Qualitative Correlation of Marine Mammals With Physical and Biological Parameters in the Ligurian Sea

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***Abstract*—In support of its acoustic risk mitigation policy, NATO SACLANT Undersea Research Centre (SACLANTCEN) is sponsoring a series of sea trials, entitled "Sirena" to collect a multiyear integrated oceanographic, biological, and hydrographic data set, the goal being to explain, based on these parameters, the distribution of marine mammals found in specific locations. By understanding how ocean dynamics affects the distribution and behavior of whales and the organisms forming the food web upon which the whales feed, it may be possible to conduct acoustic exercises in areas of low cetacean density. The first two Sirena multidisciplinary cruises were conducted in the Ligurian Sea in late summer time frame during 1999 and 2000. The focus of this analysis is to determine whether remotely sensed satellite data can indicate nutrient-rich regions in areas where the oceanography is known and to determine if these regions of higher productivity, coupled with knowledge of cetacean presence from all available sources, could be used as an indicator of marine mammal presence for acoustic risk mitigation purposes. For the two years of data examined here, cooler sea-surface temperature data correlated with high levels of chlorophyll production as seen by remotely sensed images. This remotely sensed data correlated well with measured subsurface values of the same parameters. Coincident sightings of three species of marine mammals indicated that fin and sperm whales generally preferred the deep, nutrient-rich portion of the basin while Cuvier's beaked whales preferred a submarine canyon where there is a frontal influence, as indicated from satellite data and historical oceanography. This paper is intended as a contribution to the longer term objective of developing the means to accurately predict cetacean presence from physical oceanographic characteristics.**

***Index Terms*—Marine habitat, marine mammals, remote sensing.**

I. Introduction

TO ADDRESS the worldwide public concerns about the potential effects of anthropogenic noise on the marine environment [1]–[4], the impact that acoustic energy may have on the marine environment, especially on marine mammals, must be understood, and when appropriate, mitigated. In response to this concern, NATO SACLANT Undersea Research Center (SACLANTCEN) has initiated a project entitled Sound, Oceanography and Living MArine Resources (SOLMAR), whose ultimate goal is to develop the tools and/or procedures with which an experimenter can ensure there are no marine mammals near a sonar source prior to and during its use. By striving toward this goal, SOLMAR seeks to establish a paradigm for monitoring and conserving marine species. SACLANTCEN approaches acoustic risk mitigation by [5] the following.

- Determining regions of high and low cetacean density through oceanographic, biological and historical means, and then using this information as a basis for selecting regions for the conduct of acoustic trials where the potential for cetacean presence is low.
- Employing visual and acoustic monitoring techniques during acoustic trials.

While acoustic and visual procedures provide on-scene support, selection of trial areas can be accomplished in advance. The selection of the trial area may be influenced by knowledge of the cetacean species that are known to inhabit an area. By understanding how ocean dynamics affect the distribution and behavior of whales, it may be possible to use circulation and ecosystem models coupled with satellite remotely sensed data to predict areas of low cetacean density.

An integrated approach to the understanding of cetacean ecology has been presented by Winn *et al.* [6] and Croll *et al.* [7] in which the authors related the temporal and spatial relationship of marine birds and mammals to the structure and variability of their environments in a region off the coast of California. The SOLMAR project has expanded on this integrated approach by including satellite remotely sensed data, measurements of deep oceanographic parameters, and the use of advanced passive acoustic sensors to map out acoustically the cetacean presence in an area. By understanding the mechanisms associated with animal presence, one hopes to identify regions of low cetacean density to conduct acoustic measurements. The correlation of marine mammal presence with satellite images and *in situ* measurements of environmental parameters is discussed in this context.

II. Methodology

The SOLMAR project has successfully conducted two sea trials in the Ligurian Sea in an ongoing at-sea measurement program entitled Sirena, designed to evaluate the methodology for effective acoustic-risk mitigation and to collect supporting environmental information. Both cruises have collected relevant environmental parameters that could be correlated with mammal

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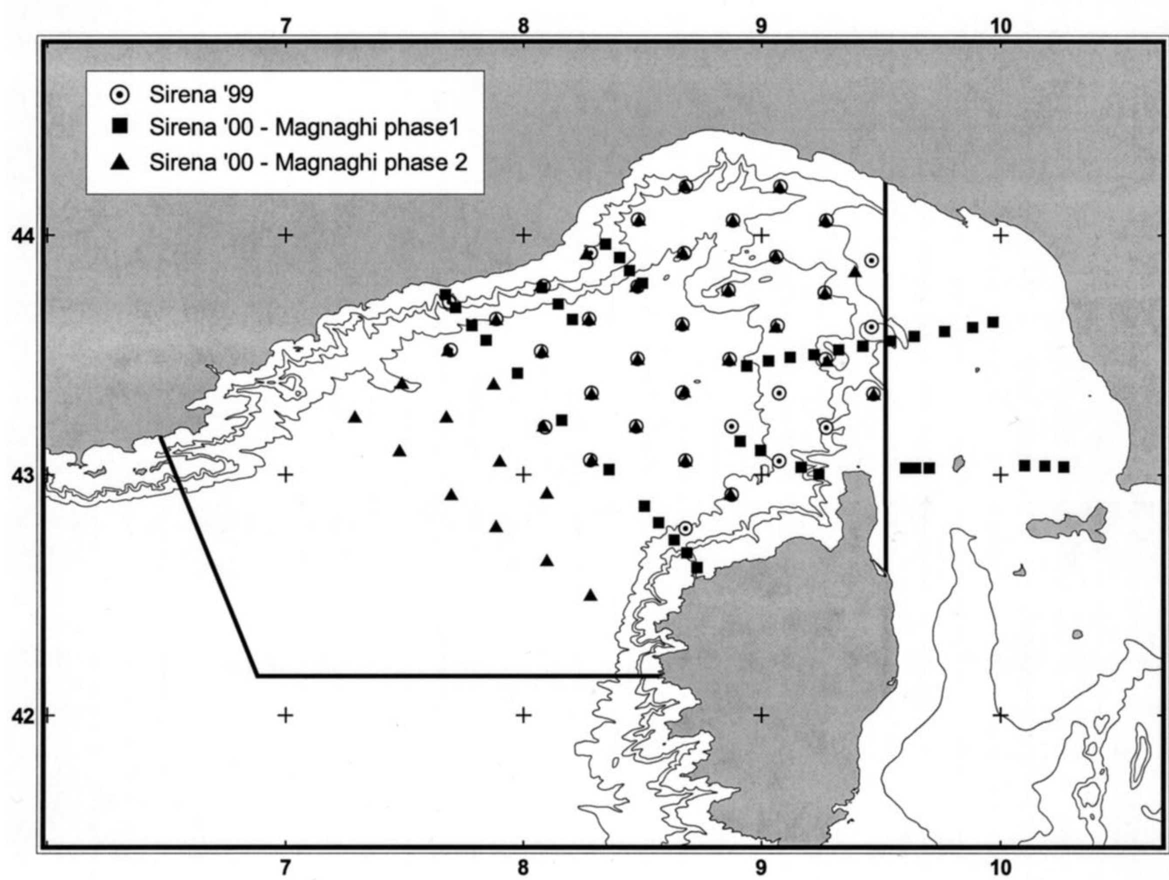


Fig. 1. Sirena'99 and Sirena'00 operational area. Bathymetric contours are plotted (600, 1000, 2000 m). Locations of CTD stations during Sirena'99, Sirena'00 Phase 1 and Phase 2 are shown.

presence. Insight has been gained on the effectiveness of both current methodologies and new technologies for acoustic risk mitigation such as a low-power active acoustic whale finding sonar [8] and acoustic tags [9].

The Ligurian Sea is a deep basin located in the northwestern Mediterranean Sea bounded to the north by the Italian and French Riviera, to the south by the northern portion of Corsica, and to the southeast by the shallow-water shelf of the Tuscan archipelago, while it is open to the Mediterranean Sea along the western boundary. The Ligurian Sea provides a natural laboratory for manageable studies of acoustic, physical, and biological parameters as it is rich in marine mammals and appears to form a semi-enclosed system. As such, it was designated as the first International Marine Sanctuary in the Mediterranean Sea in November, 1999 [10]. Eight species of cetaceans are commonly found in the Mediterranean Sea. These include seven species of odontocetes: *Delphinus delphis* (common dolphin), *Globicephala melas* (pilot whale), *Grampus griseus* (Risso's dolphin), *Stenella coeruleoalba* (striped dolphin), *Tursiops truncatus* (bottlenose dolphin), *Physeter macrocephalus* (sperm whale), *Ziphius cavirostris* (Cuvier's beaked whale), and one species of mysticete (*Balaenoptera physalus* fin whale) [11] and [12]. During the Sirena cruises, all species were detected by visual and/or acoustic means. The subsequent discussion will focus only on the observed distribution of three species: two deep diving whales (sperm and Cuvier's Beaked whales) and the only baleen whale (fin whale) found frequently in the Mediterranean Sea. The fin whale population has been estimated to be from 1200 [13] to 3500 individuals [14], [15] with an approximate concentration of 900 individuals in the summer in the Ligurian Sea [16], which is thought to be their primary feeding ground [17].

