ORDER AND CHAOS IN THE NATURAL WORLD: EXPLORING AND UNDERSTANDING VARIABILITY IN THE LAGOON OF VENICE

C. SOLIDORO[1], R. PASTRES[2], G. COSSARINI[1], D. MELAKU CANU[1] & S. CIAVATTA[2]
[1]Dipartimento di Oceanografia, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Sgonico, Italy.
[2]Dipartimento Chimica-Fisica,Università di Venezia, Venice, Italy.

ABSTRACT

Sometimes it is possible to discover regularities and general principles behind the variability, complexity, and apparent unpredictability of observations of nature. The research of such principles represents a fundamental step toward a keener understanding of the functioning of the real world and is a prerequisite for the sustainable management of natural resources. The lagoon of Venice is the largest in the Mediterranean Sea, and is an example of a complex transitional ecosystem subjected to strong anthropogenic influences. It has been studied by both local and international scientific communities. Only recently, however, have systematic, basin-wide, monitoring and research efforts been taking place. Here we show that differences in meteorological conditions cause substantial interannual variability in the water quality parameters of the lagoon of Venice. Indeed, even though nutrient loads originating in the drainage basin are, on an annual basis, roughly constant, an analysis of the time evolution of the spatial distributions of the concentration of nutrients and chlorophyll a reveals remarkable interannual differences, superimposed on a well recognizable seasonal pattern. These differences are related to the amount of rain in spring and summer. In all the three years analyzed, a clear spatial structure is present. The existence of a strong correlation of distribution of trophic variables with salinity and residence times indicates that the lagoon can be described almost *in toto* by the balance achieved by its freshwater input, tidal flushing, and the annual cycle of solar radiance.

Keywords: climate, gradient, MELa, monitoring, rain, Venice, water quality, WFD.

1 INTRODUCTION

Nature is the realm of complexity, variability, and exception to rules. Sometimes, however, it is possible to discover hidden order behind the complex pictures through which nature reveals itself. In such cases, it appears that nature is, at the very least, a two-faceted coin: chaos and unpredictability on the one side, order, metrics, and underlying natural principles on the other.

The research of such principles is a fascinating goal. In fact, it is a fundamental step toward a better understanding of the functioning of the real world and, therefore, toward a real appreciation of its beauty. In addition, understanding nature is a prerequisite for any attempt at a rational planning of the sustainable management of natural resources.

Lagoons are transitional environments in which different sources of disturbances interact and coexist, and in which most of the parameters show different scales of variability, both in space and in time. Parameters may change in space as a result of inputs from rivers, exchange with the sea, tidal agitation, and also in time, as a consequence of the seasonal cycle, which drives most of the biological processes, and of the stochastic inputs of rivers. Anthropogenic impact represents an additional source of variability, both in space and in time, superimposed on those listed above. A high range of variability, therefore, is the rule, more than the exception, in water quality parameters measured in this environment, a fact that environmental authorities should bear in mind when defining water quality targets and environmental indices to be applied to a whole water body or when selecting reference sites for good and bad conditions (EU WFD 2000/60).

The lagoon of Venice (Italy) is the largest in the Mediterranean Sea, covering an area of about $500 \, \text{km}^2$. Its average depth is less than $2 \, \text{m}$, but its morphology is characterized by the presence of large shallow areas and a network of deeper channels. Three narrow inlets connect the lagoon to the

Adriatic Sea. The amount of water that flows in and out during each tidal cycle amounts to around a third of the total volume of the lagoon [1]. The drainage basin conveys into the lagoon approximately 4.6×10^6 kg of nitrogen and 0.21×10^6 kg of phosphorous per year [2]. In addition, port and industrial activities have a negative impact on water and sediment quality and on the ecosystem. In spite of that, this system still hosts highly valuable typical habitats, as well as several economic activities that depend on the ecosystem's health, such as fisheries, recreational activities, and tourism. At present, local authorities are discussing several interventions that could have a substantial effect on nutrient cycling and eutrophication of the lagoon. The most discussed one is probably a set of interventions that include the temporary closure of the inlets, in order to prevent the flooding of the city in concomitance with exceptionally high tide. However, there is rising concern about the fact that such a closure, and the infrastructures which support the mobile gates, may reduce the exchange with the sea, with unforeseeable consequences to the ecosystem's dynamics.

