiotic components such as different trophic level (match/mismatch hypothesis, Cushing, 1990; Sydeman and Bograd, 2009). Temperature may induce shifts in the timing of seasonal growth and activity patterns, which may lead to a mismatch between food supply and demand if predator and prey respond differently to warming (Edwards and Richardson, 2004).

Eutrophication

In a healthy lagoon the nutrient mass balance results in a moderate trophic state that supports a rich biological community without producing the negative effects associated with eutrophication. This balance depends on several inputs including water renewal and the types of primary producers (de Wit et al., 2001; Viaroli et al, 2005; Bartoli et al., 2008). Eutrophication also increases the frequency and intensity of phytoplankton and macroalgal growth, which can generate hypoxia/anoxia and turbid conditions. Increased nutrient inputs to lagoons usually result in high primary productivity with organic matter production rates that exceed the food web throughput, thus leading to biomass accumulation within the system. Organic matter from primary production that is not consumed in the foodweb or exported from the lagoon may accumulate into the system leading to oxygen consumption (Nixon, 1982; Valiela et al., 1992) and, possibly to saprobic conditions.

Over the last century, one of the main stressors for lagoons was nutrient over-enrichment and eutrophication (Sfriso et al., 1992, 2003; Solidoro et al., 2010; Viaroli et al. 2010). There is high probability that this will continue further. Population growth and land uses that will likely take place in the watershed of LoVe will increase nitrogen loads, via a variety of sources, e.g. wastewater from residences, sewage treatment plants, use of fertilizers, increased atmospheric deposition of nitrates and ammonium. Runoff of nutrients from the watershed is related to the amount of precipitation (de Wit and Bendoricchio, 2001; Collavini et al., 2005; Zuliani et al., 2005). In estuaries, the export of nutrients was found to be directly proportional to the residence time of freshwater (Dettman, 2001). This has been demonstrated in the LoVe where in the innermost, less flushed, parts of the lagoon the concentration of nutrients is higher (Solidoro et al., 2004; Pastres and Petrizzo, 2006). Cossarini et al. (2008) found a logarithmic relationship between the annual nutrient loads and the annual precipitations in the LoVe during the years 2001-2003. On this base and using the RCM precipitation projection for B2 and A2 scenarios, they calculated a possible increase of 6-15% in autumn-winter loads and a decrease of 1-9 % of spring-summer loads, eventually triggering a mean reduction in the plankton productivity of LoVe. In these simulations, however, possible changes in loads from urban and industrial sources are not considered, as well as mitigation strategies are not explicitly considered. High intensity of agriculture and livestock farming produce nitrogen that in part seeps into the soil with the infiltration of rain. The groundwaters of the eastern part of the watershed have widespread nitrate pollution with values exceeding 50 mg NO_3^- l^{-1} (the maximum allowable concentration for drinking waters). Groundwater concentrations above 50 mg NO_3^- l^{-1} have been measured in the recharge area above the spring belt in the province of Treviso, which feeds both the pressurised aquifers and spring plain rivers, the Dese and Marzenego, which in turn can transport nitrates into the LoVe (Ferronato et al., 2006).

The Regional Management Plan (Piano Direttore, 2000) estimated that 80% of the total annual load of phosphorus to the LoVe is conveyed by rivers and the remaining 20% results from industrial and urban wastes. Seasonal fluctuations of macro-nutrients depend mostly on seasonal loading from rivers and the seasonal cycles of assimilation by primary producers (Sfriso et al., 1992). It was experimentally demonstrated that macroalgae in the LoVe are limited by phosphates, but the amount of nitrate present was sufficient for a very high biomass production (Teichberg et al., 2009). Great attention should be paid in the future to the possible consequences of P and N increases. Great amount of P and N can also be released from sediments following organic matter mineralisation and alteration of biogeochemical buffers in redox conditions (Viaroli et al., 2010).