Sirena 1999 (Sirena'99) and Sirena 2000 (Sirena'00) were conducted in the Ligurian Sea in the region shown in Fig. 1 during the time periods of August 3–13, 1999 and August 21–September 15, 2000, respectively. The general study area encompasses about 31000 km^2. Two ships were deployed in the basin during each study period. The NATO research vessel, NRV Alliance, an acoustically silent ship, provided a stable platform for visual observations and acoustic measurements. Visual observations were made while the ship was transiting at 6 kts. Acoustic measurements were made using a towed horizontal line array with real-time passive beamforming capability, described in [9]. Oceanographic, lower, and middle trophic level measurements and cetacean visual observations were made on board the Italian Navy's Hydrographic Office research vessel, Nave Ammiraglio Magnaghi. The Nave Magnaghi's primary objective was to collect vertical oceanographic measurements at fixed stations on a 12-nm grid throughout the study area to build a three-dimensional picture of the oceanography. Visual observations were made on station and between stations, while the ship was transiting at 6 kts. Concurrent

TABLE I
SUMMARY OF VISUAL AND ACOUSTIC MONITORING EFFORTS

		Sirena '99	Sirena '00 Phase 1	Sirena '00 Phase 2
Research Vessel	NRV Alliance	3-13 Aug. 1999	22-29 Aug. 2000	22Aug.–7Sept. 2000
	ITN Magnaghi	3-13 Aug. 1999	22 Aug.– 6 Sept. 2000	
NRV Alliance	Length (nm) of track (daylight only)	736	648	524
	Hours of visual observations	154	112	126
	Length (nm) of track with towed array deployed	668	1061	179
	Hours of passive acoustic monitoring	148	192	32
Nave Magnaghi	Length (nm) of track (daylight only)	375	552	249
	Hours of visual observations	140	224	

satellite data were collected and processed at SACLANTCEN. All data have been geo-referenced using ESRI ArcView Geographic Information System (GIS) Version 3.1 and plotted on a geographic (equal-spaced) latitude–longitude grid, with horizontal data contouring done with ArcView 3-D Analyist. The 600, 1000, and 2000 m bathymetric contours are shown in all figures for comparative purposes.

A. Cetacean Sightings

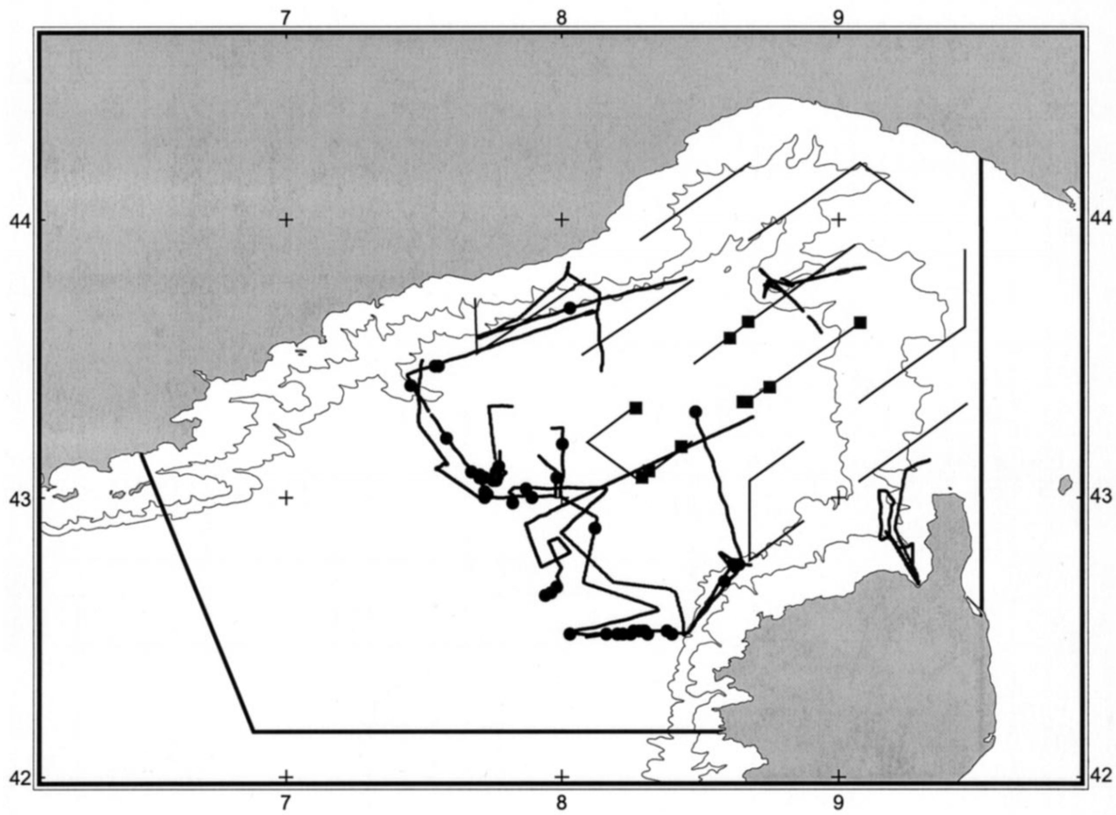
The objective of the Sirena'99, acoustic survey from the NRV Alliance was to locate marine mammals so that passive acoustic signatures could be obtained concurrently with visual sightings. Sirena'00 was conducted in two phases. Therefore, the NRV Alliance tracks during both Sirena'99 and Sirena'00 Phase 2 reflect the animal's movements and are predominately located in the center of the Ligurian basin. Sirena'00 Phase 1 conducted a wide-area acoustic and visual survey through the Ligurian basin on a predetermined track, so that cetacean density could be determined. During this phase, the ship moved at approximately 6 kts following linear track segments spaced 12 nm apart.

Marine mammal visual sighting data were collected by trained observers during daylight hours from both research vessels. Visual sightings were also made from military aircraft provided by the Italian Navy's Sea King Helicopter Squadron (Sirena'99) and the 30° Aerostormo (ELMAS) marine patrol aircraft (Sirena'00). The NRV Alliance supported the larger of the two teams of trained visual observers due to space limitations aboard the Nave Magnaghi, which could influence the number of sightings made from each vessel. Two visual observers stood a 2-h watch on a rotational basis on the NRV Alliance. On the Nave Magnaghi, one dedicated trained visual observer stood a rotational watch, supported by nontrained observers.

Experience during the Sirena cruises has shown that visual observations are limited by light, sea state conditions, size of the animal, and the height of the observing platform from the sea surface. Trained observers improve the probability of success [18]–[20]. The methodology developed for daytime observations in Sirena'99 [20] proved successful and was used in Sirena'00 [21]. During both cruises, fin whales were often sighted alone or in pairs. All sightings of sperm whales were of single animals. Sightings of Cuvier's beaked whales numbered from 1–3 animals in a group. When geo-referencing visual observations, daytime ship tracks are shown to indicate observing periods and location of the ship.

During both cruises, the NRV Alliance conducted passive acoustic measurements, 24 h a day, along the track using a horizontal line array. During Sirena'99, a 32-element array was used with real-time beamforming (750 Hz–4.1 kHz). During Sirena'00, a 128-element array was used to provide greater spatial resolution and frequency coverage (200 Hz–8.6 kHz) [8], [9]. For the three species of cetaceans discussed in this article, passive acoustic monitoring techniques to determine animal presence were used only for sperm whales, as their broadband echolocation clicks were easily detected on the beamformed towed horizontal array deployed by the NRV Alliance [8], [9], [22], [23]. If signal reception on the beamformer was very strong, it was assumed that the animal was close to the vessel and its location was marked as an acoustic presence located on the portion of the track during which the acoustic array was deployed. Acoustic presence was combined with visual observations. This methodology has been used for sperm whales and dolphins [24] in other studies conducted in the Ligurian Sea. The acoustic signature of fin whales in the Mediterranean Sea is centered at approximately 25 Hz, [22], [23], [25]–[27], therefore, they were not detected on the towed array due to the array's low-frequency limitation. The acoustic characteristics of Cuvier's beaked whales as described in [28] were not detected on the towed array during the cruises, possibly due to the array's high-frequency cut off.

Table I summarizes the visual and acoustic monitoring efforts during both trials.