Because of its peculiarity, the lagoon of Venice has attracted the interest of both local and international scientific communities. However, until recently, the majority of the investigations concerning it were addressed to the analysis of specific processes and there was a lack of concerted, multidisciplinary, systematic, lagoon-wide efforts, which resulted in a rather poor quantitative knowledge of the functioning of the lagoon ecosystem as a whole [3].

In this paper we present an analysis of water quality data collected in the first and, so far, only systematic monitoring effort covering the whole lagoon for a large period. The program, named MELa1, was promoted by the Consorzio Venezia Nuova on behalf of the Venice Water Authority (Magistrato alle Acque), in order to gain a reliable figure of water quality status before the setting up of major anthropogenic interventions, and was launched only four years ago. Data were collected once a month for over three years (September 2000–December 2003), in a monitoring network made of 30 stations, and designed with the aim of obtaining a good coverage of both the shallow area and the channels in the water body. Each sampling cycle, which usually requires two days, was performed, whenever possible, in neap tide conditions and at the slack water phase of the tidal cycle, in order to minimize the variability caused by the tidal mixing. The results allowed us to draw a first and rather consistent picture of the spatial and temporal variability of the dissolved nutrients and of chlorophyll a, which is considered here as a proxy to the abundance of the phytoplanktonic community.

Time evolution and spatial variability of experimental findings are described in the next section, while the following two sections are devoted to the identification of keys to understand and interpret patterns of variation in, respectively, time and space.

2 EXPLORING COMPLEXITY: THE EXPERIMENTAL DATA AND A CONCEPTUAL MODEL

The space and time variability in observed data are summarized, quantified, and depicted in Figs 1–3 for chlorophyll, dissolved inorganic nitrogen, and dissolved inorganic phosphorus, respectively. The upper parts of the figures illustrate the time evolutions of the spatial distributions of the important water quality parameters, obtained by spatial interpolation of the values in the 30 sampling points, while in the bottom panels of the figures box plots summarize and provide a graphical representation of monthly evolutions of spatial averages that facilitate a quantitative appreciation of the differences among different months.

