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Circulation and biomass distribution during warm season in the Gulf of La Spezia (north-western Mediterranean)

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ABSTRACT

Hydrographic and current measurements permitted to attain some insight in the dynamic conditions of the Gulf of La Spezia. It was shown that its circulation is the result of the interaction of two driving mechanisms: the estuarine circulation present in its interior and the large scale coastal circulation influencing the Gulf through its open boundary. The response of the Gulf to the wind is mainly baroclinic, in agreement with the expected response of the background two-layer system. The good correspondence between physical and biochemical parameters evidences the key role played by circulation in determining the biomass distribution along the Gulf littoral.

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1. Introduction

Coastal areas are frequently of considerable interest due to high anthropogenic pressure and need to protect them against pollution. These issues become even more relevant in towns and ports, which may be affected by industrial discharges and anthropogenic contaminants (Darbra et al., 2005). If the ecosystem can not assimilate the organic material, the trophic state can reach harmful levels. In small regions characterized by restricted exchange of water masses, circulation within the harbors and between the harbors and the surrounding water bodies has a key role in the transport and removal of material that enters the water bodies.

The Gulf of La Spezia (Fig. 1) is a good example, where several of the above mentioned characteristics are present. It is located on the eastern side of the Ligurian coast (northwest Italy) and has approximately 100,000 inhabitants. The most relevant activities are a commercial harbor, several naval industries, a military base and an electric power-plant. Furthermore, industrial and commercial activity develops very close to areas of high environmental value (UNESCO site: http://whc.unesco.org/en/list/826) and tourist interest.

Delimited by Tino and Palmaria islands on the west and by Punta Bianca promontory on the east, the Gulf is surrounded by mountains. Northwest–southeast oriented, it is 5 km wide while its length is about 10 km. A dam (length of 2.2 km) separates the Gulf in two areas: inside the dam there is the harbor having a mean depth of about 10–11 m; the outside part, representing transition to the open sea, is deeper and has an irregular bathymetry. Depth of the Gulf progressively increases in a westward direction: the maximum depth (about 25 m) is in proximity of Palmaria and Tino islands, where the bathymetry becomes very steep. Two passages, at the dam ends, permit exchange between the inside and outside part of the Gulf (Fig. 1). The western opening is wider (360 m) than the eastern one (180 m), and is deeper: 15–16 m in the west against 11–12 m in the east. While the main connection with the open sea is through the Gulf open boundary and the passage between Palmaria and Tino islands, some exchange is also possible through the Portovenere channel (between land and Palmaria island), although the channel is very narrow (150 m wide) and very shallow (the sill depth is 3 m).

During the past years the Gulf has been the object of some studies related to anthropogenic activities along its borders. The investigations concentrated on the internal part of the Gulf, inside the dam, but only a small number of publications are available, most results being presented in the internal technical reports (ENEA, 1996 and 2000). From published information (Marri et al., 1991; Borella et al., 1992) we know that the freshwater discharges (natural and anthropogenic) of the town of La Spezia and the cooling system of an important electric power-plant, located inside the harbor (Fig. 1), are able to significantly influence hydrographic conditions and circulation of the Gulf interior. As for the two dam openings, major exchange occurs through the western one, primarily because it is wider and deeper and therefore

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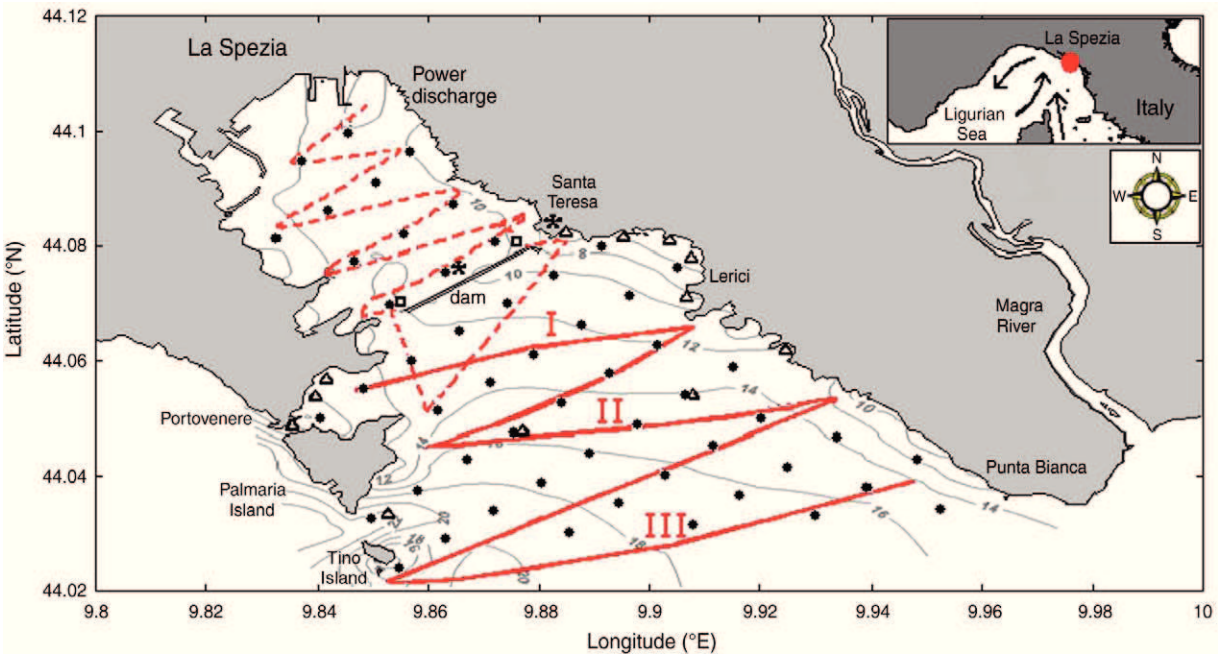


Fig. 1. The Gulf of La Spezia. Stars indicate hydrographic stations, open triangles biological stations, open squares current meter moorings, asterisks meteorological stations; ADCP tracks corresponding to 19 June 2007 and 4 May 2006 are indicated by continuous and dotted lines, respectively. Roman numbers refer to vertical sections of the current field presented in Fig. 9. The large scale circulation is indicated by arrows in the small map.

ensures a more efficient connection with the open sea. The eastern opening, being narrower and shallower, seems to have a minor role (ENEA, 1996). Direct current measurements evidenced the importance of high frequency variability. More specifically, a 70 min period oscillation accounts for a high percentage of current variability, while tidal components and inertial oscillations appear to be significantly less important (Borella et al., 1992).

Little information exists on the outer part of the Gulf, where it is subjected more to open sea dynamics. The wide open-sea boundary puts the Gulf under the influence of the large scale Ligurian circulation (Astraldi et al., 1979; Astraldi and Gasparini, 1985), which is characterized by a cyclonic, east-to-west flow (Fig. 1). Furthermore, the Gulf is located in a transition region where Ligurian and Tyrrhenian currents meet: the Tyrrhenian current is more important during the colder seasons, while during the warmer ones the Ligurian current prevails (Astraldi and Gasparini, 1992). The Magra river runoff may have certain relevance for the hydrodynamics of the Gulf: characterized by a large variability (from 5 m^3/s to more than 1000 m^3/s and a mean value of 40 m^3/s), its signature is mainly evident during the rainy periods (Astraldi et al., 1979).

The objective of the present study is to describe oceanographic conditions of the entire Gulf, using previously unpublished data, especially those collected inside the dam, and considering new observations, concentrated outside it. The available data, even if not always homogeneous in space and time, may support a comprehensive overview of the Gulf dynamics. Possible relationship between physical conditions and chemical (nutrients)/biological (phytoplankton) signature observed in the Gulf is also considered.

The new observations have been acquired in the framework of the MREA (Marin Rapid Environmental Assessment) experiment LASIE (Ligurian Air Sea Interaction Experiment, http://geos2.nurc.nato.int/lasie07/) in the Ligurian Sea, and in particular as a part of the coastal experiment POET (Predictive Oceanographic Experimental Trial) that focused on the Gulf of La Spezia. This paper intends to provide researchers involved in the POET experiment, mainly addressing the MREA objectives, with a background knowledge of main circulation patterns and related hydrographic conditions.

2. Data and methods

A hydrographic cruise has been carried out on 18 June 2007, covering the entire Gulf with 53 stations and using the multiparametric probe IDRONAUT measuring CTD, dissolved oxygen and fluorescence. Outside the dam, at nine littoral stations of particular environmental interest (Fig. 1), sampling was performed with the CTD probe as well as using the water bottles in order to determine nutrients (nitrates, silicates and orthophosphates) and chlorophyll concentration (which also permitted the fluorimeter calibration by a linear regression). These stations have also been visited in order to determine the distribution of potentially toxic benthic microalgae (*Ostreopsis ovata*).

Sea water samples were taken using a 5 l Go-flo bottle. The nutrients have been determined through colorimetric analysis by a continuous flow system multichannels (AutoAnalyzer Bran+Luebbe III Generation), following the Hansen and Koroleff (1999) procedures.

The chlorophyll concentration (μg/l) was measured by a spectrophotometer (ULTROSPEC 2000, Pharmacia Biotech) following the method of Strickland and Parsons (1968). The trichromatic formula of Lorenzen and Jeffrey (1980) was applied to calculate the pigment concentration.

Furthermore a net (diameter 35 cm and pore size 20 μm) was used for the phytoplankton sampling at each station. Samples were fixed with Lugol solution and the Utermohl method (Hasle, 1978) was applied for the phytoplankton qualitative/quantitative analysis.