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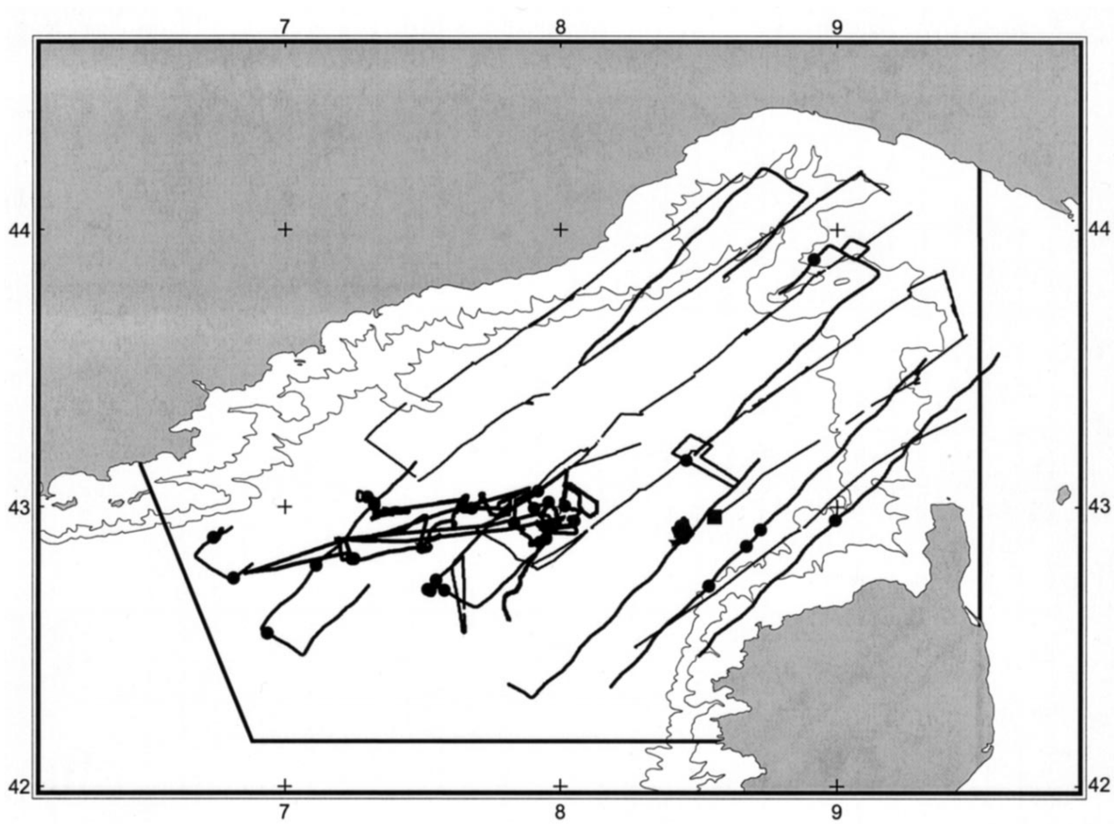

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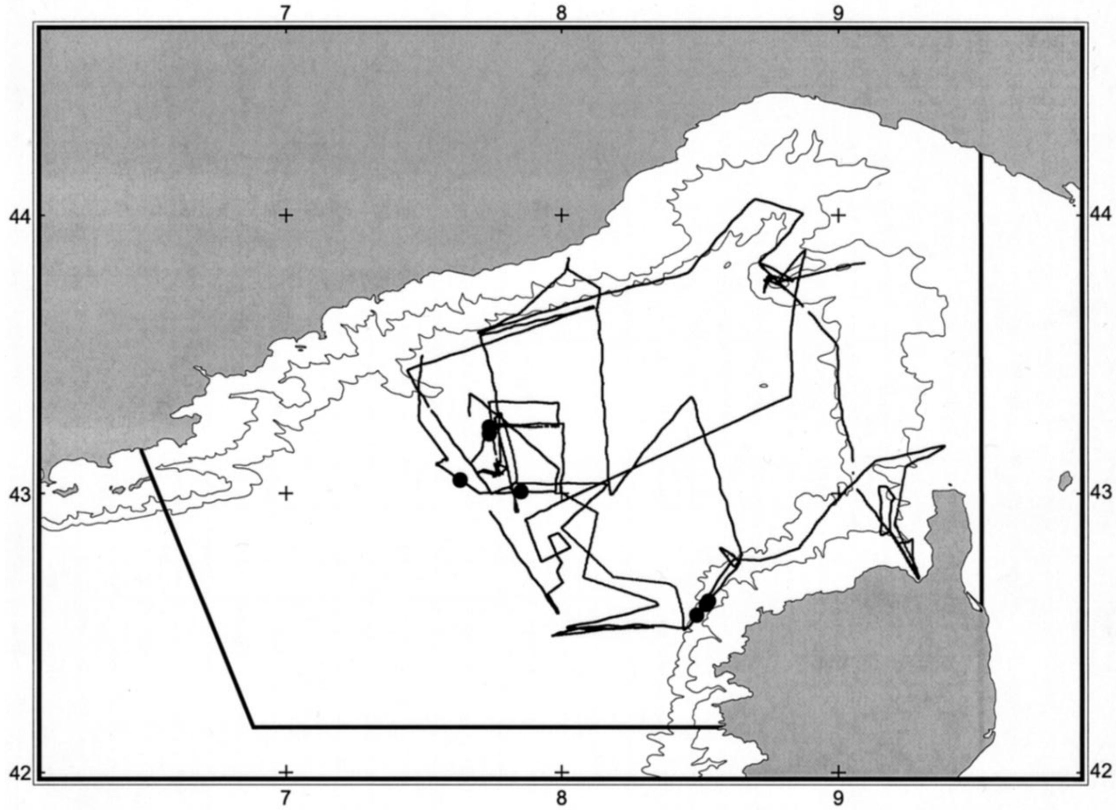
Fig. 2. (a) NRV Alliance (thick line, black circles) and Nave Magnaghi (thin line, black squares) fin whale visual sightings during Sirena'99. Ship's daytime tracks are shown to indicate regions where visual observations were made. The 1000- and 2000-m bathymetric contours are shown. (b) NRV Alliance (thick line, black circles) and Nave Magnaghi (thin line, black squares) fin whale visual sightings during Sirena'00 Phases 1 and 2. Ship's daytime tracks are shown to indicate regions where visual observations were made. The 1000- and 2000-m bathymetric contours are shown.



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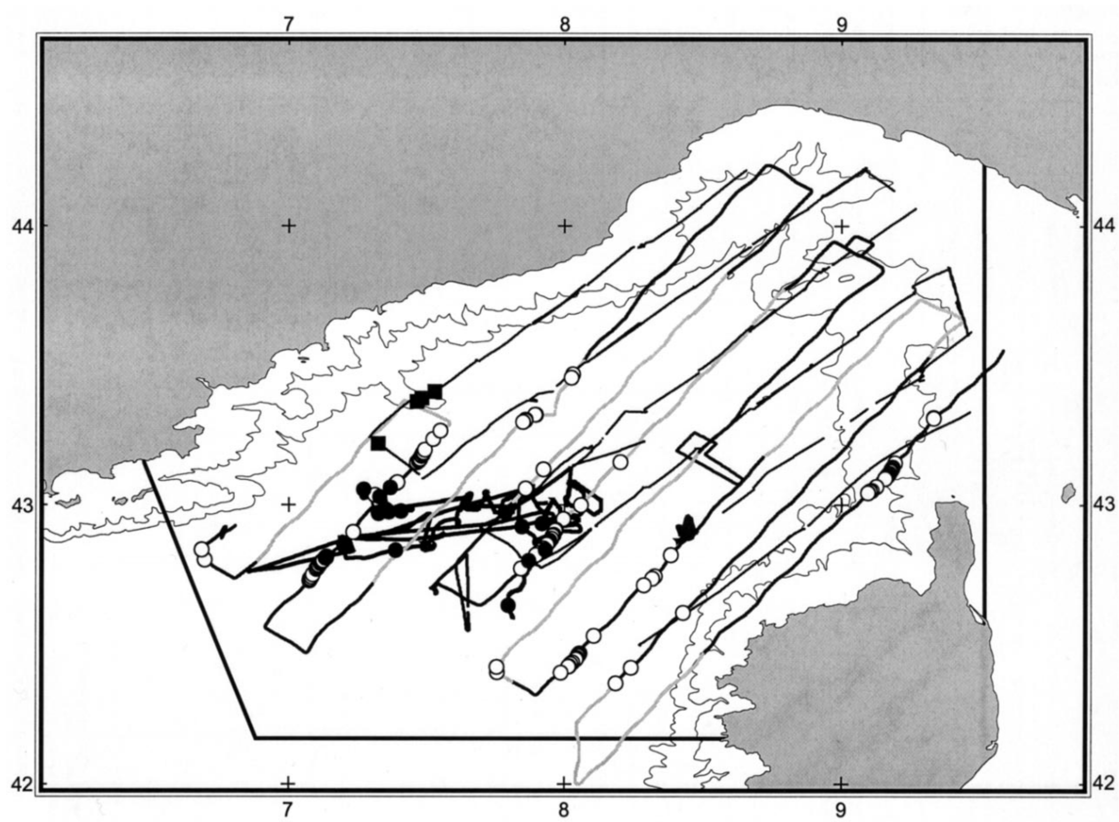
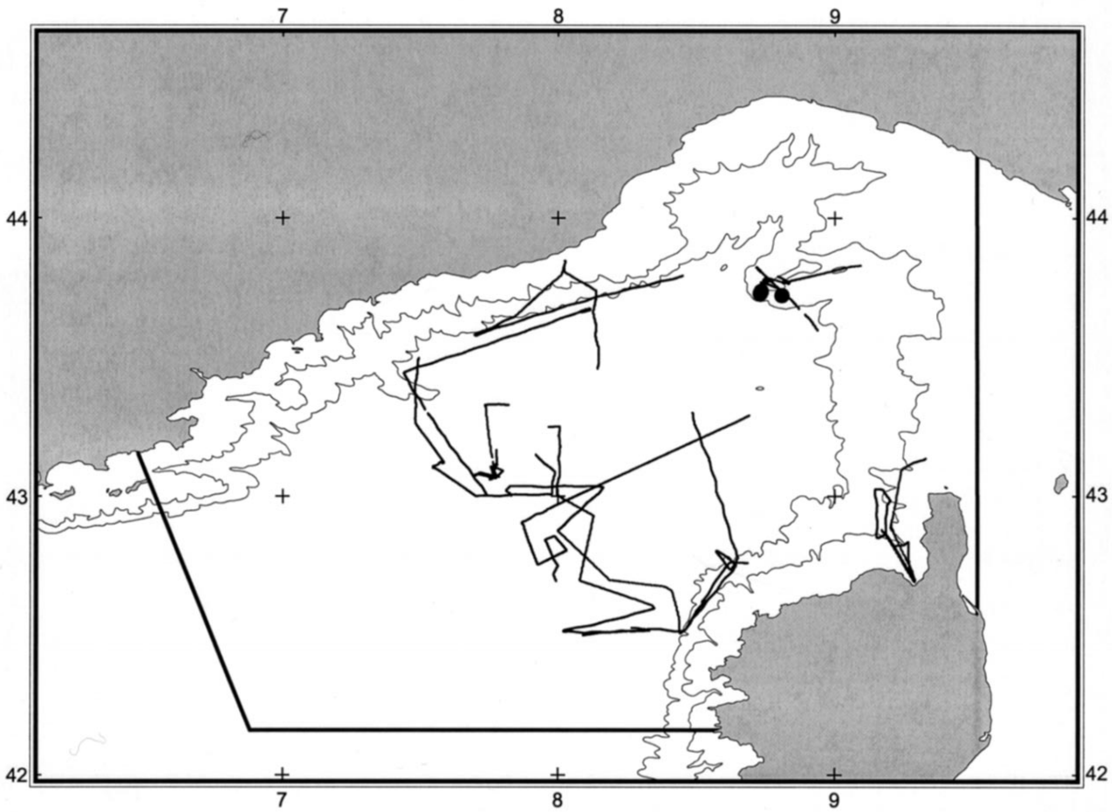