© giorgio bertossi - Macroalgal growth along the Venice canals

Eutrophication leads to a change in biological communities. There is a succession of aquatic vegetation along increasing eutrophication gradients, from perennial benthic macrophytes (mostly seagrasses) to fast growing epiphytes, to free floating macroalgae and phytoplankton and finally to picoplankton and cyanobacteria (Valiela et al., 1997; Sfriso et al., 2003; Sfriso and Facca, 2007, Viaroli and Christian, 2003). In turn, the decomposition of the vegetation biomass excess can trigger oxygen depletion (hypoxia-anoxia), anaerobic processes and dystrophic crises leading to deep changes in the benthic community (Gray, 1992; Gray et al., 2002; Levin et al., 2009). A persistent hypoxia (i.e. chronic hypoxia) results in a permanent shift in benthic community structure toward more tolerant species and a decrease in species diversity through the loss of less tolerant species. Relationships between the magnitude of organic input and changes in macro-benthic assemblages have been studied for a long time (Leppäkoski, 1975; Pearson and Rosenberg, 1978; Hyland et al., 2005; Magni et al., 2009). These studies have shown that the number of species and their abundance and the biomass vary in a characteristic way according to the organic matter input. The seriation of species goes from sensitive to organic enrichment species characterized by a K-strategy toward opportunistic species, characterized by a r-strategy (Pianka, 1970). Sensitive species are usually long-lived, with large body size, among them there are many bivalves. Opportunistic species have short life cycle, small body size, fast growth, and often polivoltine reproduction. Changes driven by variations in organic input foresee the reduction in the number of species as well as the characteristic maxima and minima of abundance and biomass. Trophic guilds shift from a dominance of suspension-feeders towards an almost complete dominance of deposit-feeders. This roughly corresponds, in terms of systematic groups, to a passage from a bivalve-dominated assemblage toward a polychaete-dominated one. A very similar pattern was found by Guelorget and Perthuisot (1983) in lagoons but it was attributed to sea water renewal more than to organic enrichment. Probably the observations of Pearson and Rosenberg and Guelorget and Perthuisot describe two different aspects of the same phenomenon which is a gradient of organic enrichment (and nutrients) moderated by a water renewal gradient. These patterns were observed in many Mediterranean lagoons (Ceccherelli et al., 1994; Reizopoulou et al., 1998; Tagliapietra et al., 1998; Arvanitidis et al., 1999; Koutsoubas et al., 2000; Mistri et al., 2000, 2001; De Biasi et al., 2003; Nonnis Marzano et al., 2003; Reizopoulou and Nicolaidou, 2004; Nicolaidou et al., 2005; Nicolaidou et al., 2006; Rossi et al., 2006; Maggiore and Keppel, 2007; Bandelj et al., 2008; Como and Magni, 2009; Tlig-Zouari et al., 2009). These generalizations must be accepted with caution. Suspension feeder bivalves may be severely affected by increasing loads of fine sediments and lowering

© frank müller - Burano boat equipped for lagoon clam fishing of the "Tapes philippinarum"

of water currents. Suspension feeding can be problematic in muddy sediments due to the clogging action of resuspended particles and the destabilizing effect of deposit feeders on the sediment (Rhoads and Young, 1970; Levinton, 2001; Gamito and Furtado, 2009) A lot of lagoonal bivalves are switchers, that is they can feed both by filtering or sucking deposits. Bivalves with both types of feeding perhaps will not be so affected. For example, *Abra segmentum*, or *Scrobicularia plana*, two typical lagoonal bivalves, can support environments with low currents, fine sediments and high organic content and extreme physical parameters variation. Low water renewal can lead to extreme environmental conditions (such as high salinity variation) that only some species can cope with. These highly physically stressed environments do not necessarily have high organic matter contents, depending on the extent of organic input and the rate of its decomposition. However, the species present in these stressed environments are r-selected opportunistic species, also present in organically enriched environments. For example, in Ria Formosa lagoon (Portugal) both types of confined, low hydrodynamic, environments are present, they present slight differences in species composition but all species are opportunistic (Gamito, 2008).

A trophic mismatch due to seasonal changes in temperature and nutrient runoff was modelled by Melaku Canu et al. (2010) for the end of century. These authors found that the change in precipitation patterns would increase nutrient concentrations during the cold season when they would not have been exploited by phytoplankton. The unused nutrients would have been exported to the Adriatic Sea. This would cause a mismatch cascade between nutrient supply and primary production and between primary producers and secondary producers. This mismatch coupled with negative effects of temperature on clam growth, would cause a significant reduction in Manila clam harvesting (about -10%) and a consequent relevant economic loss. The uncertainty about the physiological adaptation to temperature of both plankton and bivalve suggests taking these simulations as indicative of the worst possible scenario. Simulations also suggests that proper implementation of mitigation plans, possibly based on adaptive management principles, can mitigate adverse effects of CC on clams rearing. Many lagoonal benthic bivalves filter everything that is suspended, hence a lot of resuspended particulate organic matter and microphytobenthos, such as benthic diatoms. This can, for instance, facilitate *Ruditapes philippinarum*, in case of scarcity of phytoplankton. Some insight on the effects of climate-driven changes on the Northern Adriatic food web, that could have reflections on the lagoon food web, was given by Libralato and Solidoro (2009). Changes in precipitation pattern could produce a mismatch between the freshwater delivery and the biological clock of anadramous species, disrupting migratory patterns. Temporal mismatches can have cascading effects on the entire food web, particularly when sensitive life stages (larval and juveniles) are affected. *Figure 3* shows the main effects on biota of Climatic Change agents (from ICES 2008, adapted for lagoons).

