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Upwelling regime off the Cabo Frio region in Brazil and impact on acoustic propagation

Leandro Calado,[1] Orlando Camargo Rodríguez,[2] Gabriel Codato,[3] and Fabio Contrera Xavier[1]
[1]*Admiral Paulo Moreira Marine Research Institute (IEAPM), Brazilian Navy, Arraial do Cabo, Rio de Janeiro, 28930-000, Brazil*
[2]*Laboratory of Robotics and Engineering Systems–LARSyS, Campus de Gambelas, Universidade do Algarve, PT-8005-139 Faro, Portugal*
[3]*Universidade Federal Fluminense, Rio de Janeiro, Brazil*
leandro_calado@hotmail.com, orodrig@ualg.pt, gabrielcodato@gmail.com, fabiofcx@gmail.com

Abstract: This work introduces a description of the complex upwelling regime off the Cabo Frio region in Brazil and shows that ocean modeling, based on the feature-oriented regional modeling system (FORMS) technique, can produce reliable predictions of sound speed fields for the corresponding shallow water environment. This work also shows, through the development of simulations, that the upwelling regime can be responsible for the creation of shadow coastal zones, in which the detection probability is too low for an acoustic source to be detected. The development of the FORMS technique and its validation with real data, for the particular region of coastal upwelling off Cabo Frio, reveals the possibility of a sustainable and reliable forecast system for the corresponding (variable in space and time) underwater acoustic environment.

[DRB]
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1. Introduction

Acoustic propagation in the ocean is a complex phenomenon with important applications. Ranging from sonar systems, through source detection and localization problems, and covering geoacoustics, tomography, communications, passive and active methods (and modeling), the development of any acoustic system requires intensive interdisciplinary research, which is driven by the huge complexity of the marine environment; key to many problems (e.g., source localization) is a detailed description of sound speed. Given the different time scales of many ocean processes (e.g., ocean processes time variability) the long term operation of an acoustic system depends critically on feeding the system with updated information of sound speed, something that is cumbersome to do with standard sampling techniques. An alternative is to feed the system with forecasts of an ocean circulation model, which has been properly adapted to the specific conditions of the region where the system operates.

The main goal of the discussion presented here is to describe a particular forecast model developed for the specific conditions of the upwelling regime off the Cabo Frio region in Brazil and to show, from data obtained during a local sea campaign performed in 2010, that the model is capable of producing reliable environmental predictions, which can be of extreme importance for the problem of source detection. To this end, this work is organized as follows: the upwelling off the Cabo Frio region is described in Sec. 2, while the OAEX2010 sea trial was developed within the context of the multi-disciplinary and multi-institutional Ocean Acoustic Exploration project (Ocean Acoustic Exploration, 2012). This experiment is described compactly in Sec. 3; Sec. 4 explains the preparation of the ocean model for the production of reliable environmental forecasts and Sec. 6 discusses the importance of forecasts for the problem of source detection. The conclusions and future work are presented in Sec. 7.

2. Upwelling off the Cabo Frio region in Brazil

Coastal upwelling is a complex oceanographic phenomenon characterized by an upward motion of cold deep waters, which are rich in nutrients and provide an ideal environment for biological productivity of marine species. Although upwelling regions represent less than 1% of the ocean surface they contribute to approximately 50% of fishing activities worldwide (Rodrígues, 1973). The Brazilian coast in the Cabo Frio region develops a unique coastal-oceanic system when the coast orientation changes and shelf break topography reinforces the interaction between the oceanic and coastal

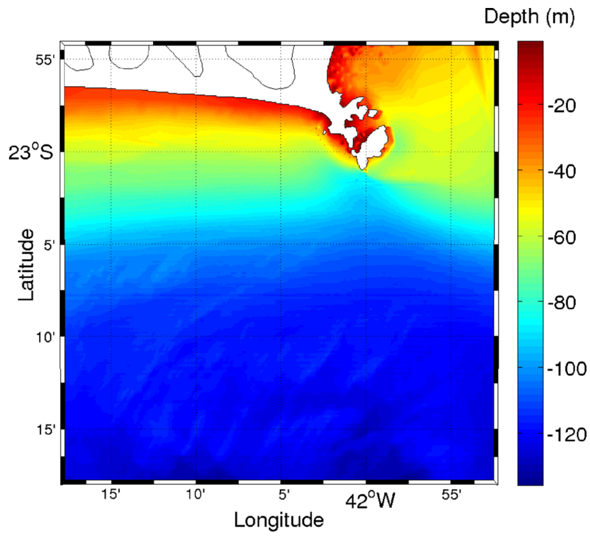

Fig. 1. (Color online) OAEX2010 site bathymetry.

