Effect of anthropogenic low-frequency noise on the foraging ecology of *Balaenoptera* whales

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Abstract

The human contribution to ambient noise in the ocean has increased over the past 50 years, and is dominated by low-frequency (LF) sound (frequencies <1000 Hz) from shipping, oil and gas development, defence-related and research activities. Mysticete whales, including six endangered species, may be at risk from this noise pollution because all species produce and probably perceive low-frequency sound. We conducted a manipulative field experiment to test the effects of loud, LF noise on foraging fin blue (*B. musculus*) and (*Balaenoptera physalus*) whales off San Nicolas Island, California. Naive observers used a combination of attached tracking devices, ship-based surveys, aerial surveys, photo-identification and passive monitoring of vocal behaviour to examine the behaviour and distribution of whales when a loud LF source (US Navy SURTASS LFA) was and was not transmitting. During transmission, 12–30% of the estimated received levels of LFA of whales in the study area exceeded 140 dB re 1 μPa. However, whales continued to be seen foraging in the region. Overall, whale encounter rates and diving behaviour appeared to be more strongly linked to changes in prey abundance associated with oceanographic parameters than to LF sound transmissions. In some cases, whale vocal behaviour was significantly different between experimental and non-experimental periods. However, these differences were not consistent and did not appear to be related to LF sound transmissions. At the spatial and temporal scales examined, we found no obvious responses of whales to a loud, anthropogenic, LF sound. We suggest that the cumulative effects of anthropogenic LF noise over larger temporal and spatial scales than examined here may be a more important consideration for management agencies.

INTRODUCTION

The human contribution to ambient noise in the ocean is believed to have dramatically increased over the past 50 years (Urick, 1986; National Research Council, 1994). This contribution is dominated by low-frequency sound (LFS – sounds at frequencies less than 1000 Hz), primarily emanating from shipping, oil and gas development, defence-related activities and research (Richardson *et al.*, 1995). The vast majority of marine organisms are unlikely to be affected by human-produced LFS, but the mysticete whales may be particularly at risk. All mysticetes, including six endangered species, recorded to date produce loud, species-specific low-frequency signals and their ears are well adapted for low-frequency hearing (Thompson *et al.*, 1979; Clark,

1990; Ketten, 1992). For a few species, sounds are known to be communication signals (e.g. Tyack, 1981; Clark, 1983), and it is assumed that this is true for the other species. However, it is not yet clear if mysticete low-frequency sounds are used for other functions such as orientation, navigation, or detection of predators and prey as are the high frequency sounds in odontocetes (Norris & Turner, 1966; Watkins & Watzok, 1983). Disruption of any of these functions could interfere with normal activities and impact the reproductive success of individual whales, and ultimately populations. However, it is difficult to predict the impact of low-frequency noise on important social and ecological functions in *Balaenoptera* whales because of the paucity of data on both the function of their vocalizations and the amount of human-produced LFS in the ocean (National Research Council, 1994). For the few mysticete whales that have been extensively studied (bowhead (*Balaena mysticetus*),

humpback (*Megaptera novaeangliae*) and right (*Eubalaena glacialis*) whales), sounds are used as contact calls, mating displays, and for maintaining the cohesion of the migratory herd (Tyack, 1981; Clark, 1982; Silber, 1986; Clark & Ellison, 1989). There is also some evidence to support the use of sounds by bowhead whales in under-ice navigation (Ellison, Clark & Bishop, 1986; George *et al.*, 1989).

Two of the five species of the genus *Balaenoptera* (blue and fin: *B. musculus* and *B. physalus,* respectively) produce intense, long, patterned sequences of signals in the 10–100 Hz band which have been recorded over ranges of hundreds of miles (Watkins *et al.*, 1987; Gagnon & Clark, 1993; Stafford, Fox & Clark, 1998). While some have speculated that these signals are male reproductive displays, they are also produced during feeding and migration and during the summer months in high latitudes when animals are not believed to be breeding (Clark, 1996; Clark & Fristrup, 1997).

The paucity of data on the function of mysticete sounds, coupled with growing public concern over human-produced LF noise on the marine environment, and the difficulties encountered by public agencies responsible for regulating such sound sources underline the need for research on the effects of LFS on marine mammals. In a review of the impacts of human-produced noise on marine mammals, Richardson *et al.* (1995) noted that some marine mammals tolerate continuous sound at received level above 120 dB referenced to (re) 1 µPa, but others avoid sounds around 120 dB. They speculated that 'it is doubtful that many marine mammals would remain for long in areas where received levels of continuous underwater noise are 140+ dB at frequencies to which the animals are most sensitive.' We examined this hypothesis in a study of the response of foraging blue and fin whales to human-produced LFS at received levels in excess of 120 dB re 1 µPa.

Specifically, we examined whether periodic (not continuous) exposure to LFS levels exceeding 120 dB re 1 µPa produced by the US Navy's SURTASS LFA (Surveillance Towed Array Sensor System Low Frequency Active) sonar system caused significant changes in the abundance or distribution of whales, or the rate of their vocal activity. We examined whether disturbance reactions were elicited over time scales of several weeks, and distances of tens of kilometers. We do not address effects over shorter (hours to days, kilometers) or larger (months to years, 100s of kilometers) spatio-temporal scales. Effects at shorter scales are addressed in a separate report (Clark, Tyack & Ellison, 1998), while larger scale effects are beyond the scope of this study.

METHODS

We used a variety of techniques in combination with the US Navy SURTASS LFA sonar system to examine the effects of this human-produced LF noise on the distribution, abundance, diving behaviour and vocal behaviour of foraging blue and fin whales. The SURTASS LFA system is capable of producing 100–500 Hz sounds with received levels (RL) at ranges of 1 km or less that exceed 180 dB re 1 µPa (Clark *et al.*, 1998).

Four aspects of the natural history of whales were examined: foraging behaviour, distribution and abundance, vocal behaviour and residency. We used attached time–depth recorders, hydroacoustic surveys of prey fields, net sampling of prey with bongo nets and scat analysis to determine the distribution and abundance of prey and the diving behaviour of whales (Croll *et al.*, 1998, Fiedler *et al.*, 1998). Ship-based and aerial surveys of whales at the surface were used to examine the distribution and abundance of whales. Passive acoustic monitoring (bottom-mounted hydrophones and ship-based hydrophones) was used to measure RLs of the LFA signal and changes in whale vocal behaviour. Photo identification mark–recapture was used to ascertain whether animals located in the study area represented a limited pool of a few individuals or a larger pool of individuals moving into and out of the foraging area during the study period. All results are expressed as mean (± SD) unless otherwise noted, and all values of sound pressure level in dB are referenced to 1 µPa.

Study Area

The study was conducted in the southern California Bight near the continental shelf break west of San Nicolas Island, Channel Islands, CA (33°15′ N, 119°45′ W; Fig. 1) from 13 September through 19 October 1997. This region was selected because: (1) it has seasonally high densities of foraging whales and high rates of whale vocal activity from July into late October (Hill & Barlow, 1992; Mangels & Gerodette, 1994; Barlow *et al.*, 1995; Calambokidis & Steiger, 1995; Clark & Fristrup, 1997; Fiedler *et al.*, 1998; Curtis, Howe & Mercer, 1999), and (2) the *R/V Cory Chouest* with the SURTASS LFA sonar system was berthed nearby and could be made available by the US Navy for this research. An additional benefit was the possibility of conducting acoustic monitoring via two Navy hydrophone arrays (SOSUS) terminated on San Nicolas Island.

Prior to the arrival of the *R/V Cory Chouest* with the sound source in the study region, an area of high whale abundance and zooplankton density was identified using a combination of aerial surveys and ship-based marine mammal and zooplankton surveys (described below). This area of high foraging activity served as the primary study area for most of the subsequent research activities (Fig. 1).