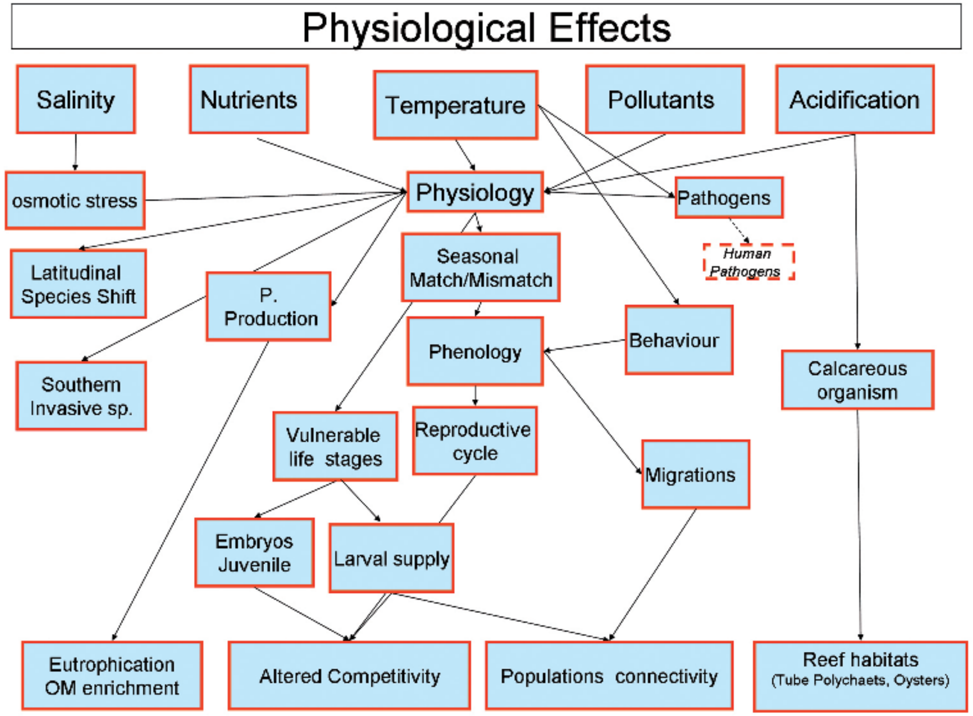

Figure 3:
Physiological effects of Climatic Change Agents (from ICES 2008, adapted for lagoons)

Effects of Sea Level Rise

The sea level rise threatens the City of Venice not only through the major frequency of floods, but also by the increased imbibition of foundations and walls of the city's fabric. Even today, the bricks are in contact with the water rising by capillarity, which causes great harm undermining the physical structure of the city. The rise in sea level also affects the functioning of waste-water pipes, drains and septic tanks, reducing their efficiency and increasing the risk and spread of human pathogens. Form and function of the City, once closely intertwined, are less and less in harmony. The shape of the City no longer reflects historical processes, its livability, its activities. Rather, it is functional only with tourist activity. SLR will alter the global hydrodynamics of the lagoon, thus impacting also on this activity. The A2 projection of 51 cm over the actual mean sea level of Venice would correspond to an average increase in water residence time of 15% (1.6 days) in the lagoon, due to the augmented volume of the lagoon, without taking into consideration any possible closure of the sea inlets and landform modification (Umgiesser et al., in press). If residence time increases and currents slow down, siltation of the basin can occur.