systems, Fig. 1. The most important coastal feature in the Cabo Frio region is the upwelling. During the summer months, when coastal upwelling is more frequent and sustained due to favourable wind conditions over the Cabo Frio area, the surface temperature difference between the Brazil Current front and upwelled waters near the coast is most of the time greater than 10 °C and can extend offshore along more then 50 km (Carriére *et al.*, 2010; Calado *et al.*, 2008). The enrichment of nutrients promoted by the coastal upwelling plays a fundamental role in the high fishing productivity of the area (Matsuura, 1996). Coastal upwelling in the region results from the break in orientation of the coastline, combined with the persistence of strong northeast (NE) winds, specially during spring and summer. After flowing during several days parallel to the coast and as a result of Ekman's dynamics, the NE wind pushes the coastal waters and generates the upwelling of central waters of the south Atlantic, generating high thermohaline gradients which strongly affect the stratification of the water column.

3. The OAEX2010 experiment

The OAEX2010 and took place along the coast of Cabo Frio, southeastern Brazil, during the period of 19–22 November, 2010. The campaign involved oceanographical and acoustical surveys performed by the Brazilian Navy vessels R/V Aspirante Moura and EDCG Guarapari; the campaign included 100 oceanographic stations variably spaced in the range of 5–10 km, reaching depths in the interval 12–120 m, which allowed observations of three days of upwelling evolution. Complete CTD samplings were performed yielding profiles of temperature and salinity; the corresponding data were interpolated using a multiscale objective analysis (OA) scheme, with 1 km of horizontal resolution and 30 vertical levels, revealing a complex structure of the upwelling field [described in details by Gangopadhyay and Robinson (2001), Shaji and Gangopadhyay (2007), and Calado *et al.* (2008)]. Acoustic transmissions were conducted using a Lubell high-fequency transducer, towed by R/V Aspirante Moura in the depth interval of 5–10 m, transmitting continuous wave (CW) multi-tones from 500 Hz to 2 kHz with nine intermediate frequencies, and linearly frequency modulated (LFM) signals in the intervals from 500 Hz to 1 kHz (lower frequencies), and from 1 to 2 kHz (higher frequencies). The EDCG Guarapari carried a vertical array with eight hydrophones, equally spaced at depths from 10 to 31 m.

Bathymetry for the area was obtained from nautic charts and from ETOPO-1 data and it is shown in Fig. 1; bottom properties are discussed in the work by Simões *et al.* (2012) and are shown in Table 1. Generally speaking, isobaths are parallel to the coast and are mostly distributed along lines of constant longitude; lines of constant latitude are perpendicular to the coastline, with depth increasing from the coast to the ocean. The particular shape of the coastline, combined with the narrow continental shelf (70–80 km), allows the generation of an efficient upwelling regime and contributes to the development of the coastal stream vortex, which is itself an intensifier mechanism of upwelling (Calado *et al.*, 2008).

Table 1. OAEX2010 bottom properties.

Parameter	Units	Value
Density	kg/m^3	1800
Compressional speed	m/s	1626
Compressional attenuation	dB/λ	0.5

4. Feature-oriented regional modeling system (FORMS)

In a general sense the FORMS technique is based on the construction of synoptic ocean structures, using a parametric or "feature model" (FM) approach. (Gangopadhyay and Robinson, 2001; Shaji and Gangopadhyay, 2007; Calado *et al.*, 2008). Feature models are simple mathematical representations of ocean features (e.g., fronts and eddies), which are parameterized by their typical temperature-salinity field. The philosophy of the FORMS is to develop a first-order system (features model) for a very complex non-linear system, such as a regional ocean, where most processes strongly interact with each other and therefore can not be studied separately. Once the first-order structures are placed within the dynamical framework of a numerical model, the nonlinearity stimulates further interaction among features and allows for the creation of realistic four-dimensional complex fields. Thus, the FORMS technique allows the model setup from a dynamically adjusted initial field, e.g., the simulation starts from a desired scenario. A detailed discussion of the FORMS technique can be found in Gangopadhyay *et al.* (2011) and Calado *et al.* (2008).

