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Focus

Spatial patterns in coastal lagoons related to the hydrodynamics of seawater intrusion

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A B S T R A C T

Marine intrusion was simulated in a choked and in a restricted coastal lagoon by using a 3D-hydrodynamic model. To study the spatiotemporal progression of seawater intrusion and its mixing efficiency with lagoon waters we define Marine Mixed Volume (V_{MM}) as a new hydrodynamic indicator. Spatial patterns in both lagoons were described by studying the time series and maps of V_{MM} taking into account the meteorological conditions encountered during a water year. The patterns comprised well-mixed zones (WMZ) and physical barrier zones (PBZ) that act as hydrodynamic boundaries. The choked Bages-Sigean lagoon comprises four sub-basins: a PBZ at the inlet, and two WMZ's separated by another PBZ corresponding to a constriction zone. The volumes of the PBZ were 2.1 and 5.4 millions m^3 with characteristic mixing timescale of 68 and 84 days, respectively. The WMZ were 12.3 and 43.3 millions m^3 with characteristics mixing timescale of 70 and 39 days, respectively.

1. Introduction

Coastal lagoons are transitional water bodies located at the continent-ocean interface. On the one hand these systems are partially confined and weakly connected to the open sea; on the other hand they are fed with waters from the watershed. These water flows carry solutes and suspended materials, including pelagic organisms. Knowledge of these transport flows is most important for understanding the ecology and biogeochemistry of these environments. In addition, coastal lagoons are spatially complex environments. Zonation patterns of benthic and pelagic communities that occur are often linked to the hydrodynamics spatial patterns.

This study focuses on how spatial patterns in coastal lagoons can be specifically related to the dynamics of seawater intrusion. In general, connectivity with the open sea is a chief driver for pelagic and benthic communities. For example, the spawning grounds of catadromous fish and invertebrate species that inhabit coastal lagoons are located in the coastal sea (Mercier et al., 2012; Morat et al., 2014). The larvae and juveniles of these organisms use water movements to enter the lagoon where they benefit from shelter and high productivity for their growth (Isnard et al., 2015). Using descriptions of benthic communities and their spatial distribution in coastal lagoons, Guelorget and Perthuisot (1992) defined the concept of confinement. This was based on the assumption that faunal community patterns are structured by their distance from the inlets assuming that confinement increased with increasing distance from the inlet. Hence, a large number of taxa in benthic communities, including macrofauna (Borsa and Millet, 1992) and particularly foraminifers of the meiofauna, have been found to be indicative of the most confined areas of lagoons (Murray, 1991; Favry et al., 1997; Debenay, 1995; Debenay et al., 2006). Nevertheless, the distance from the inlet is not always a good proxy for the degree of hydrodynamic confinement in coastal lagoons.

Modern approaches in community ecology are aiming at developing mechanistic and more quantitative approaches for explaining community structures and their spatial patterns in ecosystems. Depending on the ecological mechanism, transport and exchanges between adjacent communities can be major drivers for community structures. For the smaller and medium-sized organisms the transport and exchanges between communities are determined to a very high degree by hydrodynamic flow patterns and mixing. Mass effect is a term used in community ecology that focuses on the effect of immigration and emigration on the population dynamics at local sites. It describes a situation whereby certain species thrive at a given location, despite the fact that these species are bad competitors in this local environment. Their abundance in this local environment is, however, explained by the fact that they have immigrated from

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communities where they are good competitors (Leibold et al., 2004). As such mass effects in community ecology contrast with the niche assembly hypothesis. This hypothesis states that communities comprise the species that are most competitive under the ecological conditions prevailing in the local environment, i.e. the species that are best fitted to the ecological niche. The non-competitive species will disappear due to competitive exclusion. Finally, the concept of species sorting considers migration patterns but hypothesizes that niche assembly will prevail by selecting in the local environment those species that are best adapted to the ecological niche (Leibold et al., 2004). For fish communities in lagoons mass effects have been described when the role of immigration overwhelms niche selection processes within the lagoon (Mouillot, 2007). Mass effects are possible for both pelagic and benthic communities, because many species in the sedentary benthic communities have planktonic stages in their early life cycles. Phytoplankton and zooplankton communities in the lagoon may largely result from recruitment from coastal marine communities. Therefore, the study of the mechanisms of community assembly in coastal lagoons relies to a very large part on detailed knowledge on the hydrodynamic exchanges. Exchanges with the sea are also important when the main question focuses on the issues of eutrophication or re-oligotrophication of coastal lagoons. A capacity to export dissolved and suspended matter to the sea is paramount to counterbalance eutrophication and facilitate re-oligotrophication.

Hydrodynamic models have been used for many years for providing a typology of these water bodies. Indicators have been defined on the scale of the entire water body, e.g., the flushing time based on water flows through the inlets (Monsen et al., 2002). Other indicators have been defined locally as residence time (Monsen et al., 2002; Cucco et al., 2009) and exposure time (De Brye et al., 2013). The latter takes water re-entries into account. The residence time in an estuary has also been referred to as local renewal time (Koutitonsky et al., 2004). To avoid the confusion created by use of different terminologies and improve coherence, Cucco and Umgiesser (2015) use Transport Time Scale (TTS) as a generic term reflecting renewal features by accounting for spatial heterogeneities of water bodies. These tools and derived indicators are helpful to understand the relative contribution of the different processes that drive the hydrology and biogeochemistry of these water bodies (Grifoll et al., 2013; Gao et al., 2013).