Low-frequency sound source and sound levels – SURTASS LFA

The source of anthropogenic LF noise for the study was the US Navy's SURTASS LFA sonar system; a vertical line array of 18 sound transducers centered 60–180 m below the *R/V Cory Chouest*. During sound playback, the system was operated in two modes referred to here
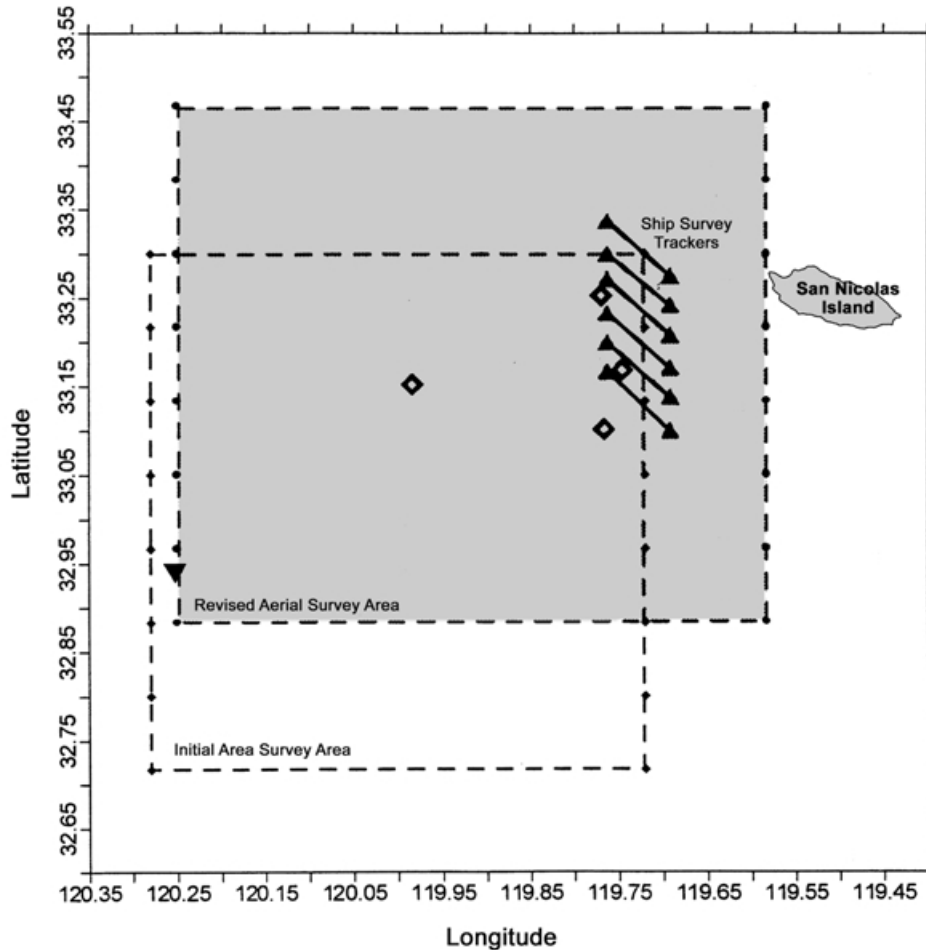
Fig. 1. San Nicolas Island, California study area. Aerial-based survey area shaded, ship-based survey track shown with lines, location of pop-up hydrophones shown by open diamonds, and location of South SOSUS array shown by closed triangle (North SOSUS array located at 33.242°N, 120.530°W).

as distant mode and approach mode (see Clark *et al.*, 1998 for details). For logistical reasons, the distant mode was only used in the morning, while the approach mode was used only in the afternoon. In the distant mode the entire 18-element array was used, generating a horizontal beam of sound energy with a vertical beam angle of approximately 5°. This beam was refracted downward due to ocean thermal structure and subsequently bounced off the sea floor and redirected to the surface at ranges varying from 11.1–16.7 km (6–9 nmi) from the vessel, dependent on the water depth. In the approach mode, only two elements of the array were used and LFS was projected omni-directionally.

Two types of LF signals were used: Low-LFS and High-LFS. Each type consisted of a sequence of nine individual sounds for a total duration of 42 s. The frequency band of the Low-LFS type was 130–160 Hz, while the frequency band of the High-LFS type was 260–320 Hz. A playback consisted of alternating transmissions of the two LFS types with transmissions occurring once every 6 or 10 min. The sound field was controlled so that the RL at whales did not exceed 155 dB re 1 µPa as estimated by the location of the *R/V Cory*

Chouest, the location of whales and the environmental transmission conditions. At the initiation of a playback series the LFS source level was 155 dB re 1 µPa, and increased by 10 dB in each successive transmission until the source level required for the initial playback transmission was reached. The source level of subsequent transmissions followed pre-selected and tabulated values (see Clark *et al.*, 1998 for details).

Playback experiments were conducted during daylight hours between 18 September and 5 October. Although the LFS playback experiments occurred on a schedule of several days with sound transmission interspersed with days of no transmissions, for the temporal/spatial scale of the study reported here the entire time period between 18 September and 5 October is considered to be the experimental period (i.e. sound stimulus present). Pre-experimental and post- experimental periods occurred from 13–17 September and from 6–19 October, respectively. The potential impact of the LFS transmissions on whales was evaluated by testing for differences in whale distribution, abundance and vocal behaviour between the three study periods (pre-experimental, experimental and post-experimental).

Sound exposure levels

Sound exposure includes the history of the experience over some period as well as the RL throughout that experience. For this study, we used RLs for LFS transmission as a proxy for exposure since it is a major component of the acoustic experience. Sound levels for each transmission were empirically measured using two calibrated hydrophones. Hydrophones were deployed to depths of approximately 10 and 85 m from an independent observation vessel, the 85′ schooner, *R/V Dariabar*. Hydrophone depths were selected as being representative of the depths of a whale travelling near the surface and a whale diving to feed. Exact depths of the RL hydrophones were monitored using an attached time-depth recorder (TDR). All data were synchronized by Global Positioning Satellite (GPS) clock and local position of the vessel was logged by GPS every 15 s.

During post-processing, the RL of each LFS transmission as recorded on the *R/L Dariabar*'s hydrophones was recomputed using the Canary sound analysis software (Charif, Mitchell & Clark, 1995). Received level was measured as the average LFS signal intensity over the 42 s transmission. For each transmission the locations of the *R/V Dariabar* and *R/V Cory Chouest* were recorded by GPS. Transmission loss predictions for each LF transmission were computed using the Navy's parabolic equation model (version 3.3) based on the positions of the two ships, the daily local sound speed profile and bathymetry. Empirical sound levels were compared to predicted levels and used to adjust model parameters so as to bring the model predictions into agreement with the empirical measurements (see Acoustic Integration Model, below).

Acoustic Integration Model

The Acoustic Integration Model (AIM) was used to estimate overall anthropogenic LF noise exposure of whales in the study region. The model integrates sound field exposure as a function of time, range and bearing to the sound source, and depth (Ellison, Weixel & Clark, 1993, 1999). Because the sound source and the whales were constantly moving during the sound exposure period, we calculated the cumulative sound field exposure for 50 randomly selected locations at depths of 50 and 200 m within the ship-based survey grid. A second cumulative sound field exposure estimate was generated in a similar manner for 50 randomly selected locations within the aerial-based survey grid. These model estimates served as measures of general sound exposure for whales in the study area. Data input to the model include sound source characteristics (for each ping: location, depth, beamwidth, bandwidth and source level), received location parameters (location and depth), and acoustic environment conditions (sound speed profile, ambient noise, bathymetry and bottom loss). Model outputs and measured RL aboard the *R/V Dariabar* agreed on an average basis within ±5 dB.

Prey type, prey-field mapping, and ocean thermal structure

The species of prey taken by whales was determined through analysis of whale faecal samples collected opportunistically with a dip net and preserved in 70% ethanol. In the laboratory, a sub-sample was taken of a well-mixed homogeneous sample and all right mandibles of euphausiids were removed and classified to species using keys developed by Kieckhefer (1992) or unpublished keys developed separately by two of us (D.A.C. and B.R.T.) from net-sampled specimens.

