Acoustic and photographic monitoring of coastal maritime traffic: Influence on the soundscape

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ABSTRACT:
Due to the absence of Automatic Identification System data (used by 3.7\% of the Calvi bay fleet), the acoustic monitoring of coastal environments presents difficulties. A specific visual monitoring protocol has been set up on a photographic observatory using the wide-angle camera GoPro\textsuperscript{6}. The detection and localization of boats were carried out by image processing algorithms and allowed the creation of a map of maritime traffic for a surface of 3.48 km\textsuperscript{2}. The ocean noise is described through two different scales (the individual scale and the global scale) which are linked to the traffic information. The Sound Pressure Level characterizes the individual sources and correlates with the distance of the nearest ship, whereas the Ambient Noise Level characterizes the background without individual sources and correlates with the number of boats present. A high spatial and seasonal variability due to coastal maritime traffic is observed in the broadband [100 Hz–30 kHz]. Closest to the traffic, the acoustic is punctuated by diel patterns of biological sounds and the use patterns of the boats. In spite of an important diurnal flotilla (more than 550 boats per day), the nocturnal activity of fish remains an important element on the soundscape (average and median levels higher during the night). © 2020 Acoustical Society of America. https://doi.org/10.1121/10.0001321

I. INTRODUCTION
Noise is composed of a set of sound sources that can be studied on two different scales: the individual scale (identifiable noise sources) and the global scale (ambient, or background noise).\textsuperscript{1} This duality between individual sources and ambient noise is found during the monitoring of the maritime traffic which is the main contributor to anthropogenic ocean noise. From an individual point of view, boats are characterized by a source level (SL). On the other hand, the presence of maritime traffic influences the global soundscape. The growth of the deep-sea traffic is changing the global acoustic landscape.\textsuperscript{2,3} Since the 1960s, the maritime traffic creates an increase in ocean noise that may exceed 10 dB in some areas.\textsuperscript{4} In 2010, in response to this observation, the Marine Strategy Framework Directive (MSFD)\textsuperscript{5} recommended the monitoring of two specific third octave bands: 63 and 125 Hz. The contribution of maritime traffic in these frequency bands is an identifiable characteristic of deep-sea traffic.\textsuperscript{5} Quantifying may be accomplished either by direct observation or modelling. The localization of the vessels using Automatic Identification System (AIS) (Automatic Identification System) data allows the generation of maps showing the ambient noise in deep-sea.\textsuperscript{7}

\textsuperscript{a)Note: This paper is part of a special issue on The effects of Noise on Aquatic Life.
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highlighted using a scatter plot display and a linear regression ($r = 0.44$).

Section II presents the equipment and methods used for the acquisition and treatment of acoustic and photographic data in the bay of Calvi. To overcome the absence of AIS data, a photographic acquisition protocol has been specially set up. Acoustic data are described through two acoustic descriptors: the sound pressure level (SPL) characterizing the individual sources and the ambient noise level (ANL) characterizing the ambient level present by mitigating the contribution of each source. Section III presents the map of the maritime traffic obtained by image processing. A link between acoustic descriptors and two indicators of maritime traffic is examined. The acoustic database is composed of recordings made at two different positions during three seasons. The data are compared using different combinations, allowing the study of diurnal/nocturnal, spatial, and temporal variability on two scales: the daily scale and the seasonal scale. The daily evolution of the maritime traffic is analysed in comparison with a reference level estimated during the periods of “less noise.” Section IV discusses the influence of biological activity, the validity of the choice of a single acoustic indicator to study all coastal sites, and proposes a protocol for the selection of acoustic descriptors for coastal monitoring of maritime traffic.

