Potential Prey of Killer Whales in Puget Sound: A Pilot Study

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1 Summary

As a first effort to characterize foraging interactions of southern resident killer whales and their prey, echosounders and a multibeam sonar were deployed during fixed and adaptive transects throughout the San Juan archipelago. Relative densities of surf smelt, larger targets, and a mixed layer were quantified for all transects using 38kHz echosounder data. A midwater trawl was used to confirm species presence and to collect length frequency samples. Marine mammal observers counted and identified all animals within a 180^{o} swath in front of the survey vessel. The echosounder efficiently characterized fish densities throughout the water column. Relative fish densities of the three backscatter categories differed among days, locations, and depths. Largest fish concentrations were observed within Haro Strait. Individual and groups of killer whales were observed in the vicinity of and in the absence of the three backscatter categories. Quantitative analysis of multibeam data was not currently possible but images of whales and fish schools were observed on the screen during adaptive transect sampling.

2 Introduction

Limited information is available on prey preferences of southern resident killer whales (*Orcinus orca*). Evidence that southern residents preferentially forage on salmonid species is based on visual observations at the surface, necropsies of stranded animals, and collections of fish scales in the vicinity of killer whale surface activity (Ford *et al.* 1998). Chinook salmon (*Oncorhynchus tshawytsha*) is the one dietary item that was consistently found in all three types of feeding samples (Ford *et al.* 1998). Dietary specialization of southern residents on salmonids and preferentially on chinook, starkly contrasts to the predation of killer whales on herring (*Clupea harengus*) in the northeast Atlantic (Nottestad and Axelsen 1999; Domenici *et al.* 2000).

Spatial and temporal distributions of potential prey species have not been examined within the summer range of the southern residents. Correlations between the success of the recreational sport fishery (e.g. Heimlich-Boran 1986) or catch-per-unit-effort statistics from the Department of Fisheries and Oceans, Canada (R. Osborne, personnel communication) and the frequency of killer whale sightings have been examined, but maps of prey densities or direct observations of predator-prey interactions are conspicuously absent. Underwater acoustics provides an obvious technique to quantitatively describe distributions of fish as potential prey of killer whales.

Underwater acoustic techniques are used to monitor the distribution, abundance, and habitat use of fish within ecosystems. Acoustic surveys are appealing for mapping and counting pelagic organisms as large volumes of water can be continuously sampled at high spatial and temporal resolutions. The primary challenge and the primary limitation of using sound as an aquatic sensing tool, is the identification of targets to species (Horne 2000). Conventional methodology combines the use of fishing gear such as trawls to document species composition and length distributions in the geographic area of interest. These biological samples are used to partition, interpret, and match acoustic patterns to constituent species.

Narrow beam, high frequency echosounders have been used to document killer whales feeding on herring in Norwegian fjords (e.g. Nøttestad 1998; Nøttestad and Axelsen 1999; Domenici *et al*. 2000). Scientific echosounders provide the constant signal generation needed to quantify fish densities, sizes, and to discriminate among species. Acoustic backscatter differences among salmon or other species within Puget Sound are not known. Supplementary biological knowledge of fish size and habits combined with net sampling is the accepted method used to confirm species identification and to obtain length frequency distributions.

The use of acoustic techniques also enables observation of the predation strategy used by killer whales when foraging on individuals or groups of fish. Confirmation of fish consumption below the water surface is lacking for Puget Sound southern resident killer whales. Knowledge of salmonid spatial and temporal distributions has traditionally depended on commercial and recreational fishery data. Despite ongoing data collections, little has been published on the foraging and food habits of southern resident killer whales. Circumstantial evidence consists of correlations between whale sightings and fish catch data. These results confirm the co-location of salmonids and killer whales but do not provide any information on the presence and potential consumption of other pelagic fish species by killer whales. What are the trophic linkages among forage fish, salmonid species, and southern resident killer whales in Puget Sound?

3 Methods

In this pilot study, we combined acoustic survey techniques with net trawling to quantitatively describe the distribution of pelagic fish and killer whales within the summer range of the southern resident killer whale population.

3.1 Equipment

3.1.1 EchoSounder

A splitbeam Simrad EK60 echosounder operating at 38 kHz (beam width of ~12° between half power points) and 120 kHz (beam width of ~7° between half power points) was used throughout the study. Transducers were mounted on a dead-weight towbody and suspended 1 meter below the surface on the starboard side of the boat. Speed of the vessel during acoustic transects ranged from 2-5 knots.

Pulse lengths of 0.512 ms were transmitted at a sampling rate of 1 pulse per second from 9/15/2004 until 16:53 (local time) 9/16/2004. The sampling rate was changed to 2 pulses per second at 16:53 (local time) 9/16/2004 for the remainder of the cruise. The system was fully calibrated in August 2004 using a tungsten-carbide sphere under field conditions (temperature and salinity) similar to those experienced during the survey.

3.1.2 Multibeam Sonar

A Simrad MS20 multibeam sonar operating at 200 kHz was used during the survey to image larger volumes of the water column. The transmit beam is composed of 128 electronically focused beams, creating a 120° swath by 20° or 1.5° fore-aft angle depending on transmitter settings. Each beam is divided in 782 intervals when quantifying reflected echo energy. The effective range of the sonar is approximately 200 m.

The sonar transmit and receive heads were deployed on a pole mount attached to the starboard side of the vessel. Two configurations of heads were used to detect and record fish schools and orca behavior (Figure 1). In the "typical" configuration, the sonar head was facing outward at a 36° or 42° angle to scan a thin vertical slice of the water column from surface to bottom as the vessel moved. The second configuration projected the 120° swath of the beams in the horizontal plane, with the head mounted on a computer-controlled rotator that panned vertically from the surface to an angle of 30° down.

3.1.3 Net monitoring gear

A Simrad PI30 trawl monitoring information system was used to monitor depth of the headrope and door spread of the net during each midwater trawl. Battery powered sensors were attached to each of the doors and the head rope. A hand-held hydrophone was suspended over the side of the boat during trawling to receive signals transmitted by the sensors.

3.1.4 Midwater Trawl

A Nordic Rope Trawl 164 manufactured by Net Systems (Bainbridge Island, WA) was used to sample fish in the water column. A pair of 2 m^2 Alloy midwater trawl doors was used to fish the net. The trawl was deployed to confirm species presence and to collect samples for length frequencies. The net was deployed for 15-50 minutes on high fish density areas located using the echosounder.

All vertebrates caught in each trawl were identified to species and counted. Length frequency samples were obtained in each haul. In large catches, 100 randomly selected individuals were measured for total length (mm) and counts were estimated volumetrically.

3.1.5 Conductivity, Temperature, and Depth (CTD) Sampling

A Seabird SBE 19 plus SEACAT Profiler sampling at 2 Hz was used to obtain a vertical profile of water temperature and salinity. These values were used to check the speed of sound in the water for the acoustic system. The CTD was deployed at 1 ms^{-1} following most hauls to determine water conditions.

3.2 Survey Strategy

We followed a fixed grid (i.e. Eularian) transect design in Haro Strait, Boundary Pass, Strait of Georgia, Rosario Strait, San Juan Channel, and Presidents Channel (Figure 2). In the presence of killer whales, the vessel often switched to a Lagrangian sampling mode. In this mode individuals or groups of killer whales were “followed”. The vessel moved at a slow speed or drifted as long as the whales were in proximity. In addition to collecting data with the echosounder, the MS20 sonar was deployed if whales were within 200m of the boat. We maneuvered the boat to keep the whales within range, following at a distance that did not interfere with their movements or activities. During these sampling events, a marine mammal observer identified whales to the individual and recorded associated behaviors. After the Lagrangian sampling, the boat was used to do a fine grid sampling in the area of the killer whales or resumed echosounder recordings along previously sampled transects line. Because the time and locations of these high resolution surveys were determined by the presence of killer whales, these sampling efforts are called adaptive transects.