A total of five surveys were completed from the *R/V John Martin* between 16 September and 4 October 1997. One survey occurred during the pre-experimental period and the subsequent four occurred during the experimental period. No surveys were conducted in the post-experimental period due to severe weather conditions. The distribution of marine mammals was recorded using standardized visual survey methods. The density and distribution of prey (krill) in relation to whale distribution was recorded following the methods described by Croll *et al.* (1998).

Vertical and horizontal distributions of krill were measured along seven track lines that were 14.8 km (8 nmi) in length and separated by 3.7 km (2 nmi) at a ship speed of 10 knots (Fig. 1). Acoustic backscatter was measured using two Simrad EY-500 echosounders operated at 200 and 38 kHz. The survey area was selected as a region where both whales and krill were concentrated as determined by preliminary aerial and ship-based surveys. The echosounder systems were calibrated before and after the study using the standard sphere method (Johannesson & Mitson, 1983). Detailed descriptions of echosounder data analyses are presented in Croll *et al.* (1998) and Hewitt & Demer (1993). For statistical comparisons of prey abundance, backscattering area per 3.42 km^2 (1 nmi^2) of sea surface (s_A) was calculated from S_V values for every 0.9 km (0.5 nmi) of survey line, giving a total of 112 s_A sample units per survey. A random subset of 60 s_A values was sampled from this total to provide estimates of mean s_A for each of the five surveys for statistical comparisons. Comparisons of mean s_A values for each survey were made using Kruskall–Wallis one-way ANOVA. Multiple comparisons were made using a Dunn's test (Jandel Sigmastat V. 2.0).

Identification of krill schools in the echogram was confirmed by targeted 1 m bongo net tows. Zooplankton collected in net samples was split with a standard zooplankton splitter and sorted to major planktonic group for comparison with whale faecal samples. To relate the vertical distribution of krill to ocean thermal structure, a grid of six Conductivity and Temperature at Depth (CTD) stations were visited during the 30 September survey. Upwelling indices for the study region during the study period were downloaded from Pacific Fisheries Environmental Laboratory/NOAA web site for 33°N 119°W (www.pfeg.noaa.gov). The indices are based on estimates of offshore Ekman transport driven by geostrophic wind stress derived from 6-hourly synoptic

surface atmospheric pressure fields (Bakun & Nelson, 1991). The 5-day mean of the daily upwelling indices was calculated and plotted with a 10 day offset to account for time lags between upwelling and peak primary production.

Whale foraging behaviour

To examine whale diving behaviour in relation to prey distribution, we attached microprocessor-controlled time-depth recorders (TDRs) to two fin whales foraging in the study area (Croll *et al*., 1998). Dive depth was sampled every 1 s. Attached recorders also allowed a qualitative examination of the effects of low-frequency pings on diving behaviour.

Ship-based whale surveys

Concurrent with the collection of prey distribution, we recorded the distribution and abundance of large whales encountered along the track line using standard techniques developed by the National Marine Fisheries Service (Barlow, 1994; Croll *et al*., 1998; Fiedler *et al*., 1998). Three marine mammal observers surveyed from the track line out 90° abeam using 7×50 reticle binoculars from the flying bridge (5 m above sea level). Species, number of individuals, sighting cue, behaviour, location, time and weather conditions were recorded at the time of each marine mammal sighting. In addition, ship position along the track line was recorded every 15 min. Because all surveys were conducted in sea states of Beaufort 3 or less, no adjustments were made for sea state. Due to overall low sighting rates, density estimates typically have low statistical precision (large coefficients of variation), and the statistical power to resolve differences between estimates is generally low (Barlow, 1994). Thus, we followed Barlow's (1994) convention and calculated encounter rates (number whales per nautical mile surveyed) rather than whale densities for qualitative comparisons of whale abundance between surveys.

Aerial surveys

Aerial surveys were centred in the study area directly west of San Nicolas Island (Fig. 1). The survey grid was shifted slightly between the 17 and 19 September 1997 surveys to better centre the grid on areas with whale and prey concentrations as identified from ship-based surveys (revised Aerial Survey, Fig. 1). Eight parallel survey lines were spaced at 9.25 km (5 nmi) intervals with lines running east–west. Two pre-experimental, five experimental and two post-experimental aerial surveys were completed between 14 September and 14 October 1997.

Surveys were conducted using a twin-engine Partenavia P-68 outfitted for aerial surveys. Transect lines were flown using standard line-transect methodology at an altitude of 305 m and airspeed of 100 kts. Four personnel were used on most surveys: pilot, recorder/navigator and two side observers.

When a sighting was made, the aircraft continued on transect until the sighting was abeam and the observer had determined the angle to the sighting using a hand-held clinometer for correction of animal location relative to the aircraft track line. Biological data collected on all marine mammals sighted included: aircraft position, time, species, number of animals, perpendicular distance from the transect line, direction of travel and general behaviour.

To correlate marine mammal sightings with physical features, the survey region was subdivided into blocks that measured approximately 18.5 (10 nmi) (north–south) by 15.7 km (8.5 nmi) (east–west). Within each block, 90–119 equally spaced geographical points (depending on the size of the block) were selected and a suite of environmental parameters was assigned to each point.

The refined marine mammal positions and the block points were matched with six environmental variables using Geographic Information System (GIS) programs (Idrisi for Windows 2.0; RETRO.EXE, Ecological Consulting Inc; and ArcView for Windows 3.0). Variables included depth, percentage depth slope, sea surface temperature (SST) and nearest distances to: (1) shore (San Nicolas Island), (2) the 200 m shelf break and (3) the 2000 m isobath. Geographical and bathymetric variables were calculated from the NOS Hydrographic Survey CD-ROM (Ver. 3.3).

Daytime (approximately 22:00 GMT or 15:00 PDST) sea surface temperature (SST) images were downloaded from the NODC NOAA Coast Watch Active Access System (http://cwatchwc.ucsd.edu/cwatch.html) and georegistered. To avoid errors in SST due to sparse cloud cover, we qualitatively rated images and only used images with 20% or less cloud cover. Refined SST values were assigned to marine mammal sightings and block points for statistical comparisons.

Whale vocal behaviour

To determine changes in vocal behaviour, a measure of vocal activity was calculated as the number of species-specific whale calls per 15-min interval. Recordings were made from: (1) two permanently bottom-mounted US Navy SOSUS (Sound Surveillance System) hydrophone arrays located offshore of San Nicolas Island (see Fig. 1, Clark *et al*., 1998), and (2) four bottom-mounted autonomously recording hydrophones deployed for the study (pop-up hydrophones) (described in detail by Clark & Fristrup, 1997, see Fig. 1 for locations). Pop-ups sampled continuously at 2000 Hz, and were deployed on 29 September and recovered on 9 October. Thus, they sampled for 7 days during the experimental period and 3 days during the post-experimental period. The SOSUS arrays sampled continuously during pre-experimental, experimental and post-experimental periods.

Blue and fin whales produce long, patterned sequences of simple low-frequency sounds and can be automatically detected using recently developed techniques

(Potter et al., 1994; Mellinger & Clark, 1995; Clark & Fristrup, 1997). Data collected from pop-ups were low-pass filtered at 100 Hz and down-sampled to 250 Hz. Data from the two San Nicolas SOSUS arrays were already restricted to the low-frequency band and did not require additional pre-processing. Automatic detection of whale calls was done by counting the number of occurrences when sound energy in a whale-specific frequency band exceeded both a given threshold above ambient noise and fell within the duration range of the sound for that species. For the blue whale detector, 48–53 Hz was the frequency band representing the third harmonic of the eastern North Pacific blue whale 'B' call, and the duration range was 5–12 s. For the fin whale detector, the frequency band was 15–25 Hz and the duration range was 0.1–2 s. The proper detector threshold was established by regression analysis for 100 h of data comparing 15-min call counts as noted by two independent expert analysts and as computed by the detector. A range of detector thresholds were used: (3, 6, 9, 12, 15 and 18 dB) and the detection threshold yielding the highest regression coefficient was selected as the best threshold.