(b)

Fig. 3. (a) NRV Alliance sperm whale acoustic detections during Sirena'99. The 1000- and 2000-m bathymetric contours are shown. (b) NRV Alliance (black thick line for day tracks, gray thick line for night tracks, black circles for visual, white circles for acoustics) and Nave Magnaghi (thin line, black squares) sperm whale visual sightings and acoustic detections during Sirena'00 Phases 1 and 2. Ship's daytime tracks are shown to indicate regions where visual observations were made. The 1000- and 2000-m bathymetric contours are shown.



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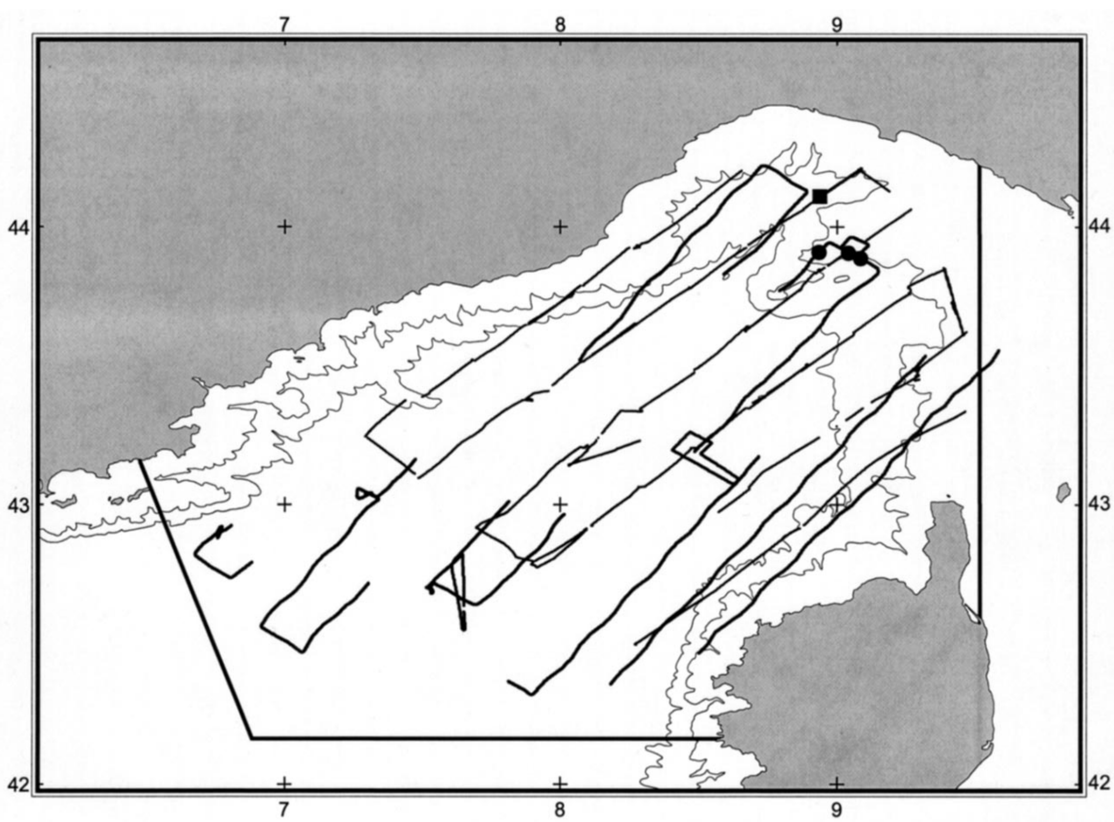
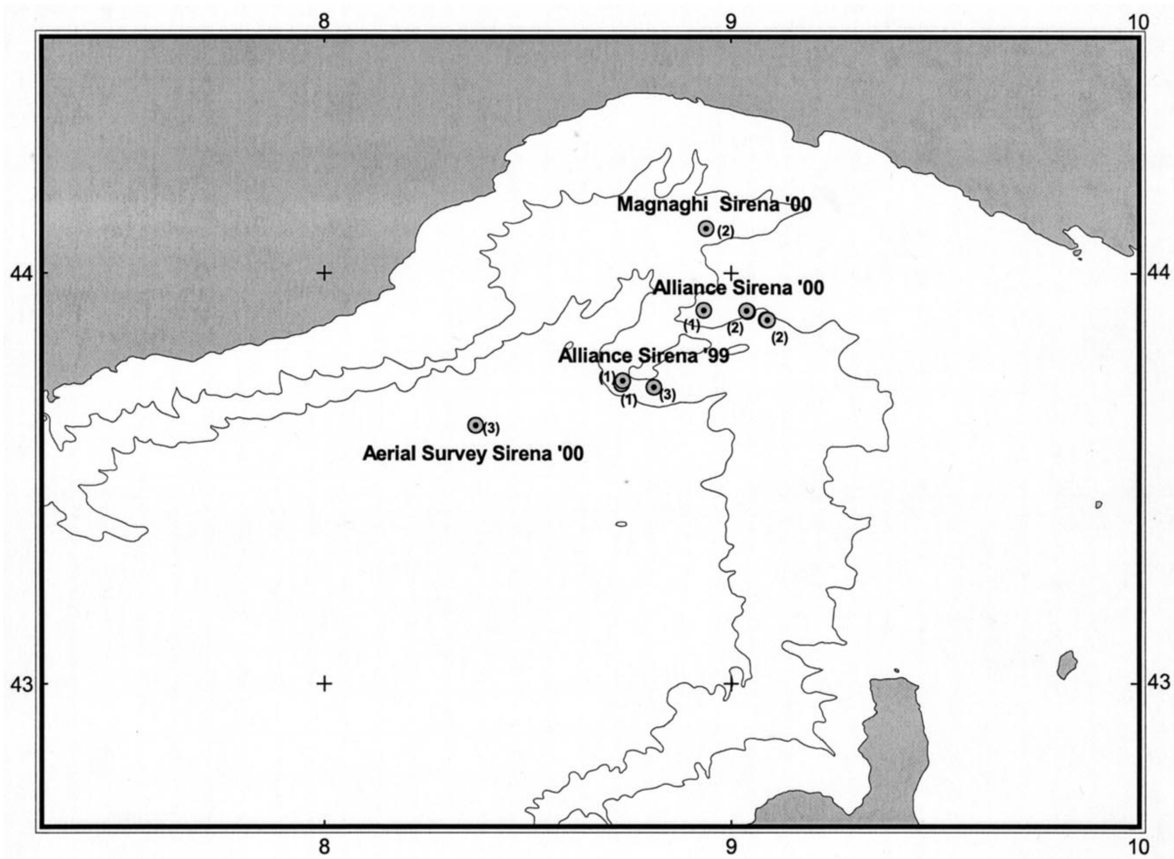


(b)

Fig. 4. (a) NRV Alliance Cuvier's beaked whale visual sightings during Sirena'99. Ship's daytime tracks are shown to indicate regions where visual observations were made. The 1000- and 2000-m bathymetric contours are shown. (b) NRV Alliance (thick line, black circles) and Nave Magnaghi (thin line, black squares) Cuvier's beaked whale visual sightings during Sirena'00 Phases 1. Ship's daytime tracks are shown to indicate regions where visual observations were made. The 1000- and 2000-m bathymetric contours are shown.



