Acoustic prediction using a feature-oriented regional modeling system and acoustic inversion

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Abstract

Acoustic predictions usually suffer from uncertainties in ocean forecasts, due to the extreme sensitivity of acoustic propagation to the ocean environment. In this regard, the acoustic prediction systems require the best possible specification of initial conditions, demanding high accuracy and synopticity on the ocean circulation modeling. The current work assesses the feasibility of combining a Feature-Oriented Regional Modeling System (FORMS) with acoustic inversion outcomes, for acoustic prediction in the Cabo Frio (Brazil) coastal area. First, the oceanographic prediction model is tested for acoustic applications. Two numerical acoustic simulations were performed, with an acoustic model having as input two different initial fields: i) in situ hydrographic data from the OAEx10 sea trial, and ii) the oceanographic modeling system outputs. The simulations were compared in terms of transmission loss (TL), detection probability and acoustic channel impulse response. The

TL differences exhibit standard deviations ranging between 2.29 and 4.32 dB, demonstrating the feature-oriented regional model skill for sonar applications. The quality of the results degrades with distance, as observed in correlations between the impulse responses. This can be explained by an accumulation of forecast error effects during propagation. Another interesting result is that the coastal upwelling may prevent the detection of submarine targets. The second stage of this work concerned acoustic data-model comparison, for OAEx10. Experimental impulse responses correlated fairly well with modeled ones corresponding to the forecasts, with values between 0.72 and 0.89. In an attempt to increase these values, the acoustic data was inverted, for the basement compressional speed, whose estimates led to increased impulse response correlations of as high as 0.96. In summary, the prediction of the acoustic field can be well accomplished by combining a FORMS technique with an acoustic inversion scheme.

Keywords: Acoustic prediction, feature model, acoustic inversion, coastal upwelling, model validation

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1. Introduction and background

Acoustic propagation is extremely sensitive to the physical oceanographic environment, through the sound speed field. The latter is set as a function of density in sea water, which forces the temperature and salinity distribution, stratification and dynamics, to play a key role on the propagation of acoustic energy. Furthermore, multiple interactions of sound waves with the seabed lead to peculiar propagation effects, especially in shallow waters (Kuperman and Lynch, 2004). A significant research effort has been triggered in this respect, recognizing ocean-acoustics as an interdisciplinary science. In particular, there is a special interest in understanding the impact of environmental variability on acoustic predictions and sonar performance. This question has been adressed in past work (Robinson et al., 2002; Abbot and Dyer, 2002; Robinson and Lermusiaux, 2004; Lam et al., 2009). Acoustic prediction uncertainties have been quantified, with the results explained through dynamical sensitivities (Lermusiaux et al., 2002, 2010). In summary, the above studies emphasized that the error of the predicted acoustics is highly dependent on the ocean forecast error and the accuracy of bathymetric/geoacoustic properties. For this reason, methods and systems built to forecast the acoustic field, must be sustained by increasingly sophisticated oceanographic modeling systems, and reliable bottom data.

This work aims to evaluate the feasibility of combining a Feature-Oriented Regional Modeling System (FORMS) with acoustic inversion outcomes, for acoustic prediction in the Cabo Frio – Brazil (23°S) coastal area. The FORMS consists of a technique which is based on the construction of realistic oceanic structures, using a 'feature model' approach (Gangopadhyay and Robinson, 2002). Feature models are simple mathematical representations of the ocean features (e.g. currents, fronts, eddies), which are parameterized in terms of their synoptic characteristis: temperature *(T)*, salinity *(S)*, and velocity components *(u,v)*. The philosophy of this approach is to develop a first-order system for a very complex nonlinear system such as a regional ocean, where most processes strongly interact and where processes cannot be studied separately. Once the first-order structures are placed within a numerical models dynamical framework, the nonlinearity stimulates further interaction among features and should create realistic four-dimensional complex fields (Calado et al., 2008). In this regards, the feature modeling technique is widely used to supply nowcasting and forecasting systems with realistic ocean data (Robinson et al., 1988; Spall and Robinson, 1990; Cummings et al., 1997; Gangopadhyay et al., 1997; Shaji and Gangopadhyay, 2007; Calado et al., 2008, 2010; Gangopadhyay et al., 2011).

In the past, feature models were also pointed out as a feasible means of interfacing ocean dynamical models to underwater-acoustic propagation models (Robinson and Lee, 1997). It was shown that the feature models can reproduce the main acoustic properties of the ocean environment (Small et al., 1997). In the current study, an ocean forecasting model was initialized by a parametric feature model for the Cabo Frio coastal upwelling system. The guidelines of the present approach are to represent the dynamics of the Cabo Frio coastal region in a realistic fashion. In that region, the upwelling is of utmost importance, both in oceanographic and acoustic terms, due to the induction of strong horizontal temperature gradients. The latter cause a strong impact on the acoustic pressure field, as shown in previous works (Carriére et al., 2009; Codato et al., in press.). In the present work, the effect of upwelling on the prediction of transmission loss (TL), detection probability (DP) and the acoustic channel impulse response was investigated, the former two being fundamental for tactical purposes. The channel impulse response, though not commonly considered in the majority of acoustic prediction studies, is a standard tool in signal processing and acoustic inversion approaches, hence considered here.

The first stage of the present work quantifies the skill of the feature-oriented ocean forecast system for acoustical applications. Two numerical acoustic simulations were performed, with a propagation model having as input: (i) the *in situ* oceanographic data from the Ocean Acoustic Exploration 2010 (OAEx10) sea trial, and (ii) the oceanographic modeling system output. In the second stage, the acoustic predictions are compared with acoustic data acquired on the OAEx10 experiment, in order to quantify the forecast uncertainty. In predicting the acoustic field, an acoustic inversion technique is used to provide accurate ocean bottom information for the purpose. In general, inversion techniques are employed in acoustical oceanography, to infer parameters which characterize the environment. In the context of acoustic prediction, the inversion techniques are valuable in providing environmental information, in at least two possible situations: i) the knowledge of geologic/geometric properties is incomplete/uncertain; ii) the environmental information is accurate, with the exception of some properties which are important to define the acoustic field, and whose erroneous values are used to predict that field (e.g. bathymetry, sedimentary layers, compressional sound speeds, etc.). In the past, it was already observed, through data/model comparisons, that acoustic inversion methods can play an important role in minimizing the variance of sonar performance prediction (Martins et al., 2008; Martins and Jesus, 2009). In the current study, the acoustic data was inverted for the basement compressional speed, in an attempt to 'fine tune' the geoacoustic parameters on the subjacent acoustic prediction system.

This article is organized as follows: Section 2 describes the OAEx10 experiment and the oceanographic-acoustical prediction system; Section 3 presents numerical simulation results and data/model comparisons; Section

4 concludes the paper.