Photo-identification

Photographic identification (photo-ID) effort was conducted using standard procedures successfully employed in past research off California (Calambokidis et al., 1990, 1998a). The data were collected primarily from a 5.3 m Rigid-Hull Inflatable (RHIB) and from the R/V Dariabar, and the R/V John Martin. On the R/V Dariabar, a dedicated photo-identification specialist attempted to photograph all focal animals and as many ancillary animals as possible during all days at sea. On the R/V John Martin, a member of the research crew attempted to photograph animals during all tagging efforts. The RHIB was used to photo-identify as many animals as possible during the pre-experimental, experimental and post-experimental periods. Additional photo-ID data were also available through separate, ongoing photo-ID research conducted by Cascadia Research (Olympia, Washington) (Calambokidis et al., 1998a). Photographs of both the right and left sides of whales (where possible) were taken using 35 mm cameras with 300 mm telephoto lenses. Time, date, and location of all photographs were noted. In the laboratory, photographs were carefully scrutinized and individual whales were identified (Calambokidis et al., 1998a).

RESULTS

Sound exposure

The R/V Cory Chouest emitted a total of 586 LF sounds throughout both the ship- and aerial-based survey areas (Fig. 1). Of these, 186 and 92 LFS transmissions were measured from the R/V Dariabar shallow and deep hydrophones, respectively. All transmissions received by the R/V Dariabar exceeded 95 dB re 1 µPa (Fig. 2). The RL of most transmissions exceeded 120 dB re 1 µPa (87% and 88% in the shallow and deep hydrophones, respectively); and 42% and 16% of transmissions exceeded 140 dB re 1 µPa for the shallow and deep hydrophones, respectively. No transmissions were received that exceeded 150 dB re 1 µPa.

Received levels were estimated using the AIM model for all 586 LF transmissions emitted by the R/V Cory Chouest. For the ship-based survey area, 56% and 57% of estimated RLs exceeded 120 dB re 1 µPa for the shallow and deep locations, respectively. Also, 30% of both shallow and deep estimated RLs exceeded 140 dB re 1 µPa (Table 1). For the aerial-based survey area, 48% and 54% of estimated RLs exceeded 120 dB re 1 µPa for the shallow and deep locations, respectively, while 11% and 14% of shallow and deep estimated RLs, respectively, exceeded 140 dB re 1 µPa (Table 1).

Whale foraging

Blue and fin whales fed on dense aggregations of euphausiids off the continental shelf break west of San Nicolas Island. Hydroacoustic surveys showed that the density and distribution of these aggregations varied throughout the study period (Fig. 3). Euphausiid abundance declined from the initial survey (pre-experimental) to a low on 9/30/97, but increased substantially by the last survey (during the end of the experimental period) on 10/5/97 (Fig. 3). The decline and subsequent increase in euphausiid abundance tracked the upwelling index for the region (Fig. 3).

Directed bongo net samples of the aggregations revealed that Euphausiids were the dominant sound scatterers in the water column. A total of five Euphausiid species was found (% by number of individuals): Euphausia pacifica (46.3%), Nematocilis dificilis (40.3%), Nyctiphanes simplex (27.6%), Euphausia goboides (17%), Stylocherion spp. (6.6%). Analysis of three faecal samples collected from fin whales foraging in the study area revealed that the whales fed exclusively on four of these species and another species, Thysanoesa spinifera (% by number of right mandibles: Euphausia pacifica (47.7%), Thysanoesa spinifera (25.2%), Nyctiphanes simplex (23.6%), Euphausia goboides (1.7%), and Nematocilis dificilis (1.7%)).

Euphausiid distribution in the water column, measured through hydroacoustic surveys, had a bimodal distribution: one peak in concentration was found between 50 and 100 m, and a second peak occurred between 160 and 250 m (Fig. 4). The shallower layer was comprised of a mixture of juvenile and subadult euphausiids, while the deeper krill layer was comprised almost exclusively of adults. CTD casts made in the study area revealed a pronounced thermocline between 25–50m. The upper layer of juvenile and subadult krill was found just below this thermocline (Fig. 4).

Tags were attached to foraging whales for 9 and 26 hours on 9/21/97 and 10/4/97, respectively. The distribution of whale foraging dives mirrored the distribu-
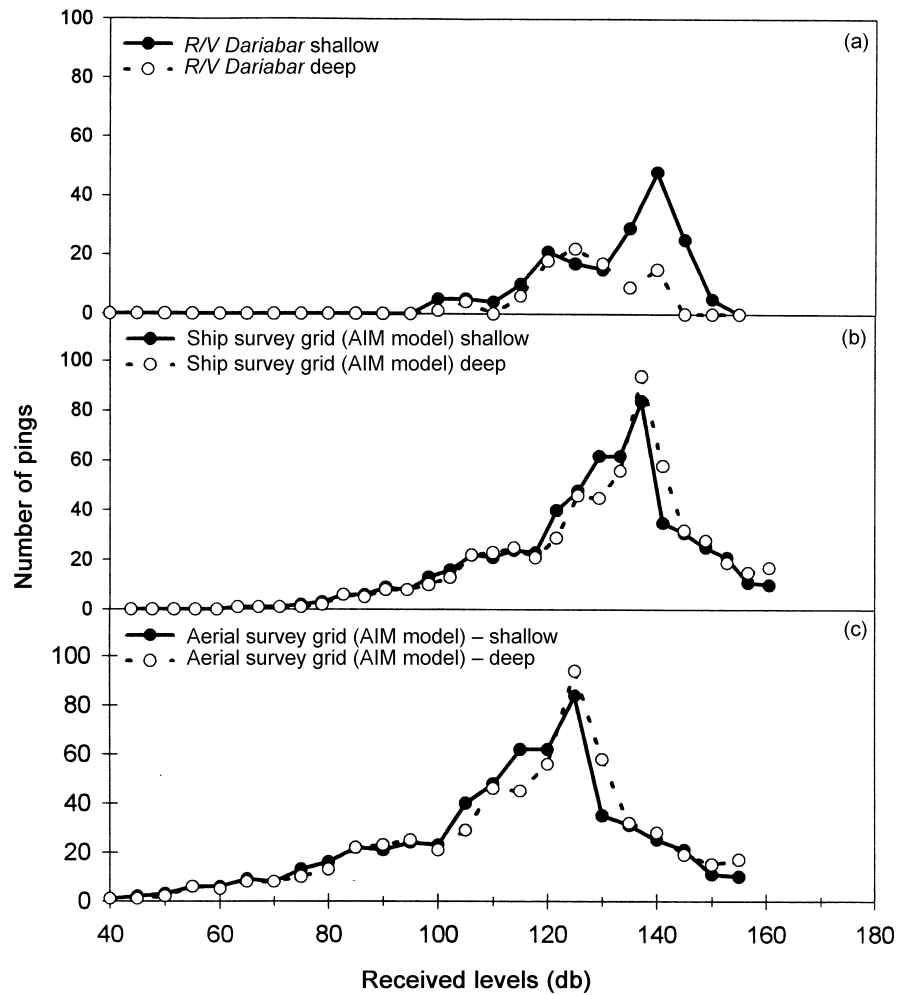
Fig. 2. Levels of anthropogenic LF noise (a) received by *R/V Dariabar* (ship-based) in San Nicolas Island, California study area, (b) estimated for the ship-based survey area using an acoustic integration model (AIM), and (c) estimated for the aerial-based survey area using an acoustic integration model (AIM). The shallow hydrophone was towed at 10 m, the deep hydrophone was towed at 83 m. The acoustic integration model (AIM) was run for shallow (50 m) and deep (200 m) depths

Table 1. Measured (*R/V Dariabar*) or estimated (AIM model) received levels of anthropogenic low frequency noise in the ship-based and aerial-based survey regions off San Nicolas Island, CA

Location	No. pings ≥ 120dB (%)	No. pings ≥ 140db (%)	Total no. pings
R/V Dariabar (measured) – shallow	160 (87.0)	78 (42.4)	184
R/V Dariabar (measured) – deep	81 (88.0)	15 (16.3)	92
Ship survey (AIM model) – shallow	330 (56.3)	175 (29.9)	586
Ship survey (AIM model) – deep	335 (57.2)	173 (29.5)	586
Aerial survey (AIM model) – shallow	279 (47.6)	66 (11.3)	586
Aerial survey (AIM model) – deep	319 (54.4)	79 (13.5)	586

See Methods for detail of measurement and model

tion of krill in the water column, with one peak around 75 m and a second peak between 200–250 m (Fig. 4).