(c)

Fig. 4. *(Continued)*(c) Group sizes of Cuvier's beaked whale sighted during Sirena'99 and'00. The 600-, 1000-, and 2000-m bathymetric contours are shown.

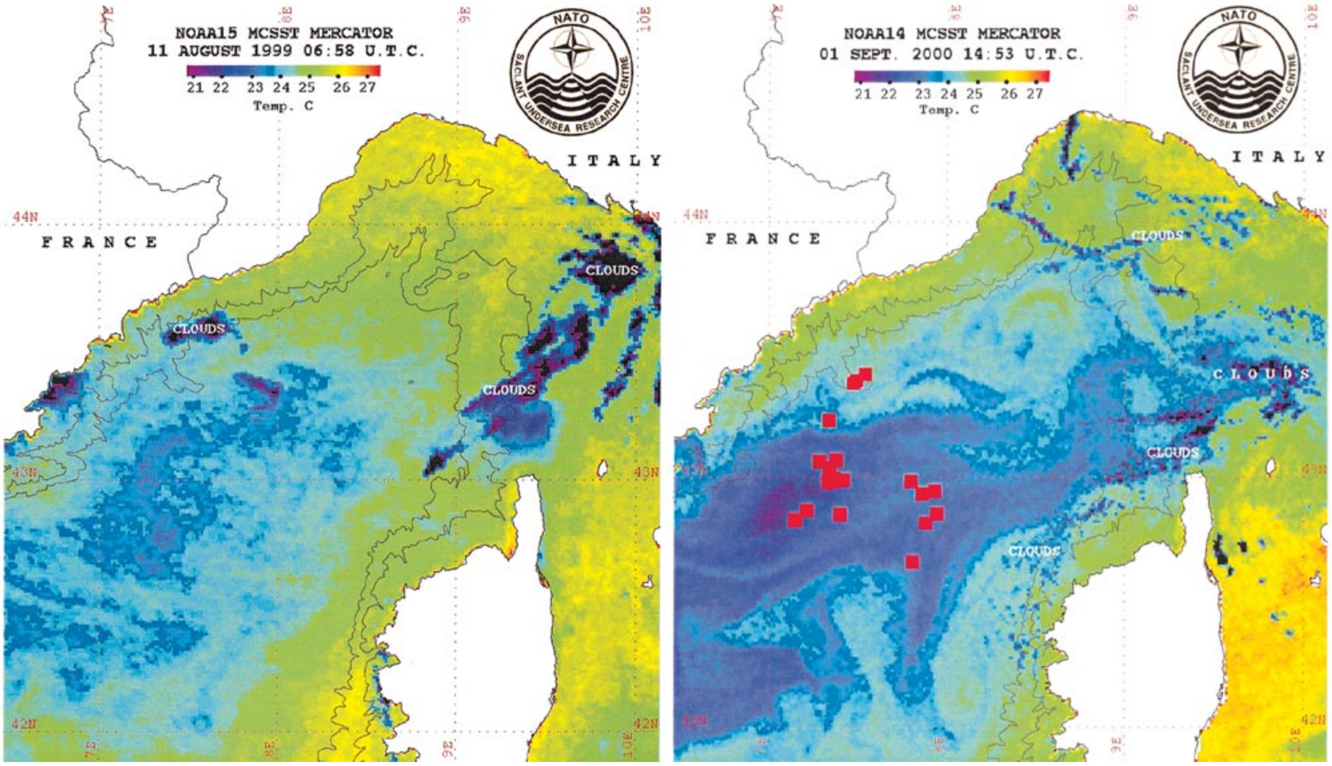
B. Remote Sensing

Satellite remote sensing provides a wide variety of oceanographic parameters such as sea-surface temperature, surface currents, surface roughness, and ocean color. As satellite data are available routinely, the focus of this analysis is to explore if the satellite data can indicate nutrient-rich regions in areas where the oceanography is known and to determine if these regions of higher productivity, coupled with knowledge of cetacean presence from all available sources, could be used as an indicator of mammal presence for acoustic risk mitigation purposes.

During Sirena'99 and Sirena'00, remotely sensed data from Sea-Viewing Wide Field of View Sensor (SeaWIFS) ocean color and Advanced Very High Resolution Radiometer (AVHRR) sea-surface temperature sensors were collected and processed at SACLANTCEN. These data were used to help understand mesoscale physical and biological oceanographic patterns in the Ligurian Sea during the time frame of the field trials. Areas of upwelling can be located on AVHRR images by cooler sea-surface temperature signatures. SeaWIFS produces daily images of chlorophyll-a (chl_a), a proxy for phytoplankton biomass, which can show regions of high biological productivity. Representative ocean color and sea-surface temperature images for both Sirena'99 and Sirena'00 are presented in Section III-B. The images selected as representative were taken on relatively cloud-free days, and depict the general features present during the time period of the cruises. These images have been geo-referenced so that the surface data could be compared with the measured oceanographic conditions and the cetacean presence recorded during the cruises. The sea-surface temperature and the ocean color (mg/m^3 of chl_a) have been processed on the same color scale, respectively, so that the images obtained during both years can be compared.

C. Oceanographic Parameters

The general circulation of the Ligurian basin is the combined result of two major branches of waters, the West Corsican Current, and the Tyrrhenian Current flowing through the Corsica Channel. Several authors have pointed out how mixing and turbulent instabilities can be detected in this merging zone, roughly located at north of Capo Corso [29], [30]. In this area, a frontal region is commonly found at the limit of the cold core of the cyclonic Ligurian Sea circulation, and of the warm waters moving parallel to it. The influence of the eastern branch of water coming from the Tyrrhenian can be traced, on average, by the surface water of the Ligurian Sea, as it is fresher and cooler (and therefore denser) than the Tyrrhenian Sea. When these water masses join together, they create a cyclonic pattern in the Gulf of Genoa that eventually enters the Gulf of Lions. This pattern may be seasonally persistent, however, the current variability in the Ligurian Sea has been shown [31] to have a



(a) (b)

Fig. 5. (a) Representative AVHRR sea-surface temperature for the Ligurian Sea during Sirena'99 (August 11, 1999). Cloud coverage shown in black. Data courtesy of F. Askari, authorized NASA/SeaWIFS Research Ground Station). The 1000- and 2000-m bathymetric contours are shown. (b) Representative AVHRR sea-surface temperature for the Ligurian Sea during Sirena'99 (September 1, 2000). Cloud coverage shown in black. Data courtesy of F. Askari, authorized NASA/SeaWIFS Research Ground Station). Locations of sperm whale visual sightings shown as red squares. The 1000- and 2000-m bathymetric contours are shown.

sudden increase in the flow along the coastal and central part of the basin that has no counterpart increase along the west coast of Corsica.

