Journal of Marine Systems 145 (2015) 37–52

Contents lists available at ScienceDirect

Journal of Marine Systems

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

Inshore/offshore water exchange in the Gulf of Naples

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A R T I C L E   I N F O

Article history:
Received 5 March 2014
Received in revised form 4 January 2015
Accepted 6 January 2015
Available online 10 January 2015

Keywords:
HF coastal radars
Ocean circulation
Coastal currents
Numerical models

Regional index terms:
Mediterranean Sea
Tyrrhenian Sea
Gulf of Naples

A B S T R A C T

The Gulf of Naples is a coastal area in the south-eastern Tyrrhenian Sea (western Mediterranean). Zones of great environmental and touristic value coexist in this area with one of the largest seaports in the Mediterranean Sea, industrial settlements and many other pollution sources. In such an environment, water renewal mechanisms are crucial for maintaining the ecological status of the coastal waters. In this paper, we focus on the water exchange between the interior of the Gulf and the neighbouring open Tyrrhenian Sea. The surface dynamics of the Gulf have been investigated based on measurements carried out with a high-frequency (HF) radar system. The vertical component of the current field has been provided by the Regional Ocean Modelling System (ROMS) model of ocean circulation. We present the results of a one-year-long analysis of data and simulation results relative to the year 2009. Inshore/offshore exchanges were assessed by looking at the zonal component of the surface and subsurface current field across a transect representing a sort of threshold between the interior of the Gulf and the open sea. This also allows for the reconstruction of the short-term origin of waters found inside the Gulf in the different forcing and circulation conditions.

1. Introduction

Coastal areas are complex environments in which multiple factors interact and affect the water quality and environmental state of the marine ecosystem. The factors include hydrological, geomorphological, and socio-economic conditions. In this context, the Gulf of Naples (GoN), a marginal basin in the Southern Tyrrhenian Sea, is a paradigmatic coastal area because of its particular oceanographic and morphological characteristics, and because of its highly urbanized coast, heavy maritime traffic, waste water discharges, and freshwater inputs (as reviewed in Cianelli et al., 2012). In addition, the eastern part of the GoN receives runoff from the Sarno River, a tributary carrying a heavy load of pollutants, sediment, and suspended matter that can affect the physical, chemical, and biological quality of coastal waters (Montuori and Triassi, 2012). As a result, a number of contaminants can be found in the sediments, water, and biota of the GoN, with potential repercussions on human health (as recently surveyed by Tornero and Ribera d'Alcalà, 2014). Therefore, the maintenance and improvement of the environmental quality of the GoN are critical for not only the safety of the entire ecosystem, but also for social and economic reasons.

In order to sustainably manage the environmental resources of a coastal area such as the GoN, as well as to preserve and mitigate potentially hazardous events and to monitor the water quality, understanding the surface circulation and the processes that drive the coast–offshore transport in this region is crucial. The GoN coastal area has been subject to several investigations (see Cianelli et al., 2012 for a historical overview), but prior studies have been limited by the available observational techniques. Hydrological parameters have been measured in situ in the framework of distinct oceanographic surveys, shedding light on the local dynamics but with limited sampling and very little synopticity (De Maio and Moretti, 1973; De Maio et al., 1978–1979, 1983, 1985).

Biological, chemical, and hydrological samples have been collected more regularly since 1984 in the framework of the MareChiara Long-Term Ecological Research Station (LTER-MC), although with a limited spatial resolution (Mazzocchi et al., 2011, 2012; Ribera d'Alcala et al., 2004; Zingone et al., 2010). Satellite-tracked drifters can provide Lagrangian data on circulation patterns, and the GoN has been the stage of recent Lagrangian experiments (e.g., Zambianchi, unpublished data reports relative to 2009 and 2012). Coastal-based high-frequency (HF) radar systems (see Barrick et al., 1977, and Barrick, 1978, for early accounts of this technique) are a relatively novel remote sensing technique that currently represents the most suitable tool for describing and investigating the multi-scale circulation patterns in coastal areas. This technique has the potential to provide surface current observations

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http://dx.doi.org/10.1016/j.jmarsys.2015.01.002
0924-7963/

with a synoptic spatial coverage that is not achievable with other methods (Barth et al., 2008).