Whale distribution and abundance

A total of 518 km (280 nmi) of survey lines were covered during the five shipboard visual surveys. During these surveys a total of 33 cetacean groups were sighted representing an estimated 1338 individuals. Of the 33 sightings, 22 (66.7%) were rorquals (*Balaenoptera* spp.),

six (18.2%) were common dolphins (*Delphinus delphis*), three (9.0%) were Pacific white-sided *dolphins (Lagenorhynchus obliquidens)*, and two (6.1%) were unidentified odontocetes. Low sighting rates of rorquals precluded statistical comparison of survey data, but rorqual encounter rates were generally low during the pre-experimental and most of the experimental period. We observed a substantial increase in rorqual encounter rate on the last survey conducted during the experimental period (Fig. 3). The pattern of rorqual encounter rates
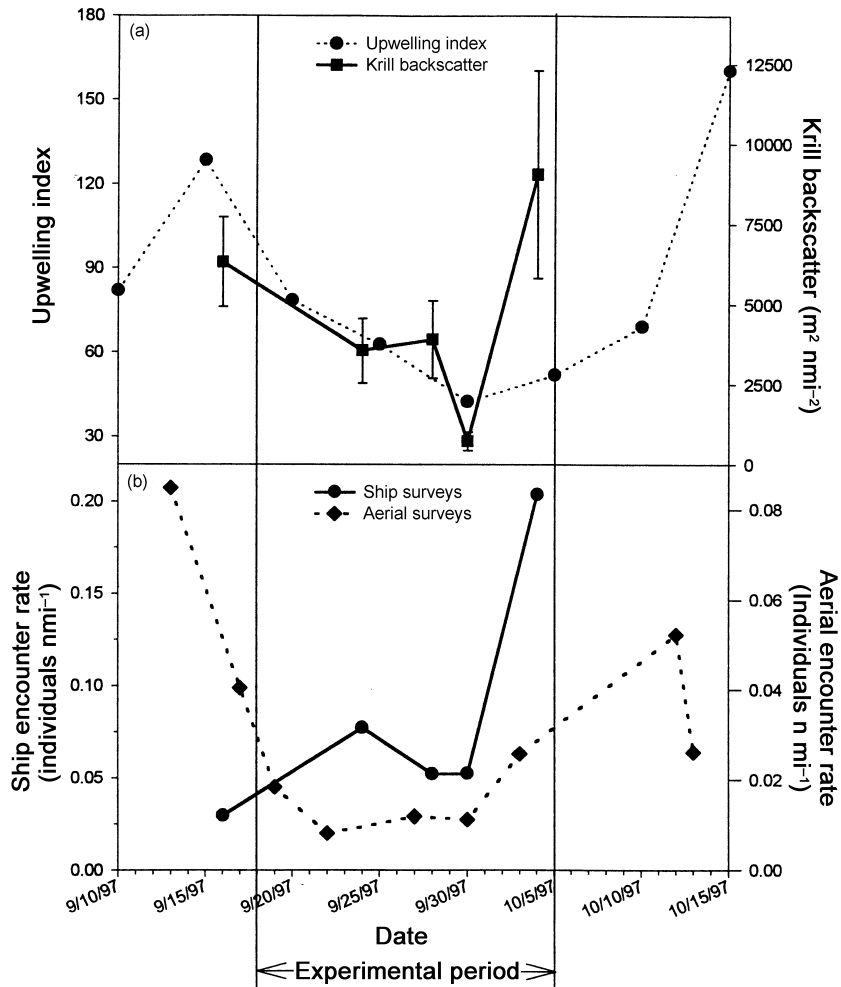
Fig. 3. (a) Bakun upwelling index (dotted line) and krill backscatter (continuous line), (b) whale encounter rate in ship surveys (continuous line) and whale encounter rate in aerial surveys (dotted line) measured before, during, and after exposure to human-produced LFS in the vicinity of San Nicolas Island, California.

during the study period generally tracked the abundance of krill in the survey area (Fig. 3).

Nine complete aerial surveys were conducted out of 11 that were initiated totalling 4568 km (2469 nmi) of on-effort flying. Two surveys were completed during the pre-experimental period (808 km), five during the experimental period (2285 km), and two during the post-experimental period (934 km). A total of 92 sightings of 4410 cetaceans representing at least seven species were made during all 11 aerial surveys (% of all sightings): rorquals (blue, fin and unidentified large whales) (52.2%), unidentified dolphins (33.7%), common dolphins (*Delphinus delphis*) (4.3%), bottlenose dolphin (*Tursiops truncatus*) (4.3%), Risso's dolphin (*Grampus griseus*) (3.3%), Baird's beaked whale (*Mesoplodon bairdii*) (1.1%), and Northern right whale dolphin (*Lissodelphis borealis*) (1.1%). Sightings of fin whales were the most common and included 33 sightings out of 50 whales. Blue whales were seen less frequently and included only seven sightings of seven animals.

Due to the low number of rorqual sightings, statistical power to detect significant differences between experimental periods was low. However, sighting rates

generally declined from the pre-experimental period through most of the experimental period. Late in the experimental period, however, rorqual encounter rate increased, concurrent with the late September increase in krill abundance (Fig. 3). Whale abundance was generally higher through the end of the post-experimental period, concomitant with the abrupt increase in upwelling in early October (Fig. 3). Sightings of whales were generally concentrated in the central and north-central portion of the revised study area (Fig. 5). While we observed no dramatic shift in distribution within the study area in relation to sound transmissions, during the course of the study period, aerial sightings gradually shifted from the central portion of the study area to the northern portion (Fig. 5), a distance of approximately 46 km (25 nmi).

Rorqual sightings were not randomly distributed, and did not appear to be related to the sound source. In comparison to random block point values, rorquals were sighted significantly closer to the continental shelf break ($t = 4.03$, d.f. = 1441, $P = 0.001$), closer to shore ($t = 3.23$, d.f. = 1441, $P = 0.001$), further from the 2000 m contour ($t = -2.86$, d.f. = 1441, $P = 0.004$), over steeper
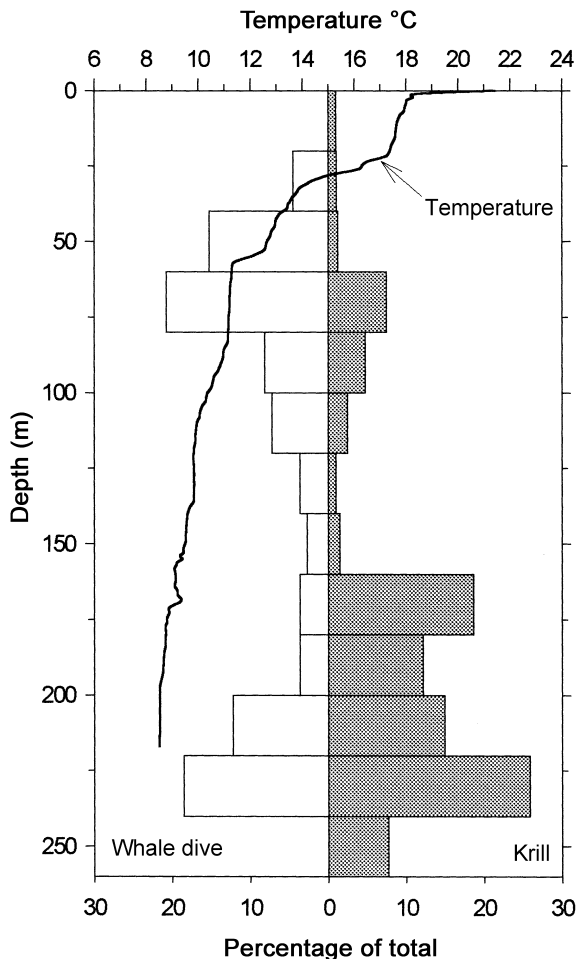
experimental (12.7 ($\pm$9.4) calls 15 min^{-1}), experimental (9.9 ($\pm$11.6) calls 15 min^{-1}), and post-experimental (7.7 ($\pm$4.2) calls 15 min^{-1}) periods (Kruskall–Wallace H = 3.2, d.f. = 2, P = 0.21). However, vocalization rates recorded on the North SOSUS array during the post-experimental period (15.2 ($\pm$6.3) calls 15 min^{-1}) were significantly higher than the pre-experimental (8.5 ($\pm$3.6) calls 15 min^{-1}) period. The experimental (10.7 ($\pm$6.2) calls 15 min^{-1}) period was not different from either pre- or post-experimental periods (Kruskall–Wallace H = 7.9, d.f. = 2, P = 0.02; Dunn's test Q = 2.6, P < 0.05 for pre- versus post-experimental periods) on the North SOSUS array. Vocalization rates were significantly different between the four pop-up locations (pop-up 2 highest 41.7 ($\pm$7.5) calls 15 min^{-1}; pop-up 4 lowest 28.2 ($\pm$14.4) calls 15 min^{-1}) and were significantly lower during the post-experimental period (29.2 ($\pm$15.26) calls 15 min^{-1}) than during the experimental period (37.5 ($\pm$7.9) calls 15 min^{-1}) (two-way ANOVA; pop-up: $F_{0.05,\ 3,36}$ = 5.2, P = 0.004; experimental period: $F_{0.05,\ 1,36}$ = 11.1, P = 0.002; interaction: $F_{0.05,\ 3,\ 36}$ = 1.0, P = 0.421).