The remainder of this section introduces a compact description. Oceanographic forecasts for the conditions of the OAEX2010 experiment were initialized by a FORMS scheme, using the regional ocean modeling system (ROMS) (Shchepetkin and McWillians, 2005). The grid used in the model had a horizontal resolution of approximately 800 m and 25 vertical terrain-following coordinate systems levels; an open boundary condition was applied on the experiment, with the climatology continuously supplying the domain. The output of FORMS consisted of adding the coastal upwelling feature to the background climatological thermohaline structure from the *World Ocean Atlas* (Locarnini *et al.*, 2006), and ultimately reshaping the upper-layer based on the sea surface temperature for November 19 of 2010 obtained from the GHRSST-Group of High Resolution Sea Surface Temperature (Team, 2008). The coastal upwelling feature model employed in this work is derived from a technique developed by Gangopadhyay and Robinson (2001) and Shaji and Gangopadhyay (2007), which was updated by Calado *et al.* (2008) and Carriére *et al.* (2010), respectively. The ROMS was forced with the wind stress derived from the level 2 along-track Advanced Scatterometer-ASCAT (Project, 2011) dataset interpolated to the model grid, and with a tide obtained from the global model of ocean tides TPXO 7.2 (Egbert and Erofeeva, 2002). Due to the high volume of data produced by the simulation, the forecasting results to be discussed in Sec. 5 will not consider the temporal variations of the upwelling regime.

5. Forecasting results

Two transects, one "horizontal" and one "vertical," were considered to verify the accuracy of forecasts (see Fig. 2). Depending on bathymetry one can consider that the horizontal transect, aligned along a constant longitude, corresponds to a range-independent section (i.e., a section with constant bottom depth); the vertical transect, aligned along a constant latitude, corresponds to a range-dependent section, with bottom depth increasing from the coast to the open ocean. Both transects are shown in Fig. 2 on top of sea surface temperature records for November 19 of 2010, which were also incorporated into the ocean model.

Real data and forecasts of temperature and salinity were converted into sound speed using the formula of Chen and Millero (1977). Predictions from the ROMS model using the FORMS technique were interpolated along the vertical sections corresponding to each transect. The results are shown in Fig. 3 together with sound speed fields calculated from real data. Clearly the forecasting reproduces in detail the range and depth structure of real sound speed, demonstrating that the ocean prediction is indeed reliable. The impact of the upwelling regime on acoustic propagation is discussed in Sec. 6.

6. Detection probability issues

The work developed in Codato *et al.* (2012) addresses a preliminary discussion of acoustic data and shows that there are no significant differences in acoustic predictions produced with real or predicted sound speed fields. Therefore, it can be concluded that

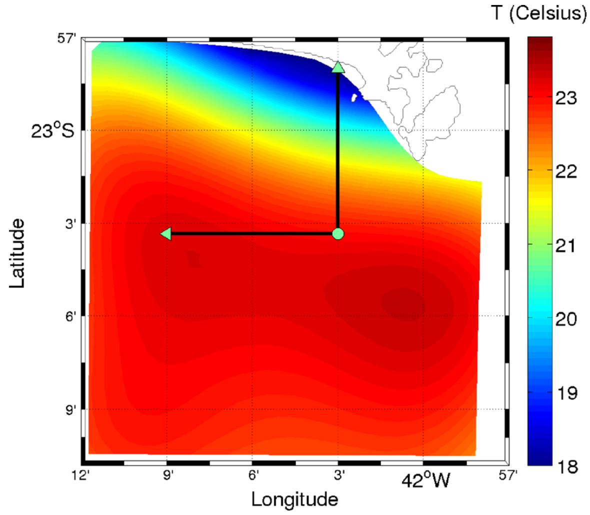

Fig. 2. (Color online) Range-independent (horizontal line) and range-dependent (vertical line) transects considered for forecasting: the circle indicates the position of the acoustic source, the background represents sea surface temperature.

the ocean forecasts indeed represent reliable representations of the real environment and can be used for accurate predictions of acoustic propagation.

Within this context, this section addresses a problem of logistic importance, namely, the determination of to what degree the upwelling field and the complex local bathymetry will affect the probability of detection of an acoustic source. To address this, a two-dimensional acoustic model is run along N different tracks of bathymetry, centered on the acoustic source (this procedure is called $N \times 2D$ modeling). The following is a compact description:

- For a given pair of longitude and latitude coordinates of the acoustic source idealize a vertical cylinder, whose base is a disk on the longitude/latitude plane, with a radius of 10 km.

