Estuarine, Coastal and Shelf Science 170 (2016) 1–9

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Impact of an intrusion by the Northern Current on the biogeochemistry in the eastern Gulf of Lion, NW Mediterranean

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ARTICLE INFO

Article history:
Received 27 July 2015
Received in revised form
22 December 2015
Accepted 23 December 2015
Available online 28 December 2015

Keywords:
Northern Current
Gulf of Lion
Intrusion
Continental shelf
Biogeochemical modelling
Regime shift

ABSTRACT

We present the results from the RHOMA2011-LEG2 campaign that took place in the eastern Gulf of Lion from 7 to 17 Oct 2011 and combine them with remote sensing observations and results from a 3D coupled hydrodynamic-biogeochemical model to study an intrusion event of the Northern Current (NC) onto the continental shelf in the Gulf of Lion (NW Mediterranean). Our analysis shows that during the intrusion, the previously upwelled nutrient-rich water present on the shelf is replaced by warmer and mostly oligotrophic NC water within a matter of 2–3 days. This has a marked impact on the local biogeochemistry in the Gulf with pre-intrusion Chl-*a* concentrations in the surface layer of over 0.5 mg m^{-3} dropping to near the detection limit within less than 72 h. The intrusion event leads to a dramatic albeit short-lived regime shift in the limiting nutrient for primary production: prior to the intrusion most of production on the shelf is nitrogen limited while the intrusion induces a shift to phosphorous limitation. The relatively high frequency of occurrence of these intrusions in combination with their impact on the local ecosystem make them primary targets for future study.

1. Introduction

The continental shelf of the Gulf of Lion (GoL) in the NW Mediterranean Sea offers a typical system for studying river/shelf/open sea interactions. Due to the Rhone River and frequent upwelling events, the GoL is one of the most productive areas in a mostly oligotrophic Mediterranean Sea (de Madron et al., 2011).

The circulation in the GoL is forced mainly by wind, freshwater run-off and seasonal heating–cooling (Millot, 1990). The dominant circulation feature is the Northern Current (NC, Fig. 1a), a slope current that passes along the continental slope off the GoL, where it bounds and controls shelf circulation, effectively separating the typically nutrient rich shelf from the oligotrophic open Mediterranean. It originates from the confluence of the Eastern and Western Corsican Currents and flows from the Ligurian to the Balearic Sea forming part of the general cyclonic circulation in the Western Mediterranean.

The NC exhibits a seasonally variable flux (maximal in winter) between 1 and 2 Sv which is comparable to the fluxes through the Strait of Gibraltar (Alberola et al., 1995). The NC is wider and shallower in summer (50 km and 250 m respectively) when it flows further off-shore. In winter, it moves in-shore where it narrows and deepens (ca. 30 km and 450 m) reaching maximal velocities of over 50 cm s^{-1} (Andre et al., 2009). Particularly in winter, the NC also becomes baroclinically unstable and produces important mesoscale meanders which can penetrate onto the GoL shelf (Millot, 1999; Petrenko, 2003; Rubio et al., 2009).

These intrusions of the NC can occur at various places along the shelf. Most frequently, they tend to occur at the eastern entrance to the Gulf (Petrenko et al., 2005) and at the centre (Estournel et al., 2003), with more rare occurrences at the south-western side (Petrenko et al., 2008). Using data from 12 coastal cruises, Gatti et al. (*Intrusions of the Mediterranean Northern Current on the eastern side of the Gulf of Lion's continental shelf: characterization and generating processes, submitted to Journal of Geophysical Research 2015*) found that intrusions can occur during any season of the year and that the intrusion flux can amount to 0.37 SV or 30% of the flux of the NC itself. They also carried out numerical realistic simulations which suggest that intrusions can occur as often as three to

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http://dx.doi.org/10.1016/j.ecss.2015.12.022
0272-7714/

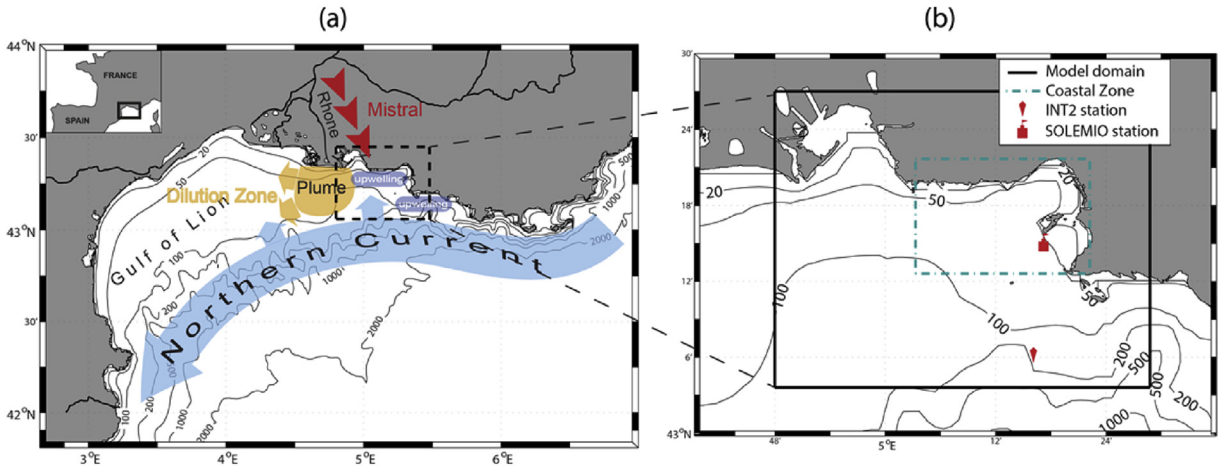

Fig. 1. (a) Map of the Gulf of Lion showing the location of the study area at the eastern entrance (dashed box) and the dominant hydrodynamic and meteorological features, including the Northern Current and its northward intrusions onto the shelf. (b) Zoom of the study area, showing the location of the coastal zone budget box and the INT2 and SOLEMIO observational stations.