3.3 Acoustic Data Analysis

Analysis of acoustic data collected at 38 kHz was divided into Eularian transects and Lagrangian sampling. A noise reduction filter set at –117 dB at 1m from the transducer and scaled through the water column using a 20log(R) time varied gain (i.e. TVG) was used to reduce or eliminate engine or electrical noise present in all samples. The integration threshold was set at –75 dB. The horizontal bin size, or elementary distance sampling unit (i.e. EDSU), was set at 250 m. The maximum vertical integration depth was set at 500 m (well below the maximum depth encountered). Fish densities in the water column are reported as Area Backscattering Coefficients (i.e. s_a, units m^2m^{-2}). This nondimensional quantity is the integral of the volume backscattering coefficient (s_v) over a range interval z_1 to z_2:

$$S_a = \int_{z1}^{z2} S_V \, dz$$

The volume backscattering coefficient is the total energy of all targets (σ_{bs}) in a specified volume V (i.e. $s_v = \Sigma\sigma_{bs}/V$).

All echo integration was performed using Echoview (version 3.2). Three backscatter categories were created for the analysis: surf smelt, larger targets, and mixed (Figure 3). The surf smelt layer included all backscatter from a depth of 3.5 meters below the surface to the bottom of the smelt schools. The larger target layer extended from the bottom of the smelt layer to the top of the mixed layer (when present). The mixed layer extended from the bottom of the larger target layer to the bottom of the water column.

3.4 Marine Mammal Observations

A marine mammal observer was on effort during all Eularian transects, during midwater fishing hauls when the net was in the water, and during Lagrangian events. Constant scanning from the Port beam to bow to Starboard beam (i.e. 180^o sweep) was used to spot animals. When a sighting was made, binoculars were used to identify species, count the number, estimate the distance, and the direction (i.e. degrees off the bow) of any sighted animals. When killer whales were within photographic range, digital photographs were taken of every individual present. The time and vessel location (i.e. latitude, longitude) of every sighting was noted as well as the proximity of the animals to the vessel, and the type of equipment (acoustic or trawl) operating at the time of the sighting. Categorical observations were made on individual and group killer whale behavior. Variables recorded include: **O**rientation (L=linear, NL=nonlinear, FL=flank), **S**peed (S=slow, M=medium, F=fast), organization (ND=nondirectional, D=directional), **D**istance between individuals (s=spread (>100m), l=loose (100m), t=tight (<100m)).

4 Results

4.1 Data Summary

The survey was conducted from the R/V Centennial from September 15 to September 23, 2004 in the San Juan Archipelago. A total of 40 transects were surveyed, 8 in an adaptive mode, and an additional 5 events in a Lagrangian mode while killer whales were in close proximity (Table 1). The multibeam sonar was deployed 14 times, in association with the presence of killer whales or to record fish schools along the shoreline (Table 2). The midwater trawl was deployed 11 times during the survey (Table 3) and 7 CTD profiles were collected in association with these trawl hauls. An additional 2 CTD profiles were collected during the cruise (Table 4).

4.2 Abundance and Distribution of Prey

4.2.1 Euclidean Prey Survey Transects

The number and composition of fish caught in the midwater trawl differed among hauls. Trawl locations are indicated as numbers on Figure 2. A total of 14,312 animals were caught in the 11 midwater trawls. Sixteen species were caught: 14 fish species and 2 invertebrate species (Table 5). CPUE among the hauls ranged from 0.26 fish per minute to 296 fish per minute. The dominance of any one species in a haul depended on the location of the haul and the depth fished. Surf smelt and/or walleye pollock were the two numerically dominant species caught in all hauls. Only seven chinook salmon were caught in 3 of the 11 hauls (haul numbers 1, 2, and 9). Lengths of numerically dominant fish caught were consistent within species and among stations (Figure 4). Lengths of larger fish not included in the frequency histograms are listed in Table 6.

Surf smelt (Hypomesus pretiosus) were the dominant species in the upper 100 m. This species formed small and very dense schools that were patchily distributed. Volumetric density and size of the schools noticeably increased in shallow waters and near the coast, especially in the vicinity of sharp bathymetric contrasts. A closer examination of the echograms revealed the presence of larger targets, often located just below the surf smelt schools. This layer consisted of scattered individual targets or clusters of dense patches producing echoes noticeably different than those assumed to be surf smelt schools (e.g. large individual targets often visible within dense patches). In deeper water (> 100 m) a mixed scattering layer was often observed. This scattering layer consisted of low density acoustic returns, in which single targets or schools were difficult to resolve (Figure 3). Echoes from larger fish were observed but were not abundant. Midwater trawls within this layer caught juvenile walleye pollock (*Theragra chalcogramma*) that ranged from 60 – 120 mm total length.

The relative abundance of the three backscatter categories at 38 kHz along each transect are summarized in a series of stick plots for Haro Strait (Figure 5) and for the remainder of the San Juan archipelago (Figure 6). Note that the s_a reference values on vertical axes of the plots can differ among days and among backscatter categories. Transects were surveyed in Haro Strait on six days (Sept. 15, 16, 17, 18, 22, 23) and extended from Cattle Pass in the south to the western entrance of Boundary Pass at Stuart Island in the north. The dominance of any scattering layer differed in location and layer on any particular sampling day. During any sampling day, high densities of fish in a single layer did not necessarily coincide with high densities of fish in all layers.

A survey loop during September 19 – 21 was conducted north from San Juan Channel, through Boundary Pass, and returning southward through Rosario Strait (Figure 6). Surf smelt and the mixed layer were most dense at the eastern edge of Boundary Pass. Concentrations of larger targets were found at the northeast corner of Boundary Pass and at the northern end of Rosario Strait. These larger targets were distributed differently than in the Haro Strait region. Larger targets did not form clusters of patches and were easier to resolve. No mixed layers were observed, which also differed from patterns observed in the Haro Strait region.

4.3 Whales and Prey

4.3.1 Whale counts

Counts of marine mammals were tabulated from sightings during Eularian transects and Lagrangian events (Table 7). Killer whales were sighted individually and as organized or disorganized groups. Other marine mammals including harbor porpoise, Dahls porpoise, and minke whales were sighted during the survey.

4.3.2 Multibeam Imaging

The multibeam sonar was deployed when killer whales were in proximity to the boat and not traveling. Combined echosounder and multibeam sonar data were recorded for five “whale encounter” events during the survey (Figure 7). A stick plot and corresponding screen capture of the multibeam sonar data are presented for each event. The sonar heads were configured horizontally or vertically during these recordings. Single killer whales, groups of killer whales, and fish aggregations are present in the multibeam images. Quantitative data from the multibeam are not available. Densities of the three fish backscattering categories recorded by the echosounder differed among events. The larger targets category was present at some locations during each of the five events.

5 Technique Assessments

5.1 Classification of Prey Assemblages

Initial scrutiny of the 38 kHz acoustic transect data resulted in the three backscatter categories used in echo integration. The surf smelt layer was easily distinguished from all other backscatter types and was consistently found in the upper third of the water column. Very little mixing of species occurred in this layer. The larger targets observed below the surf smelt schools occasionally formed distinct and dense layers but in most cases, these targets became scarcer (and smaller) as depth increased. Attempts to sample fish from these larger target regions were not very successful. Fish capable of producing distinct and strong individual echoes that were captured by the trawl and included 7 chinook salmon and 6 dogfish shark. The number of fish caught relative to the number of large targets observed suggests that these fish managed to escape the net in most instances. The remainder of the water column contained a mix of larger and smaller targets. In deep water, discriminating among species presented a significant challenge. Catches from the midwater trawls in this scattering layer showed a mix of species in every haul, all of which were dominated by walleye pollock. The presence and ubiquitous distribution of young-of-the-year walleye pollock was a surprise.