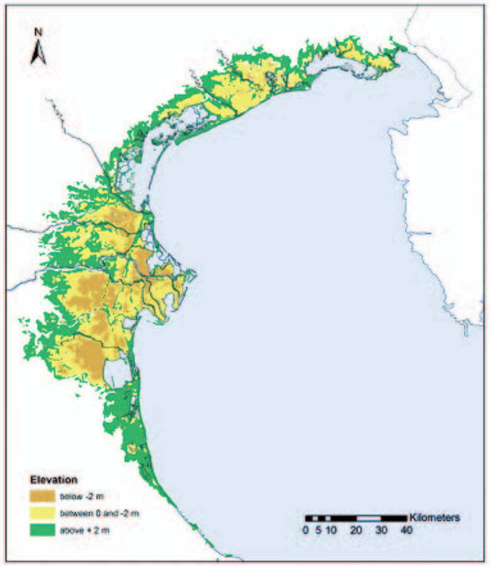

Figure 4:
Distribution of lowlands along the Venetian shores (modified from Bondesan et al, 1995 after Castiglioni, 1995)

There is doubt whether the saltmarshes will be able to keep up with sea-level rise, if not, this could lead to the loss of these valuable and productive intertidal habitats. In case of erosion there could be an increase turbidity and alteration of sediment transport. Turbidity reduces light penetration, lowering the photosynthetic potential of submerged aquatic vegetation, thus changing nutrient dynamics making lagoons more susceptible to eutrophication (Lloret et al., 2008). Sea level rise could also alter the geographic context of the whole Northern Adriatic. Along the coast there are extensive areas lying below the mean sea level. These areas were once occupied by marshes and lagoons and have been drained and converted to agriculture about one century ago. These zones are today devoted to extensive agriculture and present low population density. There are about 650 km^2 of areas laying below -2 meters on m.s.l., about 1500 km^2 between 0 and -2 m, and about 2400 km^2 between +2 and 0 m (*Figure 4*; Bondesan et al., 1995). Lowland to the North includes the reclaimed parts of the lagoon of Caorle and Jesolo, penetrating the mainland up to 15 km, and to the South, the reclaimed parts of the Comacchio lagoon and the drained coastal wetlands of the Po delta stretching inland for over 25 km. Former oligoaline and freshwater wetlands extend currently at the back of the LoVe. These areas are at risk of flooding at the end of century (ENEA, 2007). Lowlands are artificially drained and show a substantial salt content in groundwater. Saltwater intrusion is facilitated by tidal waters flowing upward and by sub-surface geomorphological structures (Carbognin and Tosi, 2003; Rizzetto et al., 2003). The foreseen rise in sea level could create further difficulties to draining and increase saltwater intrusion. Lowlands are therefore vulnerable to both freshwater and marine flooding and soil salinization.

The LoVe is located downstream of a highly industrialized and productive area and pollutants of various kinds have been spilling into the lagoon during the last century. The pollutant loads came mostly from the industrial area of Porto Marghera and from the hinterland, but also from the City of Venice itself. Some of these pollutants have been exported to the sea, others bound to sediment entered the food chain (Castellani and Barbanti, 2010). The possible fate of such a great variety of pollutants due to climate change, without knowing their future sources, is a task that goes beyond the scope of this workshop and would deserve a dedicated meeting. There is hope that in the future there will be an increasing ability to control the input of pollutants. Nevertheless, the future ability of the LoVe to withstand pollutant loads will be dependent on the volume of exchange with the sea, as well as on the chemical and physical conditions of the water and sediment determining their transformation, sequestration, or release. The rapid evolution of the industrial pole of Porto Marghera, does not allow one to make more than decadal predictions on the pressure imposed on the lagoon. The production, the presence, concentration and effects of substances produced and processed there has changed rapidly over the last century (Guerzoni and Raccanelli, 2004). It is difficult to predict the economic and technological development of the area in future economic scenarios. Planning for future industrial activities should carefully consider possible inputs in a more and more confined, fragile lagoon. In addition, the rise in sea level will likely prompt planners to reconsider the location of ports and industrial activities.

Site-specific scenarios driven by the sea level rise

The relative sea level rise could possibly indicate a gradual closure of the lagoon, a reduction of connectivity with the sea and the consequent increase of residence times. Carbognin et al. (2010) calculated the number of possible closures of the mobile gates, on the basis of the mid-range scenario A1B. About 30 closures per year were expected for a RSLR of 26 cm (i.e. the lowest value of the mid-range A1B scenario, plus 5 cm of land subsidence), whereas 250 closings/year were calculated for the highest projected level (53 cm). The SLR projections emerged from the previous UNESCO Workshop (Umgiesser et al., 2011), exceeding 60 cm, hinting at the possibility of having at the end of century a lagoon completely separated from the sea. This will lead to a progressive reduction of connectivity with the Adriatic Sea meaning that the lagoon will gradually move toward a chocked lagoon. The input from the rivers needs to be engineered and the amount of water allowed to flow into the lagoon from the rivers tributaries will determine the salinity of a LoVe that will function as a brackish coastal lake. The complete closure and total diversion of rivers was also envisaged, with possible effects on nutrient budgets and stoichiometry. For example, river damming and diversion could cause a loss of silica supply to the lagoon, with an unpredictable effect on diatoms, which are one of the main components of the food web (see for example Humborg et al., 1997).

