Abstract—The continuous monitoring of coastal processes presents a great interest both from the environmental and economic viewpoints. Passive acoustic tomography can be a good candidate to provide synoptic measurements over wide areas while a range-dependent inversion scheme allows to achieve a reasonable spatial resolution along each vertical slice section. This work develops a feature-oriented parameterization scheme for acoustic tomography purposes, enabling the tracking of the main structure of a thermal front. A Kalman algorithm filters sequentially acoustic data recorded on a vertical array, in a frequency regime corresponding to a useful part of ship noise spectrum.

I. INTRODUCTION

Oceanic modeling and prediction are highly dependent on the availability of satellite remote sensing and hydrographic in situ measurements to provide reliable and accurate results. In coastal environments the data assimilation is a difficult problem due to the lack of data, the strong coupling between state variables and forcing and the frequent model failures encountered in the modeling. In order to augment standard assimilated data set, this work is focused on the development of an acoustic monitoring tool, dedicated to the tracking of special oceanic features, here a thermal front. In this paper, a feature model provides a parsimonious representation of the Ushant thermal front, west off Brittany. A Kalman filter assimilates sequentially acoustic data to estimate the evolution of the range-dependent temperature field. A previous paper presented twin test results, i.e. the tracking of time-varying feature model parameters, inverting acoustic data synthesized with feature model realizations [1]. In this work, we present inversion results of acoustic data synthesized with temperature field variations predicted with the HYbrid Coordinate Ocean Model (HYCOM, [2]), showing that it is possible to use the feature model as a parameterization scheme for the inversion of realistic environmental scenarios.

The assimilation of acoustic measurements into ocean models was suggested in the mid-1990’s (see, e.g., [3] and [4]). Henceforth several works used acoustic tomography data in an assimilation scheme (e.g., [5]–[8]). However, most of the works are based on acoustic travel-time measurements. It is well known that such a method depends on the resolution and identification of multipath arrivals, which are often not possible in shallow environments, especially for long-range propagation and certain bottom types. Therefore, full-field acoustic measurements are proposed in the assimilation scheme, as developed in [9] for the tracking of fine-scale features of a vertical slice of a shallow water environment in the Mediterranean sea. Dividing the slice into several non-overlapping rectangular regions, the range-dependent sound-speed field parameters are tracked in a Kalman scheme. However, in the present work the monitoring is focused on a specific oceanic feature (the thermal front) which presents typically large spatial variations and dynamics. Therefore the tracked environmental parameters correspond to the principal characteristics of the front. The environmental model used in this paper is referred as a feature model [10] which uses appropriate simple mathematical function to describe oceanographic processes, especially for acoustic purposes.

The paper is organized as follows: In Sec. II, we give some details about the feature model and the regional model which serves for the synthesis of the data. In Sec. III, we present and discuss simulation results of acoustic monitoring tests. We conclude the paper in Sec. IV.

II. APPROACH

A. The Ushant front

Each summer (from May to September) the Ushant thermal front develops due to a strong tidal mixing near the Brittany coast, with an important impact on the biological and fishing activities. It is characterized by the presence of homogeneous water near the coast and stratified water off the shore. The Ushant front is highly dynamic since it generates a lot of meanders and it can move with the tidal cycles from several tens of kilometers. During the summer, the surface temperature equals 18°C to 19°C for the stratified water and falls to 16°C or less for the homogeneous part.
Satellite imagery enables the localization of the front. However the frequent cloud cover in such regions do not enable the use of satellite imagery as a continuous monitoring tool.

B. Feature model

The Ushant front has been recently modeled with ROMS [11], MARS [12] or HYCOM [13]. However, our aim is to study the sensitivity of the acoustic propagation data to the front parameters. Then, a process-oriented approach is preferable to a regional model approach since it enables a parametric study and avoid coupling with other regional features that may have an effect on the acoustic data. The process model used in this paper is referred as a feature model [10] which uses appropriate simple mathematical function to describe oceanographic processes, especially for acoustic purposes. In our case, we apply a front model to a vertical tomography section across the Ushant front. The feature model describes the temperature \( F(r, z) \) as a function of the horizontal distance \( r \) and the depth \( z \). The model is constructed as follows:

\[
F(r, z) = F_c(z) + \frac{F_h(z) - F_c(z)}{1 + e^{-2(\lambda - r_0)/L}}
\]

where \( F_c(z) \) and \( F_h(z) \) are respectively the temperature profiles in the cold side and the hot side of the front, \( L \) is the quarter length of the front and \( r_0 \) the central position of the front defined by the maximum of the temperature gradient. An example of a typical temperature field obtained with the feature model is shown in Fig. 1 with a flat bottom of 130 m depth.

