Journal of Sea Research 88 (2014) 130–143

Contents lists available at ScienceDirect

Journal of Sea Research

journal homepage: www.elsevier.com/locate/seares

Decreased seasonality and high variability of coastal plankton dynamics in an urban location of the NW Mediterranean

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A R T I C L E I N F O

Article history:
Received 7 April 2013
Received in revised form 20 January 2014
Accepted 24 January 2014
Available online 3 February 2014

Keywords:
Plankton dynamics
Coastal areas
Anthropogenic pressure
Physical drivers
Seasonality
NW Mediterranean

A B S T R A C T

Contrary to what happens in open waters, where chlorophyll values and plankton dynamics can be predicted with a reasonable accuracy on an annual basis, biological parameters analyzed for coastal waters often show slight seasonality, and are exposed to numerous and convergent forcing factors that make it difficult to draw clear patterns. On top of this large natural variability, coastal locations subjected to urban sprawl suffer further human impact that may increase the unpredictability of plankton dynamics. Here we present the results of a multi-year time series of monthly samplings carried out in a coastal location by the city of Barcelona (NW Mediterranean) that is highly exposed to anthropogenic disturbances. Our data confirm the existence of complex patterns throughout the year. Freshwater inputs proved to be an important source of nutrients, yet the response of the planktonic organisms was vague and not systematic, contrary to the results of a previous study at a nearby coastal site less affected by human activities. The severity of anthropogenic disruptions was partially masked by the co-occurrence of natural physical phenomena, e.g., waste spills often come with downpours and large river discharge. In the NW Mediterranean, there seems to be a gradient of decreasing predictability on plankton dynamics from offshore to coastal waters with little human influence, where seasonality can be largely modified by local processes but the biological response is systematic and fairly predictable, and finally to urban coastal locations, where the seasonal background is diluted by numerous perturbations and there exists a variable pattern of biological responses. Our study underlines the importance of specific coastal processes in determining the structure and dynamics of the planktonic community, and the need to characterize coastal areas setting aside some of the assumptions valid for open ocean regions (e.g., (1) in the open ocean seasonality dominates annual nutrient fluxes, which are tightly linked to mixing and turbulence, while nutrient inputs at the coast can occur anytime throughout the year and may not be coincident with increased water-column mixing (Cloern, 1996; Cloern and Jassby, 2008); and (2) in coastal regions the concentration of nutrients during nutrient pulses can be greatly imbalanced with regard to Redfield elemental ratios (Jickells, 1998; Justić et al., 1995 and references therein)).

1. Introduction

In the Mediterranean Sea, as in most temperate and subtropical oceanic areas, the annual plankton dynamics are recurrent and strongly driven by the winter mixing that initiates the most prominent production and population succession events. Mixing transfers nutrients from deep waters to the surface, where the availability of light and the stratification of the water column allow for a large phytoplankton production peak in winter–spring. Highly stratified water column conditions and diminished nutrient concentrations in summer give prominence to smaller phytoplankton species and recycling heterotrophs (Longhurst, 1995, 1998; Margalef, 1978). Lower autumn phytoplankton peaks are not uncommon when mixing starts to break the stratification. Despite the many physico-chemical factors known to influence or modulate this system dynamics, such as fronts (Mahadevan and Archer, 2000), internal waves (Kahru, 1983), mesoscale processes (Lévy, 2008), wind-driven turbulence (Gargett, 1989; Pesant et al., 2002) or atmospheric inputs (Guerzoni et al., 1999), a high degree of predictability remains in open ocean conditions.

A different picture emerges for coastal areas. Chlorophyll, as a proxy for system production, tends to have annual cycles more or less blurred by a multitude of local, site-specific factors such as river discharge, complex bottom bathymetries, local winds, tides, atmospheric deposition, among others. Thus, the strong nutrient constraint on the seasonal occurrence of phytoplankton production in the open ocean weakens in coastal waters that receive nutrient inputs from land through a range of sources and regimes (Cloern, 1996; Jickells, 1998). In addition, the growth stimulation that takes place in open waters as a result of increased light availability during the spring stratification is of less importance in many coastal areas, because the water column is shallow

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1385-1101/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.seares.2014.01.010

and the organisms are permanently within the photic layer. As a consequence, seasonality may be greatly modified and predictability at the system level dramatically decreased.

Mediterranean climate is characterized by a strong irregularity in precipitation (Cebrián et al., 1996; Font, 2000; Llasat and Puigcerver, 1997; Valero et al., 2009). Rainfall is most common in autumn and spring, but strong storms can occur anytime throughout the year and they often result in significant inputs of terrestrial runoff into the coastal zone (Liquete et al., 2009). Precipitation events affect the discharge regime of streams, including many rivulets that remain dry during long periods of time but are responsible for large short-lived discharge events (Estrela et al., 2001; Liquete et al., 2007). In the NW Mediterranean, previous studies have shown the importance of episodic forcing on the dynamics of the planktonic community and their potential to induce changes on the order of seasonal variability (Duarte et al., 1999; Guadayol et al., 2009). Guadayol et al. (2009) proposed the existence of a sequence of events that led to production peaks after episodic storm and river discharge events in Blanes Bay. This increased the understanding of plankton system dynamics in the area.