© AP Photo/Luigi Costantini - Exceptional high tide in St. Mark's Square on 1 December 2008

Given the likelihood of increases in sea level and the uncertainty of forecasts, we are going to discuss briefly two possible scenarios: the first is a relative to a RSLR of 26 cm and the second with a sea level rise exceeding 60 cm. The ecosystem effects described above will be more or less marked in relation to the degree of isolation of the lagoon and in relation to the timing of events. The first scenario could occur at the end of the century if sea level rise will be moderate, or it may occur at mid-century under the second scenario. The time in which the level of 26 cm will be reached is important since, over this century, the temperature is projected to increase non linearly.

The first scenario is still compatible with the use of mobile gates, whereas the second scenario implies, with the technological solutions available at present, the seclusion of LoVe.
This first scenario is characterized by a moderate sea level which can be counteracted, in its highest surges, by the closures of the gates, still allowing a certain water exchange especially during summer when high waters ("acque alte") are virtually absent. Hydrological models indicate an increase in residence time, although modest, as the mean sea level rises, even without the action of mobile bulkheads. A gradual shift in seasonality of precipitation is expected over the first half of this century, with drier summers, which implies less runoff of nutrients, and a possible decrease in the risk of eutrophication. We must consider, however, that the closures of the gates would be limited to situations of strong wind, when there is more chance of high water. In these situations, the residence time is less than that during calm where only the tide influences the water circulation. During this phase, temperatures would rise moderately, so in summer the production of organic matter would be only slightly higher than today, and oxygenation of water likely sufficient to prevent massive anaerobic episodes. Short-term simulations under winter conditions suggested that the closures should not affect significantly the water quality and that the lagoon seems to be able to return to its condition when the inlets are open again (Melaku Canu et al., 2001). During spring, in the more internal, less flushed areas of the lagoon, high concentration of nutrients could coincide with temperatures compatible with algal blooms. The autumn heavier rainfall will coincide with periods of maximum frequency of high waters, and highest load of sediments, nutrients and pollutants will occur during the periods of maximum closure of the inlets. If nutrients and pollutants are not biologically, chemically or geologically retained in the system, they may be flushed during the following winter. If not, they could trigger the growth of algae in the spring. It is likely, however, that the increase in residence times and temperatures will lead to an accumulation of organic matter at the sediment interface that could result in a reduction of biodiversity, with a progressive decline of sensitive species, mostly filter feeders, in favor of tolerant species, mostly deposit feeders. A slower hydrodynamic, should lead to a reduction of turbidity, but resuspension is strongly linked to the integrity of sediment and, therefore, to the extent of physical disturbance operated by fishing gears and dredging. There could be a strong reduction in saltmarshes. At this stage the effects of the lagoon seclusion could be clearly felt by migratory species, such as the flatfishes Sole (*Solea solea*) and Flounder (*Platichtys flesus*), the Sea Bass (*Dicentrarchus labrax*), the Gilt-head Brim (*Sparus aurata*) and the mullets *Mugil cephalus*, *Liza aurata*, requiring full connectivity between sea and lagoon in the autumn months. The economic impact on fisheries would be increasingly important.


© Armando De Bortol - The characterizing lagoon saltmarshes, locally known as "barene"

The second scenario, the complete closure of the lagoon, may seem to many a remote and hardly practical way. However, if the predictions of climatologists and hydrologists are correct, we will have only a few decades to prepare us to face even this eventuality. It is the most challenging scenario for ecologists. This scenario implies a drastic change in land use in the watershed, a change in the use of the lagoon and a change of the City's infrastructures (e.g. sewage system, port, boat traffic). If in the next decades the inputs in the lagoon remain similar to the present or worsen, a lagoon closure would result quickly in an ecological collapse.