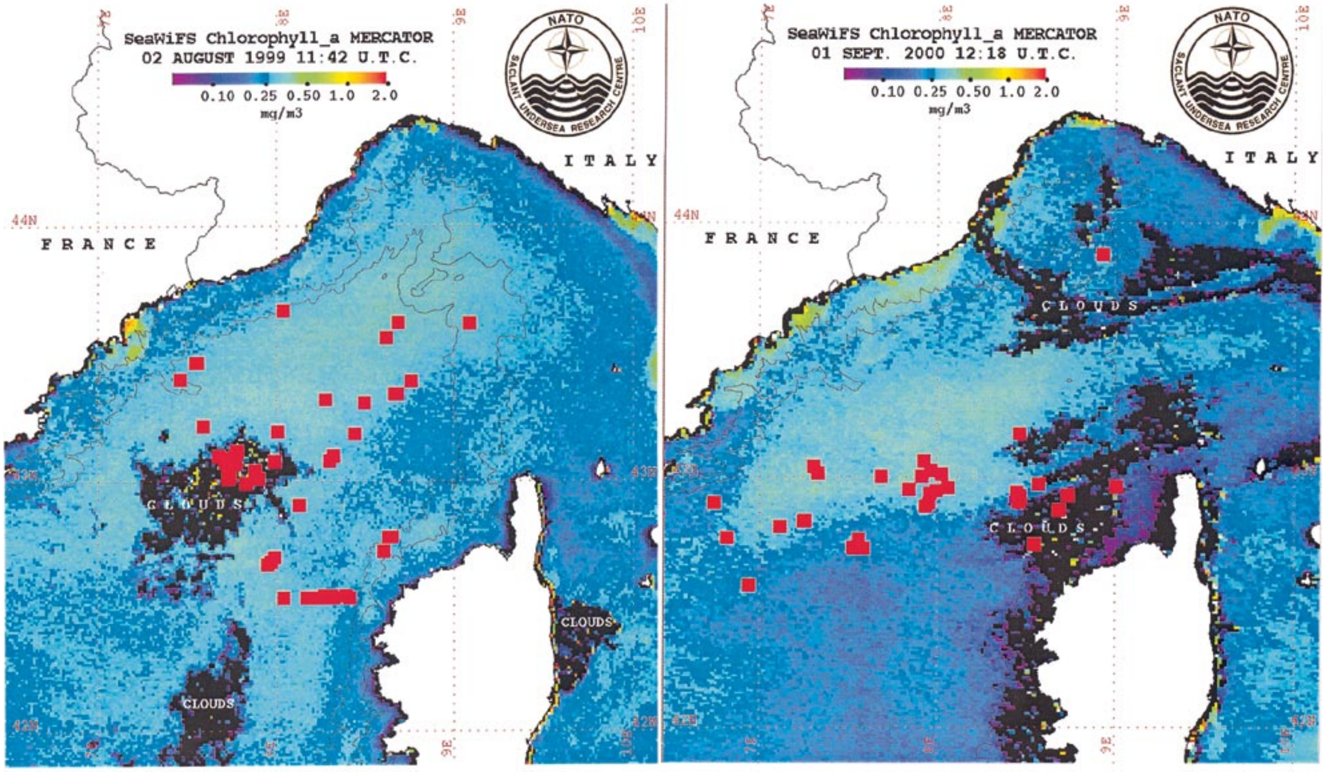
The bathymetry of the Corsican channel acts as a strong constraint for the flow between the Tyrrhenian and Ligurian seas. The predominant direction of the currents is northward with a seasonally varying intensity. It seems that transport during winter time accounts for more than half of the total annual value, and therefore, the exchange between the Tyrrhenian and the Ligurian Sea occurs during the six months of weak stratification conditions [32].

Even if a general clockwise wind circulation is accepted, winds in the area are known to be quite irregular. A statistical analysis of the wind measured at Genoa station shows that winter winds are generally south–southeast, therefore reinforcing the cyclonic circulation. In summer, the prevailing winds are generally from the north and tend to modify the existing circulation in the area. Nevertheless, the winds are heavily influenced by local topography [32] so that a southward surface circulation is possible even though it is not very frequent.

In situ measurements of temperature, salinity and fluorescence as a proxy for chlorophyll and dissolved oxygen (Sirena'00 only) were made from the Nave Magnaghi at each station shown in Fig. 1. An Idronaut 317, the conductivity, temperature, depth (CTD) sensor with a seapoint fluorometer calibrated at SACLANTCEN was used in Sirena'99. In Sirena'00 Phase 1, a SEACAT CTD sensor was provided by Istituto Centrale per la Ricerca Applicata al (ICRAM) with a fluorometer provided by BAE Systems and calibrated by the manufacturer. In Phase 2, a SEABIRD CTD was deployed, with optical sensors. All CTDs used were calibrated at SACLANTCEN. *In situ* vertical profiling provides integrated biological and hydrographic feature resolution that cannot be detailed with satellite imagery. In Sirena'99 and Sirena'00 Phase 1, the maximum depth of each CTD cast was 600 and 450 m, respectively. These data were contoured on a geo-referenced horizontal plane to determine the horizontal extent of the upper water masses. The near-surface water-mass distribution is compared to the remotely sensed values and the cetacean visual sightings made when the animal was on the surface to determine if there is a correlation between the oceanographic features and animal presence.

D. Deep Oceanographic Parameters

The superficial water present in the Ligurian Sea is modified Atlantic water, usually called local Atlantic water (LAW). It enters the area both from the western side (brought in by the Western Corsican Current along the west coast of Corsica, coming from the Algero-Provencal basin), and along the eastern Tyrrhenian side (through the Corsica Channel) as well [33]. Usually, this water type extends from the surface to a 100–200-m depth region [29], [32], and its thickness varies



(a) (b)

Fig. 6. (a) Representative SeaWIFS ocean color for the Ligurian Sea during Sirena'99 (August 2, 1999). Cloud coverage shown in black. Data courtesy of F. Askari, authorized NASA/SeaWIFS Research Ground Station). Locations of fin whale visual sightings shown as red squares. 1000- and 2000-m bathymetric contours are shown. (b) Representative SeaWIFS ocean color for the Ligurian Sea during Sirena'00 (September 1, 2000). Cloud coverage shown in black. Data courtesy of F. Askari, authorized NASA/SeaWIFS Research Ground Station). Locations of fin whale visual sightings shown as red squares. The 1000- and 2000-m bathymetric contours are shown.

with the season. Surface waters mix together in the Ligurian current that afterwards moves in the prevalent southwest direction following the continental shelf of the Gulf of Lions, becoming cooler and being mixed by wind events.

The intermediate water of the Ligurian Sea is the Levantine intermediate water (LIW) that enters via two paths that seem to have common origin [33]. After having crossed the Strait of Sicily, a part of the LIW flow directly enters the Ligurian basin moving along the Tyrrhenian coast [34], while a portion of it is deviated by the east coast of Corsica and, flowing around Sardinia, enters again the Ligurian Sea along the west Corsican coast [35]. The LIW water is characterized by a maximum of temperature (13.6 ° C) and salinity of 38.5 practical salinity units (PSU) and can be detected usually within a 300–600-m depth. Its thickness is usually diminished in the central area of the Ligurian basin, confirming the presence of a cyclonic circulation gyre, where it can be detected within 200–300-m depth. The remaining water is the deep Mediterranean one (from about 600–800 m depth to the bottom), which probably has local origin.

Several deep CTD transects were conducted in Sirena'00 Phase 2, in which CTD data were collected to a maximum depth of 1500 m. In addition to measurements of temperature, salinity, and dissolved oxygen along these transects, optical parameters of turbidity and transparency were measured with a transmissometer. Turbidity is an indicator of the scattered light due to suspended particles and is measured in formazine turbidity units (FTU), Transparency is an indicator of the water opacity, the sum of the effects of absorption and scattering at visible light wave lengths (660 m).

III. Sirena'99 and Sirena '00 Observations

A. Cetacean Sightings

Visual observations of fin whales made from the NRV Alliance and the Nave Magnaghi during Sirena'99 and'00 are shown in Fig. 2(a) and (b), respectively. As the plots indicate, during the late summer time frame, fin whales were often sighted primarily in the deeper portion of the basin, in water depths of 2000 m or greater. These observations are consistent with other published sighting data [24]. However, during Sirena'99, the Nave Magnaghi observed fin whales much further to the east than observed in Sirena'00.

The western edge of the operating area was also the primary area for visual and acoustic observations of sperm whales. Fig. 3(a) and (b) summarize the visual and acoustic sperm whale detections made during Sirena'99 and Sirena'00 respectively. In Sirena'99, although no sperm whale visual observations were made from either vessel, some acoustic detections were made from the NRV Alliance. During Sirena'00 Phase 1, acoustic and visual sperm whale detections made from the NRV Alliance. No dedicated acoustic survey was performed during Sirena'00 Phase 2, so only the visual sightings along the track line are shown. The Nave Magnaghi had sperm whales