5.2 Echosounder Use

The echosounder was proficient at mapping distributions of biomass in the water column. The speed of the vessel enabled characterization of fish in the water column throughout the San Juan area. Delimitation of the bottom and fish was clear throughout the survey. The addition of constant electrical or mechanical noise on the echograms was not recognized until after the survey. The noise reduction filter combined with the integration threshold adequately removed the noise contribution from the relative fish density measurements. Potential avoidance of the vessel by fish was not quantified during the survey but is believed to be low, especially since many surf smelt schools were observed in the first 10 m of the water column. Individual fish tracks on the echograms did not appear to be ‘fleeing’ from the vessel path, normal to the vessel trajectory, or to deeper depths. If bias due to vessel avoidance existed, it is believed to be constant and minimal, and would therefore not distort the relative fish density measurements indexed using s_a values. Deployment of the towbody restricted the vessel speed to under 6 knots. The over ground (true) speed of the vessel was sometimes limited to < 2 knots due to strong tidal currents.

5.2.1 Foraging Events

A common challenge to underwater and surface marine mammal observations is determining what constitutes a foraging event. From Ford et al. (1998) descriptions of hunting behaviors at the surface included rapid acceleration, sudden direction changes, or circling. Kills were categorized when evidence of successful capture (flesh, blood, oil observed at surface) were observed. Harassments were events where killer whales were actively pursuing prey but no kill could be confirmed. Limited maneuverability of our research vessel and gear prevented the examination of whale dive locations for the collection of potential prey remains. Foraging was thought to occur when whales formed dispersed aggregations and were making prolonged dives. The multibeam sonar was deployed whenever whales were encountered and were accessible. The adaptive sampling strategy with the echosounder was used to characterize areas where whales had been making prolonged dives.

5.2.2 Potential Prey Selection

Acoustic data can be used to quantify the presence and relative abundance of backscatter types in the presence or absence of killer whales, as well as before, during, or after prolonged diving activity by killer whales in an area. Systematic transects, Lagrangian observations, and adaptive mini-surveys all differ in their areal coverage but the density distribution data is fundamentally the same.

5.3 Multibeam

The availability of multibeam sonar to fisheries scientists is still new. The attraction to this technology is the increased volume of water insonified. Unfortunately, off-the-shelf, quantitative processing and display software is just being developed and is expensive (~$35,000 US). Due to lack of calibration routines and the complexity of the data, multibeam sonar data cannot be processed in the routine way that we treat scientific echosounder data. We did not include analytic products from the multibeam data collected during this survey. This analytic effort warrants a separate research product. We did include screen captures of the beamformed data to illustrate the type of data and the potential for analysis.

5.3.1 Foraging Events

It is obvious from replaying the data through the multibeam sonar and from the screen captures that killer whales can be identified and, with access to the software, tracked as they move through the water column. Any other biomass within the beam is also visible in the vicinity of the whales. Fish and whales appear differently on the display. We believe that the combination of surface observations, echosounder data, and multibeam sonar data can be used to quantify water column depth, dive trajectories, and the relative densities of potential prey in the vicinity of killer whales. Tracking individual killer whale dives depends on the position of the vessel and the sonar beam relative to the dive (i.e. luck), and the ability to georeference the multiple sonar pulses during a dive. The use of the stepper motor to pan the sonar heads during a dive increases the potential to track an animal but complicates the translation of animal positions to 3-dimensional space.

5.3.2 Prey Selection

The resolution of the multibeam sonar will not ‘capture’ a whale consuming a single prey. Relative densities before and after a whale passes through can be quantified. Fluxes of fish out of the beam can be quantified if the beam remains stationary. An additional analysis that could be conducted is the relative density of prey categories in the presence of and in the absence of killer whales.

6 Validation Techniques

This is the first study that has used techniques other than surface observations to simultaneously observe killer whales, killer whale dive activity, and the potential prey of killer whales in Puget Sound. There has not been a mapping of potential prey in the presence and in the absence of killer whales. The use of multibeam sonar in combination with quantitative echosounders to simultaneously image predator and prey is unique to this study and, to our knowledge, is one of the few attempts in the world.

Fish distribution and intensity patterns observed during the survey were species dependent. The surface layer (<100 m) was dominated by surf smelt, which appeared as discrete aggregations in echograms. These could be distinguished from clusters of large targets and scattering layers composed of other small targets (i.e. walleye pollock). Clusters of larger targets and mixtures of large targets within mixed aggregations are believed to be salmon and dogfish sharks. Walleye pollock and other vertebrates formed mixed aggregations and layers in deeper waters (> 100 m). Targets within the larger target regions and mixed aggregations could not be definitively attributed to species.

Fish catch compositions from midwater trawls were thought to be representative of the relative abundance and species distribution in the water column, with the noticeable exception of larger target regions. Fish that aggregate near bottom may not have been proportionately represented in trawl catches as the only gear used was a midwater trawl. The relative proportion of species within this layer is not known. The abundance of young-of-the-year (YOY) walleye pollock observed in echograms and caught in the midwater trawl was larger than expected.

Ancillary surface observations confirmed the presence of salmon in the area. A harbor seal was observed with a chinook salmon in its mouth. Killer whales were present in the area just prior to this observation. Few salmon were caught in the midwater trawl but significant backscatter from larger targets suggests a more numerous presence.

7 Recommendations

The survey conducted in Puget Sound is representative of the sampling capabilities of an acoustic and trawl survey designed to examine predator-prey interactions between large marine mammals and fish. Minor changes in equipment and equipment deployment will maximize the amount of data available for analysis:

- Increase fishing effort to quantify acoustic backscatter and species identification. This is an unavoidable addition to the survey effort.
- Increase the number of gears used to fish (e.g. downriggers, trawl lines, commercial trawler). This effort will be dedicated to capture large targets such as salmon.
- Consider the use of a more maneuverable boat if individual killer whales are to be tracked. The availability of hull-mounted transducers (planned for the Centennial next year) would make a difference in survey speed and vessel maneuverability.
- Formally include use and analysis of multibeam sonar data in future surveys. Dedicated use and analysis of multibeam data in conjunction with echosounder data provides the most complete coverage possible of predator activity and surrounding prey densities.
- Expand the acoustic gear to include tagging individual killer whales. A tagged animal may be acoustically tracked through the prey field during dives.

8 References

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Table 1. Type, location, and time of acoustic transects when echosounder data was collected.