Whale residency patterns

Photographic identification revealed that most of the blue and fin whales identified were fairly transitory to the study area. Of the 23 individual fin whales identified in the study area in 1997, only three of these individuals were seen multiple times and these resightings occurred over fairly short time periods spanning distances of < 18.5 km (10 nmi). Similarly, none of the 13 blue whales that were identified in the study region were identified on more than one day. However, three of the blue whales identified in the study region were seen in other areas in 1997 (Calambokidis *et al.*, 1998*a*).

DISCUSSION

Documented, short-term responses of cetaceans to human-produced sound include longer dive times, shorter surface intervals, evasive movements away from the sound source, attempts to shield young, increased swimming speed, changes in song note durations and departure from the area (Norris, 1994, Gordon & Moscrop, 1996; Frankel & Clark, 1998). Studies of the effects of industrial noise on cetaceans have found: (1) migrating gray whales (*Eschrichtius robustus*) exhibited an 80% avoidance reaction to oil exploration sounds played at 130 dB re 1 µPa from a sound source directly in their migration path (Malme *et al.*, 1983). (2) Migrating gray whales exhibited a 10% avoidance response to airgun sounds played from a source directly in their migration path at 164 dB re 1 µPa (Malme *et al.*, 1983). (3) Bowhead whales avoided seismic exploration activities (broadband RL at >115 dB re 1 µPa) at ranges of 2 km (Richardson, Würsig & Greene, 1986) and 20 km (Richardson, 1997). (4) sperm whales (*Physeter catodon*) stopped vocalizing in response to weak seismic pulses from a distant ship (>200 km distant) (Bowles *et al.*, 1994).

Fig. 4. Frequency distribution of whale dive depth (open bars), frequency distribution of krill depth (filled bars) and water column temperature (continuous line) during exposure to human-produced LFS in the vicinity of San Nicolas Island.

topography (t = –2.02, d.f. = 1441, P = 0.04), and in colder water (t = 2.98, d.f. = 1441, P = 0.003).

Vocal behaviour

A total of 295 h and 286.5 h of acoustic data were obtained from the South SOSUS and North SOSUS arrays, respectively. Each of the four pop-ups collected approximately 240 h of continuous acoustic data from 29 September through 9 October. Comparison of expert counts of whale detections with automatic detection counts were highly correlated (correlation coefficients between 0.88–0.93 for blue whales and 0.93–0.95 for fin whales). Based on these results, automatic detection counts were accepted as representative of actual whale vocal activity rates.

No clear trends emerged from vocalization rates (calls per 15-min) recorded on either the South or North SOSUS arrays, the four pop-ups, or the HLA hydrophone (Fig. 6) in relation to experimental condition. There was no difference in vocalization rates recorded on the South SOSUS array between the pre-
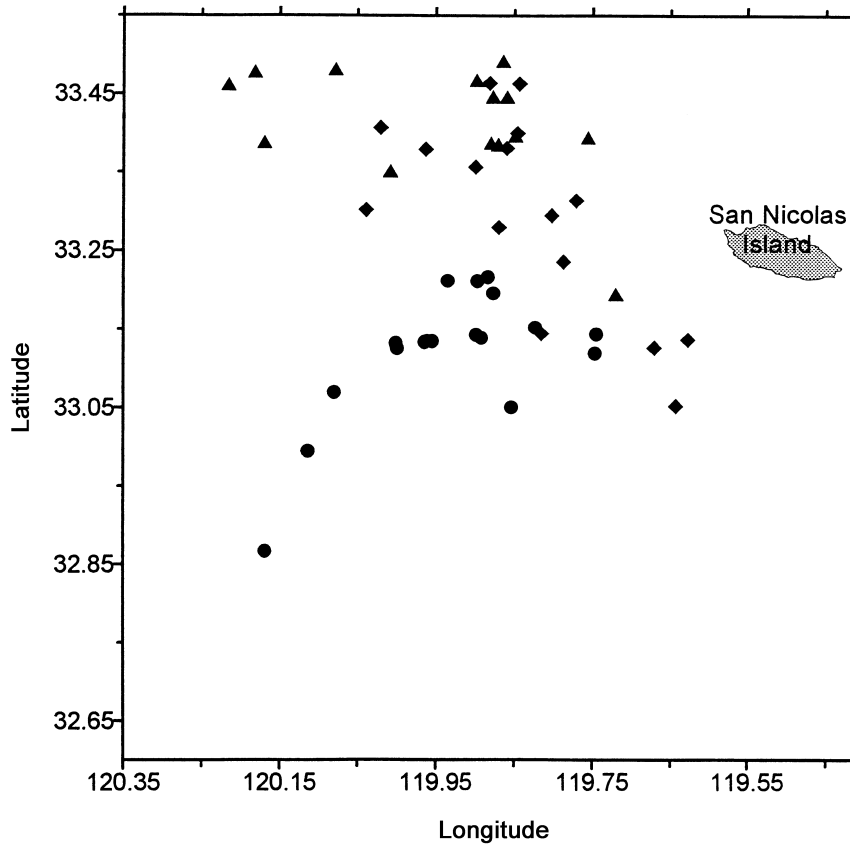
Fig. 5. Location of rorqual sightings during pre-experimental (circles), experimental (diamonds) and post-experimental (triangles) periods of exposure to human-produced LFS in the vicinity of San Nicolas Island, California.

Several authors have inferred responses of cetaceans to human-produced sonar sounds. These responses include: (1) sperm whale cessation of activities and scattering away from sonar signals between 3.25 and 8.4 kHz (Watkins, Moore & Tyack, 1985), (2) increased stranding of beaked whales (family Ziphiidae) associated with the times of military operations (Simmonds & López-Jurado, 1991; Frantzis, 1998), (3) cessation of sperm whale echolocation clicks in reaction to an acoustic thermography sound source (Bowles et al., 1994), and (4) a shift in distribution of humpback and sperm whales away from the low-frequency ATOC sound source when it was transmitting off California (Calambokidis et al., 1998b). However, a recent study found no reaction of sperm whales to human-produced sounds (Madsen & Mohl, 2000).