2. In situ dataset and coupled oceanographic-acoustical prediction system

2.1. The OAEx10 experiment

The OAEx10 sea trial occurred along the coast of Cabo Frio (southeastern Brazil), during the period of November 19–21, 2010. It was a multi-institutional and multi-disciplinary exercise, involving oceanographical and acoustical surveys aboard of two Brazilian Navy's vessels (R/V *'Aspirante Moura'* and *'Embarcação de Desembarque de Carga Geral–EDCG Guarapari'*). The region around Cabo Frio provides a unique environment, where the coast orientation changes and continental shelf break topography reinforces the interaction between the oceanic and coastal systems (Calado et al., 2006). The region can have different wind and waves regimes, depending upon the presence of meteorological frontal systems and of mesoscale oceanographic features (e.g. upwelling, eddies, meanders, etc.). In summary, the physical setting makes this area a very interesting site for ocean-acoustic research, where diverse sound-speed profiles can be found.

The oceanographical cruise was designed to obtain a synoptic horizontal grid covering the coastal upwelling feature around Cabo Frio. A complete CTD (conductivity, temperature and depth) sampling was performed along the experiment, yielding vertical profiles of temperature and salinity (Fig. 1). The combination of such profiles on a T-S diagram (see Fig. 1 – right panel) allowed to confirm the occurrence of an upwelling phenomenon during the surveys. It was found that the thermohaline index from CTD casts corresponded to the South Atlantic Central Water (SACW) water mass index, as proposed in Miranda (1985). The SACW is a water mass characterized by temperatures lower than 18 °C and salinity of 34.6–36, which rises at the surface in the vicinity of Cabo Frio, and can be a proxy to track an upwelling near the coast (Calado et al., 2010). In particular, a temporal evolution of an upwelling process was observed for three days, during the trial period. This was recorded by the displacement of the upwelling front toward the ocean and the cooling of surface waters at stations closer to the coast, which can be observed on the interpolated sea surface temperature (SST) maps generated from CTD data, shown in Fig. 2.

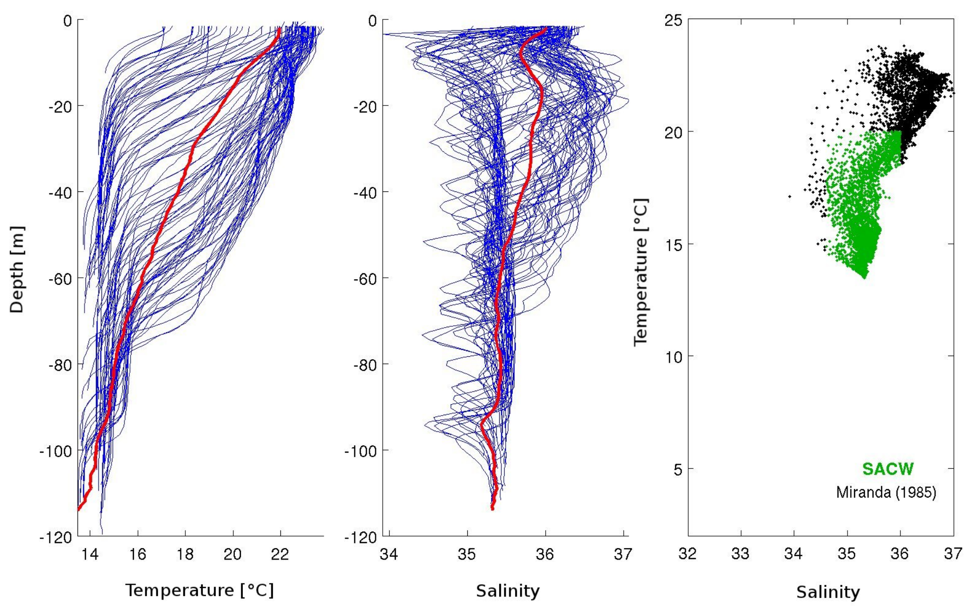

Figure 1: CTD profiles collected during OAEx10 sea trial. (Left) Temperature vs. depth. (Center) Salinity vs. depth. (Right) T-S diagram, where the green points correspond to the SACW water mass, which is an upwelling indicator.

Processed CTD data were interpolated using a multiscale Objective Analysis (OA) scheme, with horizontal resolution of 1 km and 30 vertical levels. The correlation length was 5 km for synoptic-scale, and 50 km for climatogical-scale, according to the methodology presented in Calado et al. (2008). For the first stage of this paper, the objectively analyzed T-S fields allowed to derive sound-speed sections, to use as environmental parameters for acoustic model initialization. From now on, this dataset is referred as the OAEx10 ocean-data.

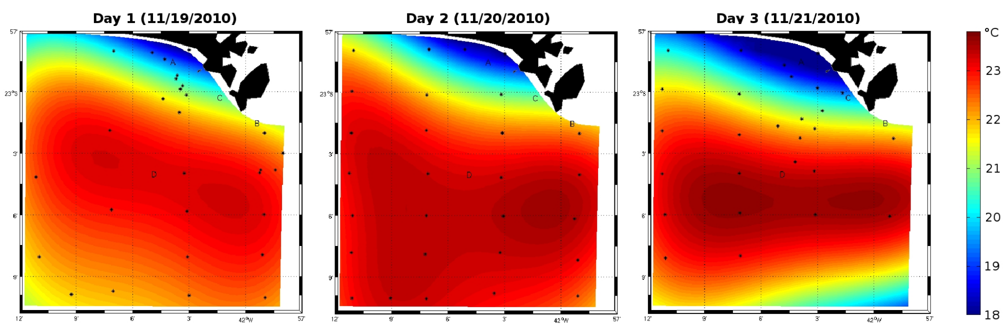

Figure 2: SST snapshots based on the interpolated OAEx10 ocean-data, showing the coastal upwelling registered on November 19th, 20th and 21th, respectively. The black points represent the CTD sampling stations.

The acoustic propagation experiments were conducted by a sound source emitting sequences of continuous waves (CW) signals and linearly frequency modulated (LFM) signals. Focus is given to the data acquired on November 19, 2010, during the active acoustic measurements on the upwelling front. The R/V *Aspirante Moura* was the transmitting ship, and deployed the sound source at 10 m depth. The EDCG *Guarapari* contained a receivers in a vertical array of 8 hydrophones 3 m equally spaced from 10 m to 31 m depth. The distance between source and hydrophone array was 1395 m. The

OAEx10 acoustic-data is composed by a sequence of ten LFM signals from 500Hz to 1kHz (lower frequencies), a sequence of LFM signals from 1 to 2kHz (higher frequencies) and a CW multi-tone from 500Hz to 2kHz with nine intermediate frequencies.