One day later (i.e. on 19 June 2007), a vessel mounted RDI 300 kHz ADCP was used to collect data along the water column in the external part of the Gulf, along five tracks (Fig. 1). The ADCP cell size was 1 m. The ADCP data have been submitted to post-processing with the RDI WinADCP Software. No detiding procedure has been applied due to the smallness of tidal signal (Borella et al., 1992). Nevertheless, the possible influence of the 70 min oscillation had to be taken into account.

Data from the Santa Teresa meteorological station, positioned on the eastern side of the Gulf at about 50 m above sea level (Fig. 1), have also been considered. The examined parameters were atmospheric

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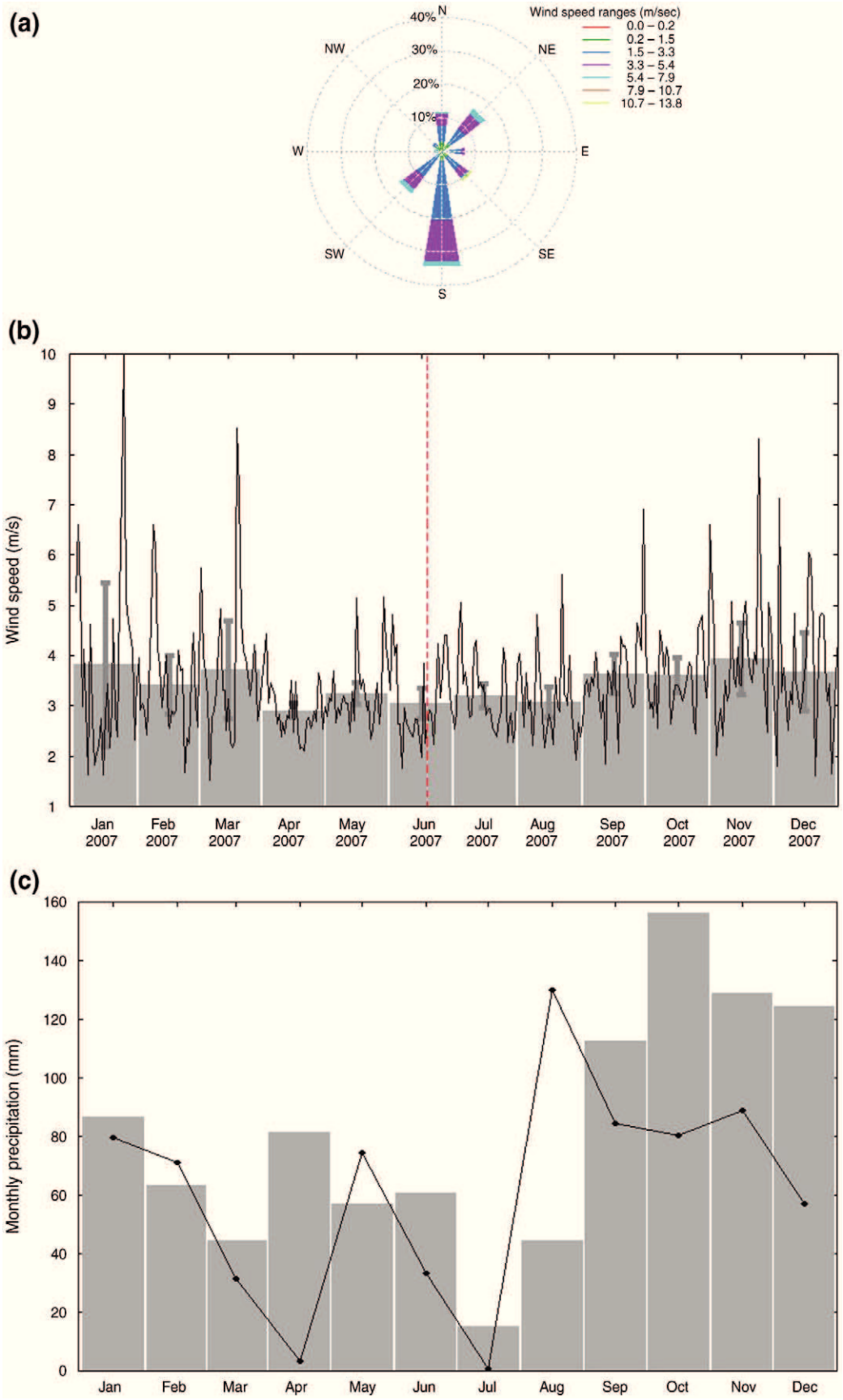


Fig. 2. Meteorological conditions at Santa Teresa station: (a) wind rose during June 2007; (b) temporal evolution of the wind speed during 2007: daily mean (continuous line) and monthly mean and standard deviation (grey bars); the vertical dashed line indicates 19 June 2007, which corresponds to the ADCP survey; (c) monthly precipitation during 2007 (continuous line) and climatology (grey bar).

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pressure, wind intensity and direction, air temperature and precipitation. Besides the meteorological data corresponding to the sea survey period, a more extended time series registered over the whole year 2007 has been examined, together with the climatological annual cycle, to permit a better characterisation of the meteorological conditions. This information has been integrated with results of an ADCP survey, carried out during the preceding year (4 May 2006) and covering the area inside the dam (Fig. 1).

Furthermore, continuous current measurements at the dam openings (Fig. 1) and meteorological parameters (wind intensity and direction) recorded at a nearby station, covering the period 23 May–18 July 1990, have been used. The current meters were positioned at two depths: 4 m and 10 m in the eastern opening and 4 m and 14 m in the western one. The associated wind measurements have been carried out at a meteorological station positioned very close to the dam (Fig. 1). The sampling time of all measurements was 10 min. The original data have been low-pass filtered to remove oscillations below 48 h and 3-hour time series have been reconstructed.

3. Results

3.1. Meteorological conditions and freshwater input

Fig. 2a shows wind patterns as observed at the Santa Teresa meteorological station (Fig. 1) during June 2007. The prevailing winds were blowing from south and along the southwest–northeast direction. The observed distribution is in agreement with climatology. Fig. 2b shows both the monthly and daily mean wind intensity during 2007. While the monthly means have almost the same value, the corresponding standard deviations significantly differ. As for June, it is characterized by lower values both in terms of mean and standard deviation. The daily values for the period of measurements at sea (18–19 June 2007) were mostly below the monthly mean value.

A detailed analysis of the hourly wind data shows a sea-land breeze regime with the wind direction oriented along the axis of the Gulf (NW–SE). The wind intensity had a mean value of 2.2 ± 1.3 m/s, with an oscillation between 0 and 4 m/s. The wind weakness and stability of the weather conditions are confirmed by the atmospheric pressure, almost stable at 1014 hPa, while the air temperature progressively increased in agreement with the seasonal trend.

The climatological annual cycle of precipitation has a minimum in July and a maximum in October (Fig. 2c, grey bar). June is one of the less rainy months and June 2007 (Fig. 2c, continuous line) was even less rainy than climatology would imply. No precipitation has been observed during the week before the experiment. The cumulative precipitation collected during the previous two weeks was 11.8 mm. The last precipitation event occurred on 6 and 7 June, approximately 10 days before the observational period, with a total precipitation of 11.4 mm. Closely related to precipitation is the fresh water input along the Gulf, which is provided by several streams of small relevance, characterized by a torrential regime, and by anthropogenic discharges. The scanty knowledge of stream discharges does not permit an acceptable estimate but, considering that a few rain events have been observed, their influence should be small. A contribution of some relevance is related to waters of anthropogenic origin, which can be estimated at a few m^3/s.

3.2. Hydrographic conditions

3.2.1. Horizontal distribution

The surface distributions of temperature (T) and salinity (S) are presented in Fig. 3. Temperature varies from higher values in the Gulf interior (25.7 °C) to lower values (23.1 °C) at the external side of the Gulf (Fig. 3a). While the first is a consequence of the warm power plant discharge (Fig. 1), the second is due to the presence of open sea water. In between there is a progressive temperature change, with a significant discontinuity found close to the dam.

The salinity distribution appears more uniform in a greater part of the Gulf ($S = 36.8$–36.9). It shows lower values inside the dam, increasing southward in the Gulf (Fig. 3b). The highest gradients are observed near the open boundary, where relatively high and low values are found. If the largest values ($S_{max} = 37.5$) indicate the open sea water, the lowest ($S_{min} = 36.6$) are the Magra river signature (Fig. 1) and are confined to the eastern entrance of the Gulf. The reduced salinity gradient between the open boundary and interior suggests a reduced freshwater discharge along the Gulf, in agreement with meteorological conditions, which indicate very few precipitation events during the previous month.

Moving deeper, we can observe a different scenario. Temperatures (Fig. 4a) are more uniform and range approximately between 22° and 23 °C: the observed high temperatures suggest that this layer is part of the surface mixed layer, the seasonal thermocline being deeper, as expected, during late June.

Temperature slightly increases from inside to outside the dam. Noteworthy is the minimum value (21.75 °C) observed in proximity of Portovenere that might be attributed to the open sea water entering the Portovenere channel, as will better be seen in the following.