It is easy to see that some regularities exist and that there are major differences among different variables, different years, and different seasons. Time evolution is the result of the superposition of a seasonal cycle and interannual variability. Chlorophyll peaks in summer, after a smaller bloom in spring. The concentration of nutrients is higher in late fall and winter, when rain and river discharge is more abundant and the uptake from biological activity is lower. However, the chlorophyll peak in 2002
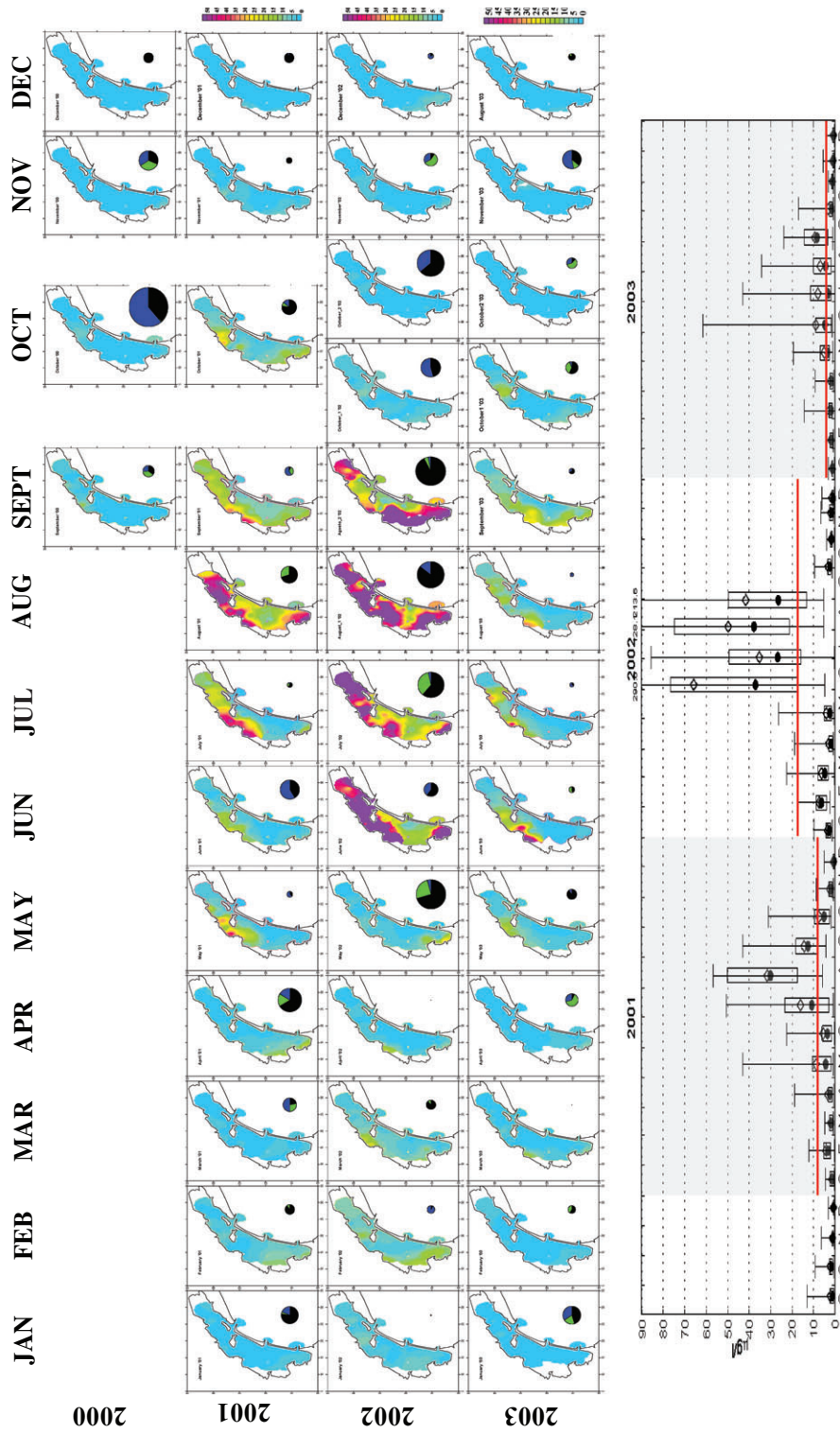
Figure 1: Time evolution of the spatial distribution of chlorophyll. The upper figure gives the spatial interpolation of the data together with an indication of the amount of rainfall in the month before the sampling (size of the circle). The box plot gives the mean, the median, and the interquartile dispersion of monthly averages. The horizontal lines indicate yearly averaged values.