2.2. Oceanographic modeling system

The oceanographic modeling system was based on the achievements of methodology presented in Calado et al. (2008), which was derived from the FORMS initialization technique developed by Gangopadhyay and Robinson (2002). This latter study have generalized feature modeling approach for strategic application to any oceanic region. The generalization can be summarized as a three-step procedure: i) a regional synoptic feature-oriented circulation template is developed via a synthesis of past observational studies in the region; ii) individual feature models for each of the features are developed from synoptic observational studies; iii) the feature model profiles on the template locations are interpolated with appropriate background climatology to obtain a three-dimensional synoptic grid ready for the numerical model applications. The present work had applied a variation of this technique for the coastal upwelling associated with the SACW water mass in the vicinity of Cabo Frio coast. The FORMS methodology employed here will be described below.

2.2.1. The Feature-Oriented Regional Model

The feature-oriented regional model consisted of the combination of a coastal upwelling parametric feature model with a background climatological thermohaline structure from the World Ocean Atlas – WOA'05 (Locarnini et al., 2006). The synoptic water mass *(T-S)* structures used for the upwelling parametrization were characterized from the 'Dinâmica do Ecossistema da Plataforma da Região Oeste do Atlântico Sul – DEPROAS' dataset, which was described in more detail in a previous work (Calado et al., 2008).

A schematic representation of the proposed feature model is shown in Fig. 3. It is derived from the continental shelf-slope front feature model developed by Gangopadhyay and Robinson (2002), and updated by Shaji and Gangopadhyay (2007) and Calado et al. (2008), respectively. The upwelling frontal temperature distribution $T(\eta, z)$ is parameterized as:

$$T(\eta, z) = T_o(z) + [T_i(z) - T_o(z)]m(\eta, z), \tag{1}$$

where

$$m(\eta, z) = 0.5 + 0.5 \tanh\left[\frac{\eta - \Theta z}{\chi}\right] \tag{2}$$

is a meld function, η is the cross-frontal distance from the axis of the front, and z is positive vertically upward. $T_i(z)$ is the inshore temperature profile, and $T_o(z)$ is the offshore temperature profile. Θ is the slope of the front, and χ is the e-folding half-width of the front $(= r/2)$.

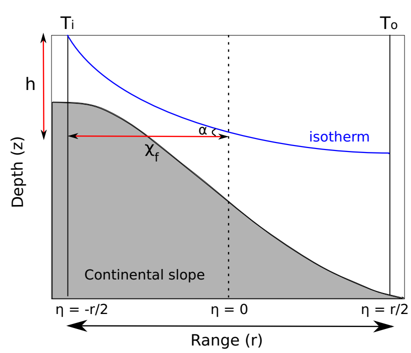

Figure 3: A schematic representation of the feature model structure and its parameters.

Using multiscale objective analysis, this theoretical structure for the coastal upwelling was melded with the climatological temperature, resulting in a three-dimensional thermal field (Fig. 4). However, this field wasn't an accurate representation of the real thermal field during OAEx10 experiment. In order to solve this, we considered that the climatological thermal field correctly describes the vertical variability. Therefore, it is possible to obtain the desired thermal field with a best vertical position of the SACW location (i.e. the one representing the experiment days), by using the vertical information from climatology in tandem with surface information from remote sensing. This basically means that the temperature is considered the following function as:

$$T(x, y, z) = [T_s(x, y) - T_b(x, y)]\phi(x, y, z) + T_b(x, y), \tag{3}$$

where the subindices s and b refer to surface and bottoms values, and ϕ are the non-dimensional vertical profiles, which can be obtainable by solving the equation for ϕ using the climatological values. Obtaining ϕ is the process of adimensionalization. This process was applied to build non-dimensional profiles which hold the shapes of the typical coastal upwelling temperature profiles, being able to be rescaled accordingly near-real-time synoptic data.

In the case of this work, the thermal field was redimensionalized using satellite SST data as T_s, and the bottom data from the previous thermal field as T_b. The input SST used was for November 18th of 2010, obtained from the GHRSST–Group of High Resolution Sea Surface Temperature. Since there were no previous salinity *in situ* data, it was used as the final three-dimensional haline field the meld between climatology and feature model for coastal upwelling, obtained in an analogous form as the temperature.

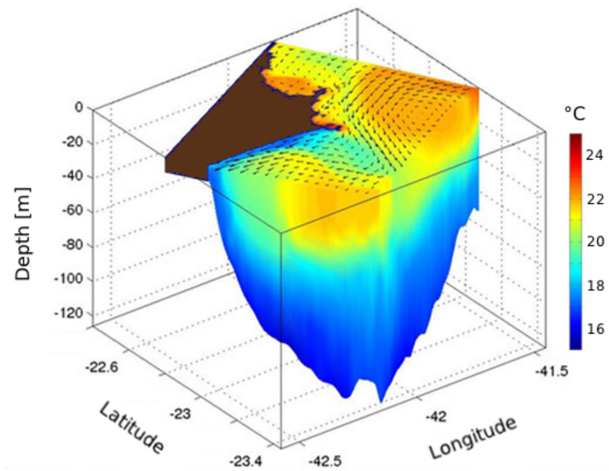

Figure 4: Three-dimensional thermal field after the interpolation between the climatology and the coastal upwelling feature model.

The FORMS final product was a 3-D thermohaline field that accurately assimilated the SST conditions for the period of 1 day before the OAEx10 experiment (November 18th). This 3-D thermohaline field was employed to initialize a numerical ocean model, in order to forecast the circulation dynamics for the next three days, corresponding to the OAEx10 experiment time (November 19th, 20th and 21th).

2.2.2. The Numerical Ocean Model

ROMS – Regional Ocean Modeling System (Shchepetkin and McWillians, 2005) was the numerical model chosen to provide the ocean forecasts. ROMS is a free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal. This model solves the Reynolds averaged form of the Navier Stokes equations and can be configured in several different ways.

In this work, it was used a grid with horizontal resolution of ≈ 800 m and 25 vertical sigma layers. The bathymetry was extracted from digital nautical charts for the region, interpolated to 1 minute of degree resolution. An open boundary condition was applied on the experiment, with the climatology from Boyer et al. (2005) continuously nudging the domain.

Both wind stress and tides were used to force the model. The wind stress was derived from the level 2 along-track Advanced Scatterometer–ASCAT (O&SI SAF Project, 2011) dataset, and was calculated using bulk formula (Large and Yeager, 2004). The tidal forcings were obtained from the global model of ocean tides TPXO v7.2 (Egbert and Erofeeva, 2002).