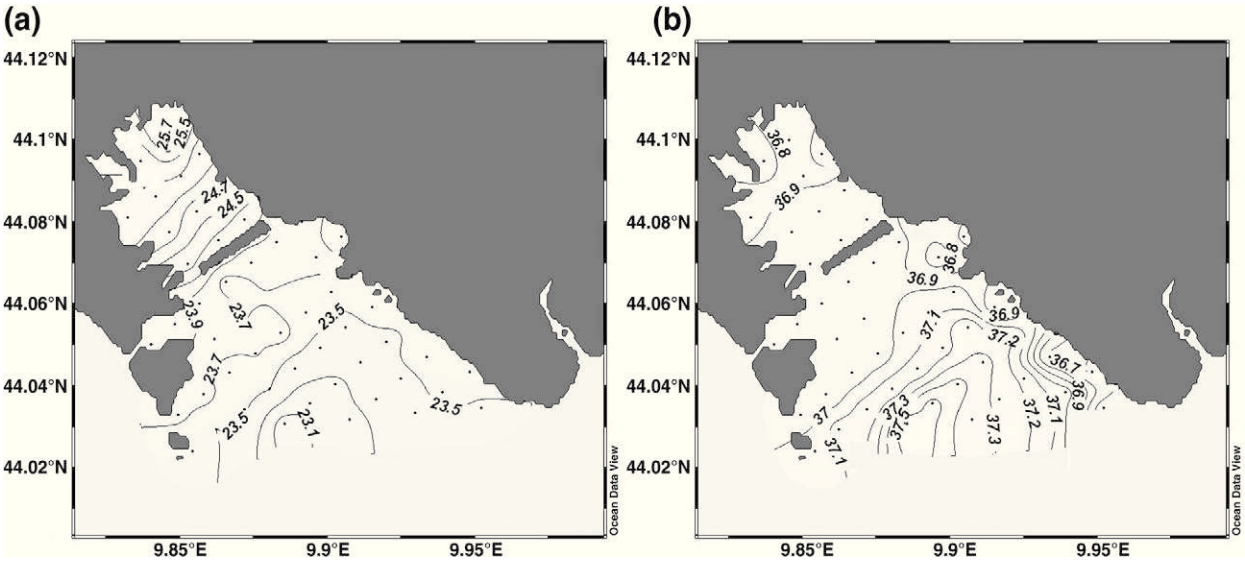


Fig. 3. Horizontal distribution at 1 m depth of (a) temperature [°C] and (b) salinity. Dots indicate measurement locations. Data were collected on 18 June 2007.

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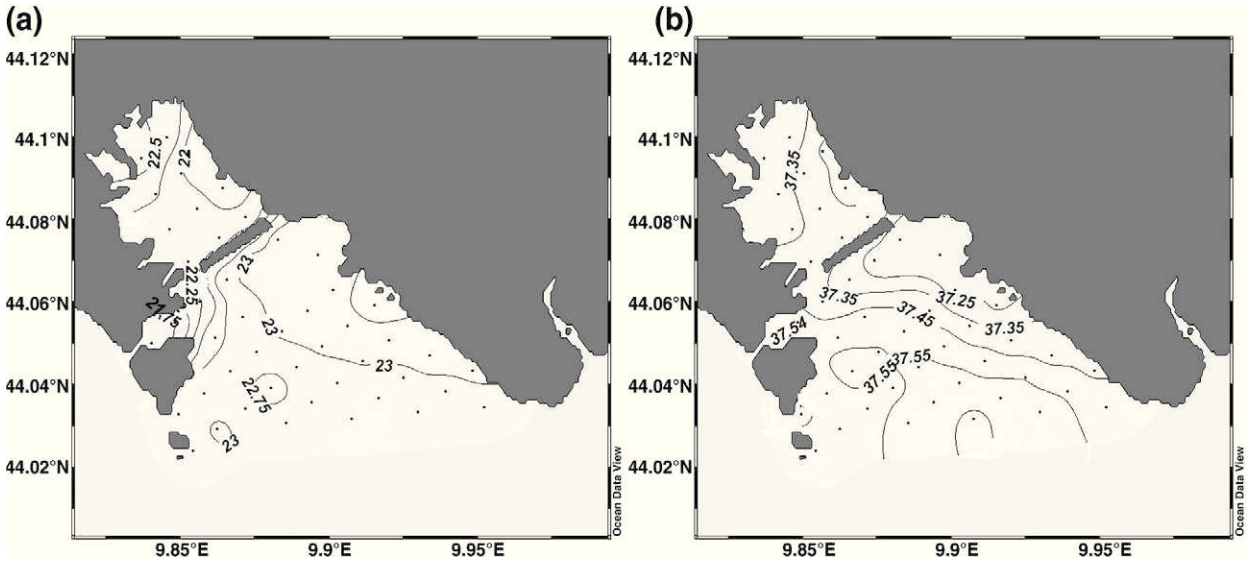


Fig. 4. Horizontal distribution at 10 m depth of (a) temperature [°C] and (b) salinity. Dots indicate measurement locations. Data were collected on 18 June 2007.

The salinity distribution (Fig. 4b) presents a similar scenario: while inside the dam we have an almost homogeneous distribution, high salinity concentrations are observed in the external western part of the Gulf. High values are also present close to Portovenere, confirming the previous finding of an open sea water inflow through the Portovenere channel. Furthermore, a specific feature is present outside the dam, on the eastern side, characterized by fresh and warm water. It has the form of an isolated cell, probably related to a reduced advection.

The density field (not shown) indicates, in the surface layer, light waters inside the dam and denser waters along the Gulf open boundary, very similar to temperature distribution. Conversely, the density in the deep layer is almost homogeneous in the whole Gulf. The highest density is found in the Portovenere channel, being the result of low temperature and high salinity described before. It further confirms a direct connection with the open sea through the channel in spite of the very shallow sill depth.

From the previous description it is evident that two water masses can be identified in the Gulf: a warmer and fresher one produced by local processes, and a colder and saltier one of remote origin. The first is positioned in the surface layer, the second mainly in the subsurface layer, as will better be shown by studying the vertical distribution of hydrographic properties.

The horizontal distribution of chlorophyll clearly shows different conditions inside and outside the dam. The high values observed in the internal water mass (10–13 μg/l) suddenly reduce outside the dam (0.25–1 μg/l), both in the surface and deep layers (Fig. 5a and b). The lowest values are found in the central area outside the dam, more influenced by the open sea water. The high values found outside the dam close to Portovenere confirm the peculiarity of that zone also regarding the chlorophyll concentration.

3.2.2. Vertical structure

The vertical distribution of hydrographic properties inside and outside the dam allows to estimate the thickness of the two water masses described before. The section inside the dam (Fig. 6) documents how temperature, salinity and density agree to support a stratified water column. Temperature, approximately 25 °C at the surface, decreases toward values less than 22 °C near the bottom (Fig. 6a). Salinity shows a large homogeneous surface layer with values less than 37.0 (Fig. 6b). Moving deeper it appears more stratified with the

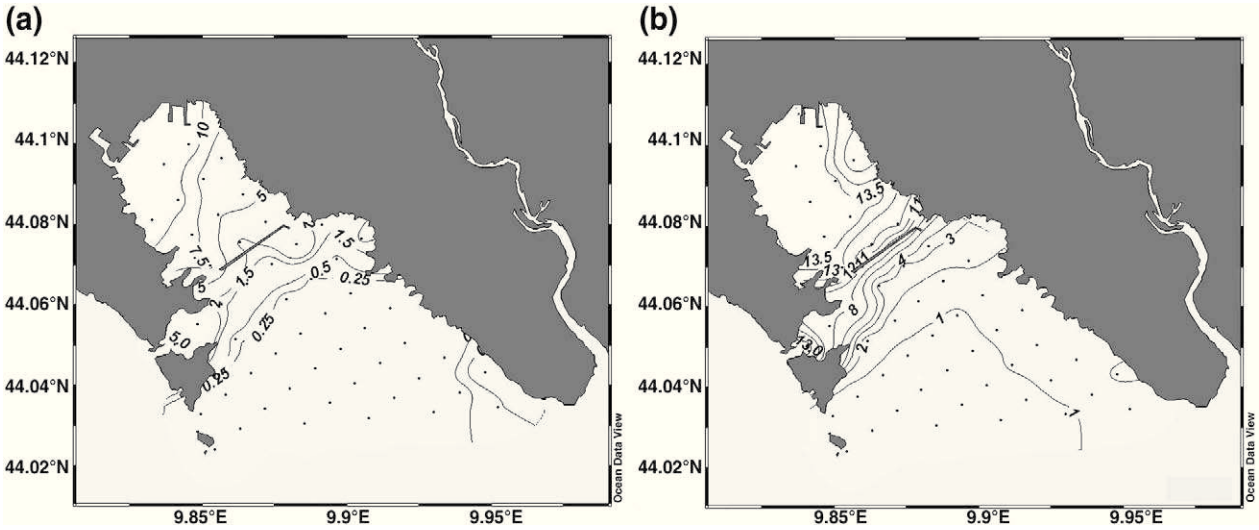


Fig. 5. Horizontal distribution of chlorophyll: (a) at 1 m and (b) at 10 m depth. Units are μg/l. Measurements were performed on 18 June 2007.