II. MATERIALS AND METHOD

A. Study site

Located in Corsica (France), the bay of Calvi is part of the Pelagos sanctuary (see Fig. 1). This sanctuary has been designated as a Specially Protected Area of Mediterranean Importance under the Barcelona Convention and is protected by the program Natura 2000 (including the protection of some species against fishing). The bay of Calvi shelters great biodiversity. The area chosen for this study corresponds more specifically to the bay at west of the Calvi Citadel (42°34’31.4”N 8°44’16.3”E); it is bounded on the east by the Citadel, then 3 km west of the Revellata peninsula, and opens north–north/east on the bay of Calvi and the Mediterranean Sea. The closed portion of this area is approximately 3.32 km² and is less than 50 m deep. The area is driven by a Mediterranean climate with an air temperature of 35°C in the summer and wind gusts between 4 and 40 knots. During summer season, more than 550 boats are cross the bay each day. This flotilla is composed of recreational, pleasure, cruising (4 per day), and tourist transport boats. The boats are predominantly short: 75.13% of the boats are less than 20 m long and 40% are semi-rigid boats. Therefore, only 3.7% use the AIS systems (according to MarineTraffic).

B. Acoustic, visual, and weather observatories

The acoustics database is composed of 685 cumulative hours of recording acquired during 4 sessions (July 2015, September 2015, October 2015, and July 2016), and at two different positions of the bay. The two summer acoustic sessions were recorded during two different periods. However, a manual account of the number of boats per day shows few variations in the average number between these two years (between 520 and 550 boats for the 2015 session, and between 450 and 550 boats for the 2016 session). The maritime traffic is determined to be constant in 2015 and 2016. The instrumentation specifications are summarised in Table I. The acoustic recorders come from the company RTsys (RTsys, France) and the hydrophones come from HTI (High Tech, Inc., Gulfport, MS).

A specific photographic monitoring protocol for the bay has been set up during the recording of July 2016 using two wide-angle GoPro® cameras (used in rotation due to low energy autonomy) with resolutions of 2594 × 1944 pixels and 4000 × 3000 pixels. These cameras have positioned at a height of 99 m above sea level, they took photographs of the bay every 5 s. This observatory allowed us to obtain 64 h of visual monitoring between 8 am and 7 pm, which corresponds to 134 GB of wide-angle photography.

C. Numerical analysis

1. Localization and creation of traffic map by image processing

The detection and the localization of the boats were carried out by two image processing algorithms developed for this study and applied to wide-angle photography. The detection of a vessel is based on motion detection. An estimation of the first order temporal derivative is calculated for the three colours of each photograph from a set of 11 consecutive images. A mesh is applied to the photograph, and for each mesh, a semi-local modeling of the background is realised using a Gaussian law (Fig. 2(B)). The two adaptive detection thresholds $\theta$ are fixed using a Constant False Alarm Rate ($P_{fa} = 10^{-12}$) which determines the difference in the shade of color from which detection is supposed, according to the moments of each Gaussian law (mean $\mu$ and variance $\sigma$): $\theta = \mu \pm \sigma \text{erf}^{-1}(P_{fa})$. 

![FIG. 1. (Color online) Localization of the traffic routes in the bay of Calvi (Corsica, France).](https://doi.org/10.1121/10.0001321)
The localization of the boat is composed of two empirical functions, providing the geo-referencing and the modeling of deformation due to the fish-eye effect. The geo-referencing is based on using 8-daymarks (landmarks on the coast dedicated to the ships localization). The modeling of the deformation is based on the estimation of the distortion coefficients of bowed segments, which in reality are rectilinear straight lines and smaller circular arcs in a calibrated image. These empirical functions (specifically developed for this study) come from a linear regression ($r^2 = 0.9838$ and 0.9750). For each arc of circle where a boat is present on the photograph, a line $D$, perpendicular to the boresight axis, is defined on the GPS map in agreement with the model of deformation. The first empirical function allows us to measure the distance on the GPS map between the camera and the line $D$ projected onto the boresight axis. The second empirical function defines the distance between the boresight axis and the boat on the line $D$ [Fig. 2(C)].

These algorithms allow drawing traffic maps at several time intervals (instantaneous, hourly, daily, and weekly), estimating the distance of the nearest vessel and annotating the number of vessels passing through a 300 and 500 m radius disk around the acoustic recorder during 1 h.