We examined whether an anthropogenic LF noise source elicited changes in whales or their prey over a time scale of weeks, and distances of tens of kilometers. We did not address effects over smaller (hours to days, kilometers) or larger (months to years, hundreds of kilometers) time scales. Specifically, we tested Richardson et al.'s (1995) hypothesis that whales would not remain in an area when exposed to noise in excess of 140 dB re 1 µPa for an extended period. We found that foraging whales were sighted throughout the study period in a region where there was an intermittent LFA sound source generating RLs >140 dB re 1 µPa for 30% of the

estimated RLs (using the AIM model). Similarly, whales were also observed throughout the study period in the aerial survey area where intermittent LFS transmission RL exceeded 140 dB re 1 µPa, for ~12% of RLs (Table 1). Although these data do not appear to support Richardson et al.'s (1995) hypothesis, sound transmissions were intermittent and whale presence was transitory in this area (see whale residency patterns, below). Rather than being influenced by LF noise, rorqual encounter rates and their diving behaviour appeared to be more strongly linked to temporal and spatial changes in physical and biological oceanographic parameters associated with prey productivity (Figs 3 & 4).

Foraging Behaviour

Whales fed exclusively on several species of euphausiid densely aggregated between 50–100 m and 160–250 m in the water column adjacent to the shelf break (Fig. 4). Euphausiids in this region appear to be supported by productivity resulting from intense upwelling off Pt. Conception (Schwing & Mendelssohn, 1997). Upwelled water is transported southward with the 9 cm s^{-1} surface flow of the California Current (Lynn, Bliss & Eber, 1982; Lynn & Simpson, 1987). Generally, peak phytoplankton abundance resulting from such upwelling occurs with a time delay of approximately 10 days, leading to a southward displacement of phytoplankton stand-
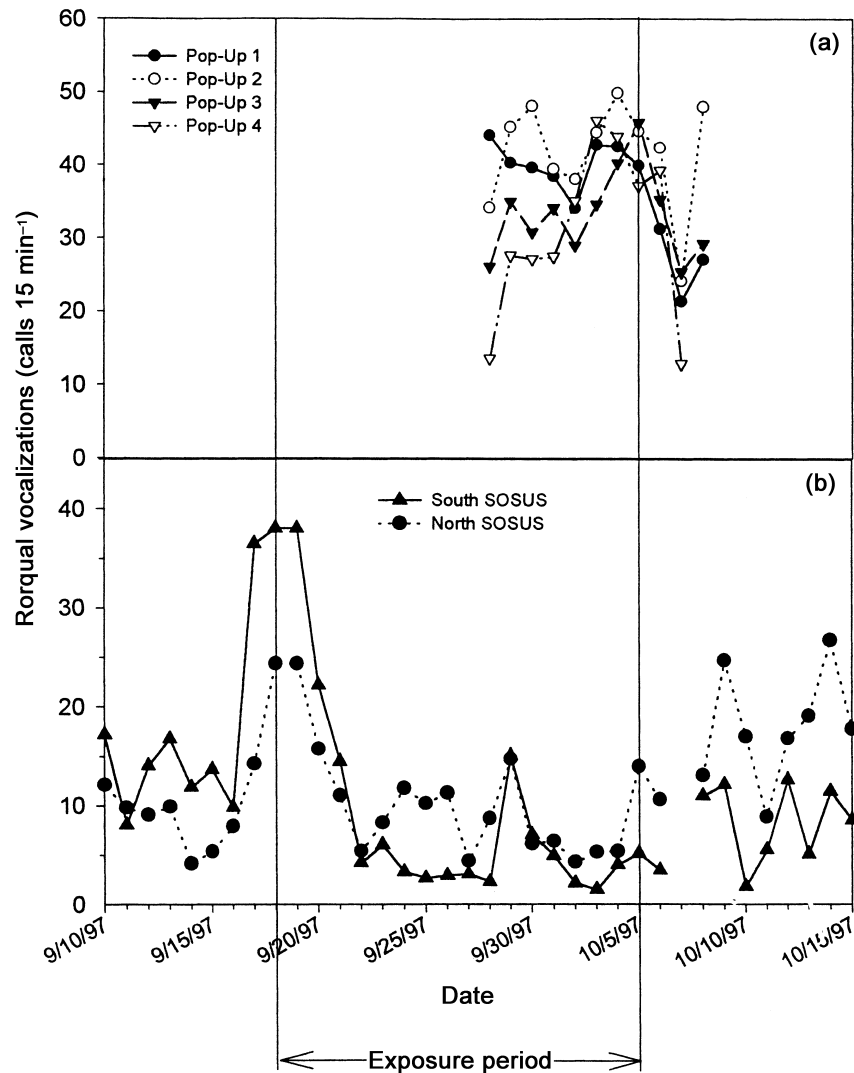
Fig. 6. Rorqual vocalization rates recorded on (a) bottom mounted hydrophones (pop-ups) and (b) bottom mounted hydrophone arrays (US Navy SOSUS array) during pre-experimental, experimental and post-experimental exposure to human-produced LFS (SURTASS LFA) in the vicinity of San Nicolas Island, CA.

ing crop about 100 km south (Fiedler *et al.*, 1998). Thus, peak phytoplankton standing crop roughly coincides with the location of the Channel Islands, and San Nicolas Island is located at the southern end of this peak in primary production (Fiedler *et al.*, 1998). Croll *et al.* (1998) and Fiedler *et al.* (1998) found peaks in euphausiid density in the Santa Barbara Channel region and a region to the northwest of San Nicolas Island. They speculated that upwelling centres work in concert with surface currents, topographical breaks (such as the San Nicolas shelf break) and euphausiid behaviour to collect and maintain concentrations of euphausiids. Rorquals are probably attracted to these concentrations that form off the shelf break west of San Nicolas Island.

Sea surface temperatures based on satellite imagery taken over the course of the study period (Fig. 7) revealed that cooler water, indicative of upwelling, was present in the central and northern portion of our study area. This area generally corresponds with the region of

highest rorqual sightings. However, water temperatures warmed over the course of the study, resulting in a lack of defined colder-water areas. Only at the end of the study, in mid-October, did some new colder water masses become discernible in the study area, due to a strong upwelling event (Fig. 3). Water column temperature measurements showed that a steep thermocline had developed by late September (Fig. 4), indicative of a general relaxation of upwelling. This stratification affected the vertical distribution of at least juvenile euphausiids: peak abundance of juvenile euphausiids between 50–100 m was below this thermocline.

Euphausiid acoustic backscatter during the study period tracked the 5-day mean upwelling index, offset by 10 days, for Pt. Conception (Fig. 3), with minimal upwelling, euphausiid abundance, and whale encounter rates occurring during the experimental period. Generally, low rorqual encounter rates make it impossible to absolutely attribute temporal changes in whale
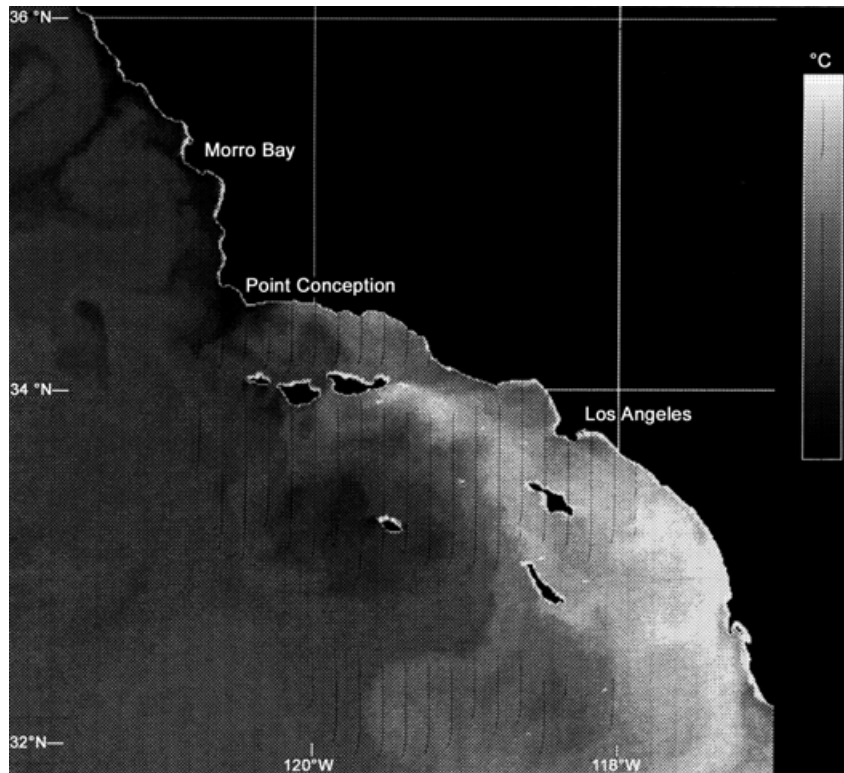
Fig. 7. Sea Surface Temperature (SST) recorded by the NOAA AVHRR satellite in the Southern California Bight, California region on September 10, 1997. San Nicolas Island (white arrow) is located in upwelling plume, indicated by colder water, south of Pt. Conception.