The more severe the climatic effects, the more the lagoon would be closed. With the closing of the lagoon, there would no longer be water exchange, currents and/or tidal fluctuations. The rivers would be adjusted hydraulically, salt and water balance would be preponderantly linked to precipitations and groundwater as inputs, and evapotranspiration as outputs. The circulation and water mixing would be due almost exclusively to the wind. Under this hydrodynamical regime, the lagoon would be subject to severe morphological changes, with flattening of landforms. Loss of intertidal habitats, and loss of land-sea gradients would also occur. No longer influenced by the effect of the incoming tide, water temperatures will follow atmospheric fluctuations more closely, largely in the shallows, with very high summer temperatures but also with the possibility of some winter frost. The stratification of the water will possibly increase, especially in the deeper canals during the summer with calm winds. The high summer temperatures will decrease the concentration of physically dissolved oxygen, which could drop to critical levels if not compensated by the oxygen produced by photosynthesis. The exclusion of rivers could lead to a strong reduction of nutrient loads, but if the use of the lagoon and the land does not change, this reduction may be far from sufficient for an isolated coastal basin to avoid the risk of eutrophication. Due to the absence of water exchange, the lagoon will have to rely almost exclusively on the internal metabolic processes for the assimilation and mineralization of nutrient inputs, making the balance very delicate. Primary producers would increasingly shift toward macroalgae and phytoplankton with strong seasonal variations in productivity. Higher temperatures will lead to elevated metabolic rates, microbiological organic matter degradation would accelerate, with resulting high sediment oxygen demand and dominant anaerobic processes and development of toxic catabolites. This selective environment would force benthic communities to become structurally similar to those currently inhabiting the inner parts of the lagoon, sensitive species would disappear in favor of the presence of opportunistic and tolerant detritivores and deposit-feeders. The increased frequency of hypoxia and anoxia would limit the development of fish communities. There will be a significant loss of biodiversity. The separation from the sea and the rivers would negate the migratory patterns and make genetically isolated the populations of the lagoon. The nursery function of the lagoon would be lost. Impairment and loss of fisheries would also be a likely result.
A different use of the lagoon and the adoption of measures addressed to minimize inputs, pressures and impacts, could be, however, implemented. In this case the picture would be quite different.
Long-term policies for land use should be adopted early, to early limit land runoff and nutrient inputs. Crop typology, extensive reforestation, recalibration of livestock, land cover, as well as wetland restoration should all be addressed. Attention should also be paid to the impacts generated by the City of Venice and other islands, which would lie inside a closed lagoon and for which an increasing pressure from tourism is expected in the coming decades. The use of the best available technologies for waste water treatment and emission control should be encouraged. New rules and technologies should be applied to the City and the lagoon, lowering the level of public and private transport.

Conclusions


© Provincia di Venezia - Landscape of the Northern Lagoon with well preserved habitats of mudflats and saltmarshes

Projected climate change will give the Northern Adriatic lagoons a more Mediterranean character. The rainfall will still be higher than in the current Mediterranean lagoons, with more frequent flash floods. This implies an increasing relevant load of nutrients and pollutants from runoff. Migration northwards of bioclimatic zones can lead the LoVe to loose its ecological uniqueness, with features of the Atlantic European coast.

The effects of the CC, at the very least, will result in bio-complexities further exacerbated by nonlinear and cascading processes (Boesch, 2002).

The effects of the CC, however, will depend on the future use of the watershed. The LoVe is, in fact, placed downstream an intensively exploited and urbanized watershed with a high density of zootechnical and industrial activities from which it receives most of the pollutants and nutrients. The socio-economic development and the future prudent productive structuring and landscape of the watershed will be absolutely crucial in defining the inputs that the lagoon will receive. These inputs will interact with the agents of climate change, and the intensity of their interaction will determine the impacts on the lagoon.

In addition to global effects of the CC, the LoVe will face changes that are specific, if not unique in the world, due to the threats that the SLR has on the very existence of the City. The adaptation of LoVe and the protection of its natural and historical heritage to climate change and RSL is an immense task particularly when the objective is to reconcile the protection of the historic heritage and the conservation of natural communities in the lagoon. The necessity to manage the lagoon inlets through mobile barriers imply that a huge effort for eco-engineering is requested to safeguard the natural heritage as much as possible or at least to develop the ecological potential of the lagoon. This can only be achieved based on sound ecological science (Viaroli et al., 2007). Currently, we can already predict that increasing closure of the lagoon will request specific measures to counterbalance the reduction of the connectivity with the sea and that watersheds and river inputs need to be managed to combat eutrophication and desalinisation of the LoVe.