Coastally based HF radars can capture essential processes in the coastal ocean, including wind-driven (Kosro, 2005; Kosro et al., 1997) and tidal currents (Erofeeva et al., 2003; Kurapov et al., 2003; O'Keefe, 2005). The data typically cover both shelves, where the dynamics are predominantly wind-driven, and the adjacent coastal transition zone (CTZ), where the dynamics are more dominated by nonlinear interactions of jets and eddies and fed by the coastal current instabilities and separation (Brink and Cowles, 1991; Koch et al., 2010). Combined with other measurement techniques, HF radars can thus provide essential information for the study of the surface coastal circulation and can be used in a number of applications such as oil spill response, water quality monitoring, search and rescue, and safe and efficient maritime navigation.

An HF radar system has been active since 2004 over almost the entire area of the GoN and has been used in different applications in recent years (e.g. Cianelli et al., 2013; Menna et al., 2007; Uttieri et al., 2011). Most of the HF radar-based investigations focus on relatively short periods of time (from days to weeks), and only a few use radar-derived current measurements over periods of six months or longer (e.g. Cosoli et al., 2012; Gough et al., 2010; Kaplan et al., 2005; Kovačević et al., 2004; Robinson and Wyatt, 2011; Uttieri et al., 2011). This approach allows for the determination of seasonal to annual basin dynamics (i.e. surface currents, waves, tidal currents) at unprecedented spatial and temporal resolutions. In this framework, a one-year-long HF radar time series of surface currents (from January 1 to December 31, 2009) is accompanied by the results of numerical simulations, which were used to analyse the seasonal variability of current patterns in the GoN and to better understand the three-dimensional dynamics of the flow.

To this end, an ad hoc configuration of the three-dimensional numerical ocean model ROMS (Regional Ocean Modelling System) was implemented for the study area. In particular, we assessed the existence of different seasonal inshore/offshore regimes by computing the average surface current along a transect delimiting the boundary between the inner gulf and the open sea. The paper is organised as follows. Section 2 provides a detailed description of the study area. Section 3 presents a summary of the used methods. Section 4 describes the results of the analysis, which are discussed in Section 5 along with the conclusions.