The numerical model had as initial condition the 3-D mass field resulted from FORMS, and therefore was started for November 18th of 2010, as previously said. A prognostic run was performed to predict the fluid state into the future time, and the outputs of this simulation were used as environmental inputs to an acoustic propagation model, which is described in the next section. Specifically, these envinronmental inputs were based on a study case for November, 19th, using a 24-hour ocean forecast.

2.3. Oceanographic-model-driven acoustic propagation modeling

The acoustic simulations were performed using the BELLHOP propagation model (Porter and Bucker, 1987). BELLHOP is a model for predicting acoustic pressure fields, based on the Gaussian beam tracing method. This model is particularly interesting for range-dependent problems where normal mode, Fast Field Program, or parabolic models are not practical alternatives, due to computational costs.

The feature-oriented ocean forecasts provide the necessary range-dependent water column component of the environmental model to initialize the BELLHOP propagation model. To accomplish this, the predicted T-S fields from the oceanographic modeling system outputs were transformed into sound-speed, using the UNESCO 1983 polynomial (Fofonoff and Millard, 1983). Afterwards, the sound speed was interpolated into the transect containing the acoustic source and hydrophone array, with a suitable grid for acoustic modeling. The acoustic source was located at 10 m depth, emitting sound signals in the frequency of 1500 Hz. The bathymetry used here was the same as for the oceanographic model. The considered boundaries consisted of a free-surface, and an acousto-elastic bottom halfspace.

2.4. Acoustic inversion

As previously said, this work uses an inversion technique to fine tune the geoacoustic model — namely, through the basement compressional speed — for the acoustic prediction system. The inversion strategy resorts to matched-field processing, consisting of the correlation of acoustic field measures at an hydrophone array, with a number of fields, each one corresponding to a candidate value of the compressional speed. The processor assumes the structure of a broadband frequency-incoherent Bartlett processor:

$$P(\theta) = \frac{1}{K}\sum_{k=1}^{K}\mathbf{w}^H(f_k,\theta)\mathbf{R}_{XX}(f_k)\mathbf{w}(f_k,\theta), \tag{4}$$

where $\mathbf{w}(f_k,\theta)$, function of the frequency f_k and the candidate compressional speed θ, is a vector of complex acoustic pressures at the hydrophone array, and $\mathbf{R}_{XX}(f_k,\theta_0)$ is an estimate of the hydrophone correlation matrix at frequency f_k (Martins et al., 2008). An exhaustive search on the solution space of the basement compressional speed is carried out, in order to find the value that maximizes $P(\theta)$.

3. Results and discussion

Numerical simulation results are presented in this section, where the forecasted oceanographic field is compared to the ocean truth field observed on the OAEx10 experiment. The aim is to evaluate the skill of feature-oriented modeling approach for sonar applications. Additionally, the effects of coastal upwelling on the propagation of acoustic energy is also assessed here.

After validation of the ocean forecasts, a new comparison is made between the predicted acoustic field and the OAEx10 *in situ* acoustic-data. The correlations obtained in such comparison are described in the present section. At the end, the predicted acoustic field is analyzed before and after the use of acoustic inversion, in order to evaluate the gains achieved by this technique.

3.1. Feature-oriented modeling skill for acoustic prediction

As said in the Sec. 2.2, the initial mass field for ROMS experiments was built upon a regional climatology background melded with the coastal upwelling feature model, consisting in a FORMS initialization scheme. For this reason, the outputs of the ROMS simulations are referred as feature-oriented ocean forecasts. The current section contains the results of two acoustic simulations with BELLHOP, fed with the two different physical fields: (i) the OAEx10 ocean-data and (ii) the feature-oriented ocean forecasts. Four 10-km long transects were defined with basis on the OAEx10 ocean-data SST map shown in Fig. 5, in order to observe the influence of different physical patterns on sound propagation characteristics relevant for sonar applications.

The ROMS outputs were interpolated for the same transects, and sound-speed sections were derived from the ocean-data and the feature-oriented ocean forecasts, respectively (see Fig. 6). Such sections were computed to serve as the initial fields to BELLHOP propagation model. The sections contrast in the range-dependence of bathymetry and sound-speed: section 1 is almost range-independent; sections 2 and 3 are slightly range-dependent; and section 4 is strongly upslope and crosses the upwelling front.

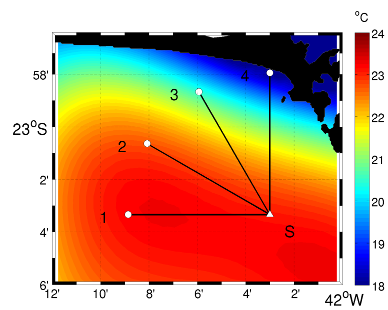

Figure 5: OAEx10 ocean-data SST map. The transects 1, 2, 3, and 4 represent the sound-speed sections employed in BELLHOP simulations. The triangle symbol denotes the source (S) position, and circle the receivers.

The difference between the transmission loss (TL) computed with BELLHOP, using the two different sound-speed fields, is plotted in Fig. 7, for each section. The acoustic field is best modeled for the first 5-km range (area in orange), and the error acumulates with distance. The TL differences exhibit standard deviations ranging between 2.29 and 4.32 dB, acceptable for some sonar applications (Robinson et al., 2002). In particular, in section 4, no error exists at ranges greater than 7.5 km, due to vanishing acoustic signals predicted with both the *in situ* data and the skilled ocean forecasts. This pattern is the result of the interaction between the acoustic signals and the strong

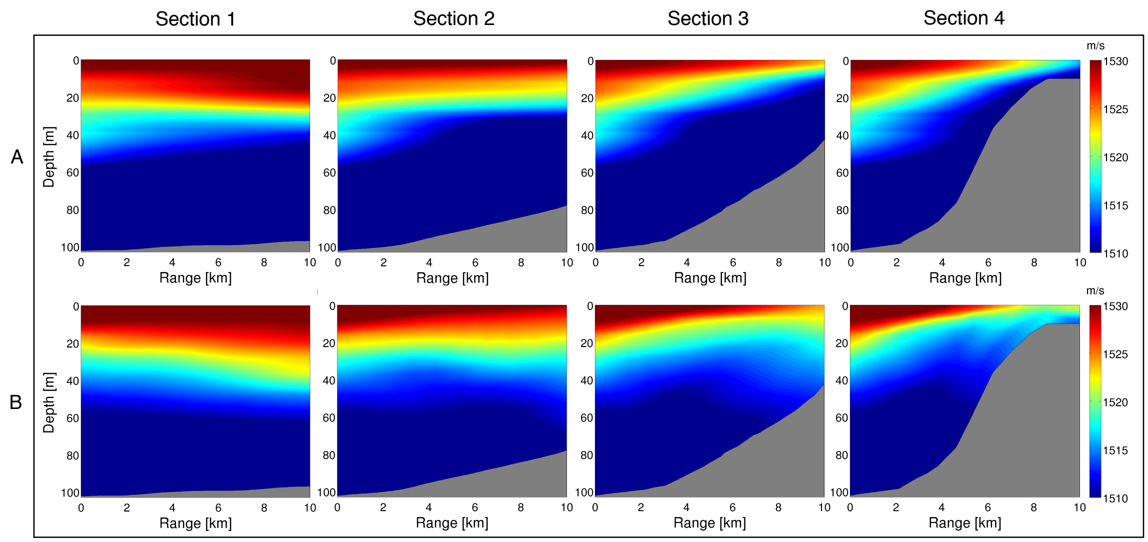

Figure 6: Sound speed sections for the transects in Fig. 5, derived from (A) OAEx10 ocean-data, and (B) feature-oriented ocean forecasts.