abundance to changes in euphausiid abundance or anthropogenic LF noise. However, temporal patterns in whale encounter rates are best explained by temporal trends in euphausiid abundance rather than LF noise (Fig. 3). This explanation is supported by the abrupt and concurrent increase in upwelling, euphausiid abundance and whale encounter rates prior to the end of the experimental period.

Overall, water temperatures were high in the study area in 1997 as warm water arrived in the study area in September (mean SST for the region July 1997 = 16.5°C, anomaly = –0.1; August 1997 = 18.4, anomaly = 0.6; September 1997 = 19.6°C, anomaly = 2.2°C; Pacific Fisheries Environmental Group, NOAA, Pacific Grove, CA) as the effects of the strong 1997/98 El Niño event began to be measured off Southern California. The unusually warmer waters in 1997 may have led to a decline in rorqual occurrence through the region and resulted in low encounter rates.

Vocal behaviour

Vocal behaviour data are more difficult to interpret. We did not find any significant change in vocal activity in the study area between the experimental periods on the southern SOSUS array. However, vocal activity measured on the northern SOSUS array increased significantly from experimental to the post-experimental period, tracking changes in euphausiid and visual survey encounter rates. In contrast, vocal activity measured by the pop-ups declined from the experimental to the post-experimental period. These confounding results may have been due to either an overall movement of whales out of the study area (where pop-ups were deployed) into an offshore area to the west near the northern SOSUS array, or the high variability in vocalization rates from one day to the next (Fig. 6). Thus, it is likely that variability in vocal rates over short periods of time is more a result of change in the vocal activity of individual whales than changes in whale numbers. However, there is good coincidence between whale vocal activity and whale numbers on a seasonal basis (Curtis *et al.*, 1999). The challenge is to find a measure of acoustic activity on an intermediate scale that is correlated with relative abundance. Knowing more about the functions of these vocal signals and the vocal behaviour of individual animals will aid in understanding the significance of changes in signalling rate, but at the present time little is known about the sex, age, or social status of these vocalizing animals.

Whale residency patterns

Photographic identification revealed that most of the blue and fin whales were fairly transitory to the study area. As a result, the whales counted in surveys and recorded in passive acoustic monitoring represented a turnover of individuals rather than a population of resi-

dent animals. Tershy (1992) found that fin and blue whales feeding in the Gulf of California, where anthropogenic LF noise is very low (C. W. Clark pers. obs.), were also relatively transient. It is not clear whether this trend is consistent in other populations. However, Tershy (1992) hypothesized that high prey consumption needs for these whales required constant movement over large distances in search of dense aggregations of prey.

The transience of the whales in the study area is important in interpreting the effects of sound exposure on *Balaenoptera* whales. While whales did not avoid the area, individuals did not remain in the area. Thus, it could be argued that naïve whales entered the study area, were exposed to human-produced LF noise, and left the area within a short time in response to the presence of the sound. However, if transience were a normal attribute of blue and fin whales, it would reduce their cumulative exposure to LF noise production from a single loud source. Limited photographic identification of blue whales in this same general study region in 1995 (identification of 50 individual blue whales between 8 August and 6 October) also found animals to be generally transient with few resightings of the same individuals (J. Calambokidis, unpubl. results).

Larger spatio-temporal scales

At the spatial and temporal scales we examined, we found no obvious responses of rorquals to the presence of anthropogenic LF noise. It is possible (perhaps likely) that brief interruption of normal behaviour or short-term physiological responses to LF noise at RLs of approximately 140 dB re 1 µPa have few serious welfare implications and no serious effects on survival and reproductive success in cetacean populations. However, long-term impacts (e.g. displacement, masking of biologically important signals), while more difficult to identify and quantify, may be biologically significant through reductions in foraging efficiency, survival, or reproductive success.

Anthropogenic LF noises in the ocean that mask sounds associated with foraging can decrease an animal's ability to find and capture food. This can decrease population growth rates if: (1) population growth is limited by food rather than predation or disease; (2) the species in question does not regulate the population size of its prey. In addition, many marine animals use sound to maintain contact between group members (e.g. females and their offspring), or for other forms of communication, particularly for reproduction. Again, anthropogenic noise in the ocean that masks these communication sounds can decrease the ability of individuals to establish or maintain contact with group members or potential mates. For example, Payne & Webb (1971) estimated that LF noise pollution from shipping may have reduced the area over which blue and fin whales could communicate by several orders of magnitude. They estimated reductions from *c.* 2.1×10^6 km^2 (6×10^5 nmi^2) under pre-shipping conditions to *c.* 2.1×10^4 km^2 (6×10^3 nmi^2) under present shipping conditions, equivalent to a range reduction from 2.1×10^3 km to 2.1×10^2 km. Examples of the potential effects of such reductions could include: increased calf mortality, changes in group spacing from optimal or inability to locate and maintain mates.

Consequently, the most serious potential impact of anthropogenic LF noise is its potential contribution to a long-term decrease in a marine animal's efficiency in foraging, navigating or communicating. The California blue whale population has continued to increase as anthropogenic sound levels have increased (Barlow, 1994). It is not clear whether this trend will continue if anthropogenic sound levels continue to increase.

Because some marine animals (especially large social odontocete cetaceans such as sperm whales, *Pyseter catadon*, bottle nosed whales, *Hyperoodon* spp, and large beaked whales, *Berardius* spp.) have extremely low potential population growth rates, are poorly known and difficult to study, small decreases in their reproductive rate could have serious impacts on population size yet be undetected by any known monitoring system. In addition, recovery of endangered populations of mysticetes (e.g. blue, fin, sei (*Balaenoptera borealis*), humpback, right and bowhead whales) that were severely reduced by commercial whaling may be hampered if anthropogenic LF noise affects long-term reproductive success or survival in these species. While this study expands our knowledge of the short-term, smaller scale effects from an intermittent sound source, in many cases the basic information needed to understand the long-term consequences of more continuous and widely spread anthropogenic LF noise sources is missing.

Noise from commercial vessel traffic, by far the most dominant source of anthropogenic noise in the ocean, is continuous, ubiquitous and shows no sign of decreasing. The intense signals generated by various military sonars and seismic operations, although typically operated only for periods of weeks in limited areas, are being used increasingly throughout the world's oceans. The acoustic probes used increasingly in oceanographic research projects are usually high intensity. While none of these individual sound sources has been shown to cause prolonged disturbance to a biologically important behaviour, their cumulative effect may be profound. Examples of a difference between the impact of a single versus multiple sources of environmental pollution include the cumulative effects of carbon dioxide gas sources on global warming, or the cumulative effects of many hundreds of coal-burning power plants on acid rain in eastern North America. Given the present lack of scientific knowledge on the impacts of anthropogenic sound in the ocean, we recommend that a cautionary approach is most appropriate. Furthermore, given the present state of uncertainty, we believe that the risk of cumulative impact on a habitat that is broadly critical for many animal groups is unacceptable. A source-by-source approach to the problem of noise impact will probably not prove fruitful, since cause and effect are difficult to identify. Instead, a broad legislative approach that addresses the cumulative effect of many underwater sound sources

over long periods of time will probably prove most effective.

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