2. Acoustics descriptors

To characterize the duality between ocean noise and ambient noise, two acoustic descriptors have been used. The acoustic descriptor characterizing individual sound is the SPL root mean square, expressed in decibels under the reference of 1 $\mu$Pa [dB re 1 $\mu$Pa] and is estimated using the following formula:

$$\text{SPL} = 20 \log_{10} \left( \sqrt{\frac{1}{T} \int_{t=0}^{T} \frac{P(t)^2}{P_{\text{ref}}} \, dt} \right),$$

where $P_{\text{ref}}$ is the reference sound pressure (1 $\mu$Pa), $T$ is the integration time chosen (10 s), and $P(t)$ is the sound pressure estimated after filtering on the frequency band selected: the wide band of 100 Hz to 30 kHz, and the one-third octave bands levels between 10 Hz and 20 kHz.

The acoustic descriptor ANL characterizes the ambient level without an individual source. This level is an estimation of the noise floor of the SPL, estimated at 60 s, over 1 h of computation time. The average value of the distribution of SPL is estimated using quantiles method. This method
allows to estimate the average value of a Gaussian distribution by keeping two values of centiles and by avoiding extreme values integration. This level is expressed in decibels under the reference of 1 μPa [dB re 1 μPa]

\[ \text{ANL} = \frac{f(2Q_1)P_{Q1}(\text{SPL}) - f(2Q_2)P_{Q2}(\text{SPL})}{f(2Q_1) - f(2Q_2)}, \]

where \( P_{Q1} \) and \( P_{Q2} \) correspond to the value of the centiles \( Q1 (=0.3) \) and \( Q2 (=0.5) \) of the SPL is obtained after filtering in the same frequency bands cited above, and \( f \) corresponds to the function \( \text{erf}^{-1} \) defined as

\[ \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} \, dt. \]

3. Method for the analysis of spatial and temporal variability

To overcome the diurnal/nocturnal variability due to biologic activity, a 24-h day was divided into two parts, day and night between sunrise and sunset. The broadband level between 100 Hz and 30 kHz was used for this analysis. The analysis of the distribution of acoustic descriptors was carried out considering several points. Each distribution was characterized into three levels: the median level, the average level, and the most probable level (corresponding to the level associated with the maximum level of the probability density function). The analysis of the distribution functions and probability density functions were estimated. Moreover, the exceeded percentage of the acoustic level compared to 6 predefined thresholds during a day/night period and 10-min session were used. The thresholds are defined as an addition to a reference level, the daily most probable level, of 0, 3, 5, 10, 15, and 20 dB. A temporal analysis was performed by comparing the results obtained for the position far from the traffic during three different sessions. The spatial analysis was performed by comparing the results obtained during July for the tow positions in the bay.

III. RESULTS

A. Maritime traffic maps and localization uncertainty

The two image processing algorithms for detection and localization of boats present in Sec. II allowed for the creation of a map of maritime traffic map on the bay up to a distance of 1.6 km, which represents an area of 3.48 km² (58.0% of the bay). Several exclusion zones due to the masking by the geographic landform (5.8% of the bay) were observed. Figure 2(D) shows the maritime traffic map obtained for a 1 week time scale. Mooring areas (surrounded with a dotted circle) and the two main maritime routes “Revellata-Citadelle” and “Revellata-Alga” appear on the map.

The localization uncertainty was estimated by comparing the GPS coordinates of eight reference boat trips to the trajectories obtained through the localization by the image processing algorithm. This uncertainty increases as the vessel takes an eccentric position on the photograph and as the distance from the visual observatory increases. But it stays lower than 16% of this distance: 20 m of uncertainty for a 300 m distance and 230 m of uncertainty for a 1.5 km distance. The implications of the localization uncertainty in the SL estimation are below 1.2 dB [considering loss transition as \( TL = 15 \log_{10}(D) \) where D is the source/receptor distance]. Adding the GPS coordinates of one of these reference trips as a day mark allows a reduction by two the maximum localization error.