This study has a complementary focus to the above-mentioned studies. It uses hydrodynamic modeling to study the timescale of seawater intrusion and its mixing with lagoon waters. Hence, rather than providing a static view, it represents a dynamic approach that describes chronologies. The study of seawater intrusion is particularly useful for the studies of community ecology in the lagoon and complementary to the approaches most commonly used for eutrophication studies that focus on the role of inputs from the watershed. In addition, it is also useful when the coastal sea represents a source for contamination or nutrient loading into the lagoon. It is tempting to use the salinity gradient in coastal lagoons as a proxy for the degree of marine influence. However, while salinity is a conservative tracer, it should be considered that the local salinity is the outcome of marine inflow and mixing, diffusion and transport, evaporation and residence time. In most of the major high-energy estuaries, the salinity gradient reflects the tidal mixing of fresh and marine water inflows and the zonation of communities is indeed linked to salinity gradient (Tagliapietra and Ghirardini, 2006). In contrast, most microtidal or even nanotidal (tidal ranges $<$0.5 m) Mediterranean lagoons with weak river inputs are low-energy environments where wind is a more important driver for mixing than tidal exchange. Due to locally varying residence time, low mixing efficiencies in the lagoon and evaporation, the local salinity may depart significantly from the marine salinity. Hence, in most coastal lagoons salinity is not a good proxy for marine influences and cannot be used directly for describing connectivity and confinement. Accordingly, Tagliapietra et al. (2012) pointed out that the lagoon zonation patterns are better described by other environmental variables such as the seawater renewal time. Recent modeling studies have been developed with the aim of providing maps of the lagoons hydrodynamic patterns (Solidoro et al., 2004; Ferrarin et al., 2010; Ferrarin et al., 2013) or a better characterization of the coastal lagoons confinement based on the hydrodynamic functioning rather than on standalone biotic descriptors (Frénod and Goubert, 2007; Frénod and Rousseau, 2013; Melaku Canu et al., 2012). This was based on adding a conservative tracer homogeneously in the adjacent sea at a given time point and simulate its intrusion through the inlets and its transport within the lagoon. We follow this approach using a numerical model and operationally define a Marine Mixed Volume (V_{MM}).

The aim of the present study is to characterize the timescale of the marine intrusion and its mixing efficiency in coastal lagoons to have a better proxy for connectivity of the lagoon with the sea. A second aim is to map the marine influence in the lagoon as a contribution for understanding spatial patterns in coastal lagoons. We address these issues by following the increase of the V_{MM} with time and map its propagation into the lagoon (marine mixed area). At selected time points, maps of the marine mixed area are presented, allowing identifying hydrological provinces within the lagoon. These maps can be used for studies that are focused on studying spatial patterns in coastal lagoons and particularly for community ecology when passive transport of organisms may have a paramount impact on the community composition.

2. Material and methods

2.1. Calculation methods and definition of the Marine Mixed Volume

A spatially explicit approach is needed to address the objectives of this study. Before introducing the spatial dimensions we discuss the basic mathematics developed for a Continuous Stirred-Tank Reactor (CSTR). Considering a coastal lagoon as a CSTR implies the hypothesis that the coastal lagoon is an idealized constant-volume system, which is only connected to the open sea. Hence, seawater entering the lagoon is instantaneously and evenly mixed throughout the entire lagoon and the same amount of inner water is exported toward the open sea. Accordingly, in such an ideal reactor, the flushing time (T_f^{CSTR} expressed in days) as defined by Monsen et al. (2002) allows to fully characterize the mixing processes. Under these assumptions the flushing time of the CSTR is defined as the ratio of the volume of a bounded system (V_{CSTR} expressed in 10^6 m^3 - i.e. the CSTR representing the lagoon), to the constant volumetric flow rate through the system (Q expressed in 10^6 $m^3 \cdot d^{-1}$).

Using a conservative tracer at a constant concentration in the sea (constant source C_{sea}), the time course of its concentration in the CSTR representing the lagoon, i.e., $C_{CSTR}(t)$, can be described by the following exact solution:

$$C_{CSTR}(t) = C_{sea}\left\{1 - exp\left[-t/T_f^{CSTR}\right]\right\} \quad (1)$$

Obviously natural lagoons do not behave as a CSTR because its two main assumptions are not fulfilled. First the water volume in the lagoon is not constant as the direction of flows in the inlet alternate due to tides and atmospheric forcing. Second, the mixing of the incoming seawater and lagoon water is not complete and heterogeneous in space.

In order to use constant volume as an approximation while also accommodating the alternations of the direction of flows in the inlet we integrate the exchanges between the sea and the lagoon over time periods ($T_{I/O}$) for which the volume of water entering from the sea is compensated by an equivalent outflow of lagoon water. Therefore this exchanged period $T_{I/O}$ can be assessed according to the Eq. 2 and during this period the exchanged volume $V_{Exch}(T_{I/O})$ can be assessed according to the Eq. 3.

$$\int_{t=0}^{t=T_{I/O}} \left[F_{sea}^{in}(t) + F_{lag.}^{out}(t)\right].dt = 0 \quad (2)$$