In addition to the variability of natural forcing factors, there are human-induced perturbations. Human pressure along the world's coasts has increased during the last decades, and the impacts on the coastal environment have consequently multiplied (IPCC, 2007). Continuous human pressure can induce progressive changes in the water properties that may alter the natural dynamics of plankton or the community composition, and drive gradual, long-term ecosystem shifts. Eutrophication of coastal waters, along with the artificial stabilization of the coastline through dikes and harbors, are but two consequences (Claussen et al., 2009; Justić et al., 1995; Tett et al., 2003, 2007). The combination of excess nutrients and limited water mass movements can foster the emergence of chronically polluted areas or favor the development of algal blooms (Vila et al., 2001). Beyond long-term changes, human-induced perturbations may interact with the natural forcing variability on shorter time scales to affect coastal plankton dynamics (Romero et al., 2013).

The city of Barcelona and its nearby littoral is a good example of a densely populated coastal area. The metropolitan region houses about 3 million inhabitants, but over 4.6 million people live within the catchment area of the two major rivers that flow into the city's nearshore waters, the Besòs River and the Llobregat River (ACA, 2005). Coastal management in the area may thus benefit from a better understanding of the combined effects of natural and anthropogenic forcing on coastal plankton dynamics. Apart from the intrinsic pressure related to urban sprawl in terms of air and water pollution, impacts exerted by human activities on the coast are highly variable, both in form and in time. In the summer, touristic and recreational activities (bathing, leisure crafts) involve a direct and continuous perturbation of coastal waters, but their effects are usually restricted to a narrow water strip close to the coastline. On the contrary, in autumn and spring, urban sewage spills that come with freshwater flushes and rainfall overflows affect extensive areas, though the impact is limited in time and fairly uneven along the coast (ACA, 2005; EEA, 1999; UNEP/MAP/MED POL, 2003).

Within this framework, we hypothesize that the seasonal signal characteristic of open Mediterranean waters is blurred in the littoral fringe, particularly near densely populated areas, since nutrient inputs can be expected to be large and occasionally uncoupled from meteorological forcing. In order to address this issue, the present study focuses on the dynamics of plankton in a highly urbanized coastal location by the city of Barcelona, using time series data. We compare this study site to the results described for Blanes Bay (70 km north from Barcelona, Guadayol et al., 2009), and to a 13-year time series from Banyuls-sur-mer (200 km north from Barcelona), two stations where the natural forcing conditions are fairly similar to those found in Barcelona, but where the anthropogenic influence is lower.

2. Material and methods

2.1. Sampling area and sampling scheme

The study was conducted ca. 0.5 km offshore of Barceloneta beach, in Barcelona's coastal waters (NW Mediterranean, 41°22′55″ N, 2°11′58″ E, Fig. 1). The sampling station has a depth of about 10 m with a sandy bottom. The predominant current acting near the coast is the southwest littoral drift, a by-product of the Liguro–Provençal Current, which is the main oceanographic current in the Catalan margin (Flexas et al., 2002). An accurate description of the Barcelona continental shelf and its main geological, hydrographic and oceanographical features are given in Liquete et al. (2007). The area receives the discharge of two rivers, the Besòs River to the north and the Llobregat River to the south, and is influenced by numerous human activities (tourism, recreational sailing, dredging for beach maintenance, works on coastal infrastructures). In addition, the sampling site is located between two storm overflows (Fig. 1).

We carried out monthly samplings from October 2005 to October 2008, framed within a larger regular sampling program (the Coastal Oceanographic Observatory, COO) running since 2002 that has provided basic variables also included in the analyses (namely inorganic nutrients, chlorophyll *a*). Water was taken from a depth of 3 m by means of a Niskin bottle, and immediately transferred to 2.5 L polycarbonate carboys that had previously been washed with a dilute solution of hydrochloric acid, milli-Q water, and sample water. Carboys were carefully protected from sunlight and taken to the laboratory. CTD vertical profiles of salinity and temperature were also obtained (Sea-Bird Electronics SBE 25 CTD SN97 probe).

2.2. Hydrological and meteorological time series

Meteorological data was provided by the Spanish Meteorological Agency. Data was acquired from a meteorological station located at the seafront, close to our sampling site (41°23′27″ N, 2°12′05″ E, 21 m height, Fig. 1 inset). They supplied hourly-accumulated rainfall and hourly-averaged data for air temperature, wind speed and wind direction. Wind parameters were measured at 10 m above the ground and consisted of vectorial averages. Time series for the Besòs River discharge was provided by the Catalan Water Agency. Wave height and water temperature were obtained from a directional wave buoy deployed southwards of our sampling station (41°19′18″ N, 2°12′24″ E, Fig. 1) over a depth of 68.5 m (REDCOS network, Puertos del Estado). When necessary, data from a second buoy placed near the Llobregat River mouth (41°16′42″ N, 2°08′29″ E, 45 m depth, XIOM network, Generalitat de Catalunya) were used to fill gaps in the time series, applying a simple linear model that explained >96% of the variance. Both buoys provided hourly-averaged data. Storm sewer outflow data was obtained from Clavegueram de Barcelona S.A. (CLABSA). Barcelona's sewer system has underground deposits to collect rainfall and terrestrial runoff for routine sewage disposal, but when large downpours occur, part of these waters are jointly released into the sea through storm overflows. Outlet flow rates are not measured directly but are determined from measurements of the water level. Only values above a minimum threshold (0.1 m) are considered, and this hinders the detection of low-volume discharges. We analyzed the data from their station L20, north of our sampling station (41°23′31″ N, 2°12′10″ E, Fig. 1).

2.3. Analytical procedures

Inorganic nutrients (nitrate, nitrite, ammonium, phosphate and silicate) were determined with an Alliance Evolution II autoanalyzer following the methods in Hansen and Koroleff (1999) with minor modifications. Samples were kept frozen at −20 °C until analysis.