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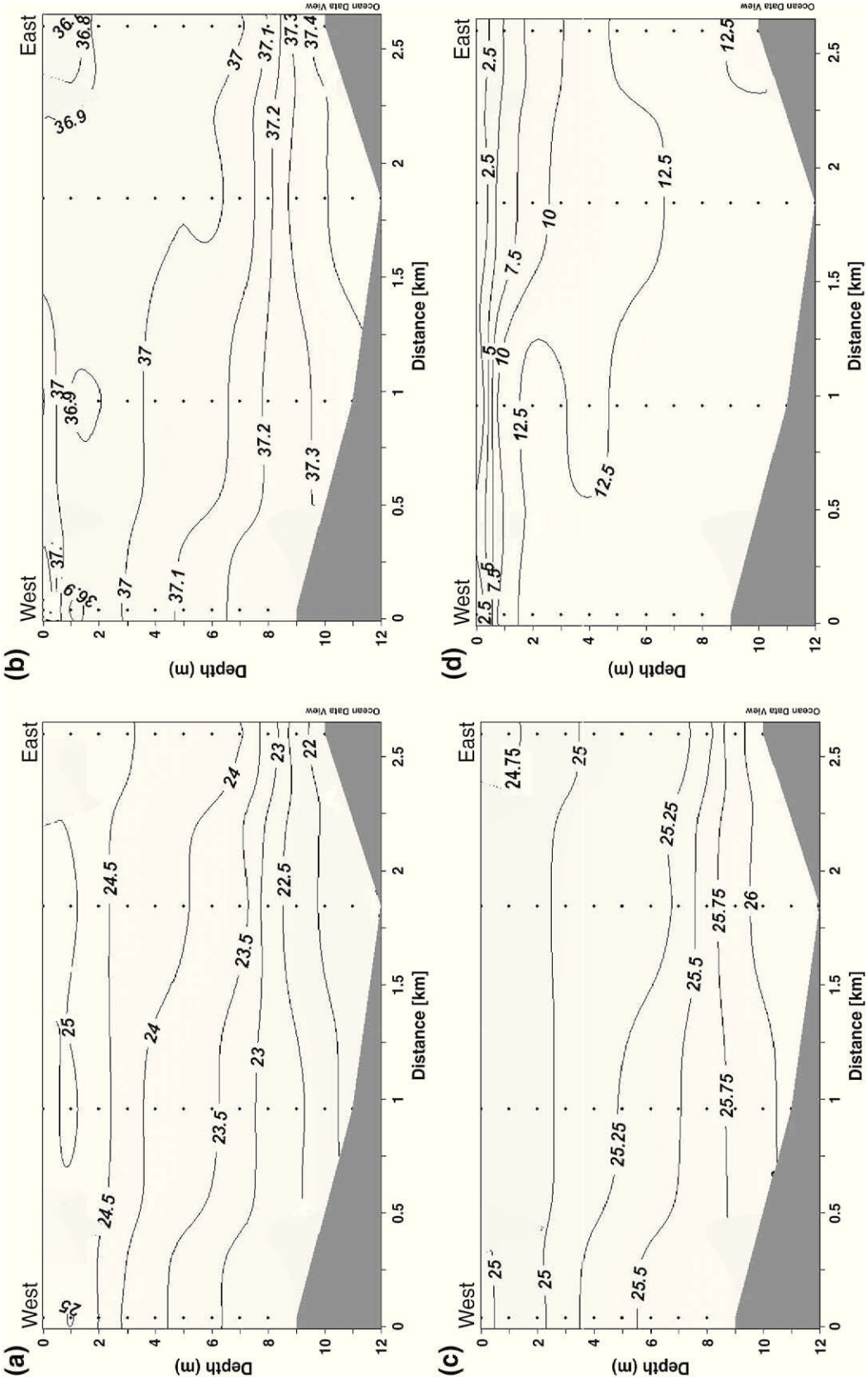


Fig. 6. Hydrographic conditions along an internal section (the third moving from the dam inside): (a) temperature [°C], (b) salinity, (c) density [kg/m^3] and (d) chlorophyll [μg/l]. Dots indicate the location of the hydrographic profiles. Measurements were performed on 18 June 2007.

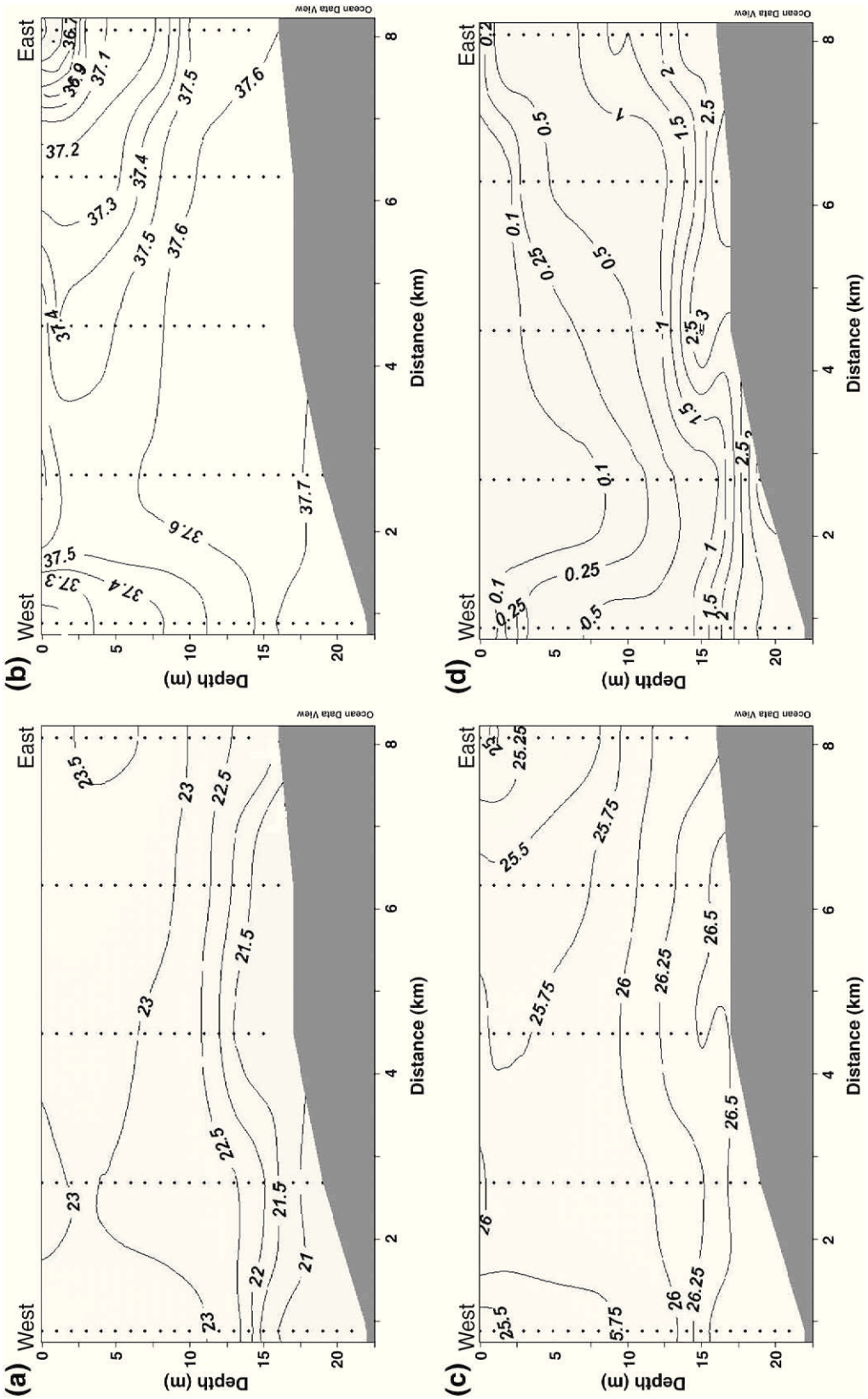


Fig. 7. Hydrographic conditions along the open boundary section of the Gulf: (a) temperature [°C], (b) salinity, (c) density [kg/m^3] and (d) chlorophyll [μg/l]. Dots indicate the location of the hydrographic profiles. Measurements were performed on 18 June 2007.

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highest values near the bottom (37.5). The isopycnal displacement is very similar to the previous parameters (Fig. 6c). If we assume as interface the isopycnal 25.5, we can observe a clear slope: positioned at about 3.5 m on the western side, it is found at about 7 m on the eastern side. The same slope is evident in temperature and salinity as well (Fig. 3). Concerning chlorophyll (Fig. 6d), it appears more homogeneous and high values are found along the entire water column, especially on the western side. Low chlorophyll concentrations are found only in a very thin surface layer.

Along the open boundary section, we have a different situation. Temperature is almost homogeneous in the upper 10 m (Fig. 7a). Going deeper, a significant temperature decrease corresponds to the top of the seasonal thermocline. The salinity distribution (Fig. 7b) shows two different signatures at its borders: on the eastern side there