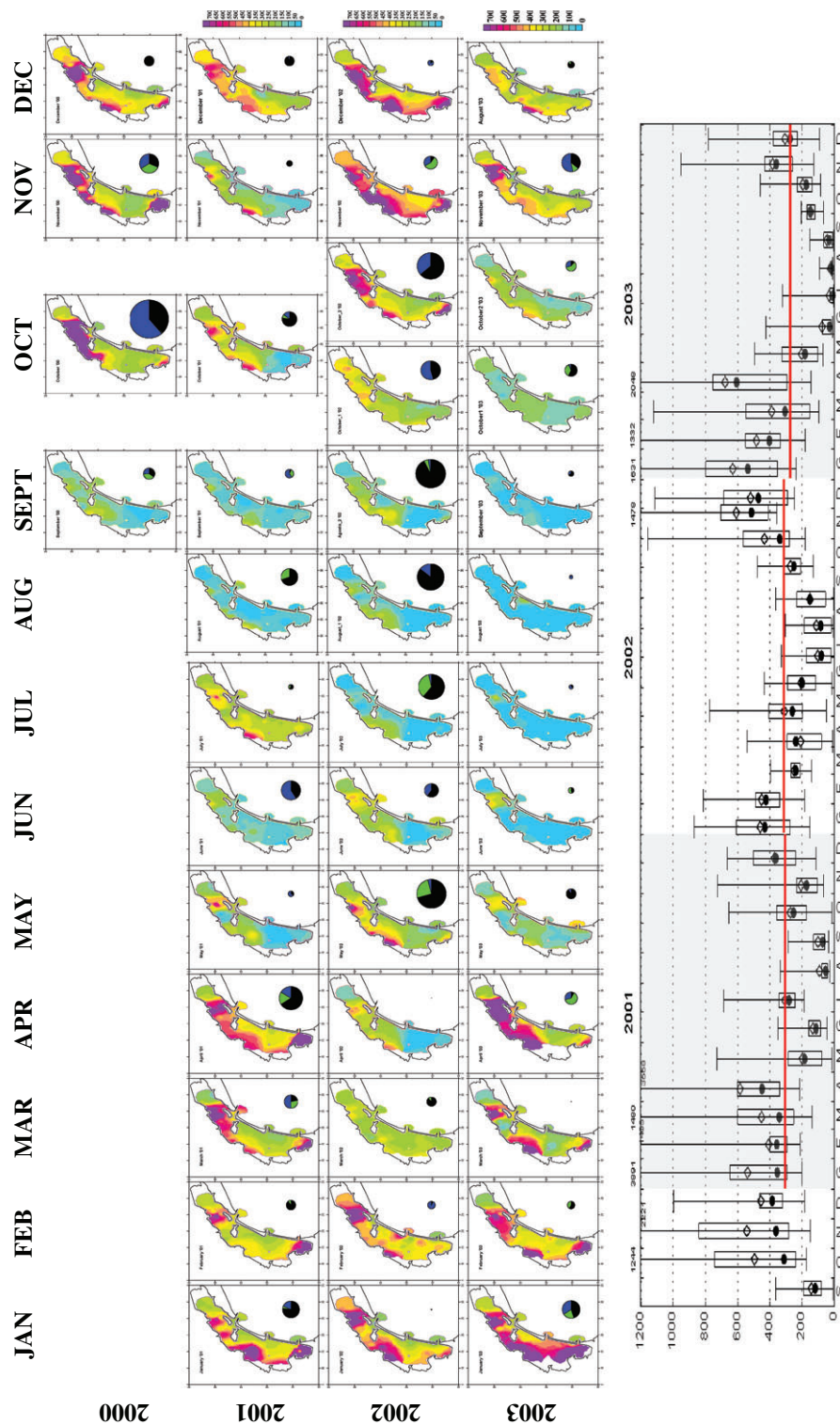
Figure 2: Time evolution of the spatial distribution of nitrate. The upper figure gives the spatial interpolation of the data together with an indication of the amount of rainfall in the month before the sampling (size of the circle). The box plot gives the mean, the median, and the interquartile dispersion of monthly averages. The horizontal lines indicate yearly averaged values.
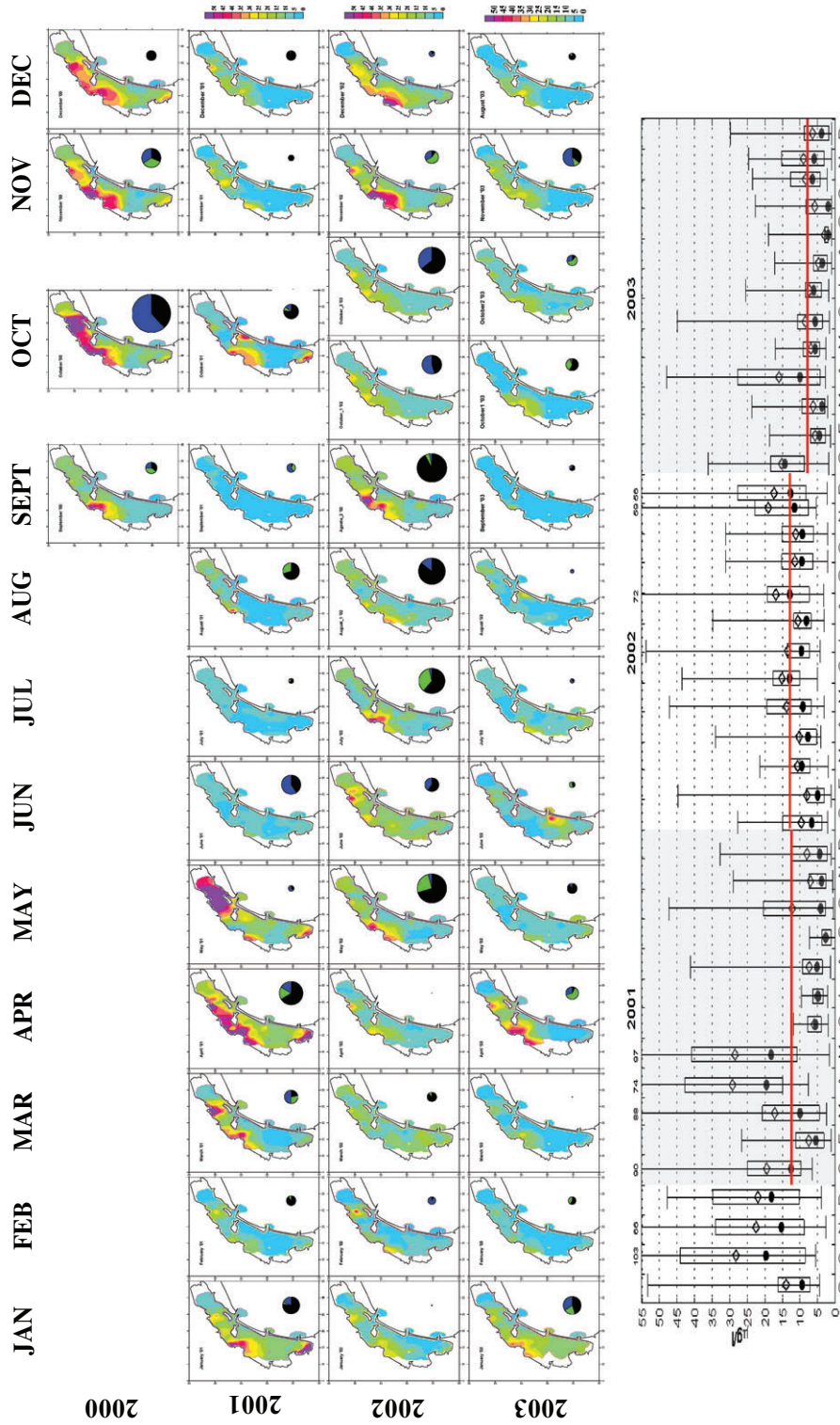
Figure 3: Time evolution of the spatial distribution of phosphate. The upper figure gives the spatial interpolation of the data together with the indication of the amount of rainfall in the month before the sampling (size of the circle). The box plot gives the mean, the median, and the interquartile dispersion of monthly averages. The horizontal lines indicate yearly averaged values.