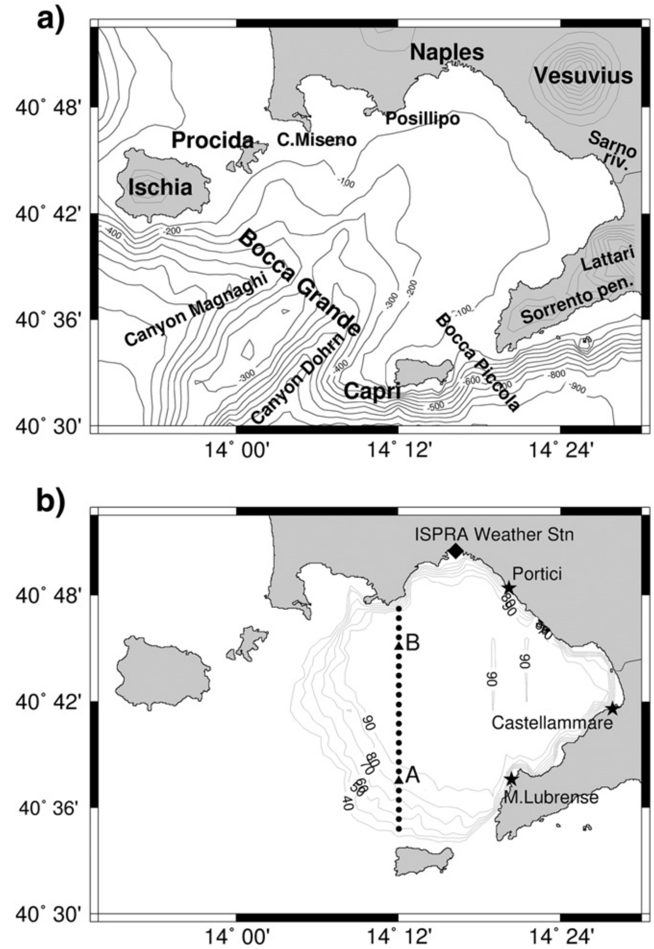

Fig. 1. a) Map of the Gulf of Naples (GoN) with bathymetry and all geographical locations mentioned in the text. b) Position of the analysed Capri–Posillipo transect with the selected points A and B; location of the three CODAR stations installed in the GoN (star symbols) and map of radar coverage percentage; location of the ISPRA weather station in the Port of Naples (diamond symbol).

2. Study area

The GoN (Fig. 1) is a semi-enclosed basin located in the south-eastern Tyrrhenian Sea (western Mediterranean). The Gulf is delimited by the Sorrento Peninsula and the island of Capri in the south and Capo Miseno and the islands of Procida and Ischia in the north. Its average depth is 170 m, and it covers an area of approximately 900 km^2 (Carrada et al., 1980). Exchanges with the adjacent basins are guaranteed by different openings (Aiello et al., 2001): with the southern Tyrrhenian Sea through the Bocca Grande (between Ischia and Capri); with the Gulf of Gaeta to the north via the shallow Ischia and Procida channels (12-m and 22-m maximum depths, respectively); and with the Gulf of Salerno to the south through the Bocca Piccola (between Capri and the Sorrento Peninsula), a sill with a depth of 74 m steeply sloping down to the 1000 m isobath. The Magnaghi and Dohrn canyons, with depths of up to 800 m, represent the main bathymetric feature of the Bocca Grande area and control the transport of sediments from the shelf to the continental slope (on the subject of vertical flows in correspondence of canyons see e.g. Canals et al., 2013). Also, local orography shows intricate features, with the Vesuvius volcano (elevation: 1281 m) and hills in the city of Naples (elevation up to 450 m) in the northern part, and the Lattari mountains (Mount Faito: 1131 m) in the south (Fig. 1a).

Several factors acting at different spatial and temporal scales drive the surface circulation in the GoN, while the deeper circulation is more directly influenced by the interaction between the currents along the water column and the complex bottom topography of the basin (Gravili et al., 2001; Grieco et al., 2005). The drivers of the surface circulation can thus be differentiated between local and remote forcings (Gravili et al., 2001).

The main local factor influencing the surface circulation of the GoN is wind (De Maio et al., 1985; Menna et al., 2007; Moretti et al., 1976–1977). Seasonal wind regimes are recognisable (Menna et al., 2007). Intense NNE–NE winds are typical of the winter season, with occasional alternations with SW winds associated with the transit of depressionary systems (Menna et al., 2007).

Owing to the deviating effect of Vesuvius and of the hills surrounding Naples, a coast–offshore jet current develops under the effect of NNE–NE winds (Cianelli et al., 2012, 2013; De Maio et al., 1983, 1985; Gravili et al., 2001; Grieco et al., 2005; Moretti et al., 1976–1977), enhancing the renewal of waters (Cianelli et al., 2013; Menna et al., 2007). In contrast, south-westerly winds induce the formation of cyclonic and anticyclonic structures, and surface currents are mostly directed towards the coast, favouring stagnation (Cianelli et al., 2013; Menna et al., 2007). In late spring and summer, the main wind regime is represented by breeze. The wind field rotates clockwise over a 24-h period as a result of the alternation of the sea-breeze (during night hours) and land-breeze (during day hours), owing to the different heat capacities of water and land (Menna et al., 2007). The absence of stronger, larger-scale wind forcing (e.g. the transit of low pressure systems) during this period of the year is typically due to the reinforcement of the Azores anticyclone, which makes this circulation scheme persistent over the entire spring–summer seasons. The circulation of the basin responds directly to this stressor, showing a consistent rotation of the surface current field over the length