B. Link between acoustic and traffic information

1. The SPL determines the distance of the nearest boat

The visualisation of the SPL as a function of the base ten logarithms of the nearest distance takes the form of a right triangle. This triangle is explained by the variability of SLSs (the diversity of vessels and speeds) and the positioning in the bay and masking by stable ambient noise. Due to this masking effect, a listening range of 450 m is observed. It is defined as the greater distance of the listening rings where the probability of exceeding the ambient level is greater than 50%. Thereby, an anti-correlation is observed between these two values, corresponding to the mathematical relation

\[ \text{SPL} = \text{SL}_0 + k \log_{10}(D), \]

where \( D \) the distance to the nearest boat [m], \( \text{SL}_0 \) corresponds to the SL without anthropogenic activity, and \( k \) is the slope coefficient. These relations depend on the frequency and are characterized using the Spearman correlation coefficient values. This rank correlation coefficient allows for the study of the correlation without the linear relationship between the two variables. The absolute value of the correlation reaches a maximum for the third octave band of 1250 Hz and is greater than 0.4 for the third octave bands from 200 to 3150 Hz (Table II). This decrease of correlation at low frequency seems to be due to the appearance of a cutoff frequency which is the consequence of shallow water attenuation of long wavelength signals.

2. The ANL correlates on the number of boats near the listening point

The ANL correlates with the number of boats crossing a radius arc during 1 h, up to a distance of 500 m, and for an optimal distance of 300 m. The link between these two variables increases as the number of boats observed exceeds a minimum number and corresponds to the mathematical relation

\[ \text{ANL} = \text{ANL}_0 + k \log_{10}(N_{H,N>N_{\text{min}}}), \]

where \( \text{ANL}_0 \) corresponds to the ANL without anthropogenic activity, \( N \) is the number of boats in a given radius, and \( N_{\text{min}} \) is the minimum number of boats (12 boats for a 300 m radius, and 15 boats for a 500 m radius). This relation depends on the frequency (Table III). Maximum for the
2500 Hz octave band, the Spearman coefficient values are greater than 0.6 for the one-third octave bands of 125 Hz to 4 kHz. The coefficient drops down outside this band. The decrease of correlation in low frequency band seems to be due to the occurrence of the cutoff frequency.

### 3. Joint analysis of the Spearman correlation coefficient values

The number of boats is not correlated with the distance of the nearest boat and the acoustic indicators measure noise from two different angles. However, a consistency between the correlation coefficient values of the two equations according to the frequency band is observed (Fig. 3) and is characterized using a linear regression ($r^2 = 0.896$).

### C. Spatial and temporal monitoring of acoustic descriptors

#### 1. Diurnal-nocturnal variability

The diurnal-nocturnal variability is expressed differently depending on the proximity to maritime traffic (Table IV). The nocturnal fish and benthic activity are significant factors which shape the acoustic landscape of the bay. Some species of the bay are protected from fishing; there are no fishing boats during night. The increase in daytime maritime traffic tends to reduce diurnal-nocturnal differences, or even to reverse them. At the closest point to the maritime traffic, the diurnal-nocturnal differences observed in the average, median, and most probable levels are lower than 1.3 dB. Thus, the contribution of the noise generated by the maritime traffic is reflected during the day by: higher levels of high percentile values and an increase in the number of extreme values. For a position away from marine traffic, the diurnal-nocturnal variability becomes more pronounced. Average, median, and most probable values are lower during the day (difference between 1.43 and 4.5 dB), as for the percentile value [until the 91st percentile for the SPL and for all percentile for ANL—Figs. 4(B) and 4(C)].

#### 2. Spatial and seasonal variability

The spatial and seasonal variability is observed by comparing the SPL and ANL distribution functions for a given radius.
geographical location (temporal variation between three seasons), and for a given season (spatial variation between two positions) [Figs. 4(B) and 4(C)]. The geographical distance from the maritime traffic route and temporal distance from the summer season have a similar effect on distribution functions. They are characterized by a decrease in the levels associated with each percentile and a decrease of the number of extreme values. Regarding the spatial variability, the differences between the distribution functions are weak during the night, but significantly higher during the day. Higher differences between the most probable value and the average values are observed close to the traffic, and decrease with geographic distance (Table IV).

3. Daily variability

Closest to the maritime traffic, the daily evolution highlights the biological rhythm and the rhythm of the boaters. In terms of presence density, days are characterized by a strong anthropogenic activity and a moderate biological activity, whereas nights are characterized by a low anthropogenic activity, and a strong biological activity [Fig. 4(D)]. The strong benthic and ichthyologic activities at sunrise and sunset caused a number of sessions where the acoustic level was higher than the reference threshold - significantly higher during the night than during the day. The night sessions (51.7%) exceed the threshold reference more than 8 min per 10 min, against 2.3% of the day sessions. This contribution becomes less important for an excess of 3 dB and the maritime traffic becomes the main contributor, for excess levels greater than 5 dB. Such an overtaking is noted during 2.3% of the day for the ANL and 21.5% of the day for the SPL.