temperature gradient in the upwelling front. Apart from refraction mechanisms, the energy conservation law implies that a decrease in sound speed, along a ray trajectory, will cause the ray's amplitude to decrease (Jensen et al., 1994). As compared to the other sections, the upslope bathymetry is also a determining factor in reducing the range of the acoustic signals, by inducing much significant bottom interaction and consequent signal loss (Lermusiaux et al., 2010).

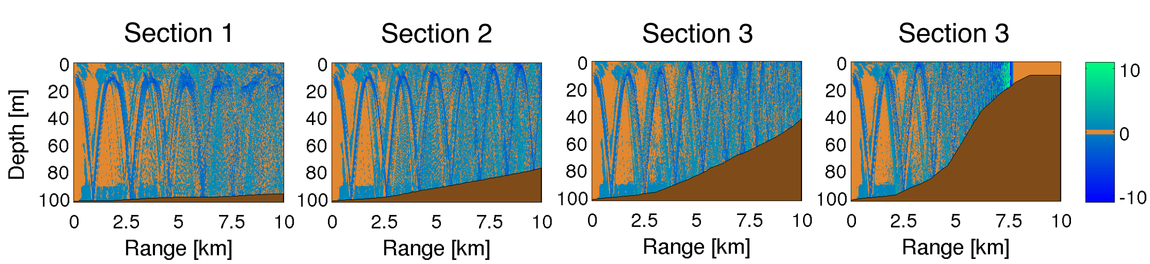

Figure 7: TL errors [dB] for the sections in Fig. 6.

In order to evaluate the relevance of the TL errors for an operational application, the TL predictions are used to calculate the detection probability (DP). To do so, a hypothetical scenario with a passive sonar was considered, using the simulated TL field and typical values for environmental noise and figure of merit (Urick, 1983), to solve the signal excess equation, as proposed in Ferla and Porter (1991). The BELLHOP calculated the DP ranging between 0 (no detection capability) and 1 (certain detection). The DP for each section, computed from both the OAEx10 ocean-data and the ocean forecasts, is shown in Fig. 8. An interesting result is that, though the subtle differences in the TL fields, the main features of the detection probability were successfully predicted for all sections. It is evident that the simulations using the ocean forecasts had produced a satisfactory spatial distribution of the DP zones, notably matching the simulations initialized by the *in situ* data.

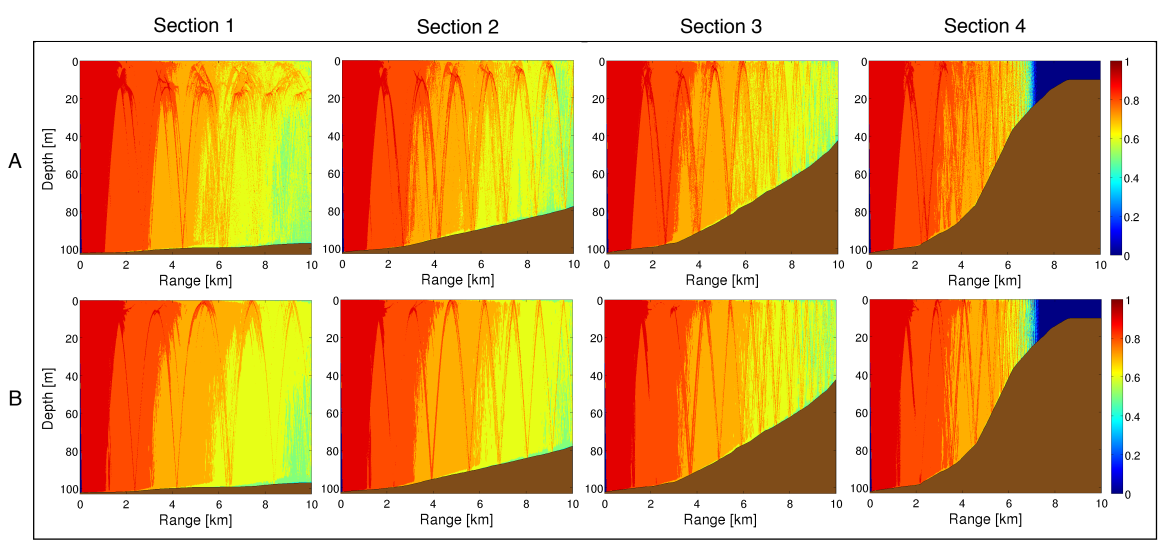

Figure 8: Detection probabilities for the sections in Fig. 6. BELLHOP initialized by (A) OAEx10 ocean-data, and (B) feature-oriented ocean forecasts.

Additionaly, it is noted that the coastal upwelling phenomenon imposes severe changes on the detection pattern (Fig. 8 - Section 4). It is clear that the DP becomes close to zero when the acoustic energy crosses the upwelling front (after 7.5-km range), representing the inability of detecting the hypothetical underwater target. This inability is probably a combination of the thermal front effects with the strong upslope bathymetry. The thermal front changes the propagation trajectories, turning the acoustic ray's directions closer to the horizontal, as shown in Fig. 9. This fact implies in a decrease of the vertical insonification of the water column. Thus, if the hydrophones are deployed at randomly chosen depths, the probability of receiving the acoustic signal should be lower. This explains how the coastal upwelling acts to reduce the DP, and how important is the synoptic monitoring of such feature for guiding tactical/operational decisions.

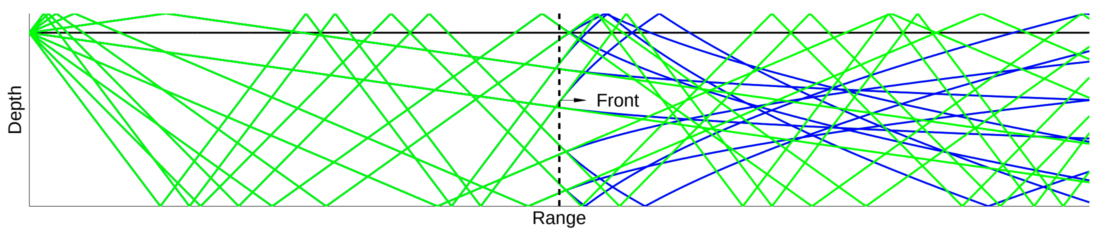

Figure 9: Acoustic ray paths through: i) an homogeneous water column (green line), and ii) an hypothetical upwelling front (blue line).