C. HYCOM regional model

The HYbrid Coordinate Ocean Model (HYCOM, [2]) is a primitive equation ocean general circulation model that evolved from the Miami Isopycnic-Coordinate Ocean Model (MICOM, [14]). To test the monitoring scheme on a realistic environmental scenario, HYCOM modeling outputs of the Iroise Sea during the summer are used to synthesize acoustic data.

An example of a temperature field prediction from the HYCOM model is shown in Fig. 2. The thermal front appears clearly on the sea surface temperature.

In this work, six parameters are retained to construct the feature model: the front central position \( (r_0) \), the front quarter length \( (L) \), three EOF-coefficients to parameterize the hot temperature profile \( (F_h) \) and one temperature value for the cold temperature profile \( (F_c) \), assumed to be isotherm. The EOF database is here constructed from the HYCOM predictions. Bathymetry and bottom properties are assumed to be known.

III. Results

Our feasibility study focuses to detect changes in the front location and temperature. For this purpose we will consider an acoustic source and a vertical array at fixed positions, respectively on the left and the right sides of the transect shown in Fig. 2. The propagation range between the two is approximately 26 km.

The acoustic source is located at 5-m depth off shore and the seabottom is modeled as an halfspace composed of gravel \((\rho = 2.0 \text{ g cm}^{-3}, c = 1800 \text{ m s}^{-1}, \alpha = 0.6 \text{ dB m}^{-1})\). The very shallow depth of the source is chosen to mimic a typical depth of the acoustic center of ship machinery noise.

To test the monitoring scheme in a twin experiment, the HYCOM temperature field predictions are first fitted on the feature model. Fig. 3 shows the 48-h evolution of the six parameters that best fit the HYCOM transect modeling output, as obtained by a nonlinear least-squares data fitting. The much too large values for the front length are explained by the fact that on the selected transect the cold profile is not correctly modeled by an isotherm. Here, the front length parameter becomes an \textit{ad hoc} parameter that allows to force a stratification on the cold part of the transect. In the same time the cold temperature cannot be directly associated to a physical temperature of the environment, but corresponds to a virtual cold profile extrapolated outside of the transect bounds.
The pressure field is synthesized at three frequencies: 200 Hz, 400 Hz and 600 Hz. The VRA is composed of 16 elements 2-m spaced, spanning the water column from 30 m to 60 m. New acoustic measurements are assimilated every 15 minutes. For multiple frequency tests, it worth be noticed that the Kalman filter jointly filters the observations at the multiple frequencies.

Figure 3 shows the Kalman tracking of the six front parameters during 48 hours. This result was presented in [1]. Each parameter is very well tracked, but the cold temperature value shows larger errors than the other front parameters. This is explained by the fact that for this transect the cold temperature parameter is only a virtual parameter (see above) and therefore has a weaker impact on the acoustic propagation.

The second test involves acoustic data synthesized directly with the predictions of the HYCOM model, i.e., without a preliminary projection on the feature model parameter space. As expected, the performances are deteriorated, but the principal parameter (the front position $r_0$) is roughly tracked during 40 hours, before diverging, when the model mismatch becomes too important. This tracking was realized with 16 frequencies, from 200 Hz to 500 Hz with a step of 20 Hz, to increase the robustness of the filter.

Figure 5 compares the sound-speed field predicted by HYCOM, and its reconstruction using the feature model parameter estimates shown in Fig.4. Different features can not be reproduced by the feature model, especially the mixing near the coast, but the global structure of the front is well tracked. A more complex feature model, e.g., with an second EOF parameterization for the cold profile, should certainly enhance the quality of the temperature field reconstruction, and consequently the robustness of the filtering scheme.

IV. CONCLUSION

In this paper the feasibility of the assimilation of full-field acoustic measurements in an environmental model of a thermal front is investigated. The front is parameterized with a basic feature model which involves the principal characteristics of a thermal front. The data assimilation is based on the Kalman filtering of multifrequency acoustic measurements on a vertical receiver array. The synthetic source is placed at shallow depth to mimic the location of a ship noise source.

Simulation results show the ability of full-field acoustic tomography to provide an efficient monitoring tool for the thermal front position. Application of this scheme on realistic temperature predictions gives encouraging results, with a reasonable tracking of the main structure of the front.

The ship traffic is intensive in the Ushant region, with two important and well-surveyed merchant traffic lanes. The feasibility of using the noise radiated by a ship as an opportunity source has already been demonstrated for acoustic tomography and geoaoustic inversion purposes [15], [16]. The idea of deploying a passive acoustic tomography network in area with intense traffic seems then to be realistic and is worth being examined in details. In the future our assimilation scheme is envisioned to be implemented using ship noise as source of opportunity.

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Fig. 5. One-day tracking of the HYCOM sound-speed field predictions. Each plot shows a different snapshot of the true (top) and estimated (bottom) sound-speed field. The time index of each snapshot is indicated at the top of each plot. The vertical black line and the asterisk on each plot show the location of the 16-hydrophone array and the source position, respectively.

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REFERENCES