Category	Area	Number	Date	Start Time (Local)	End Time (Local)	Comments
EULARIAN						
Transect	Haro Strait (Cattle Point to Lime Kiln Pt.)	1	9/15/2004	10:35	12:44	Haul 01 just after (at 1256)
Adaptive	Haro Strait (False Bay to Eagle Pt.)	2	9/15/2004	14:40	15:40	Whale search path
Transect	Haro Strait (Mitchell Bay to False Bay)	3	9/16/2004	9:09	11:00	Haul 02 at 959
Transect	Haro Strait (W side of Henry Is.)	4	9/16/2004	13:40	15:00	Trying to find the whales
Adaptive	Haro Strait (W side of Henry Is.)	5	9/16/2004	15:00	15:10	Fine-grid survey (whales in area)
Adaptive	Haro Strait (W side of Henry Is.)	6	9/16/2004	15:12	15:38	Fine-grid survey (whales in area)
Adaptive	Haro Strait (W side of Henry Is.)	7	9/16/2004	15:44	16:10	Fine-grid survey (whales in area)
Adaptive	Haro Strait (W side of Henry Is.)	8	9/16/2004	16:12	16:39	Fine-grid survey (whales in area)
Adaptive	Haro Strait (W of Spieden Is.)	9	9/16/2004	16:55	17:24	Fine-grid survey (whales in area)
Adaptive	Haro Strait (W of Spieden Is.)	10	9/16/2004	17:34	18:48	Fine-grid survey (whales in area), CTD @ 1802
Transect	Haro Strait (Bellevue Pt. to Open Bay)	11	9/17/2004	10:00	10:23	
Transect	Haro Strait & Strait of Juan de Fuca (Henry Is. to Hein Bank)	12	9/17/2004	13:27	16:51	Haul 03 just before (at 1230)
Adaptive	Haro Strait & Strait of Juan de Fuca (Hein Bank to Eagle Pt.)	13	9/17/2004	17:00	17:43	Heading toward the whales
Transect	Haro Strait (Cattle Pt. to False Bay)	14	9/18/2004	11:00	14:45	Haul 04 at 1212, Haul 05 at 1325, repeat of T1
Transect	Haro Strait & Strait of Juan de Fuca (Middle Bank to Hein Bank)	15	9/18/2004	15:22	16:42	
Transect	Strait of Juan de Fuca (Hein Bank to Middle Bank)	16	9/18/2004	17:05	18:13	
Transect	San Juan Channel to President Channel (W Shaw Is. to Flattop Is.)	17	9/19/2004	8:51	9:47	Haul 06 just after (at 1009)
Transect	President Channel (Flattop Is. to West Bank)	18	9/19/2004	11:55	13:46	
Transect	President Channel to Boundary Pass (b/w Sucia Is. and Waldron Is.)	19	9/19/2004	13:48	14:38	Haul 07 just after (at 1455)
Transect	Boundary Pass (Patos Is. to Stuart Is.)	20	9/19/2004	16:13	18:30	CTD just before (at 1603)
Transect	Boundary Pass & Haro Strait (SW side of Stuart Is.)	21	9/19/2004	18:32	18:52	
Transect	Haro Strait (S side of Stuart Is.)	22	9/20/2004	9:36	10:02	
Transect	Boundary Pass to Strait of Georgia (N of Patos Is.)	23	9/20/2004	12:07	13:18	
Transect	Strait of Georgia (Alden Bank to Pt. Roberts)	24	9/20/2004	13:18	15:16	
Transect	Strait of Georgia (S of Pt. Roberts to N of Patos Is.)	25	9/20/2004	15:16	15:44	
Transect	Strait of Georgia (N of Patos Is. NW ward)	26	9/20/2004	15:45	17:04	
Transect	Strait of Georgia (N of Patos Is. NW ward)	27	9/20/2004	17:04	17:25	Haul 08 just after (at 1740)

Transect	Strait of Georgia (N of Matia Is. to N Lummi Is.)	28	9/21/2004	8:36	10:32	Haul 09 just after (at 1135)
Transect	Rosario Strait (Lummi Is. to Pt. Colville (SE Lopez Is.)	29	9/21/2004	13:10	16:20	
Transect	Rosario Strait / Strait of Juan de Fuca (S Lopez Is.)	30	9/21/2004	16:20	17:10	
Transect	Middle Channel (SW Lopez Is.)	31	9/21/2004	17:10	17:42	
Transect	Middle Channel (SW Lopez Is.)	32	9/21/2004	17:55	18:23	
Transect	Haro Strait (Henry Is. to Cattle Pt.)	33	9/22/2004	9:34	13:22	
Transect	Haro Strait (Cattle Pt. to Deadman Bay)	34	9/22/2004	13:23	16:10	Haul 10 at 1430, repeat of T1 (T14)
Transect	Haro Strait (Deadman Bay to False Bay)	35	9/22/2004	16:16	16:58	
Transect	Strait of Juan de Fuca (Hein Bank to Eagle Pt.)	36	9/23/2004	9:54	10:38	Haul 11 just after (at 1047), CTD at 1140
Transect	Haro Strait (False Bay to Henry Is.)	37	9/23/2004	13:12	14:58	Partial repeat of T1 (T14, T34)
Transect	Haro Strait (Henry Is. to False Bay)	38	9/23/2004	15:12	17:37	Partial repeat of T12
Transect	Haro Strait (off False Bay)	39	9/23/2004	17:38	18:09	
Transect	Haro Strait (False Bay to b/w Eagle Pt. and Cattle Pt.)	40	9/23/2004	18:29	18:49	

LAGRANGIAN

Event	Haro Strait (Eagle Pt. to Pile Pt.)	L01	9/15/2004	15:40	18:54	Following whales
Event	Haro Strait (Eagle Pt. to Pile Pt.)	L02	9/17/2004	17:43	19:02	In whales
Event	Middle Channel	L03	9/22/2004	18:09	18:51	In whales
Event	Haro Strait (off False Bay)	L04	9/23/2004	12:11	13:00	In whales
Event	Haro Strait (Andrews Bay to Henry Is.)	L05	9/23/2004	14:00	15:00	In whales

Table 2. Date, time, and location of multibeam sonar deployments.

Date	8.1.1.1.1	Area	Start Latitude	Start Longitude
9/15/2004	1541	Haro Strait (Lime Kiln Pt.)	48.4543	123.0837
9/17/2004	1010	Haro Strait (W of Mitchell Bay)	48.5470	123.1765
9/17/2004	1112	Haro Strait (W of Henry Is.)	48.5898	123.2097
9/17/2004	1134	Haro Strait (W of Henry Is.)	48.5888	123.2063
9/17/2004	1159	Haro Strait (W of Henry Is.)	48.5862	123.2013
9/17/2004	1653	Haro Strait (Hein Bank to Middle Bank)	48.3918	123.0478
9/17/2004	1743	Haro Strait (off Eagle Pt.)	48.4477	123.0552
9/19/2004	1618	Boundary Pass (b/w Patos Is. and Waldron Is.)	48.7645	122.9942
9/19/2004	1827	Boundary Pass (NW of Waldron Is.)	48.6982	123.2482
9/20/2004	0935	Haro Strait (S Stuart Is.)	48.6603	123.2045
9/22/2004	0930	Haro Strait (NW Henry Is.)	48.6158	123.1912
9/22/2004	1808	Middle Channel (S of Long Is.)	48.4303	122.9358
9/23/2004	1211	Haro Strait (W of False Bay)	48.4598	123.0635
9/23/2004	1400	Haro Strait (W of Mitchell Bay)	48.5368	123.1895

Table 3. Date, time, and location of midwater trawl stations. Eq is the time the net reached equilibrium.

Date	Haul	Time (Local)	Area	Duration (min)	Latitude (Eq)	Longitude (Eq)	Avg. Depth (m)
9/15/2004	1	1325	Haro Strait (S of Lime Kiln Point)	31	48.4787	123.1165	78.60
9/16/2004	2	1016	Haro Strait (W of False Bay)	32	48.4828	123.1522	119.25
9/17/2004	3	1235	Haro Strait (W of Mitchell Bay)	20	48.5775	123.1937	55.47
9/18/2004	4	1230	Haro Strait (W of False Bay)	25	48.4645	123.0988	109.10
9/18/2004	5	1352	Haro Strait (W of False Bay)	21	48.4508	123.0625	122.00
9/19/2004	6	1033	San Juan Channel (W of Jones Is.)	27	48.4168	123.0500	87.86
9/19/2004	7	1527	Boundary Pass (SW of Patos Is.)	16	48.7648	123.0040	63.81
9/20/2004	8	1740	Strait of Georgia (b/w Patos Is. and Pt. Roberts)	30	48.8612	122.9873	80.33
9/21/2004	9	1151	Rosario Strait (N Lummi Is.)	49	48.6957	122.7355	47.18
9/22/2004	10	1440	Haro Strait (off Eagle Pt.)	30	48.4605	123.0617	120.25
9/23/2004	11	1102	Haro Strait (b/w Salmon Bank and Middle Bank)	16	48.4338	123.0422	123.67

Table 4. Date, location, and time of CTD profiles.