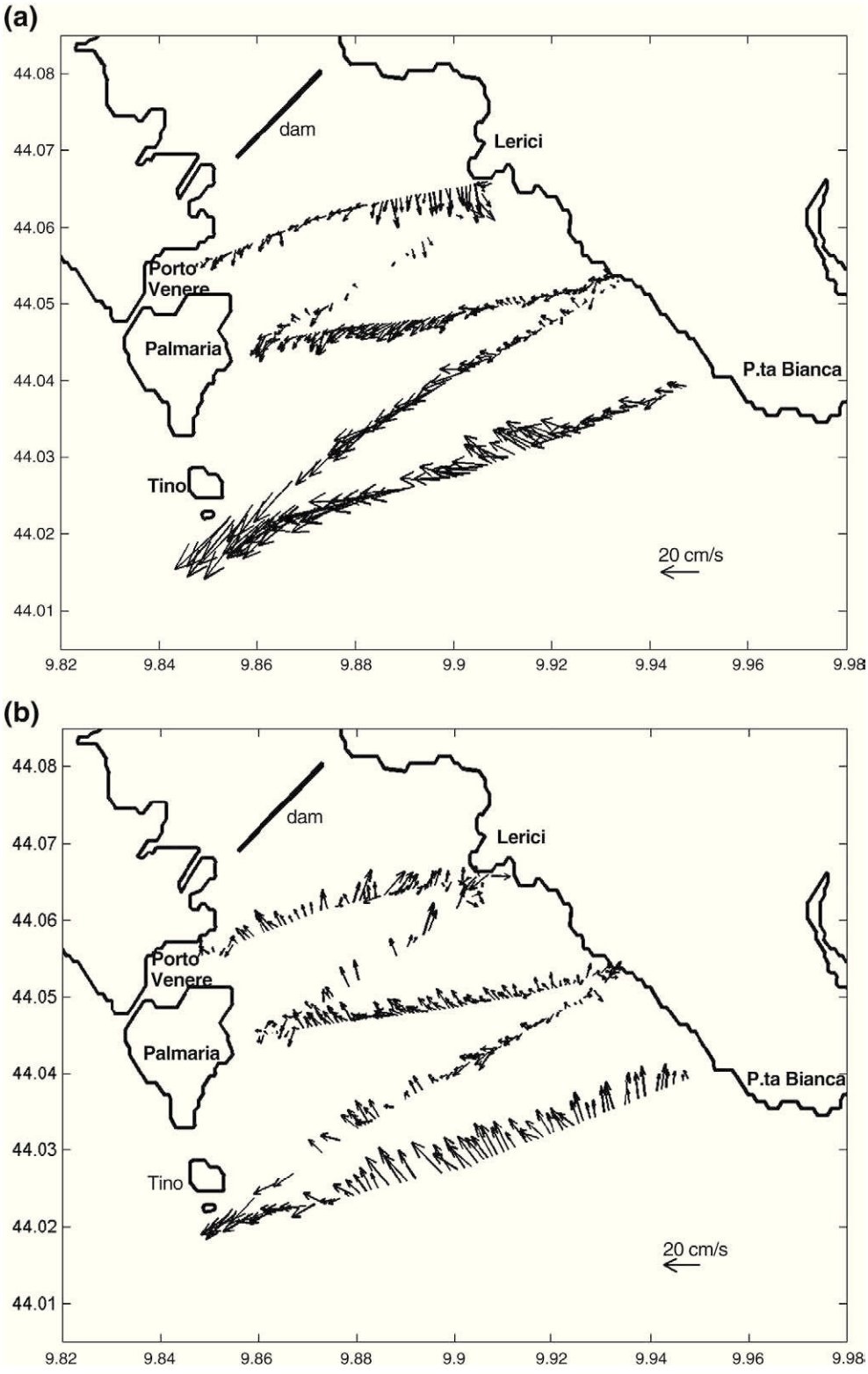


Fig. 8. Horizontal current field on 19 June 2007 along tracks indicated in Fig. 1 (continuous line) at two different depths: (a) 3 m, (b) 11 m.

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is the Magra river, on the western the open sea water prevails. In the central part of the section the deeper open sea water rises toward the surface: both *T* and *S* show a dome structure. The density structure is very similar to salinity (Fig. 7c): light waters are concentrated along the borders. Going down, below 15 m depth, the density significantly increases to 26.64. We have also to remark that the interface between the surface and deep layers (if we assume the 26.00 isopycnal) is almost horizontal, positioned at about 12 m depth.

A very different situation in the outside zone is confirmed by the chlorophyll concentrations, very low from the surface to about 15 m depth in the whole area, with a tendency to increase close to the thermocline level (Fig. 7d). This chlorophyll distribution seems

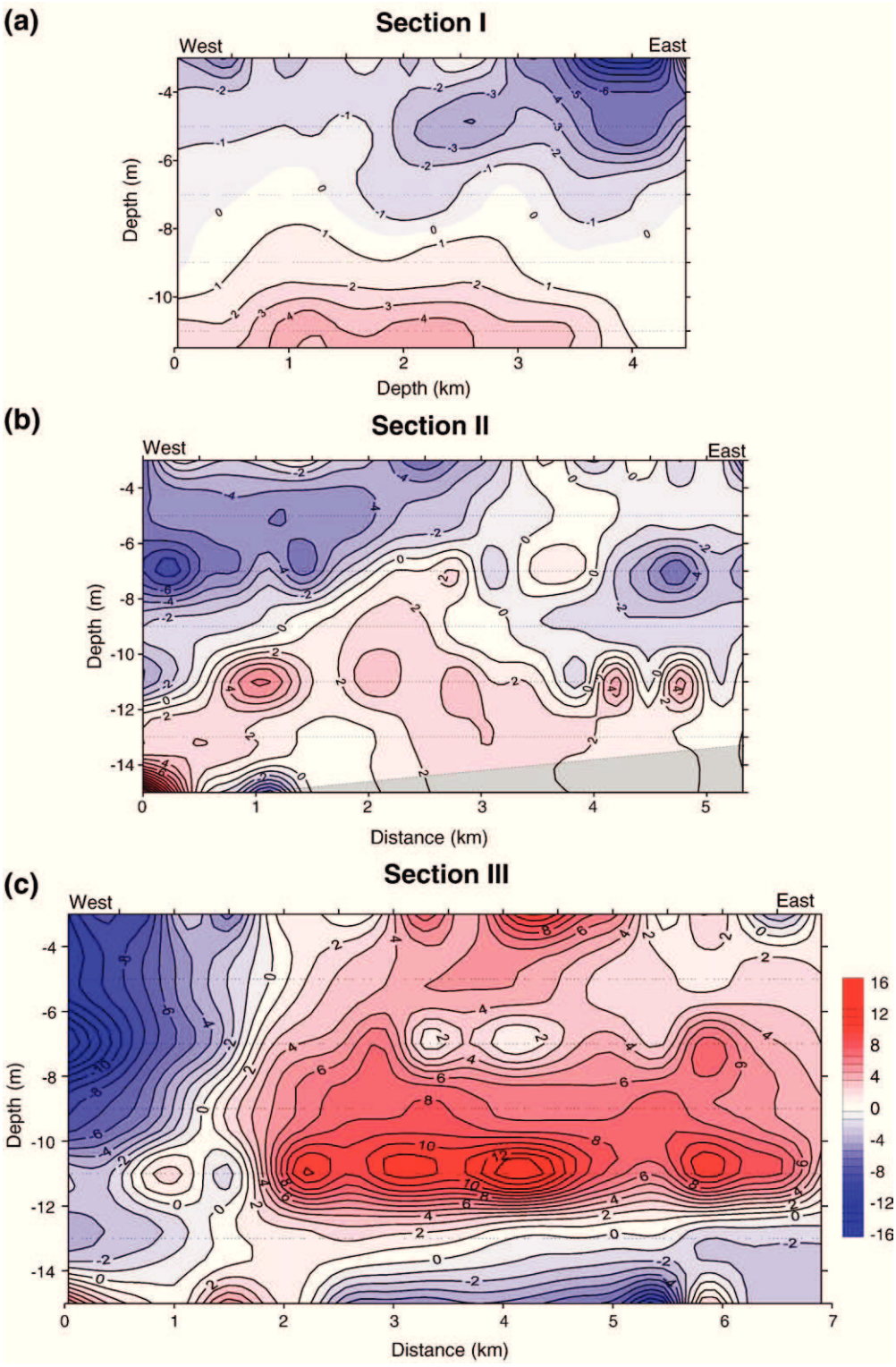


Fig. 9. Vertical distribution of the current component normal to the three sections indicated by roman numbers in Fig. 1: (a) section I, (b) section II and (c) section III. Positive values (red colour) indicate currents entering the Gulf. Units are cm/s. Measurements were performed on 19 June 2007. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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to mirror the large scale coastal conditions, where the chlorophyll maximum is usually positioned below the thermocline.

3.3. Current field

Current measurements, corresponding to the previously described hydrographic conditions in the area outside the dam (Fig. 1), are presented at two different depths: 3 and 11 m. The surface field (Fig. 8a) shows two streams both located on the eastern side: along the open boundary a stream enters the Gulf, while the other enters the surveyed region from the Gulf interior. Both streams merge in a unique outflow on the western side, in front of Tino island.

Moving to the deeper layer, an inflowing current covers a large portion of the external section with an outflow still in front of Tino