Considering the correlations between impulse responses (IR), it is revealed that the ocean forecasts lead to acoustic fields whose accuracy degrades with distance, as shown in Fig. 10. This can be explained by an accumulation of propagation erros induced by ocean forecast erros, as the energy travels. In zoom, Fig. 11 shows the IR envelopes corresponding to the highest (0.98) and the lowest (0.34) cross-correlation peaks. Interestingly, even in the lowest correlation case, the ray arrival times are very similar for the OAEx10 ocean-data and the ocean forecasted fields, indicating that the error in the IR prediction is defined mainly by a ray amplitude error.

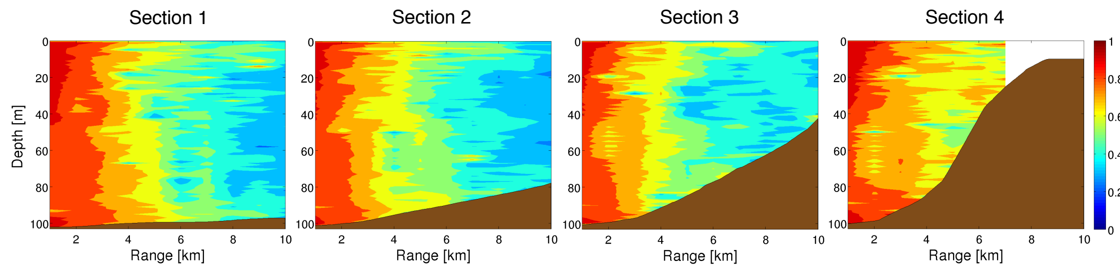

Figure 10: Correlations between IR envelopes modeled with BELLHOP, having as input either the OAEx10 ocean-data or the ocean forecasts.

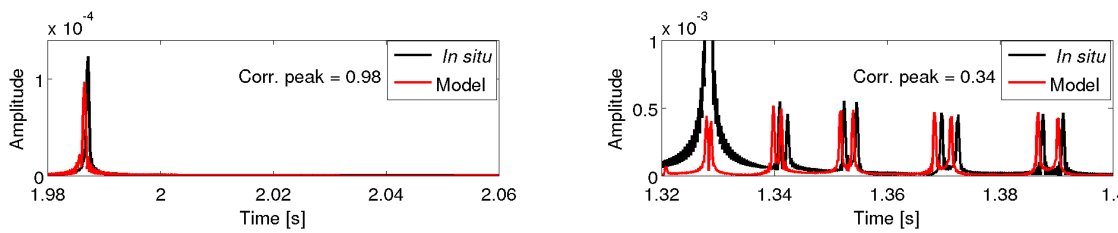

Figure 11: Impulse responses computed from the OAEx10 ocean-data (*in situ* – black line), and the ocean forecasts (model – red line), which show the highest and lowest correlation peaks (left and right panels, respectively).

3.2. Acoustic prediction in the OAEx10 experiment

Having at hand a reliable ocean forecasting system as the one initialized by FORMS, the next important step is to gather environmental information regarding geological/geometric properties, and then to use all the above information as environmental inputs for an acoustic propagation model of choice. As a preliminary study, attention was given only to the geological properties. In this regard, it is a common practice to use data from geological archives, nautical charts or historical databases, as inputs to the acoustic propagation model. Nevertheless, such data can lack accuracy, due to the sparsity of bottom measurements, or to the sometimes merely indicative character of these data (Martins et al., 2008). Here, acoustic inversion can play an important role on determining optimal values for the geological (geoacoustic) parameters to use when modeling acoustic propagation. The complete coupled prediction system proposed in the present work is depicted in Fig. 12.

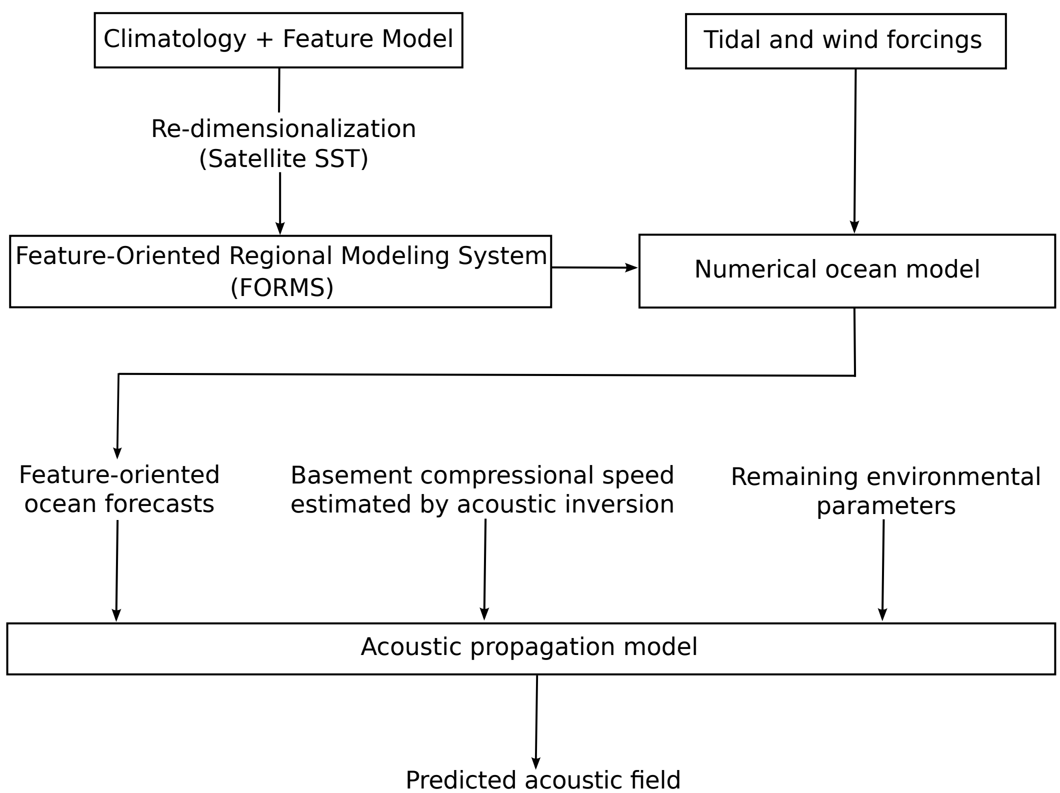

Figure 12: Complete coupled oceanographic-acoustic prediction system.