is much higher and longer than the peak in 2003, which presents the smallest bloom. Interestingly, significant differences in the yearly averaged value of chlorophyll occur even if the yearly averaged nutrient concentrations are quite similar in the three years. A closer inspection of the graphs reveals that the summer values of nutrient concentration are significantly different even when the yearly averaged values are similar. Indeed, even if the nutrient loads originating in the drainage basin are, on an annual basis, roughly constant, in 2002 the concentration of nutrients is also relatively high during the bloom and supports it, while in the summer of 2003, nutrients, and phosphorus in particular, are at very low levels, so that the bloom cannot go on. These facts suggest that it is the summer level of nutrients, more than the yearly averaged one, which regulates the magnitude of the planktonic bloom. If the runoff supplies nutrients during the summer, nutrients can be taken up by the phytoplankton, enter into the biogeochemical cycles, and efficiently stimulate primary productivity, possibly also being utilized more than once (after remineralization). Conversely, if the input of nutrients occurs in winter time, when no phytoplankton is present and environmental conditions are not suitable for phytoplankton growth, the fraction of nutrients entering the biological cycle is much smaller, and the largest part of it flows out to the sea after having spent a much shorter time in the lagoon.

The effect of rain regime can be appreciated by a comparison with the time evolution of the amount of rainfall between a sampling cycle and the previous one; here taken as a proxy of the runoff in the period and represented by the sizes of the circles linked to each monthly spatial distribution. It can be noted that the summer of 2002 was a particularly rainy one, so a greater amount of nutrients was supplied to the lagoon exactly during the blooming phase, which was then taken up and entered the biogeochemical cycle, while in 2003 the summer was particularly dry, and the runoff was negligible for several weeks in a row. The situation in 2001 is intermediate between these two extremes. The conceptual model sketched above points out the importance of the timing of the nutrient input.

A clear spatial structure of all three years, depicted by a north–south gradient and an east–west one, along with a careful comparison among spatial distributions shows the differences among different months and among different years. One such example is the spring concentration of phosphorus, which was the highest in the northern and central inner area of the lagoon in 2001, while in 2003 it was homogeneously low, where as in 2002 it was high in the central inner part and low else-where. Other examples include the winter distribution of nitrate, or the summer concentration of chlorophyll.