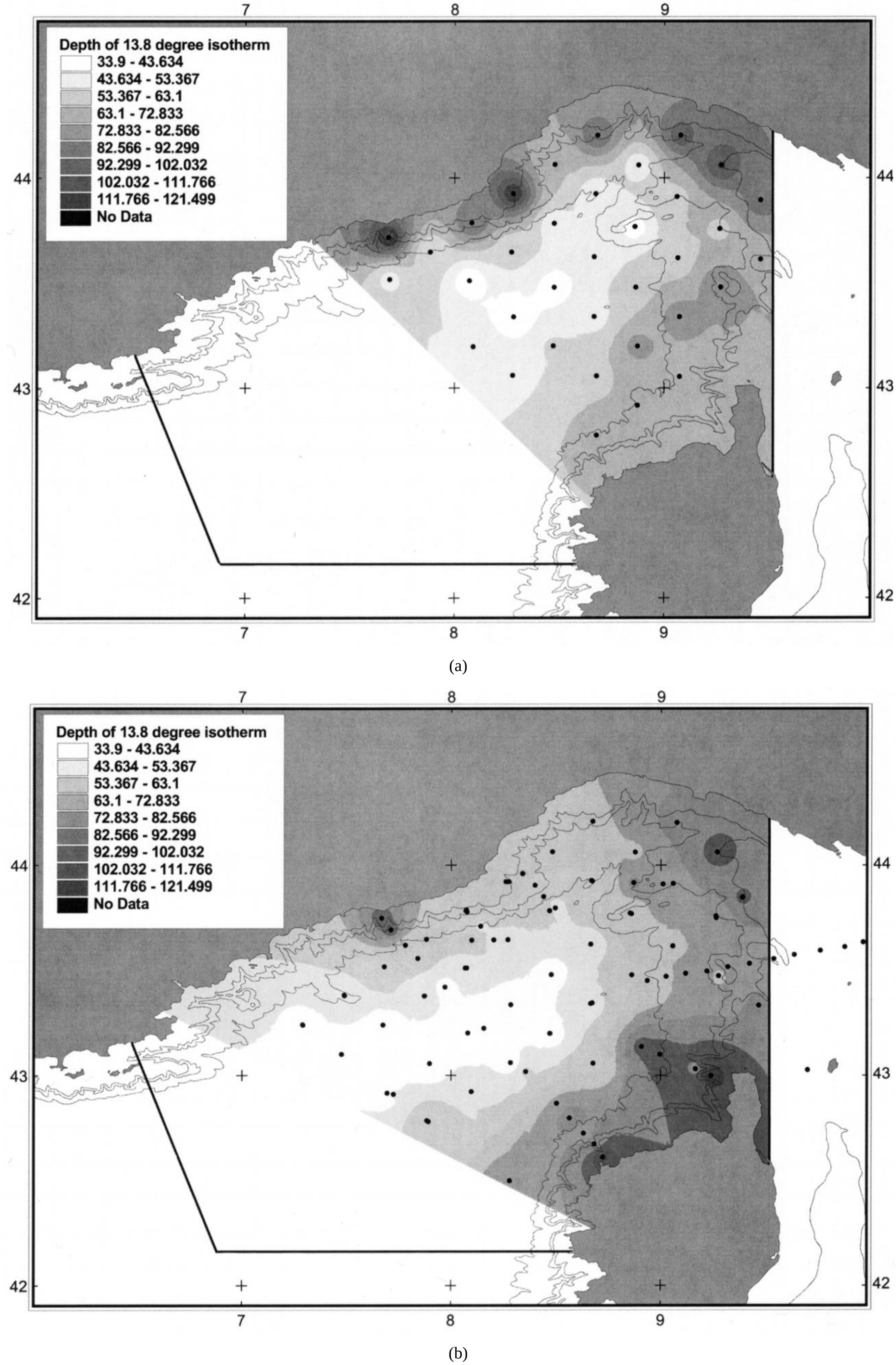
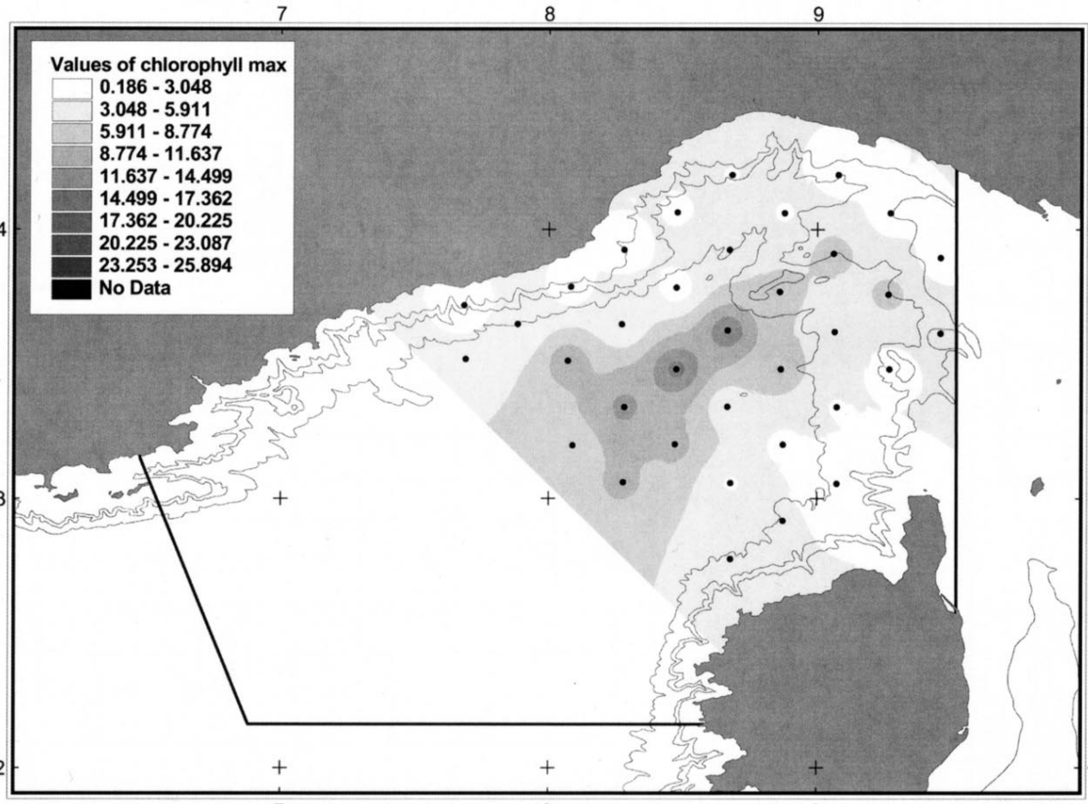


Fig. 7. (a) Sirena'99 depth (m) of the 13.8 °C isotherm. (CTD station locations shown as black dots.) (b) Sirena'00 depth (m) of the 13.8 °C isotherm. (CTD station locations shown as black dots.)



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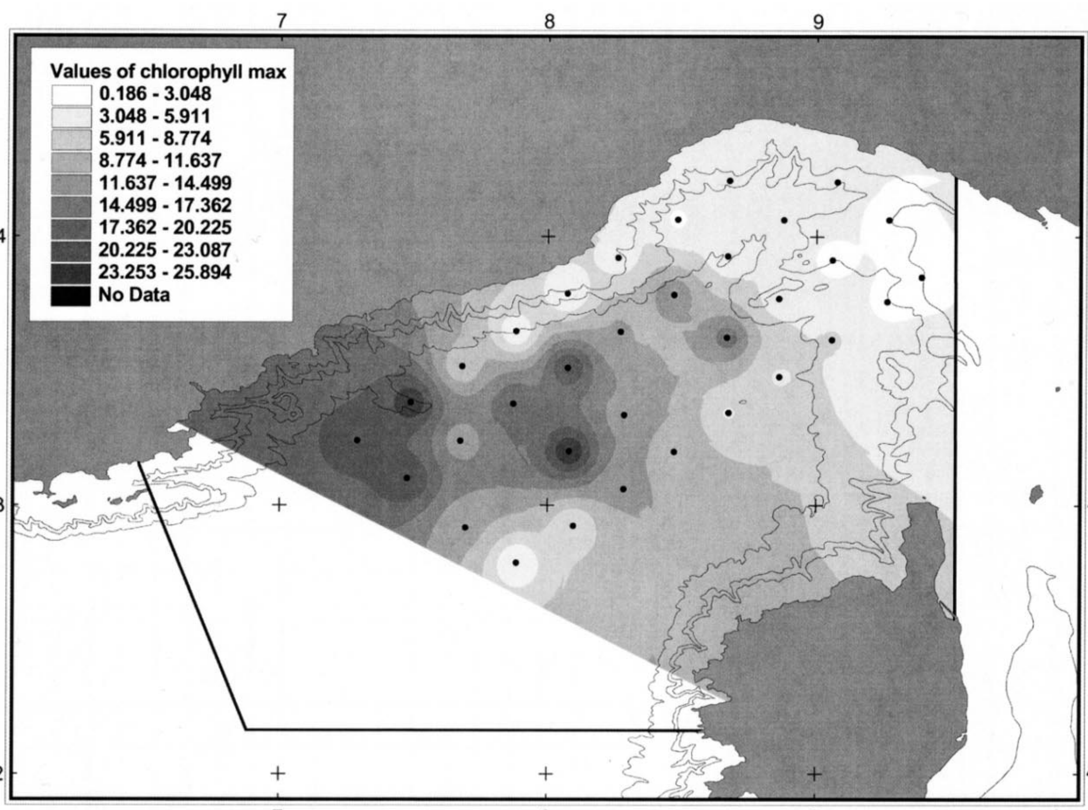

(b)

Fig. 8. (a) Sirena'99 measured maximum values of chl_a (mg/m^3, CTD station locations shown as black dots). (b) Sirena'00 measured maximum values of chl_a (mg/m^3, CTD station locations shown as black dots).

visual sightings during Sirena'00 only. As with fin whales, the predominant locations of the sperm whale were in the deeper western portion of the basin, which is also consistent with published sperm whale acoustic presence results [36].

During both cruises, the presence of the large fin and sperm whales tended to be concentrated in the deep portion of the basin. Sperm whales tended to be found further toward the western edge of the operating area. In contrast to the predominance of sperm and fin whales in this region, visual observations of Cuvier's Beaked Whale, were less frequent during both cruises and occurred only in one localized canyon region. Sightings were made from the NRV Alliance only in Sirena'99 and from both vessels in Sirena'00 as shown in Fig. 4(a) and (b). Cuvier's beaked whales were sighted in this region by the marine patrol aircraft during Sirena'00 in this canyon. Fig. 4(c) shows the number of animals (group size) associated with each stranding. It has been noted [28] that Cuvier's beaked whales prefer regions of steep bathymetry for their habitat. In the Ligurian Sea, it seems that the canyon region off Genoa is their preferred habitat, based on the observations from the Sirena cruises and other unpublished sources.