Date	Time	CTD#	Associated Haul	Area
9/15/2004	1803	1	1	Haro Strait (W of False Bay)
9/16/2004	1802	2	-	Haro Strait (S of Henry Is.)
9/18/2004	1736	3	-	Strait of Juan de Fuca (Hein Bank)
9/19/2004	1130	4	6	San Juan Channel (NW of Jones Is.)
9/19/2004	1603	5	7	Boundary Pass (SW of Patos Is.)
9/20/2004	1830	6	8	Strait of Georgia (b/w Patos Is. and Pt. Roberts)
9/21/2004	1300	7	9	Rosario St. (N Lummi Is.)
9/22/2004	1537	8	10	Haro Strait (W of False Bay)
9/23/2004	1140	9	11	Haro Strait (Salmon Bank)

Table 5. Catch by species by haul.

Species	1	2	3	4	5	6	7	8	9	10	11
Arrowtooth flounder					1						
Chinook salmon	4	2							1		
Decapod sp.		27			46	31		4			6
Dogfish shark					1	1			3	1	
Eulachon		195	1		534	5		2		2	
Jellyfish	3		5			1	12	12	19		1
Night smelt		1									
Northern anchovy	1				2						
Pacific hake				1	2					1	
Pacific herring					8					1	
Pacific tomcod		1									
Sandlance			12	2					1		
Squid			43	5	2	13	5	2	2		1
Surf smelt		38	1753	149	51	267	159	48	523	240	199
Walleye pollock		589	5	277	5575	128	17	2		3042	107
White bait smelt			106	1		13					
Total	8	853	1925	435	6222	459	193	70	549	3287	314
CPUE (# fish min^{-1})	0.26	26.66	96.25	17.40	296.29	17.00	12.06	2.33	11.20	109.57	19.63

Table 6. Lengths of less common fish caught in the midwater trawl.

Species	Total length (mm)	Haul #
Anchovy	136	1
Anchovy	180	5
Anchovy	140	5
Arrowtooth flounder	227	5
Chinook salmon	245	1
Chinook salmon	216	1
Chinook salmon	205	1
Chinook salmon	217	1
Chinook salmon	240	2
Chinook salmon	232	2
Chinook salmon	192	9
Dogfish shark	900	5
Dogfish shark	905	6
Dogfish shark	575	9
Dogfish shark	555	9
Dogfish shark	535	9
Dogfish shark	685	10
Night Smelt	135	2
Pacific Hake	82	10
Pacific Hake	100	4
Pacific Hake	100	5
Pacific Hake	77	5
Pacific Herring	220	5
Pacific Herring	225	5
Pacific Herring	244	5
Pacific Herring	233	5
Pacific Herring	217	5
Pacific Herring	235	5
Pacific Herring	170	5
Pacific Herring	226	5
Pacific Herring	170	10
Pacific Tomcod	133	2

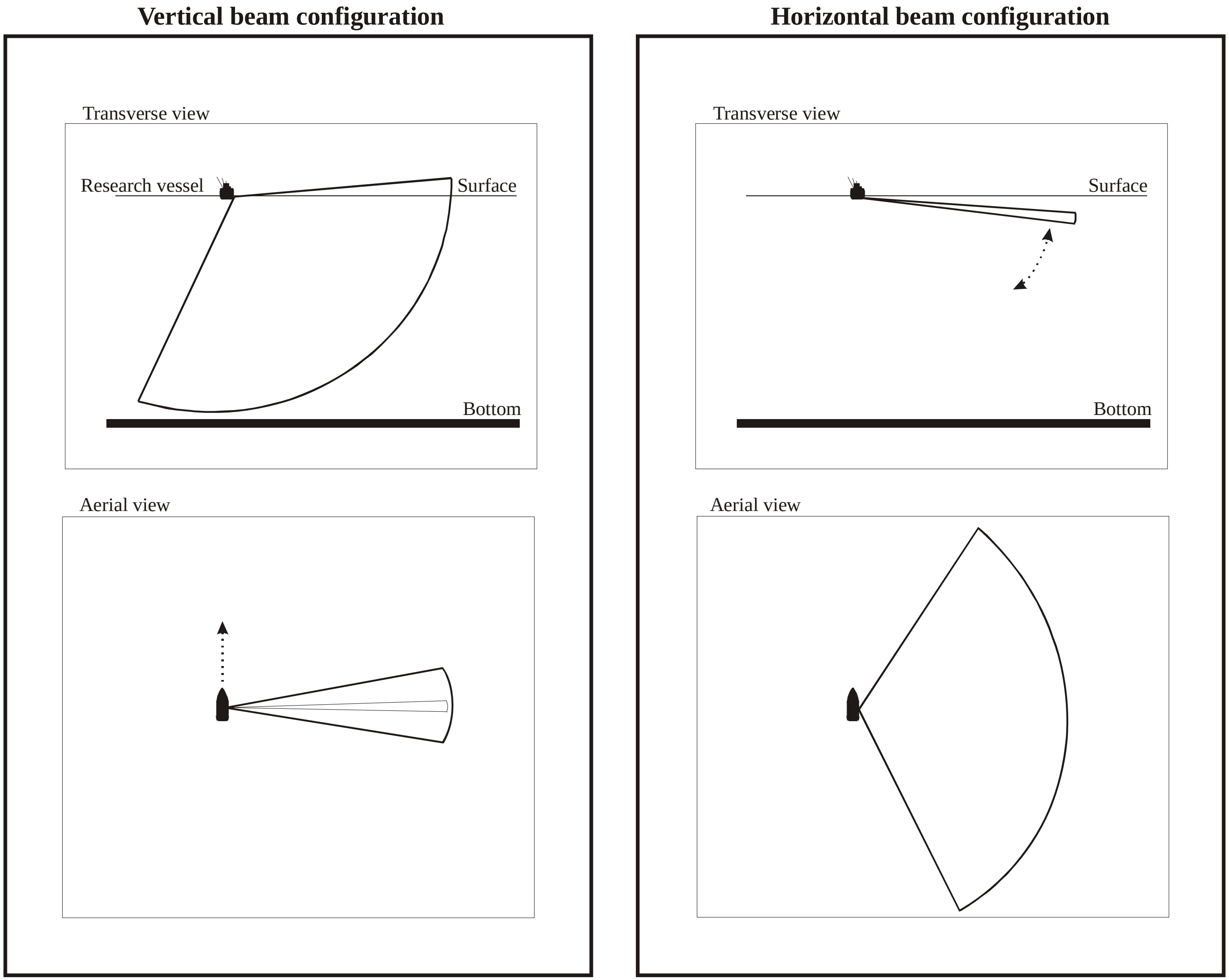
Table 7. Sightings of killer whales. See methods section for explanation of behavioral codes.