3 INTERPRETING SPATIAL VARIABILITY

In agreement with the conceptual model sketched in the previous section, there are two major factors that concur in generating the spatial gradients of nutrient and chlorophyll concentrations (Figs 1–3), namely the inputs from rivers and the exchanges with the sea through the inlets. This hypothesis can be tested in a quantitative way by performing an indirect gradient analysis [4]. The first step of this analysis is to summarize spatial variability by performing a principal component analysis (PCA) on water quality parameters. In order to emphasize the spatial variability alone, the seasonal evolution has been averaged out, by taking yearly averaged values. Multiyear trends have been removed too. The results of the PCA indicate that the first factor, PC1, explains a very large fraction of the total variability of the system (around 67.5%), so that the projection of the sample on this factor (the PC1 scores) is informative on the variability of the 'trophic/water quality' condition in the lagoon. A plot of the spatial distribution of these scores (Fig. 4) corroborates the interpretation proposed, by highlighting the presence of a spatial gradient of this synthetic indicator, which is along the direction of the rivers to the inlets.

The second step of the gradient analysis is a multiple regression analysis among PC1 scores (a proxy for the water quality condition) and physical parameters. The best results have been obtained
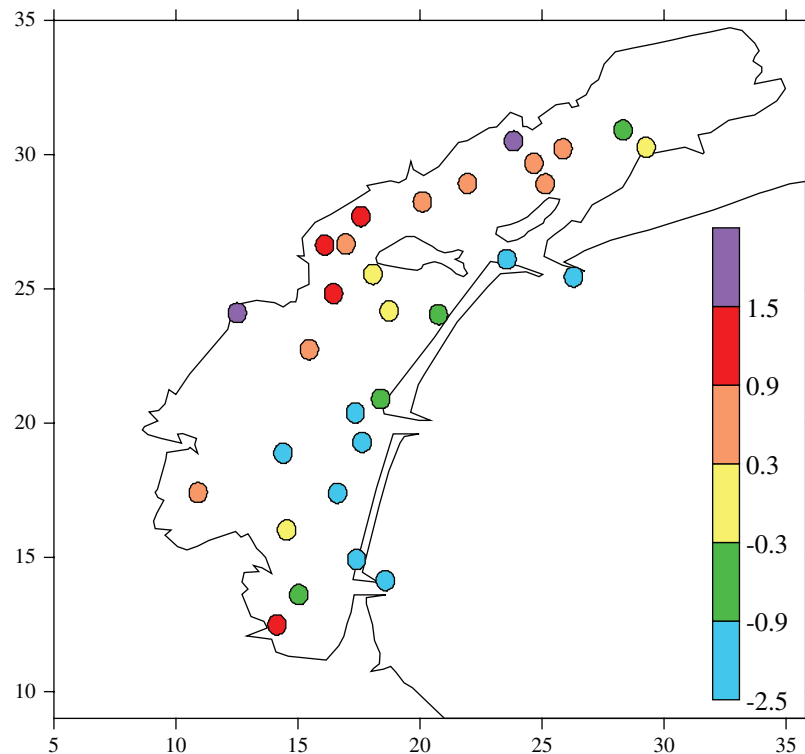
Figure 4: Spatial distribution of PC1 scores.

when considering the salinity (proxy for the influence of rivers) and residence time (proxy for the influence of the inlets) as explanatory variables.

$$y = \beta_0 + \beta_{\text{SAL}}\text{SAL} + \beta_{\text{T\_RES}}\text{T\_RES}. \tag{1}$$

In this case, the multiple regression explains a very significant share of spatial variabilities ($R^2 = 86.5\%$) as also seen in the observed vs. predicted values plot, in which most of the sample data align around the diagonal line (Fig. 5).

The existence of a strong correlation of distribution of trophic variables with salinity and residence times indicates that the lagoon can be described almost *in toto* by the balance achieved by its freshwater input, tidal flushing, and the annual cycle of solar radiance.

4 INTERPRETING TIME VARIABILITY

The analysis of time evolution of the spatial distributions of the concentration of nutrients and chlorophyll a reveals remarkable interannual differences, superimposed on a well recognizable seasonal pattern. These differences are clearly related to the amount of rain in spring and summer (Figs 1–3). Indeed, nutrient loads originating in the drainage basin, on an annual basis, present little variation, but the timing of their input in the lagoon, and, hence, the rain regime, makes a difference, as shown in the conceptual model previously described.