Previous meetings have resulted in a scenario in which the increase in sea level, at the end of the century, will no longer be compatible with the capabilities of the City to prevent permanent floods. With current available technologies, the closure of the lagoon, or part of it, will be inevitable. All the negative effects of CC, especially species impoverishment and the risk of further eutrophication, will be accentuated in a lagoon without water exchange. If the inputs of nutrients and pollutants remain close to current levels, the lagoon would face a high risk of ecological collapse, therefore, in the possibility of exclusion, the entire structure of the watershed should be revised. Ecological study and management of the LoVe must be addressed at the level of the entire watershed, including the catchment, the lagoon and coastal waters, with special attention to scale and scaling of phenomena. Biological changes, including the invasions of alien species, are also dependent on the effects of CC on the Mediterranean and Adriatic.

The sea level rise could change the entire coastal geographical context, e.g., hardening of the shore is a common feature of the coast in industrialized countries which prevent the natural re-alignment of lagoons to the new sea level. Besides coastal squeezing, there is the possibility of the formation of new lagoons and coastal wetlands. A proactive and progressive ecological restoration of undeveloped lowlands could give lagoon ecosystems a chance for survival through habitat migration. The ecological functions and services, that LoVe should sacrifice to preserve the City, may be partly compensated by those supplied by a number of new lagoon basins that may develop along the coast, especially in the lowlands with a low population density. New basins could provide provisional services such as fishing, recreational services and also aesthetic values and perform, at the same time, important ecological functions such as nursery areas for fin-fishes and invertebrates, feeding and nesting ground for birds, and migration pathways for anadromous and catadromous species. The possible location of these sites should be studied and planned carefully. An attentive adaptive policy of wetland re-creation would acknowledge and sustain the complex interaction between human activity and lagoons, safeguarding both the ecosystem services supplied by natural environment and ecological functions.

There is a need to strengthen a coordinated and large-scale research effort on the relationship between lagoon metabolism and hydrology and on the related biological patterns. Ad hoc research programs with experimental studies (e.g. mesocosm and flume experiments) and observational monitoring should be implemented to improve our understanding of ecological responses to Climate Change and to enable the implementation of adaptive management policies to face proactively the change and to mitigate deleterious effects as much as possible. The rapid adoption of a long-term strategy is needed, if not a very long-term strategy, since the forecasts over the 21st century indicate many centuries of temperature and sea level rise (IPCC, 2007). Strategies should include careful economic and territorial planning addressing the reduction of loads and pressures on the lagoon, making possible the attainment of an ecological balance even in the case of a reduced connection with the sea.
Furthermore, we have to claim for establishing a long term ecological research program for integrating studies on lagoon, coastal area and watershed on time and spatial scales which allow to capture signals of the CC effects. Moreover, this is an almost unique tool to feed modeling scenarios with experimental/field data, as well as to support a step-by-step environmental policy and management for tackling and mitigating changes' effects.

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Annex 1: Agenda

Wednsday 25 May 2011

Arrival of participants

Day 1 - Thursday 26 May 2011

09:00 Registration of participants

09:30 - 10:00 Opening remarks & Welcome:
Engelbert Ruoss, Director, UNESCO Venice Office
Davide Tagliapietra, Workshop Coordinator, ISMAR-CNR
Philippe Pypaert, Programme Specialist, Environment, UNESCO Venice Office

Session 1. Present state of the Lagoon of Venice (LoVe) and scenarios for Climate Change (CC) and Sea Level Rise (SLR)

10:00 - 11:00 Debora Bellafiore
Sea Level Rise scenarios resulting from the last UNESCO Workshop

Christian Ferrarin
Hydrological changes in coastal lagoons as a consequence of Climate Change. Hydrology of the LoVe and inlet closing frequencies

Davide Tagliapietra
Present state and main patterns of change in the LoVe and its Watershed

11:00 - 11:30 Session 1 Discussion

11:30 - 11:45 *Coffee break*

Session 2. Effects of CC & SLR on chemical properties, nutrient cycle, primary producers and organic matter degradation

11:45 - 12:45 Pierluigi Viaroli
Primary production, decomposition, biogeochemistry and vulnerability to anoxia in Adriatic coastal lagoons with different primary producers (Viaroli)

Cosimo Solidoro
Downscaling experiment for the Venice lagoon. Effects of changes in temperature and precipitation on nutrient inputs, planktonic productivity and habitat suitability for shellfish growth

Paolo Magni
Relationships between organic matter content, benthic community structure and diversity in coastal lagoons

12:45 - 13:15	Session 2 Discussion
13:15 - 14:30	*Lunch break*

Session 3. Effects of HCC on consumers and food webs

14:30 - 15.10	Fabio Pranovi *State and changes of nekton. The LoVe food webs* Michele Mistri *State and changes of lagoonal benthic fauna in response to climate change*
15:10 - 15:45	Session 3 Discussion
15:45 - 16:00	*Coffee break*