Date	Time	Lat	Long	Transect	Sp	N	Range (Km)	Beaufort	Comments
9/15/04	1018	48.4413	122.9630	n/a	ORCA	2	2.90	1	O=NL, ND, D=S, S=M
9/15/04	1048	48.4480	123.0083	1	ORCA	4	0.80	1	O=NL, ND, D=S, S=M nw
9/15/04	1124	48.4642	123.0672	1	ORCA	6	0.50	1	WHALES SPREAD OVER 1 MILE nw
9/15/04	1143	48.4732	123.0933	1	ORCA	3	1.00	2	WHALES SPREAD OVER 1 MILE sw
9/15/04	1401	48.4645	123.0837	n/a	ORCA	10	1.30	2	O=NL, ND, D=S, S=M
9/15/04	1408	48.4617	123.0798	n/a	ORCA	15	0.80	2	K21,K40,L5,L73,L84 D=L, O=NL
9/15/04	1417	48.4593	123.0725	n/a	ORCA	4	0.15	2	K21,K40,L5,L73 D=L, O=NL S=M JKL PRESENT
9/15/04	1436	48.4598	123.0832	n/a	ORCA	2	0.80	2	L74,L84 O=NL,D,D=L,S=M
9/15/04	1443	48.4558	123.0827	2	ORCA	3	0.05	2	K11,L74 50 METERS TO STARBOARD, 10 BOATS
9/15/04	1511	48.4353	123.0517		ORCA		240 M	2	K11 BELLYFLOP
9/15/04	1522	48.4387	123.0415		ORCA	15	200 M	2	J11,J27,K7,K20,K25,K27,J34 WHALES SPREAD OUT NORTHBOUND TOWARDS EAGLE PT.
9/15/04	1526	48.4443	123.0393	2	ORCA	14		2	J17, J22-J34 WHALES CIRCLED LEFT NOW NORTHBOUND
9/15/04	1533	48.4477	123.0370	2	ORCA	2	0.07	2	L92,L95 D=T,S=M, O=NL,D, n
9/15/04	1533	48.4477	123.0370	2	ORCA	9		2	J1,J2,J17,J19,J28,J35,J22,J32,J38
9/15/04	1545	48.4565	123.0482	L01	ORCA	2	0.10	2	L43,L95 D=T, n, 6 BOATS
9/15/04	1551	48.4595	123.0393	L01	ORCA	8	0.20	1	J1,J2,J14,J30,J37,J19,L43,L95 D=T, S=M n
9/15/04	1600	48.4610	123.0642	L01	ORCA	8	0.10	0	WHALES HEADING SOUTH
9/15/04	1608	48.4643	123.0652	L01	ORCA		150 M	0	L27,L55,L103,L86,L21,L47,L83,L91,L82,L26,L71,L90,K13,K34,K14,K36,J8,J16,J26,J36
9/15/04	1630	48.4550	123.0457	L01	ORCA	14		0	FOLLOWING WHALES INSHORE; se; WHALES TIGHT GROUPS, LOOSE;L POD ABREAST, 2 OTHER GROUPS HEADED…(?); L27,L55,L103,L86,L21,L47,L83,L91,L82,L72,L26,L71,L90,L92
9/15/04	1649	48.4627	123.0607	L01	ORCA	14		0	100 METERS OFF STARBOARD; J,K,MOST L POD, 1 BOAT
9/15/04	1708	48.4553	123.0637	L01	ORCA	72	0.10	0	D=T, S=S, 2 GROUPS (J,K,.5L; .5L)
9/15/04	1722	48.4705	123.0810	L01	ORCA	72		0	WITHIN 100 METERS; se OFF FALSE BAY
9/15/04	1754	48.4645	123.0707	L01	ORCA	72		0	D=T, ND
9/15/04	1815	48.4743	123.0903	L01	ORCA	72		0	WHALES PASS 30M OFF STERN s; SPLITBEAM ON
9/16/04	1011	48.4877	123.1563	3	ORCA	3	3.20	3	O=NL, D, D=S, S=M n
9/16/04	1029	48.4722	123.1400	3	ORCA	15	1.60	4	O=NL,D,D=S,S=M n TIGHT GROUPS SPREAD OUT

9/16/04	1039	48.4655	123.1310	3	ORCA	15	1.60	4	O=NL, ND, D=S,S=M
9/16/04	1257	48.5348	123.1793	n/a	ORCA	6	2.00	3	O=NL, D, D=S, S=M n CLOSE TO SHORE
9/16/04	1309	48.5568	123.1898	n/a	ORCA	3	0.30	4	L57+2FEMALES O=NL, D,D=T, S=M
9/16/04	1341	48.5962	123.2200	4	ORCA	6	0.20	3	L74,K11 O=NL, D, D=T, S=M
9/16/04	1341	48.5962	123.2200	4	ORCA	2	0.25	3	K26, UNK
9/16/04	1354	48.6035	123.2127	4	ORCA	7	0.40	3	J30, K21, K40 ALL WHALES s; WE FOLLOW
9/16/04	1422	48.5958	123.2158	4	ORCA	3	0.30	3	CROSSING IN FRONT OF ANIMALS, NORTHBOUND
9/16/04	1446	48.6035	123.2205	4	ORCA	6	0.40	2	O=NL, ND, D=S, S=S WHALES SPREAD OUT MILLING
9/16/04	1457	48.6057	123.2215	4	ORCA	2	0.20	2	L2,L78 O=F, D=T, S=M, ND
9/16/04	1558	48.6142	123.2198	7	HAPO	1	0.10	2	
9/16/04	1713	48.6353	123.2277	9	DAPO	1	0.05	2	
9/16/04	1736	48.6515	123.2480	10	DAPO	2	0.30	2	
9/17/04	939	48.5635	123.1997	n/a	ORCA	10	1.60	1	O=NL,D,D=S,S=M
9/17/04	1008	48.5515	123.1778	11	ORCA	20	0.30	1	O=NL,D,D=S,S=M L41,L57,J1 GROUPS SPREAD OUT
9/17/04	1013			11	ORCA	10	0.05	1	K40,L77,K31?,K20,L43,L74,
9/17/04	1021	48.5380	123.1743	11	ORCA	5	0.05	2	J26,J34?,L53,L87,L89,L12,L85,L32,K16
9/17/04	1026	48.5380	123.1743	n/a	ORCA	10	0.20	2	WHALES n, WE FOLLOW W/O GEAR IN WATER
9/17/04	1040	48.5488	123.1920	n/a	ORCA	2	0.20	3	L2,L78, O=NL, D,D=T,S=M
9/17/04	1112	48.5903	123.2107	n/a	ORCA	6	0.50	3	O=NL,D,D=S,S=M APPROACHING WHALES AT KELLETT BLUFF
9/17/04	1136	48.5888	123.2123	n/a	ORCA	6	0.15	3	KELLETT BLUFF, L7, L57 LOOSE, WHALES SPREAD OUT, LOTS OF ECHOLOCATION AND VOCALS
9/17/04	1153	48.5895	123.2065	n/a	ORCA	8	0.30	3	O=NL,ND,D=S,S=M MILLING SOUTHWARD
9/17/04	1519	48.4567	123.1345	12	DAPO	2	0.30	0	
9/17/04	1535	48.4428	123.1097	12	DAPO	1	0.50	0	
9/17/04	1647	48.3955	123.0522	12	ORCA	8	0.50	0	O=NL, ND, D=S, S=M HEIN BANK SPREAD OUT, MILLING
9/17/04	1654	48.3918	123.0430	n/a	ORCA	7	0.10	0	L25,L57,J26,J14,J30,J37,L12
9/17/04	1655	48.3918	123.0430	n/a	ORCA	7	0.01	0	J30, L94,L85,K28,J31,J39,L84 END ND, NOW D n
9/17/04	1708	48.3973	123.0482	13	ORCA	12	0.15	0	J11,J27,L43,L72,L95,K11,L73 O=NL,D,D=S,S=M n
9/17/04	1717	48.4095	123.0458	13	ORCA	7	0.13	0	L2,L78,L88,K21,K40 S=F
9/17/04	1727	48.4243	123.0468	13	ORCA	10	0.50	0	O=F, S=F, D=T, L L57
9/17/04	1744			L02	ORCA	2	0.15	0	L32,L87 O=F,S=M, D=D, D
9/17/04	1810	48.4777	123.0893	L02	ORCA	50	0.40	0	O=NL, S=M, D=L, ND MILLING AT PILE POINT
9/17/04	1817	48.4807	123.0965	L02	ORCA	30	0.01	0	O=F, D=L, S=M D s L25, L41, L94
9/17/04	1901	48.4512	123.0673	L02	ORCA	40	0.10	0	L2, L54, L5,J22,L43,K21,K40 O=F, S=S, D=T ENDING ENCOUNTER, PULLING GEAR