four times per month with durations of a few days to two weeks. By combining *in situ* observations and high-resolution modelling, Barrier et al. (2015) observed a total of 12 intrusion events during their 12 month study period, although they state that the amount of observational data in particular is not sufficient to capture all intrusion events and they only counted very large intrusions in their analysis.

Three kinds of wind events are likely to generate intrusions: cessations of strong Mistral events (Millot and Wald, 1980), episodes of inhomogeneous Mistral, or periods of easterly winds (Petrenko, 2003; Petrenko et al., 2013). NC intrusions onto the shelf have also been linked to the strength of density stratification and the pycnocline depth with the NC splitting into a main and a northern branch, the latter creating an intrusion if the stratification is strong and shallow (Echevin et al., 2003; Petrenko et al., 2005). However, other studies showed that intrusions at the eastern entrance to the GoL could occur independently of stratification (Petrenko, 2003). These seemingly contradicting results suggest that the real causes of intrusions are still unclear (Petrenko et al., 2005) although the shift in the local wind regime may play a crucial role (Pairaud et al., 2011; Petrenko et al., 2008). Barrier et al. (2015) suggested that intrusions on the eastern part of the gulf are mainly forced by easterly or north-westerly wind events and they found them to be most frequent in the autumn and winter months.

While the Northern Current (NC) and its intrusions onto the continental shelf in the Gulf of Lion have been widely studied from a hydrodynamical point of view (Alberola and Millot, 2003; Petrenko, 2003), including intrusions in the eastern GoL (Pairaud et al., 2011; Petrenko et al., 2008), little is known about the impact of these intrusions on the biogeochemistry. The biogeochemical functioning of the eastern GoL is complex and largely driven by the interplay of Rhone River run-off, hydrodynamics, and air-sea interactions. The Rhone River is the most significant source of freshwater and nutrients to the Mediterranean Basin with a flux of 2–20 Mt yr^{-1} (Sempere et al., 2000). This has a great impact on the biogeochemical functioning of the GoL and directly affects primary production: about 50% of the annual primary production in the GoL can be attributed to terrigenous inputs (Coste, 1974; Morel et al., 1990). Typically the Rhone River Plume extends westward but eastward intrusions of plume water into the Bay of Marseille (inside our study area) have also been observed (Fraysse et al., 2014; Gatti et al., 2006). The variability in the Rhone River run-off also has a measurable impact on the fisheries industry. In a study covering a nearly 30-year period from 1973 to 2000, a correlation was found between the interannual variability of the Rhone River run-off and the landings of Common Sole (*Solea solea*) 5 years later, particularly in the eastern GoL port of Martigues where about 50% of landings for the GoL are recorded (M. Harmelin, pers. comm.).

In addition, two dominant winds act as important forcing components: (i) north-westerlies (Mistral in Fig. 1), which favour upwelling (Millot, 1990), and (ii) south-easterly winds, which favour downwelling (Fraysse et al., 2014; Pairaud et al., 2011). During an upwelling event, cold, nutrient-rich waters are brought up to the euphotic zone (El Sayed et al., 1994), which can lead to an increase in primary production.

Here we explore the impact of intrusions by the Northern Current onto the eastern GoL shelf area, just after an upwelling event, focussing primarily on the effect on the local biogeochemistry. This is achieved through combining results from a 3D coupled hydrodynamical-biogeochemical model of the region with *in situ* (nutrients, chl, current velocities) and remote sensing observations (SST, Ocean colour). The analysis shows that NC intrusions can have a significant impact on the shelf biogeochemistry and bring about a dramatic regime shift in the local ecosystem within a rather short period of time that lasts for the duration of the intrusion event.

2. Materials and methods

2.1. Field sampling and remote sensing data

All observational *in situ* data collected between 7 and 17 October 2011 stems from the RHOMA2011-LEG2 campaign that took place in the eastern Gulf of Lion (Fig. 1). The *in situ* data was collected aboard RV Tethys II using an SBE19PlusV2 CTD that was also equipped with an optical backscatter sensor (Campbell Scientific OBS3+) and a fluorimeter (WetLabs WetStar). In addition, discrete water samples were collected at various depths for nutrient analysis and for calibration of the fluorescence data (see Materials and Methods in Fraysse et al., 2013 for details on *in situ* data collection and processing). The current velocities and directions were obtained from the 150 kHz hull-mounted Acoustic Doppler Current Profiler (ADCP) of the RV Tethys II. Currents were recorded along the vessel's track over the course of several hours each day. ADCP data for 18 October 2011 stems from the SPECIMED campaign that