In summary, the components of the environmental model to serve as input for the acoustic propagation model, come from three different sources. The water column component is the output of the oceanographic forecast system; the geometric and majority of the geological properties are given by GPS and depth sensory, nautical charts, geological cores, etc.; the basement compressional speed is determined by acoustic inversion, by processing acoustic measures on the oceanic area in which to predict the acoustic field.

In order to quantify the effectiveness of acoustic inversion in determining optimal values for the environmental model, two experiments with BELLHOP were carried out using different geoacoustic parametrizations: one from a geological database, and the other from the inversion outcomes. These predictions were compared with acoustic data from the OAEx10 sea trial, in terms of correlations between IR envelopes. In Fig. 13 are plotted the inversion results in contrast to the baseline values, from geological cores. The spatial distribution of the inversion results agree fairly well with the core values.

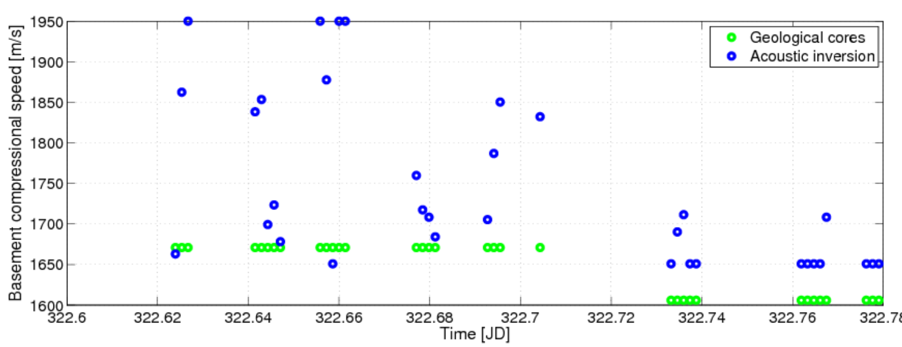

Figure 13: Inversion results for the basement compressional speed (in blue), using 9 tones in the band [500, 2000] Hz. The transmissions covered two different areas, as seen by the two different values given by geological cores (in green).

The compressional speed values obtained from acoustic inversion were used to compute impulse responses for each hydrophone channel, at the same time samples for which the inversion was performed. These impulse responses were correlated with the impulse response estimates computed from the experimental data, with the correlation peaks shown in Fig. 14, right panel. The results show that the basement compressional speed estimates led to increased IR correlation peaks in general (as high as 0.96), as compared to the corresponding values, before the inversion (between 0.72 and 0.86 —see Fig. 14, left panel). It can be seen that the improvements on the acoustic prediction were satisfactory, even when only the compressional speed was inverted for, in other words, tuned for the prediction of the acoustic field.

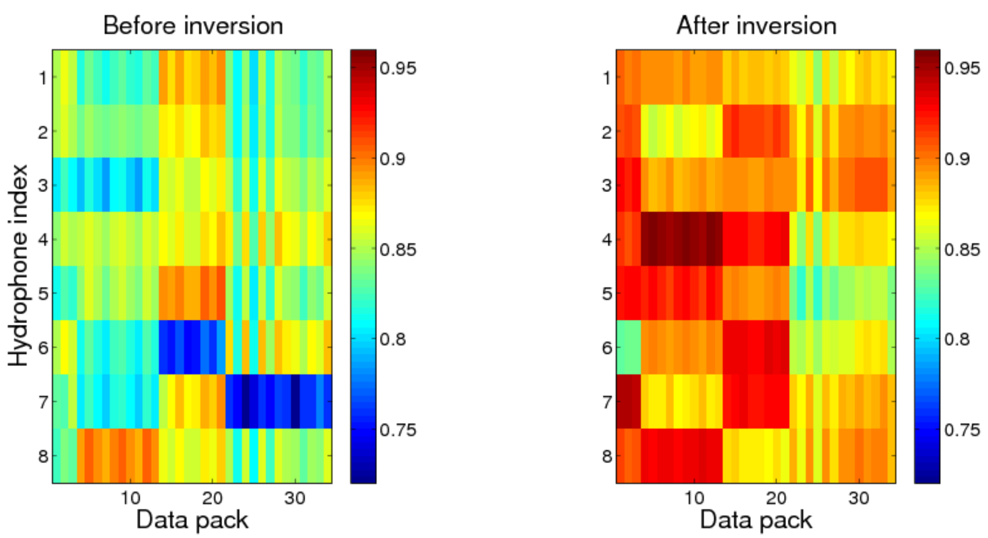

Figure 14: Correlations between predicted and experimental IR envelopes, before (left panel) and after (right panel) the acoustic inversion.

4. Conclusions

A coupled ocean-acoustic prediction approach was presented, for the coastal area of Cabo Frio - Brazil, in the context of the OAEx10 sea trial. This approach combines two robust characteristics, regarding the oceanography and the acoustics. First, a feature-oriented regional modeling system was used in the initialization of the circulation model at hand. Second, the environmental parametrization of an acoustic propagation model was defined according to both ocean model outcomes and acoustic inversion outcomes.

The feature-oriented ocean forecasts provided a realistic representation of the ocean variability. The inclusion of the upwelling feature in the ROMS initial conditions led to an estimated oceanographic field which matches well with the observed *in situ* structure. Simple climatological fields would not include this feature, which would imply a less accurate forecast of the acoustic field, by not representing the impact of the upwelling on the strong refraction of acoustic energy. We also found that the inversion technique allowed to calibrate the environmental model parameters of the acoustic propagation model, by acting as a correlator between observed and modeled acoustic fields, whose optimal point gives the parameter values that best model the observed fields. These parameter values allowed to improve the quality of modeled impulse responses, as compared to counterparts computed from historical geological data. In summary, the prediction of the acoustic field can be well accomplished by combining a feature-oriented ocean modeling approach with an acoustic inversion scheme, with important scientific/operational consequences.

In the present feasibility study, the environmental outcomes from acoustic inversion were used to make synchronous acoustic predictions. Future work will use the acoustic inversion outcomes at present times, to predict the acoustic field at future times. Moreover, work should be done in order to use the acoustic inversion outcomes to be inserted into the ocean dynamic modeling system, in a way to minimize the overall acoustic errors.

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References

Abbot, P., Dyer, I., 2002. Sonar performance predictions based on environmental variability. In: Acoustic Variability. Kluwer Academic Press, pp. 611–618.

Boyer, T., Levitus, S., Garcia, H., Locarnini, R. A., Stephens, C., Antonov, J., Jun 2005. Objective analyses of annual, seasonal, and monthly temperature and salinity for the world ocean on a 0.25 degrees grid. Int. J. Climatol. 25 (7), 931–945.