9/18/04	1114	48.4393	123.0190	14	MINKE	1	1.00	1	
9/18/04	1409	48.4665	123.1112	14	DAPO	5	1.50	1	
9/18/04	1808	48.4045	123.1213	16	HAPO	1	0.70	0	
9/19/04	1210	48.6427	123.0668	18	HAPO	1-2	0.30		
9/19/04	1215	48.6470	123.0605	18	HAPO	1	0.25	2	
9/19/04	1755	48.7158	123.1813	20	PO	4-5	1.20		
9/19/04	1806	48.7127	123.1905	20	HAPO	2	0.50		
9/22/04	1600	48.4902	123.1335	34	DAPO	4-6	0.30	0	
9/22/04	1606	48.4965	123.1470	34	DAPO	2	0.10	0	
9/22/04	1612	48.5053	123.1568	n/a	DAPO	2	0.10	0	
9/22/04	1636	48.4942	123.1558	35	DAPO	3	0.15	0	
9/22/04	1657	48.4748	123.1278	35	DAPO	1	0.25	0	
9/22/04	1814	48.4302	123.9357	L03	ORCA	40-70		0	J,K, AND L PODS IN AREA, ENC WITH K POD WHALES
9/23/04	1222	48.4632	123.0712	L04	ORCA	40-70		1	BEGIN KW ENCOUNTER, L25, L41-O=F, ND, C=L, S=S. L79 ALSO SEEN
9/23/04	1235	48.4690	123.0728	L04	ORCA	40-70			L25, L41 O=NL, ND, C=L
9/23/04	1252	48.4650	123.0757	L04	ORCA	40-70			L25, L41 O=NL, ND, C=L
9/23/04	1320	48.4728	123.0947	37	ORCA	40-70			L41, L25 O=NL, D, C=L, S=F
9/23/04	1325	48.4792	123.1130	37	ORCA	40-70		1	END FOCAL GROUP
9/23/04	1406	48.5368	123.0947	37	ORCA	40-70		1	L2, L78, L88, L67, L101, L54, and L100 O=NL, D,C=L, S=F
9/23/04	1422	48.5643	123.2005	37, L05	ORCA	40-70			SAME WHALES- O=F, D, C=T, S=F
9/23/04	1440	48.6020	123.2135	37, L05	ORCA	40-70			L2, L78, L88, L67, L101, L54, L100, L43, L72, L95, and L74 O=F, D,C=T, S=F, HEADING NORTH, WHALES ALSO PHOTOGRAPHED DURING THIS TIME: K12, K14, K16, K21, K22, K26, K28, K31, K33, K35?, K36, K37, and K40
9/23/04	1450	48.6020	123.2135	37, L05	ORCA	40-70			J, K, AND L PODS TURN AROUND AND HEAD SOUTH MEDIUM TRAVEL AFTER MILLING NON-DIRECTIONNALLY AT KELLET BLUFF. WAHELS PHOTOGRAPHED DURING THE DIRECTION CHANGE INCLUDE J1, J17, L5, L12, L25, L41, L57, L71, L73, L79, L84, L89, L90, and L94.
9/23/04	1500	48.6060	123.2132	L05	ORCA	40-70		1	ALL WHALES CONTINUE TO HEAD SOUTH, MEDIUM TRAVEL, AND LEAVE US BEHIND
9/23/04	1706	48.4938	123.1733	38	DAPO	2-3	0.40	1	SLOW ROLL
9/23/04	1715	48.4847	123.1695	38	DAPO	2-3	0.40	1	SLOW ROLL

Figure 1. Multibeam sonar configurations.



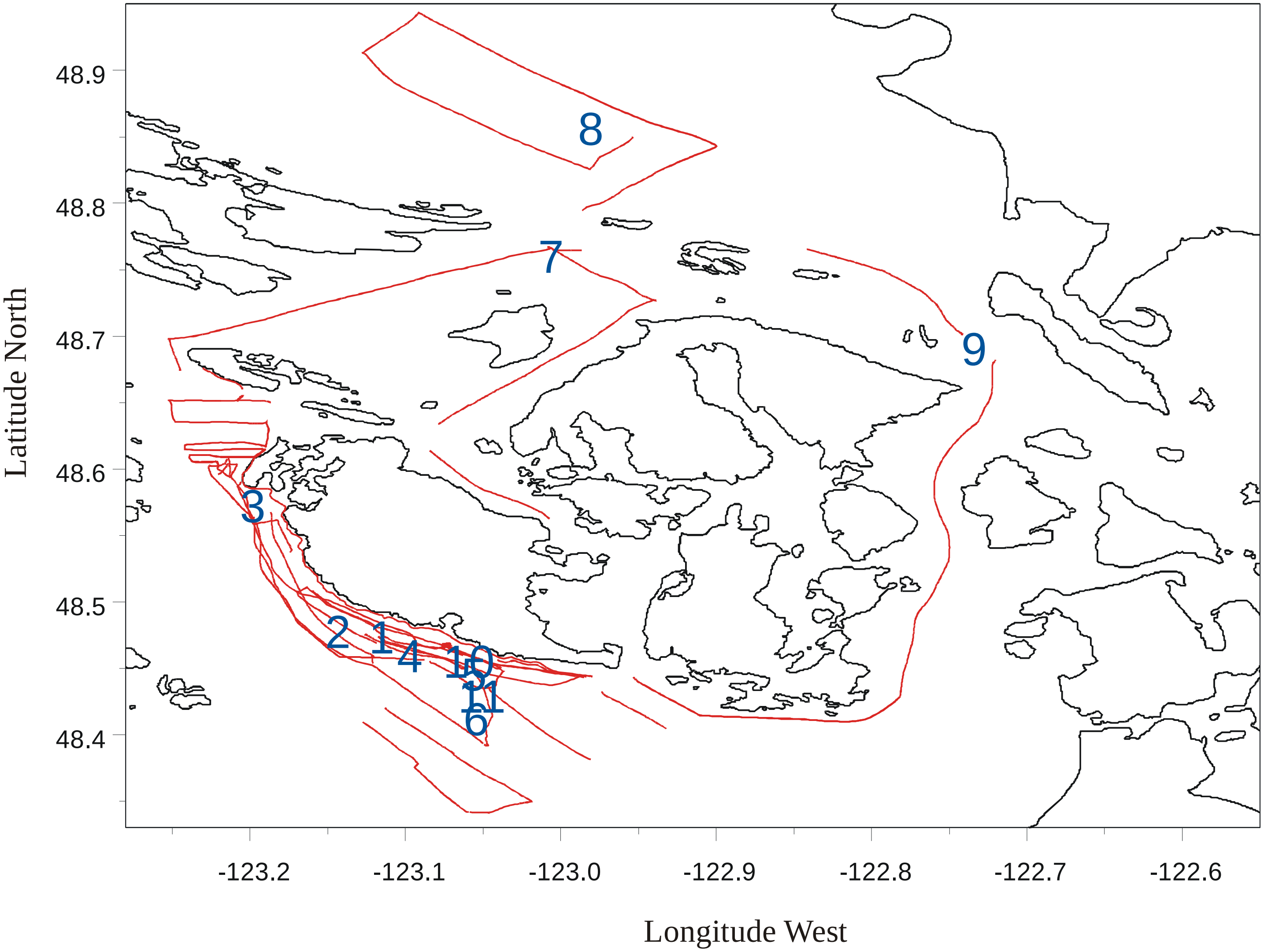


Figure 2. Survey transects (in red) and trawl locations (blue numbers corresponding to trawl stations) in the San Juan Archipelago.

Figure 3. Example of an echogram showing the three backscatter categories used in echo integration.