Therefore, differences in meteorological conditions cause substantial interannual variability in the water quality parameters of the lagoon of Venice. This result provides evidence that the impact of the regional effect of global climate change on water quality can be quite large, and sets an important
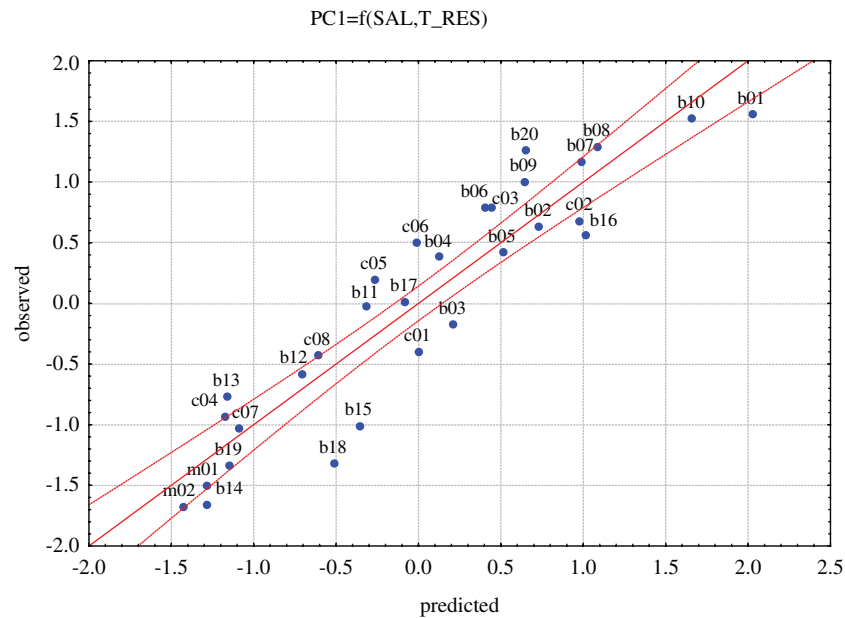
PC1=f(SAL,T_RES)

Figure 5: Mutliple regression among physical parameters (salinity and residence time) and trophic condition (PC1 scores).
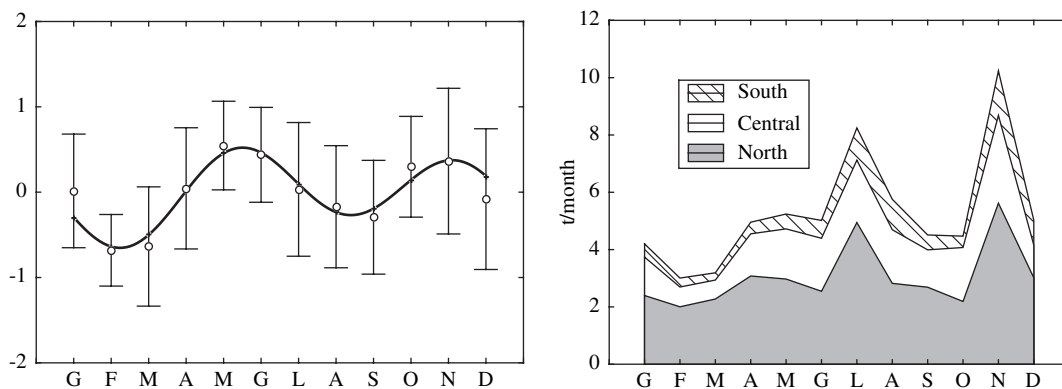

Figure 6: Comparison among reconstructed seasonal evolution of concentration of phosphorus and observed value of input of phosphorus from tributaries.

term of comparison for both assessment of the impact of the anthropogenic intervention planned in this important lagoon and future studies in the area.

Seasonal evolution, in turn, might instead be explained as the superposition of the timing of river runoff and the annual cycle of solar irradiance.

This can be confirmed by the comparison among typical seasonal evolution of nutrients, reconstructed by extraction of seasonal components in a 10-year time series analysis, and experimental information on nutrient load in tributaries measured in the frame of the DRAIN project [5]. Figure 6 shows, as an example, the case of phosphorus, but the agreement is satisfactory for all inorganic

nutrients, thus providing support for the importance of river input in the time evolution of the water quality parameter also at the seasonal level.

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