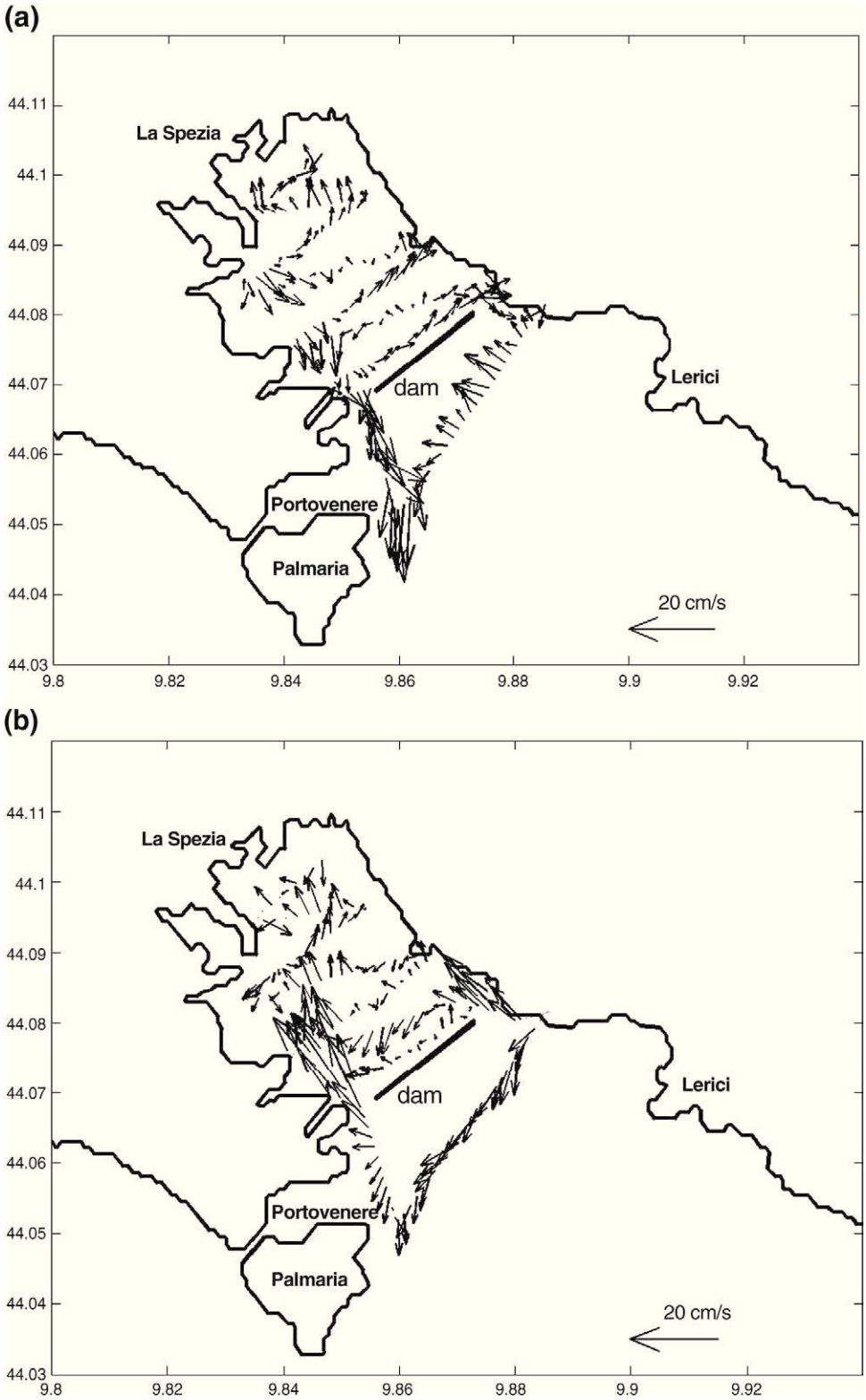


Fig. 10. Horizontal current field on 4 May 2006 along tracks indicated in Fig. 1 (dashed line) at two different depths: (a) 3 m, (b) 9 m.

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island (Fig. 8b). Along this track, surface and deep currents are very similar. The difference between the two layers tends to increase as we move inside the Gulf until oppositely directed currents, exiting in the surface layer and entering at depth, are encountered. As for the intensity, surface and deep currents have similar values.

The vertical structure of currents along three most significant sections (Fig. 9) well documents the progressive change of current field. Starting from the external section (Section III of Fig. 1), the currents maintain almost the same sign in the first 10–12 m (Fig. 9c): on the eastern side and in the greater part of the section the current enters the Gulf, while the outflow is concentrated in a narrow jet positioned on the western limit of the section and probably related to a topographic effect. Very flat on the eastern side (15 m deep), topographic features become very narrow and deep on the western side (Fig. 1). The entering vein tends to follow isobaths: due to the vorticity conservation it is forced to become narrower in order to follow the topographic constraint. The external section mainly mirrors the open sea cyclonic circulation.

Moving inside the Gulf, a two-layer system becomes evident (Fig. 9b). At Section II (Fig. 1) a more complex current field with the presence of small structures represents the transition region between the external quasi-uniform layer corresponding to the large scale circulation and the two-layer circulation generated inside the dam. Finally, at Section I (Fig. 1) we can clearly distinguish an outflow layer (about 8–9 m thick) and an inflow layer below it (Fig. 9a), in agreement with an estuarine circulation scheme.

During June 2007, no information on currents inside the dam and in the dam openings was available, and therefore we considered a current survey carried out about one year before (on 4 May 2006). That detailed survey (Fig. 10) well documents the two-layer feature of the circulation inside the dam: at 3 m depth the current direction is mainly oriented toward the open sea. Conversely, at 9 m the prevailing direction is toward the interior. The current intensity is of the order of a few cm/s, but it reaches significant values (more than 20 cm/s) in the dam openings. The surface outflow and deep inflow are more intense in the western opening, and the interior circulation along the western side appears more energetic as well, while several weaker re-circulations are present moving eastward. The possible presence of high frequency oscillations might modulate the current intensity, especially in the dam openings.

Further information comes from continuous current data collected during the period 23 May–18 July 1990 very close to the dam openings at two different depths (Fig. 1). Since the short time scales have been extensively investigated (Borella et al., 1992), we will pay attention to the sub-inertial variability.

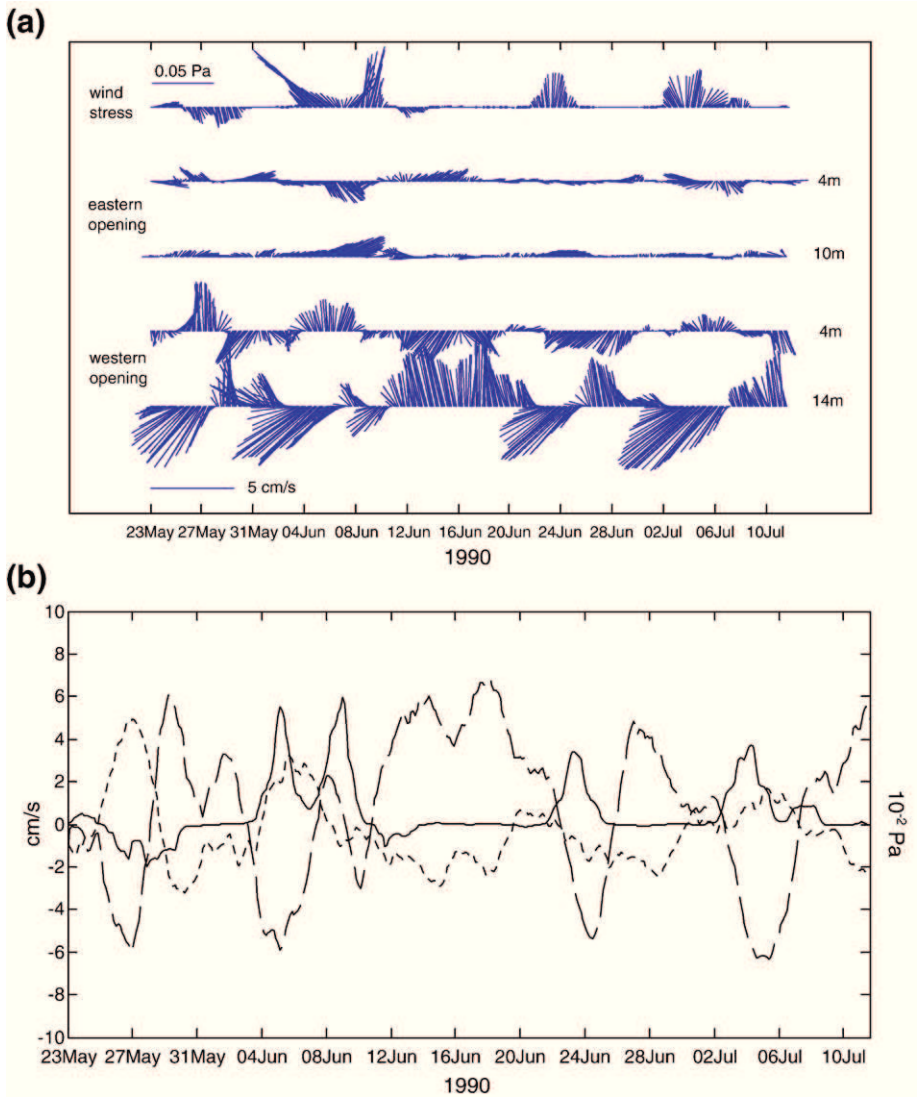


Fig. 11. (a) Stick plot of wind stress and currents at two depths (5 and 10 m, respectively) in the two dam openings; (b) time evolution of the north–south components of the wind stress (continuous line), 5 m depth current (dotted line) and the 10 m depth current (dashed line), in the western opening. The original data have been low-pass filtered to remove oscillations with periods below 48 h and 3-hour time series have been reconstructed. Data were taken between 23 May and 18 July 1990.

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Table 1
Basic statistics of currents measured in the Gulf of La Spezia dam openings between 23 May and 18 July 1990.

	Depth (m)	u (cm/s)	v (cm/s)
Eastern opening	4	0.46 ± 0.79	0.04 ± 0.63
	10	0.11 ± 0.84	0.33 ± 0.36
Western opening	4	-0.10 ± 0.63	-0.37 ± 1.67
	14	-1.31 ± 1.11	0.67 ± 3.59

The temporal evolution of the surface and deep current at each opening (Fig. 11a) shows oscillations lasting a few days on both sites, with the western current being significantly more energetic than the eastern one. The basic statistics indicate weak mean values with a standard deviation generally greater than the mean value (Table 1). The mean values confirm the existence of a two-layer system, with the deep water entering the interior part of the Gulf and the surface water exiting it. The temporal evolution of the wind stress (Fig. 11a) shows the prevalence of southern winds, alternated with calm periods. Nevertheless, the permanent weakness of winds blowing from the northern sectors suggests their probable underestimation, due to the location of meteorological station close to the dam (Fig. 1).

The current evolution at the four measurement points appears to be significantly correlated (Table 2), both vertically and horizontally, but important information comes from the relative angular displacement (Kundu, 1976). Table 2 shows that, at the two stations, the surface and deep current oscillations are almost out of phase (the angular displacements are −125° and −167° for the eastern and western opening, respectively), suggesting the existence of a local baroclinic adjustment. The horizontal angular displacement between the two openings shows a wide angle between currents in the same layer (135° and 117° for the surface and deep layers, respectively), while the angle is significantly reduced between the surface current of one opening and deep current of the other opening (−50° and −67°, respectively).