Session 4. The warmer sister of Venice; suggestions from southern lagoons

16:00 - 17.00	Nejla Aloui-Bejaoui *Effect of temperature on weight growth of the cultured mussel "Mytilus galloprovincialis", Bizerte Lagoon (Tunisia)* Sofia Reizopoulou *Biodiversity changes in the lagoons of Amvrakikos Gulf (Greece)* Bjorn Tunberg *Ecological Assessment of the Indian River Lagoon Estuary and Ecological Impact from Intensive Dredging in the Sebastian River Estuary, Eastern Florida, USA*
17:00 - 17:30	Session 4 Discussion
17:30 - 17:45	Conclusion of the day
20:00	*Social Dinner*

Day 2 - Friday 27 May 2011

09:30 - 11:00	Final presentations and discussions
11:00 - 11:15	*Coffee break*
11:15 - 12:45	Discussion and wrap-up
12:45 - 13:00	End of the workshop
13:00 - 14:30	*Lunch*

Annex 2: List of Participants

Nejla ALOUI-BEJAOUI	Institut National Agronomique de Tunisie, Tunis, Tunisia
Debora BELLAFIORE	ISMAR-CNR – Institute of Marine Sciences of the National Research Council, Venice, Italy
Rutger DE WIT	Laboratory Ecology of Coastal Marine Systems - UMR 5119, Université Montpellier 2, France
Christian FERRARIN	ISMAR-CNR – Institute of Marine Sciences of the National Research Council, Venice, Italy
Sofia GAMITO	IMAR-CMA – Marine and Environmental Research Centre, FCT University of Algarve, Portugal
Pierre LASSERRE	Université Pierre et Marie Curie, Paris, France
Paolo MAGNI	IAMC-CNR – Institute for Coastal Marine Environment of the National Research Council, Oristano, Italy; ISMAR-CNR – Institute of Marine Sciences of the National Research Council, Venice, Italy
Michele MISTRI	Department of Biology, University of Ferrara, Italy
Angel PÉREZ-RUZAFA	Ecology and Management of Marine Coastal Ecosystems Investigation Group, Department of Ecology and Hydrology, University of Murcia, Spain
Fabio PRANOVI	Department of Environmental Sciences, Ca' Foscari University, Venice, Italy
Sofia REIZOPOULOU	HCMR – Hellenic Centre for Marine Research, Anavyssos Attiki, Greece
Gil RILOV	National Institute of Oceanography and University of Tel Aviv, Israel
Cosimo SOLIDORO	OGS – National Institute of Oceanography and Experimental Geophysics , Trieste, Italy
Davide TAGLIAPIETRA	ISMAR-CNR – Institute of Marine Sciences of the National Research Council, Venice, Italy
Bjorn TUNBERG	SMS – Smithsonian Marine Station at Fort Pierce (FL), USA
Ivan VALIELA	Marine Biological Laboratory, Woods Hole (MA), USA
Pierluigi VIAROLI	Department of Environmental Sciences, University of Parma, Italy

THE FUTURE OF VENICE

AND ITS LAGOON IN THE CONTEXT OF GLOBAL CHANGE

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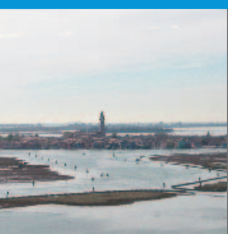
delle Ricerche

ISMAR
Istituto di Scienze Marine

The urban ecosystem of Venice and its Lagoon is among the most studied urban and environmental systems in the world. Acting as neutral broker and facilitator, UNESCO Venice Office has mobilized expertise in the interdisciplinary fields of science and culture to identify and discuss the scientific, environmental, cultural and socio-economic challenges faced by the World Heritage site of Venice and its Lagoon in the context of global change.

This report presents a summary of the results and discussions from the second in a series of four workshops that were held to gather the necessary expert inputs needed to evaluate the current situation of Venice and its Lagoon and to contribute to a shared sustainable vision for its future. While providing a shared overview of the main challenges that are being faced by the Venice Heritage Site, the workshop report *The Ecological Implications of Climate Change on the Venice Lagoon* significantly contributes to the growing body of knowledge on the effects of climate change on coastal and lagoon cities.

The results of the thematic workshops will be used by UNESCO to facilitate the vision, strategy and management plan for Venice and its Lagoon, and to prepare in collaboration with the local authorities a follow-up report to the one already elaborated by UNESCO in 1969 after the devastating *acqua alta* of 1966.



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