B. Remote Sensing

Daily sea-surface temperature maps can detail surface current patterns and define water mass motion within a basin. Fig. 5(a) and (b) shows representative sea-surface temperature for the Western Mediterranean Sea region during Sirena'99 and Sirena'00, respectively. During this time of year, the surface current flows from the Gulf of Lyons into the Ligurian Sea. Areas of upwelling may be identified by colder surface water temperature. Colder water may be drawn to the surface due to currents resulting from offshore winds and can carry nutrients to the surface which can facilitate phytoplankton growth. The Sirena'99 image was taken on August 11, 1999 at the end of the cruise period. The Sirena'00 image was taken September 1, 2000 during the middle of the cruise period. Both images show cold surface water concentrated in the center of the deep basin, where most of the cetacean sightings occurred. While both images show the region of upwelling as a region of cooler surface water, the sea-surface temperature in September 2000, is cooler, with the cooler surface water extending through a larger portion of the basin. This cooler water may be due in part to this image having been obtained later in the summer than the Sirena'99 image.

For both cruise periods, the regions of colder surface waters in the Ligurian Sea tend to be correlated with higher levels of chl_a as measured by SeaWIFS during both the Sirena'99 (taken August 2, 1999) and Sirena'00 (taken September 1, 2000) cruises, as shown in Fig. 6(a) and (b), respectively. In 1999, the higher surface chlorophyll values are more uniformly spread throughout the basin, while in 2000, the higher values are concentrated in the northern portion of the basin. This may be consistent with the predominant southwesterly winds [37] measured during Sirena'00. The wind patterns observed during Sirena'00 were more typical of wintertime conditions described in Section II-C. Based on this observation, the surface water temperature may be a marker for high chl_a values in the Ligurian Sea, although there may be a lag between the maximum chl_a values and the sea-surface temperature. It has been suggested [38] that an algal bloom develops in this region beginning in mid April extending into May. From mid May through September, the situation remains constant. The Sirena images suggest high levels of chl_a, which may be a result of this seasonal bloom. Both the SeaWIFS and the AVHRR images can be used to give an overview of the predominant oceanographic and biological features of a region.

C. Oceanographic Parameters

The depth of the 13.8 °C isotherm was selected as a marker to denote the base of the thermocline, below which the temperature remains generally constant. This depth shallows in the region of upwelling due to the doming effect and is indicated by the rise in depth of the 13.8 °C isotherm. The colder, nutrient-rich water rises to the surface in the center of the Ligurian Sea as a result of the cyclonic flow. The geo-referenced contour plot of the depth of this isotherm is shown in Fig. 7(a) for Sirena'99, and Fig. 7(b) for Sirena'00. In Sirena'00, the lower portion of the thermocline is shallower, indicating colder water nearer to the surface over a much larger area. The area of upwelling is consistent with the cold surface water shown in the satellite images shown in Fig. 5(a) and (b). The water in the center of the basin is cooler in Sirena'00, which, as mentioned in Section II-B, may be due to a combination of the predominant wind direction and the measurements being taken later in the summer. Comparing the distribution of the sperm whales, it is interesting to note that there were many sperm whale visual sightings and acoustic detections in the western central portion of the basin in 2000, when the surface and subsurface water was cooler.

When compared to the 2000 conditions, the cooler surface water seen in the satellite images in 1999 was further to the west and may indicate cooler subsurface water as well. In 1999, there were no sperm whale visual sightings, and only very limited acoustic detections. Possibly, the sperm whales may have been further west in the cooler water, however, this area was outside the operation box so there is no sighting information to confirm this hypothesis.

Fluorometer measurements were taken at each CTD station from the Nave Magnaghi during Sirena'99 and Sirena'00 Phase 1. *In situ* fluorescence is treated as a proxy for chlorophyll, which, in turn is treated as a proxy for phytoplankton abundance [39]–[41]. Small zooplankton feed on phytoplankton and fish, and larger zooplankton depend on small zooplankton. Further analysis is currently underway to look at the distribution of the low- and middle-trophic level dependencies and will be reported separately [37]–[39]. For purposes of this analysis, the distribution of the maximum value of chl_a is compared to both the satellite observations and the locations of the cetaceans. Fig. 8(a) and (b) shows the peak chlorophyll levels (mg/m^3) measured in Sirena'99 and Sirena'00 respectively. For both years, the maximum abundance of chlorophyll is consistent, both in depth and location, with the shallower thermocline [37], [39]–[41]. This suggests the upwelling caused by the cyclonic flow in the Ligurian Sea brings the colder nutrient-rich water closer to the surface, which in turn causes an increase in phytoplankton levels. As these measurements were taken in the summer, this may be the result of the late season algal bloom suggested in [38].

The sperm whale surface sightings indicate a higher presence of animals in the operational area in late summer 2000, consistent with cooler surface and subsurface temperatures. Fin whales were sighted well into the center of the basin in 1999, consistent with the location of the higher chl_a maximum values.

During 2000, the maximum values of chl-a were further to the northwest of the basin. While the chl_a values in the center of the basin were similar to the 1999 values, it appears that the fin whales may be seeking the region of upwelling where the high chl_a values indicate higher productivity.

IV. Discussion

Both Sirena trials have shown that the large (sperm and fin) whales were predominately found in the deeper portion of the basin where the doming effect caused by the counter clockwise current causes upwelling of the nutrient-rich deep water. A qualitative correlation has been shown between the distribution of three species of cetaceans and the physical features of the study area using geo-referenced images. Wide-area distribution of sea-surface temperature and chl_a can be estimated from satellite imagery. This distribution has been found to be consistent with the subsurface measured values of these parameters collected in the late summer during the Sirena cruises. Knowledge of historical oceanography and whale sighting data coupled with satellite images give an indication of marine mammal presence in the Ligurian Sea, as demonstrated during late summer conditions measured during the Sirena trials. Other parameters such salinity, dissolved oxygen, and nutrients can only be measured *in situ*, and potentially modeled by ocean circulation and ecosystem models. Geo-referencing of all the data collected allows fusion of the parameters on a spatial scale. Considering the data in this way, the interrelationship of the biological and physical observations can be observed.

Fig. 5(a) and (b) shows the visual sightings overlaid on the representative satellite sea-surface temperature images for the Ligurian Sea for Sirena'99 and Sirena'00, respectively. As discussed in Section III-C, the sperm whale distribution was consistent with the cooler water temperature temperatures observed in 2000. No sperm whales were sighted in 1999. The location of the Cuvier's beaked whale sighting both years was in the canyon off shore of Genoa. While little is known about Cuvier's beaked whale distribution in the Mediterranean Sea, it has been suggested that they prefer regions of steep bathymetry and possibly where there is a frontal zone that produces an enrichment of biomass [11], [13], [42]. Mediterranean submarine canyons have been noted as areas where there has been a coupling between mesoscale processes and time–space plankton distributions [43]. While no definitive characterization of beaked whale habitats exists, their occurrence in the vicinity of the same submarine canyon for two successive years is significant. As photo identification was not made, it is not possible to determine if the same animals were sighted each year.

Fin whales are planctivorous cetaceans. Their locations during the Sirena trials correlated well with the location of the higher chl_a values. Fig. 6(a) and (b) shows the satellite ocean color with the visual sightings from both cruises. During both trials the fin whales were located in the center of the basin, consistent with the regions of higher chl_a, indicating regions of higher productivity.

V. Conclusion

To support acoustic risk mitigation, it is useful to learn how ocean dynamics affect the distribution and behavior of whales and the organisms forming the food web upon which the whales feed. Data from the Sirena sea trials provide a multiyear, integrated data set to explain the distribution of mammals in specific locations based on oceanographic, biologic, and hydrographic parameters. In late summer, cooler sea-surface temperature data positively correlated with high levels of chlorophyll production as seen by remotely sensed images. These data correlated well with measured sub-surface levels of domed chlorophyll rich water. Coincident sightings of three species of marine mammals indicated that fin and sperm whales generally preferred the deep, nutrient-rich portion of the basin and the Cuvier's beaked whales preferred a submarine canyon where there was a frontal influence.

The trends observed in the Ligurian Sea suggest the potential for future research. Oceanographic information can be provided by oceanographic circulation models [44] that provide physical parameters such as currents, upwelling centers and water mass properties. Eventually, the ecosystem parameters such as nutrient and chlorophyll concentrations could be predicted [38], [45]–[52] from such models. These predictions, coupled with remotely sensed satellite data [52], [53], will provide clues to marine mammal distributions that support the selection of regions to conduct acoustic trials. This information has an important "Dual Use" as it can also provide support for the management of marine protected areas, such as the Ligurian sea sanctuary while also supporting NATO's objectives in developing protocols for acoustic risk mitigation.

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