A decrease in the number of boats is visually observed between 1 pm and 2:30 pm, corresponding to the boater’s meal break. This meal break is reflected in the acoustic analysis: a gradual decrease of the exceeded percentage of the ANL and stagnation below 20% of exceeded percentage of the SPL. Six peaks of the exceeded percentage of the SPL (cause exceeds more than 10 dB during less than 2 min per 10 min) are observed. Some of them (9:20 am, 11:30 am, 2:30 pm, 4:50 pm) correspond to boat rental schedules and tourist cruises according to visual observations and tourist information. Away from the maritime traffic, the influence of boating rhythm becomes less significant, while nights remain marked by biological sounds.

IV. DISCUSSION

The photographic and acoustic monitoring presented in this article was conducted only on one specific coastal environment, the bay of Calvi, and for a specific area of the bay concerning the relationships between acoustic and descriptors of traffic. The results presented cannot be generalized to all coastal environments. The proposed methodology for the remaining study may be applicable to other coastal environments, and for some of them without photographic equipment installation: many coastal sites already have cameras like webcam, GoPro®, or others, whose photographs are freely accessible via the internet. Similarly, the nonspecific tools developed for this site can be applied in other studies.

The frequency bands recommended by the descriptor 11 of the MFSD (63 and 125 Hz) do not allow to specifically and qualitatively targeting coastal traffic. The correlation coefficients with information on the traffic value for the band of 63 are between 1.7 and 2.4 times lower than the maximum observed. These values are higher for 125 Hz but stay within the base limit. This analysis suggests that these two bands are subject to the cutoff frequency due to

<table>
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<th>Acoustic descriptors</th>
<th>[dB re 1 μPa]</th>
<th>July</th>
<th>July</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Day</td>
<td>Night</td>
<td>Day</td>
<td>Night</td>
</tr>
<tr>
<td>SPL 100 Hz–30 kHz</td>
<td>Average</td>
<td>112.3</td>
<td>111.7</td>
<td>108.5</td>
<td>110.8</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>110.4</td>
<td>111.4</td>
<td>107.4</td>
<td>110.6</td>
</tr>
<tr>
<td></td>
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<td>110.6</td>
<td>106.4</td>
<td>110.2</td>
</tr>
<tr>
<td>ANL 100 Hz–30 kHz</td>
<td>Average</td>
<td>111.2</td>
<td>111.6</td>
<td>107.6</td>
<td>110.8</td>
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<tr>
<td></td>
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<td>107.3</td>
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<tr>
<td></td>
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<td>110.2</td>
<td>106.7</td>
<td>110.1</td>
</tr>
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</table>
the area bathymetry (in the limit for 125 Hz). The weather conditions impact these bands as well. In fact, a modification of the Spearman correlation coefficient values of the ANL was observed according to the frequency bands, which was due to the action of strong winds. For periods of strong winds, the ambient noise became more of the consequence of the sea-state changes than to the vessel noise contribution. Without these periods, the correlation coefficient increases significantly and becomes greater than 0.6 between 20 Hz and 6.3 kHz. Moreover, in the absence of maritime traffic, the daily activity of fish is more pronounced. For frequency bands below 1250 Hz, the spatio-temporal analysis shows that the SPL has the average, median, and most probable values elevating during the day only in absence of maritime traffic. These results raise questions about the effect of maritime traffic on the ichthyogenic sound production: Is the massive presence of maritime traffic causing a quasi-permanent masking of fish emissions, or a reduction in fish emissions due to a stress reaction in the fish? Even if a better match is observed for 250 and 500 Hz third octave bands in terms of correlation with traffic information, these frequency bands are still strongly subject to the variability of fish activity.

The results raise questions about the validity of choosing a single acoustic indicator to study all coastal sites. The approach allows for the definition of a protocol for the selection of acoustic descriptors for coastal monitoring of maritime traffic. This protocol consists of a maritime traffic/acoustics/weather data correlation study followed by a spatio-temporal study of a selection of acoustic descriptors and the evaluation of the biological activity impact on it.