Calado, L., Gangopadhyay, A., Silveira, I. C. A., 2006. A parametric model for the Brazil Current meanders and eddies off Southeastern Brasil. Geophys. Res. Lett. 33, LI2602.

Calado, L., Gangopadhyay, A., Silveira, I. C. A., 2008. Feature-oriented regional modeling and simulations (FORMS) for the western South Atlantic: Southeastern Brazil region. Ocean Modell. 25 (1-2), 48–64.

Calado, L., Silveira, I. C. A., Gangopadhyay, A., Castro, B. M., 2010. Eddy-induced upwelling off Cape São Tomé (22°S, Brazil). Cont. Shelf Res. 30, 1181–1188.

Carriére, O., Hermand, J.-P., Calado, L., De Paula, A., Silveira, I. C. A., October 2009. Feature-oriented acoustic tomography: Upwelling at Cabo frio (Brazil). No. 09. IEEE J. Ocean. Eng.

Codato, G., Watanabe, W., Calado, L., Martins, N., Ramos, A., in press. A influência da frente térmica da ressurgência costeira de Cabo Frio na perda do sinal acústico. A Ressurgência.

Cummings, J., Szczechowski, C., Carnes, M., 1997. Global and regional ocean thermal analysis systems. Mar. Technol. Soc J. 31 (6375).

Egbert, G., Erofeeva, S., Feb 2002. Efficient inverse modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology 19, 184–203.

Ferla, C., Porter, M., July 1991. Receiver depth selection for passive sonar systems. IEEE J. Ocean. Eng. 16 (3), 267–279.

Fofonoff, P., Millard, R. C. J., 1983. Algorithms for computation of fundamental properties of seawater. UNESCO Tech. Pap. in Mar. Sci.

Gangopadhyay, A., Lermusiaux, P., Rosenfeld, L., Robinson, A., Calado, L., Kim, H., Leslie, W., Jr., P. H., 2011. The California Current System:

a multiscale overview and the development of a feature-oriented regional modeling system (FORMS). J. Atmos. Ocean. Tech. 14 (6).

Gangopadhyay, A., Robinson, A., 2002. Feature-oriented regional modeling of oceanic fronts. Dyn. Atmos. Oceans 36 (1-3), 201–232.

Gangopadhyay, A., Robinson, A., Arango, H., 1997. Circulation and dynamics of the western North Atlantic. i: Multiscale feature models. J. Atmos. Ocean. Tech. 14 (6), 1314–1332.

Jensen, F., Kuperman, W., Porter, M., Schmidt, H., 1994. Computational Ocean Acoustics, 1st Edition. Modern Acoustics and Signal Processing. American Institute of Physics.

Kuperman, W., Lynch, J., 2004. Shallow-water acoustics. Physics Today 57, 55–61.

Lam, F., Haley, P., Janmaat, J., Lermusiaux, P., Leslie, W., Schouten, M. W., Raa, L., Rixen, M., 2009. At-sea real-time coupled four-dimensional oceanographic and acoustic forecasts during Battlespace Preparation 2007. Journal of Marine System, 306–320.

Large, W., Yeager, S., 2004. Diurnal to decadal global forcing for ocean and sea-ice models: The data sets and flux climatologies. Tech. Rep. 460.

Lermusiaux, P., Chiu, C.-S., Robinson, A., 2002. Modeling uncertainties in the prediction of the acoustic wavefield in a shelfbreak environment. In: Theoritical and Computational Acoustics, e-c-. shang, q. li, t.f. gao Edition. World Scientific Publishing Co., pp. 191–200.

Lermusiaux, P., Xu, J., Chen, S., Jan, S., Chiu, L., Yang, Y., October 2010. Coupled ocean-acoustic prediction of transmission loss in a continental shelfbreak region: predictive skill, uncertainty quantification and dynamical sensitivities. Journal of Oceanic Engineering 35 (4).

Locarnini, R. A., Mishonov, A., Antonov, J., Boyer, T., Garcia, H., Levitus, S., 2006. World Ocean Atlas 2005. NOAA Atlas NESDIS 1 (61), 182.

Martins, N., Jesus, S., 2009. Bayesian acoustic prediction assimilating oceanographic and acoustically inverted data. Journal of Marine Systems 78, S349–S358.

Martins, N., Soares, C., Jesus, S., 2008. Environmental and acoustic assement: The AOB concept. Journal of Marine Systems 69, 114–125.

Miranda, L., 1985. Forma de correlação T-S de massas de água das regies costeiras e oceânicas entre o Cabo de São Tomé - RJ e a ilha de São Sebastião - SP, Brasil. Bolm. Inst. Oceanogr. 33 (2), 105–119.

O&SI SAF Project, August 2011. ASCAT Wind Product User Manual. Version 1.10 Edition.

Porter, M., Bucker, H., 1987. Gaussian beam tracing for computing ocean acoustic fields. J.A.S.A. 82 (4), 1348–1359.

Robinson, A., Lee, D., May 1997. Oceanography and Acoustics - Prediction and Propagation Models, 1st Edition. American Institute of Physics.

Robinson, A., Lermusiaux, P., 2004. Prediction systems with data assimilation for coupled ocean science and ocean acoustics. In: Proc. of the

Sixth International Conference on Theoretical and Computational Acoustics. World Scientific Publishing Co.

Robinson, A., Spall, M., Pinardi, N., 1988. Gulf Stream simulations and the dynamics of ring and meander processes. J. Phys. Oceanogr. 18 (12), 1811–1854.

Robinson, A. R., Abbot, P., Lermusiaux, P., Dillman, L., 2002. Transfer of uncertainties through physical-acoustical-sonar end-to-end systems: a conceptual basis. In: Acoustic Variability, n.g. pace and f.b. jensen Edition. Kluwer Academic Press, pp. 603–610.

Shaji, C., Gangopadhyay, A., 2007. Synoptic modeling of the west India Coastal Current System using an upwelling feature model. Cont. Shelf Res. 24, 877–893.

Shchepetkin, A., McWillians, J., 2005. The regional ocean modeling system (ROMS): a split-explicit, free-surface, topography following coordinates ocean model. Ocean Modell. 9 (4), 347–404.

Small, J., Shackleford, L., Pavey, G., 1997. Ocean feature models - their use and effectiveness in ocean acoustic forecasting. Annales Geophysicae 15, 101–112.

Spall, M. A., Robinson, A. R., 1990. Regional primitive equation studies of the Gulf Stream meander and ring formation region. J. Phys. Oceanogr. 20 (7), 985–1016.

Urick, R., 1983. Principles of Underwater Sound, 3rd Edition. McGraw-Hill, New York.