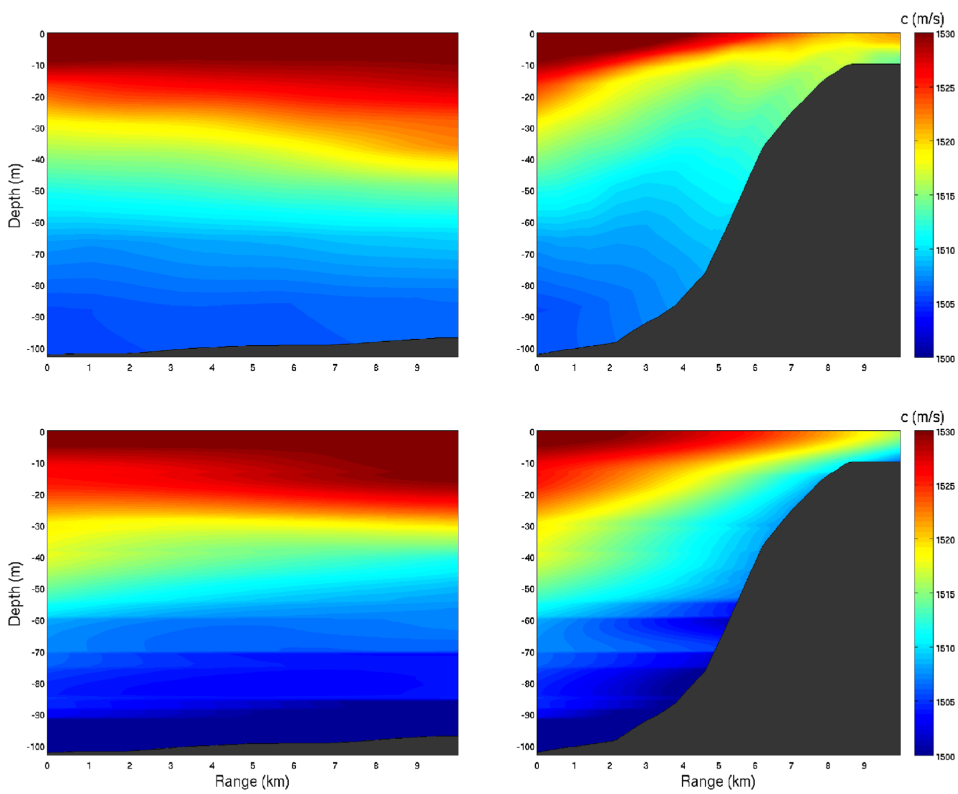

Fig. 3. (Color online) Sections of sound velocity calculated from temperature and salinity for the horizontal and vertical transects of Fig. 2 (left and right, respectively): ROMS predictions using the FORMS technique (top), and real data (bottom).

- For either base of the cylinder consider a transect on the longitude/latitude plane; the transect can be considered to be aligned relative to the longitude axis at an angle α (for instance, the vertical and horizontal transects on Fig. 2 would be aligned at $\alpha = 90^\circ$ and $\alpha = 180^\circ$, respectively); the transect can be idealized as the upper or lower edge of a vertical section; one vertical edge of the section is fixed at the source and the other edge is placed at a range of 10 km.
- Interpolate the volume forecast along the given section and use an acoustic model to produce a prediction of transmission loss (TL).
- Repeat the calculations for as many transects/sections as desired.

The calculations of TL describe the intensity of the acoustic field, but do not provide direct information regarding the detection of the source. To address this issue one needs the figure of merit (FOM), which combines together some of the terms of the sonar equation. Values of TL above the FOM indicate ranges where the source can be detected; the difference between the FOM and TL is called the signal excess (SE),

$$\mathrm{SE} = \mathrm{FOM} - \mathrm{TL}\,, \tag{1}$$

and with the SE the probability of source detection P_D becomes (Ferla and Porter, 1991)

$$P_D = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\mathrm{SE}} \exp\left(\frac{-x^2}{2\sigma^2}\right) dx\,, \tag{2}$$

where $-\infty < x \leq \mathrm{SE}$, and σ stands for the standard SE deviation, which for the specific problem was estimated to be 8 dB; the value of FOM was considered to be constant, and equal to 80 dB (Urick, 1983), verified as accurate in this region. (Validating this value for the specific conditions of the upwelling regime is expected to be discussed in the future.) Acceptable levels of P_D are to be chosen according to the operational needs of the detection system, but it is clear that values close to zero imply that the source can not be detected at all. Therefore, the final result of TL calculations was a series of "disks" of P_D, one per hydrophone depth. Calculations were organized in two groups: an "optimistic" environment without upwelling, in which sound speed is constant (and set to 1500 m/s) and only energy reflections on the complex bathymetry are responsible for a given distribution of P_D; and a realistic environment, in which the upwelling volume is interpolated along a given section and both sound refraction and boundary reflections are taken into account. Given the high variability of bathymetry and/or the variation of sound speed along each section it was decided to use the TRACEO ray tracing model (Rodríguez *et al.*, 2012; Ey and Rodríguez, 2012) for TL predictions.