For this study, the biological activity mainly impacts the band lower than 1250 Hz (fish activity) and the band of 2500 Hz (benthic activity). An increase of the ANL in the 2500 Hz third octave band was observed during the change of position in the bay. This observation raises questions about the origin and location of the benthic clicks heard. Please note that the two frequency bands which maximize the correlation with traffic indicator are strongly affected by the biological activity. These bands do not specifically and qualitatively target the maritime traffic. Therefore two types of acoustic indicators are considered: the level in the third octave band of 1.6 kHz, or the broadband level (100 Hz–30 kHz in our case) that facilitates the identification of maritime traffic while being less sensitive to environmental phenomena. The use of broadband levels seems more suitable for monitoring coastal environments. In addition to defining the optimal frequency band for environmental monitoring, the observed results question the validity of an indicator based on an absolute acoustic level. Thus, it is possible to ask whether descriptors of signal characteristics allow environmental monitoring less constrained by the variability of biological sound productions.

FIG. 4. (Color online) (A) Spectrograms during July and closest to the maritime traffic, (B) and (C) distribution functions at the same position for three sessions (B) and at two positions of the bay during July (C), (D) the daily evolution of the SPL (on the left) and the ANL (on the right) in the 100 Hz–30 kHz band at the closest point from the maritime traffic: Estimation of the percentage where the acoustic level exceeded the threshold (the most probable level during the day) per session of 10 min.
Three short-term prospects are identified. First, the correlation study between the ANL and the number of boats suggests the possible creation of a model connecting these two quantities. Then, the choice of the broadband acoustic estimation does not quantify the contribution of different actors in the acoustic landscape. It could have been done using the octave band of 800 Hz, for ichthyologic activity and the maritime traffic, the one-third octave band of 1600 Hz for the maritime traffic alone, and the levels in the band 3–30 kHz for benthic activity and maritime traffic. Finally, a complementary perspective of this work could focus on the analysis of ambient noise as a function of sea conditions.

V. CONCLUSION

During the summer the bay of Calvi is composed of a fleet of small coastal boats. Only 3.7% of this fleet uses the AIS system. To detect and locate boats, a specific wide-angle photographic monitoring has been established and two image processing algorithms have been developed. Maps of maritime traffic are created for an area of 1.6 km long and 3.48 km² of surface (58% of the bay). The localization uncertainty is lower than 16% of the distance from the observatory (34 m at a distance of 320 m), which represents an acoustic uncertainty lower than 1.2 dB.

While up to 550 boats cross the bay each day, the nocturnal activity of fish remains an important element on subject area soundscape. The average and median sound levels are higher during the night for a position away from traffic and equal for the nearest position of the traffic. The use pattern of boaters (rental hours, lunch break) is observable on the daily monitoring of acoustic levels. Each coastal environment is subject to spatial and seasonal variability due to biological activity. The validity of a unique acoustic indicator to monitor all coastal sites is questioned, and a protocol to characterize the influence of the coastal maritime traffic on underwater noise is proposed. Noise is characterized through two acoustic descriptors which reflect the duality between the noise due to individual sources through the SPL, and the ambient noise without individual sources through the ANL. The correlation between maritime traffic, acoustic data, and weather data allows the identification of the influence of maritime traffic on the coastal noise. In this case, the SPL provides information on the distance of the boat closest to the recorder in a listening range of 450 m. The ANL provides information on the number of boats present in a 500 m radius around the recorder. The appearance of the cutoff frequency is observed inside the frequency band of both levels. Then, the spatio-temporal monitoring of these descriptors facilitates assessment of the spatial and seasonal variability due to biological activity.

ACKNOWLEDGMENTS

Funding from RTSYS® supported the realization of these works. All data presented in this article are the property of RTSYS®. Scientific support from the research institute CHORUS® are gratefully acknowledged. We thank the team of the Oceanography Station STARESO® (STAtion de Recherche océanographiques Et SOus-marines) for their help and support during the experiments in Calvi and ABYSSENS® for their advice and scientific support during the writing and the continuation of this work.