The comparison between the wind stress and current evolution (Fig. 11a) shows correspondence between wind and current variability. If one concentrates on the more energetic western passage (Fig. 11b), the correlation between the northern components of wind stress and currents is found to be positive when the deep current is considered and negative with the surface current being taken into account. We can also observe a delay between the wind stress and currents, with the wind leading the current by about 32 h: there is a correlation of 0.37 and −0.16 for the deep and surface current, respectively, at a time lag of 0 h, which increases to 0.57 and −0.25, respectively, for a time lag of 32 h. The correlation wind-current at the eastern opening is less significant than in the western one and has an opposite sign: positive in the surface and negative in the deep layer, in agreement with the current correlation as previously observed.

The different current behaviour and the relation between wind stress and currents suggest the following circulation scheme: for winds blowing from the south the surface water is pushed into the Gulf mainly through the eastern opening, producing a counterclockwise recirculation inside the dam to which an outflow through the western opening corresponds. The deep layer responds with an outflow in the eastern opening and an inflow in the western one, to which corresponds a clockwise circulation inside. An inverse situation happens for the northern wind. Unfortunately, this scenario, suggested by the current field, is not adequately supported by the wind data, due to the underestimation of the winds blowing from the northern sectors. Yet, the described scenario appears to agree with the baroclinic response to the wind forcing of a two-layer semi-enclosed basin.

3.4. Mean circulation scheme

From previous hydrographic and current observations, we can try to depict a qualitative scheme of the background circulation in the Gulf. As for the surface layer (Fig. 12a), hydrographic data (Fig. 3) and direct current measurements (Fig. 8) indicate an inflow/outflow along the open boundary. Moving inside, we can observe a prevalence of the outflow, mainly concentrated along the western border (Figs. 8 and 10). The subsurface circulation (Fig. 12b) follows the surface inflow/outflow scheme at the open boundary but, moving inside the Gulf, the inflow prevails: for both the surface and deep layers, the major advection is found on the western side of the Gulf. The previous schemes summarize the mean circulation of the Gulf, which is the result of the combined effects of interior dynamic and large scale flow.

The detailed description of the current field, measured during the survey of May 2006 (Fig. 10), permits to try an estimate of the exchange through the dam and of the upward entrainment related to estuarine circulation inside it. From the current measurements, in the dam openings a deep inflow of 230 m^3/s can be estimated. It corresponds to the baroclinic transport, computed by removing the vertical mean from the current data in order to reduce the high frequency effects that are mainly barotropic. The resulting residence time inside the dam (assuming a volume of about 10^8 m^3) is of the order of 5 days. Furthermore, we know that the power plant cooling system (Fig. 1) draws, at a depth of 10 m, about 30 m^3/s of salt water from the Gulf, which is then released with a temperature increase of 7 °C. This means that the expected influence on the deep inflow, able to be upwelled toward the surface layer, is a temperature increase of 0.9 °C. Considering a classical estuarine circulation, we will have a progressive upward entrainment of the lower layer, which produces horizontal divergence Δ in the upper layer.

An estimate of the upward flux can be obtained from the following relation:

$$\Delta = \partial u / \partial x + \partial v / \partial y = w / h$$

where u and v are the depth averaged horizontal velocity components in the surface layer, h is the mean surface layer thickness and w is the upwelling velocity. Assuming a 5 m thick surface layer and computing the corresponding current field in it, we estimated a mean vertical velocity of 6.5×10^{-6} m/s (equivalent to 0.6 m/d): for the Gulf interior area of 10^7 m^2 we will have a mean upwelling of about 65 m^3/s. If we assume the same deep water inflow inside the dam, the resulting residence time will be about 21 days. This value is significantly longer than the previous direct estimate for the dam openings, which included the transient advective phenomena able to

Table 2
Vector correlation of currents: (a) correlation coefficient; (b) relative (counterclockwise) angular displacement.

	Eastern opening current at 4 m	Eastern opening current at 10 m	Western opening current at 4 m	Western opening current at 14 m
a				
Eastern opening current at 4 m	1	0.43	0.35	0.37
Eastern opening current at 10 m	0.43	1	0.53	0.67
Western opening current at 4 m	0.35	0.53	1	0.61
Western opening current at 14 m	0.37	0.67	0.61	1
b				
Eastern opening current at 4 m	0	−125	135	−50
Eastern opening current at 10 m	−125	0	−67	117
Western opening current at 4 m	135	−67	0	−167
Western opening current at 14 m	−50	117	−167	0

The data were taken in the Gulf of La Spezia dam openings between 23 May and 18 July 1990.

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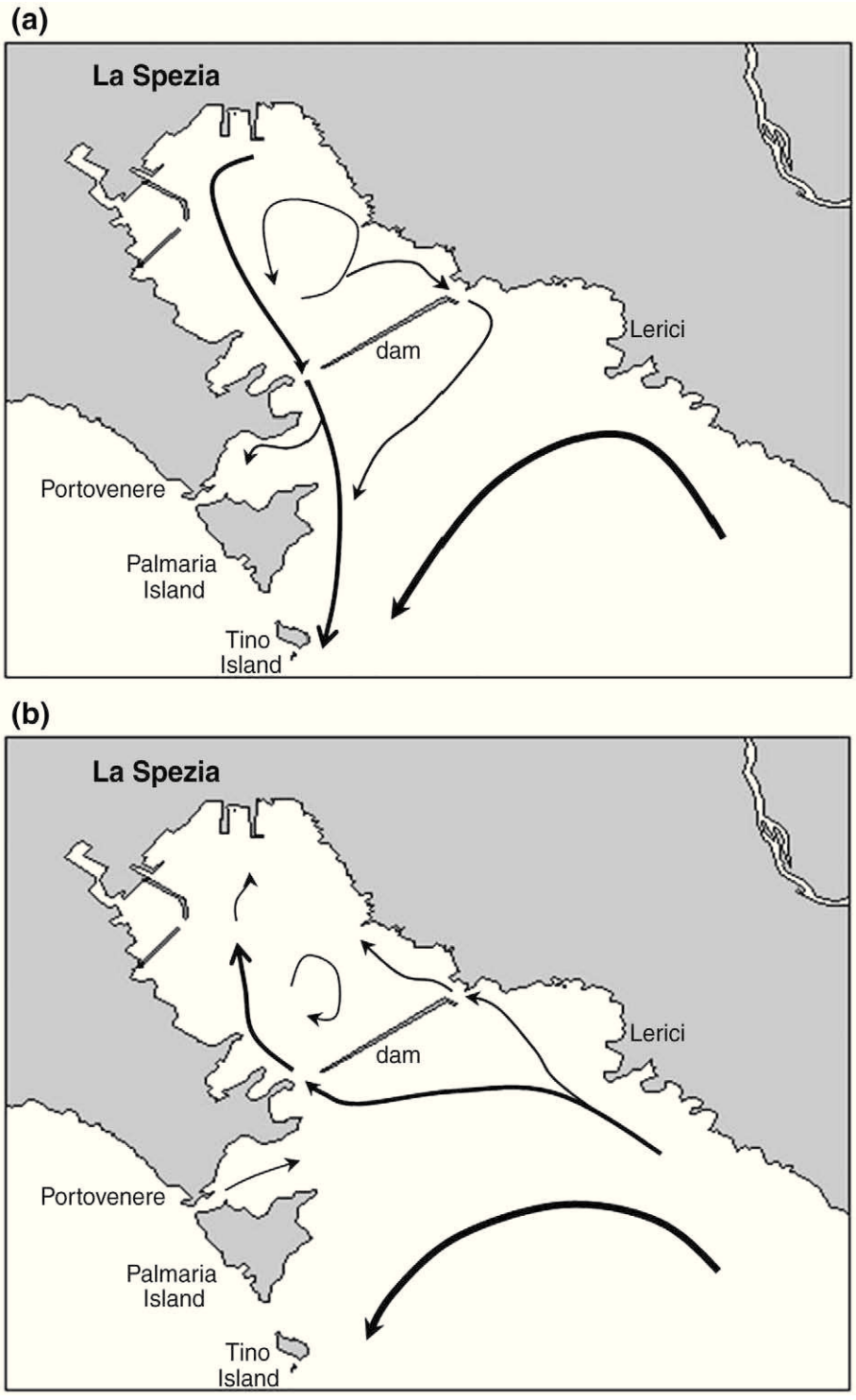


Fig. 12. Qualitative circulation scheme of the Gulf: (a) surface layer, (b) deep layer.

enhance the exchange. Nevertheless, it may be interesting to note that, if we consider the inflow estimated from the mean current values recorded in the period 23 May–18 July 1990, we find about 70 m^3/s, very close to the upwelled volume transport.

3.5. Coastal environmental characteristics

As we previously observed, there is a close connection between dynamic conditions and chlorophyll distribution. Furthermore, the main circulation paths, both in the harbor and in the open sea, may help to explain the different distributions of chlorophyll concentration. We proceed now to examine in more detail how the circulation paths may be relevant for the littoral areas of the Gulf and how they may control its environmental quality. The examined stations are very close to the land and cover the western and eastern Gulf, outside the dam (Fig. 1). Considering the complex topography of the Gulf, we may expect a high spatial variability in the environmental characteristics.

As for nutrients (Table 3), we have found almost the same phosphate concentration at all positions with a mean value of 0.123 µmol/l

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Table 3
Mean nutrient concentrations in the different zones shown in Fig. 13.

	$N–NO_3$ (μmol/l)	$P–PO_4$ (μmol/l)	$Si–Si\ (OH_4)$ (μmol/l)
Zone A	0.26	0.139	0.96
Zone B	0.23	0.113	1.01
Zone C	0.14	0.123	1.09
Zone D	0.28	0.115	0.82

Data were taken on 18 June 2007.

(±0.012). Silicate values range usually between 0.80 and 1.0 μmol/l; only at few station levels of about 1.5 μmol/l are found. The mean nitrate concentration is 0.23 μmol/l (±0.06); only at two positions we have higher values (0.80 μmol/l). The nutrient level, generally low in the whole area, confirms the oligotrophic characteristics of the Gulf outside the dam (ENEA, 1996, 2000) and suggests that terrestrial sources of nutrients are not particularly relevant.