The results are shown in Fig. 4 for a source depth of 5 m, a source frequency of 1.5 kHz, and a hydrophone depth of 9.5 m (to avoid overlapping of the disk with the coastline the position of the source was considered to be different from the one shown in Fig. 2); the results indicate that, as long as sound speed is constant, the complexity of the bathymetry is not an obstacle to prevent the detection of the source at any place inside the disk. Yet, when upwelling is considered, the situation drastically changes due to the appearance of "shadow" zones near the edges of the disk and near the coastal areas; the values of P_D are so low in such zones, that any detection system placed there would be completely "blind" to the presence of the source at the center of the disk.

7. Conclusions and future work

The discussion presented in this work shows, for the specific conditions of the upwelling regime off the Cabo Frio region in Brazil, that ocean modeling linked to the FORMS technique can be able to produce reliable predictions of sound speed fields in complex shallow water environments. The reliability of the ocean forecasts was clearly shown in Fig. 2, which compared vertical sections of sound speed from OAEX2010 data, with the corresponding oceanographic forecasting, based on the FORMS technique, also demonstrated in the work of Codato *et al.* (2012). The comparison shows that the oceanographic forecast was able to predict the vertical structure of sound speed in the area of coastal upwelling, accordingly to the one deduced from *in situ* observations. Such comparison demonstrates the accuracy of the results of the hydrodynamic forecasting system, which was perfectly able to provide predictions with a high spatial and temporal resolution. Therefore, it also reveals the potential to provide realistic estimates of the hydro-acoustic state of the ocean via hydrodynamic numerical modeling, which can be used in planning operations at sea. By feeding an acoustic

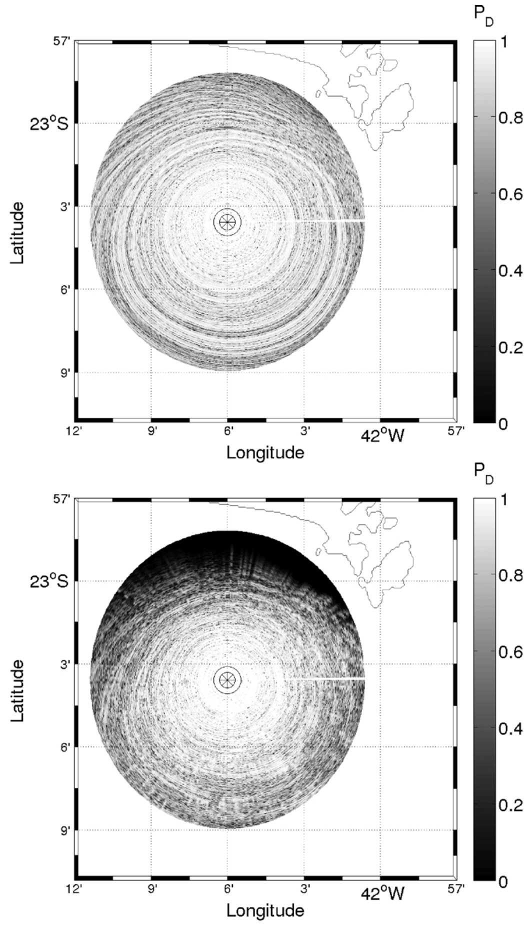

Fig. 4. Detection probability disks for a receiver at 9.5 m depth without upwelling (isovelocity case, top), and accounting for upwelling (bottom).

model with the ocean forecasts it was also shown that the upwelling regime (and not the bathymetry) is responsible for the creation of "shadow" zones near coastal areas, with nearly zero detection probability, where a detection system would be ineffective to detect the presence of an acoustic source. The results are extremely encouraging for the development of future oceanographic and acoustic campaigns, for further analysis of available acoustic data and for the development of additional forecasts, to be used for prediction systems as input data for available acoustic models, a task that requires also full (i.e., $3D$ and not $N \times 2D$) modeling of acoustic propagation. The role of refraction (i.e., propagation with and without upwelling) and the depth dependence of detection probability will also be addressed in the future.

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