The phytoplankton distribution shows a different behaviour. The cellular density ranges between a minimum value of 1000 cells/l at the eastern stations to a maximum value of 9000 cells/l along the western coast. Classes of diatoms and dinoflagellates are prevalent in the phytoplankton population. At all stations, the diatoms are most abundant (at least 90%). Four zones with different phytoplanktonic density (Fig. 13) can be recognized in the Gulf. The first zone (A) with the highest density (>7000 cells/l) corresponds to stations along the Portovenere littoral. In that area some diatoms species (*Leptocylindrus minimus*, *Leptocylindrus danicus*, *Chaetoceros affinis*, *Chaetoceros curvisetus*) are very abundant and seem to correspond to an algal bloom. Dinoflagellates are less abundant, although the presence of potentially harmful algae such as *Ostreopsis ovata* and *Lingulodinium polyedrum* has been noticed. The comparison between evaluated phytoplanktonic density and fluorimetric profiles of chlorophyll (Fig. 14) shows that almost the whole algal biomass is situated in the layer positioned at 3–7 m depth. In this area the warm and chlorophyll rich water, outflowing the harbor, lies on the colder open sea water inflowing through the Portovenere channel (Figs. 4 and 5). Due to this situation, the Portovenere littoral becomes very productive and subjected to eutrophication when the meteo-marine conditions inhibit an efficient water mass renewal.

The second zone (B) with lower density (2000–3500 cells/l) includes the stations along the Lerici littoral. Diatoms and dinoflagellates are mostly represented by the same species found in the western Gulf, but they are less abundant especially when the first class is considered. The comparison of different fluorimetric profiles of chlorophyll in this area (Fig. 14) shows that the phytoplanktonic biomass is vertically uniform.

The third zone (C: Tino channel–central Gulf) shows a density range between 1000 and 2000 cells/l. As we can conclude from circulation schemes (Fig. 12), the zone is positioned in the Gulf outflow, which is characterized by a mixture of interior Gulf and open sea waters.

Finally, the fourth zone (D) with the lowest density (<1000 cells/l) includes the two external stations in front of Lerici and the easternmost station of the Gulf: that zone is mostly influenced by the open sea current, less rich in algal biomass.

The described chlorophyll distribution combined with an almost uniform nutrient concentration confirms the previous finding on the importance of advection: the circulation appears to be mainly responsible for the environmental heterogeneity of the Gulf.

4. Discussion and conclusion

The examined data permitted to describe the Gulf of La Spezia in terms of hydrographic and current characteristics. The good agreement between temperature and salinity distributions and current field permitted to define the main circulation features. A clear estuarine pattern is maintained inside the dam and appears to be a significant mechanism for water replenishment, with a relevant role in determining the quality of harbor waters. Its influence extends outside the dam too, interacting with the large scale circulation, which enters the Gulf through its open boundary.

The orographic and topographic constraints, both natural and artificial, are crucial for hydrography and currents. The most energetic part of the Gulf is on the western side. Outside the dam, the total Gulf outflow is concentrated in a narrow stream. This is due to the bottom topography, which becomes very steep along the western border (Palmaria and Tino islands). We may also observe that a relevant portion of the exchange between the internal and external part of the Gulf occurs through the western dam opening, which is wider and deeper. On the western side, an additional factor might play some role, namely the water mass exchange through the Portovenere channel, probably driven by steric sea level difference between the Gulf and the open sea.

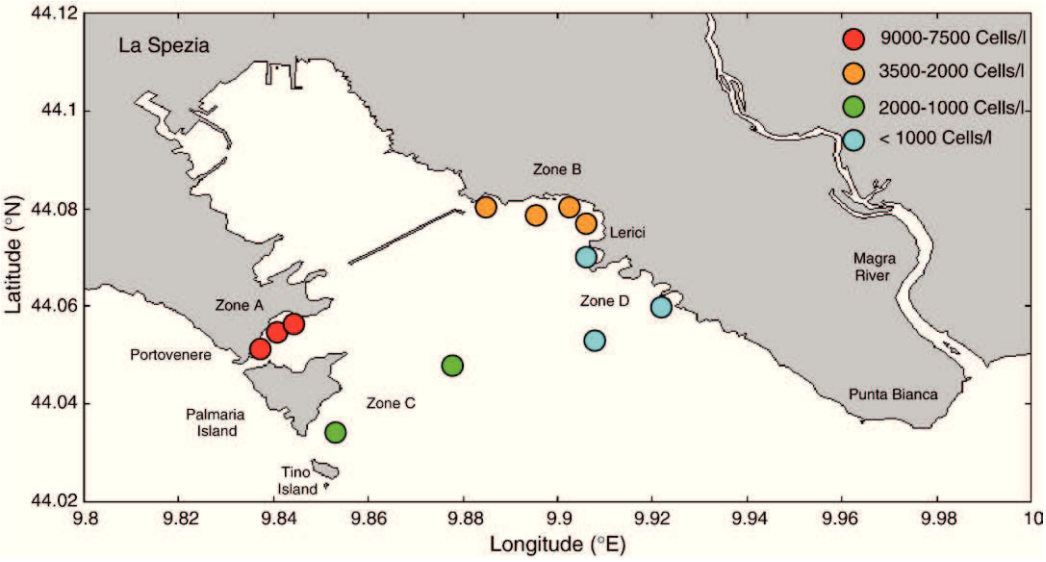


Fig. 13. Distribution of phytoplankton density in the coastal sampling stations. Different colors indicate different concentration levels, to which correspond different zones: zone A (9000–7500 cells/l), zone B (3500–2000 (cells/l), zone C (2000–1000 cells/l), zone D (<1000 cells/l). Data were taken on 18 June 2007.

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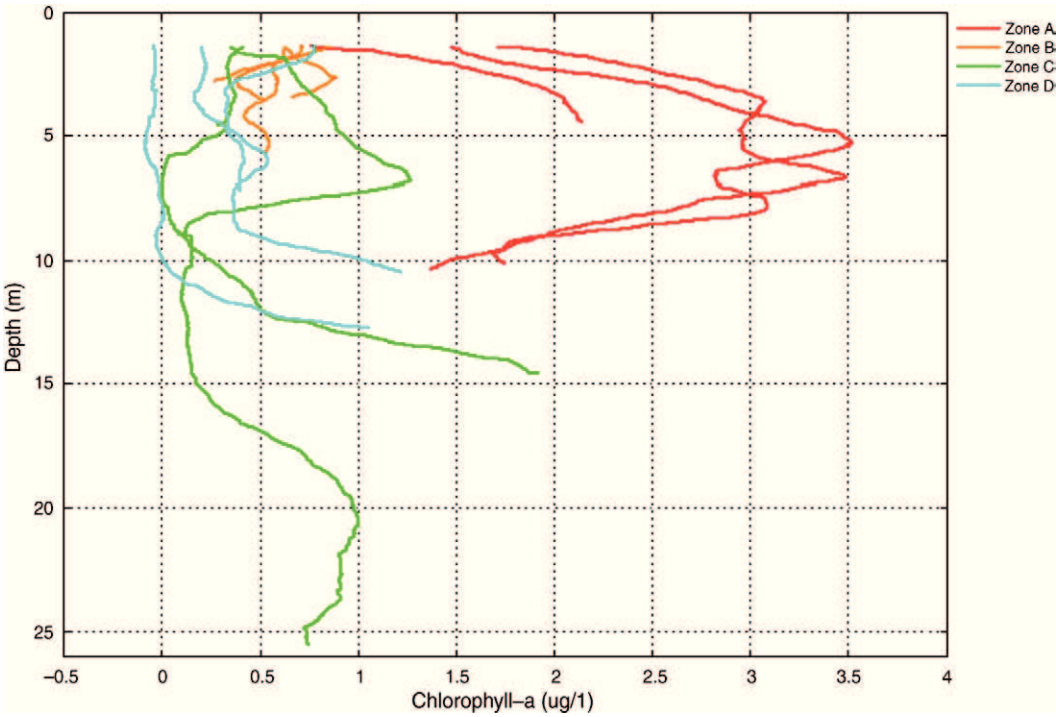


Fig. 14. Fluorimetric profiles of chlorophyll "*a*" in the coastal sampling stations. Different colors indicate the same zones as indicated in Fig. 13: red (zone A), orange (zone B), green (zone C), blue (zone D). Data were taken on 18 June 2007. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A clear correspondence was observed between *T*, *S* and fluorescence, underlying the role played by circulation in determining the environmental characteristics. This appears particularly evident outside the dam, where environmental quality changes from high to low in consequence of the prevalence of dam outflow or of the external circulation. Along the littoral sites the harbor influence is relevant, since the engine of a large part of the Gulf circulation (estuarine circulation) is located in its highly productive interior.

The thermohaline background circulation in the dam interior produces a slow current, to which corresponds an interior residence time of about three weeks. Direct current measurements document relevance of shorter hydrodynamic processes, able to enhance the renewal of the water inside the dam and to significantly reduce the residence time to about 5 days. Furthermore, the stratified system strongly influences response to the wind. The current evolution in the two dam openings shows the clear baroclinic response of the Gulf interior: a cyclonic/anticyclonic circulation of the surface layer corresponds to an anticyclonic/cyclonic circulation in the deep layer. The considered measurements, even if originating from different years (1990, 2006 and 2007), cover almost the same period of stratified season and point to similar circulation features. The observed low frequency circulation appears to be the result of the concurrent action of two main processes (large scale circulation, local estuarine circulation), which are able to strongly influence environmental conditions in the examined region.

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