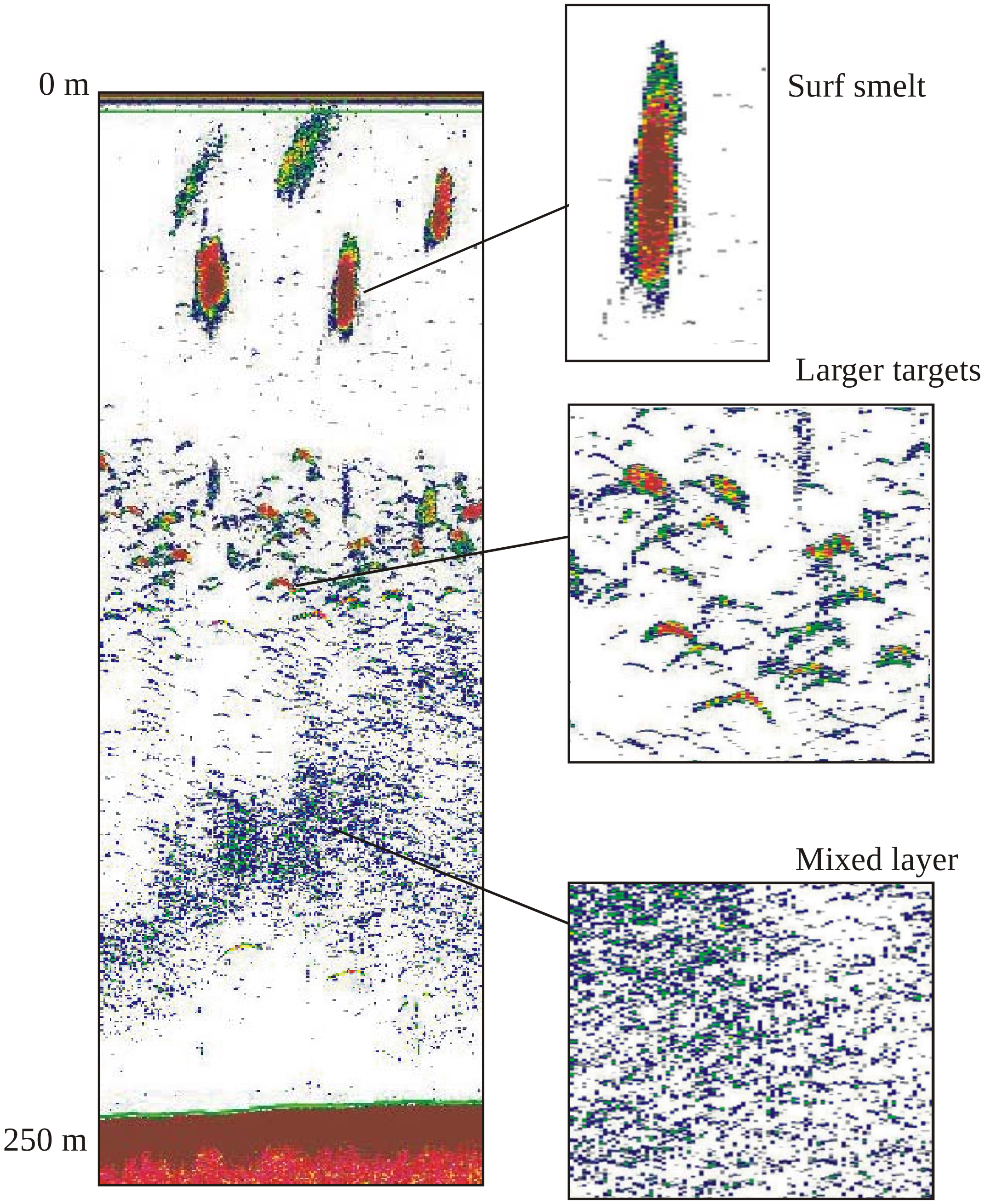


Figure 4. Length frequencies of fish caught by midwater trawl at each station.

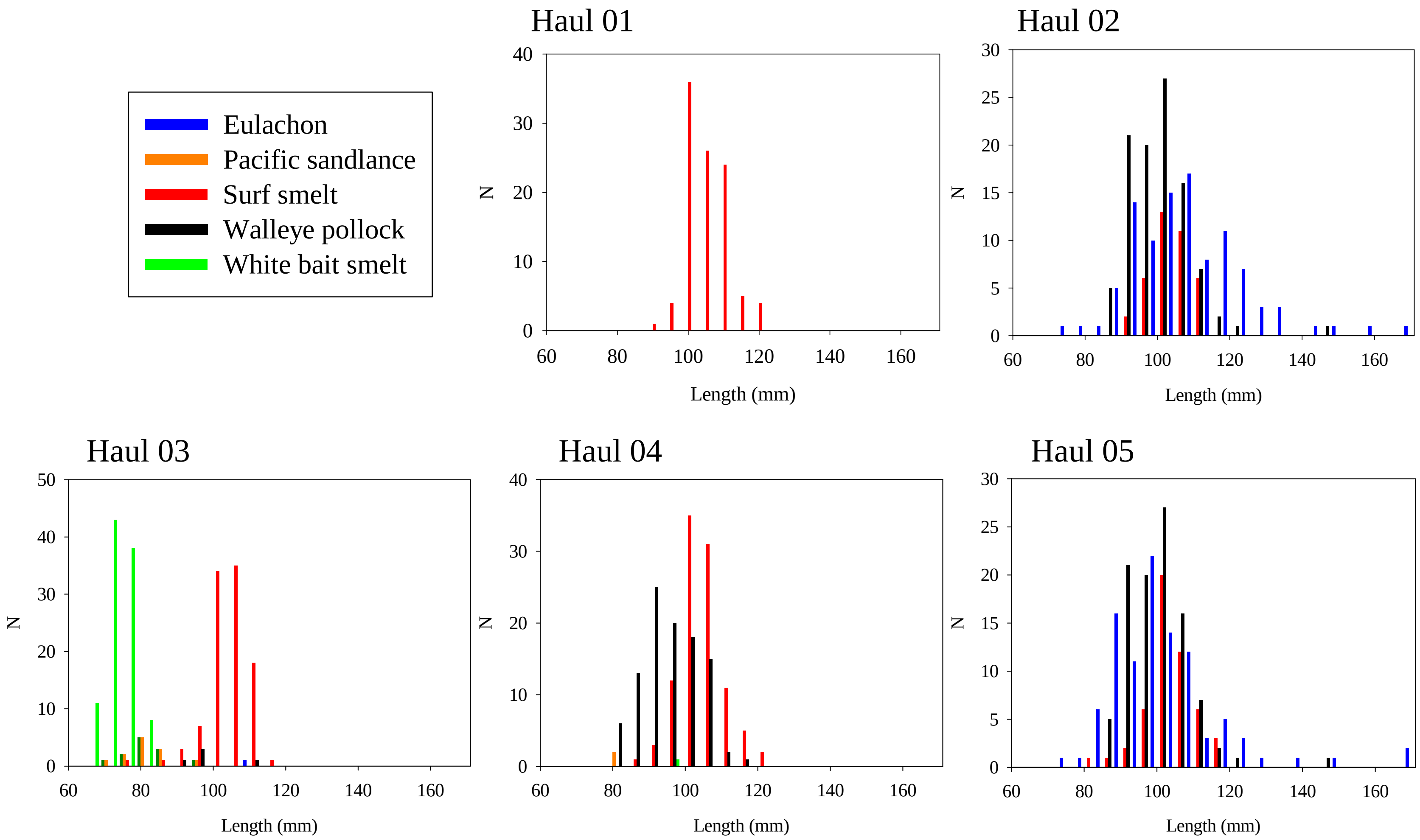


Figure 4 (cont’d). Length frequencies of fish caught by midwater trawl at each station.

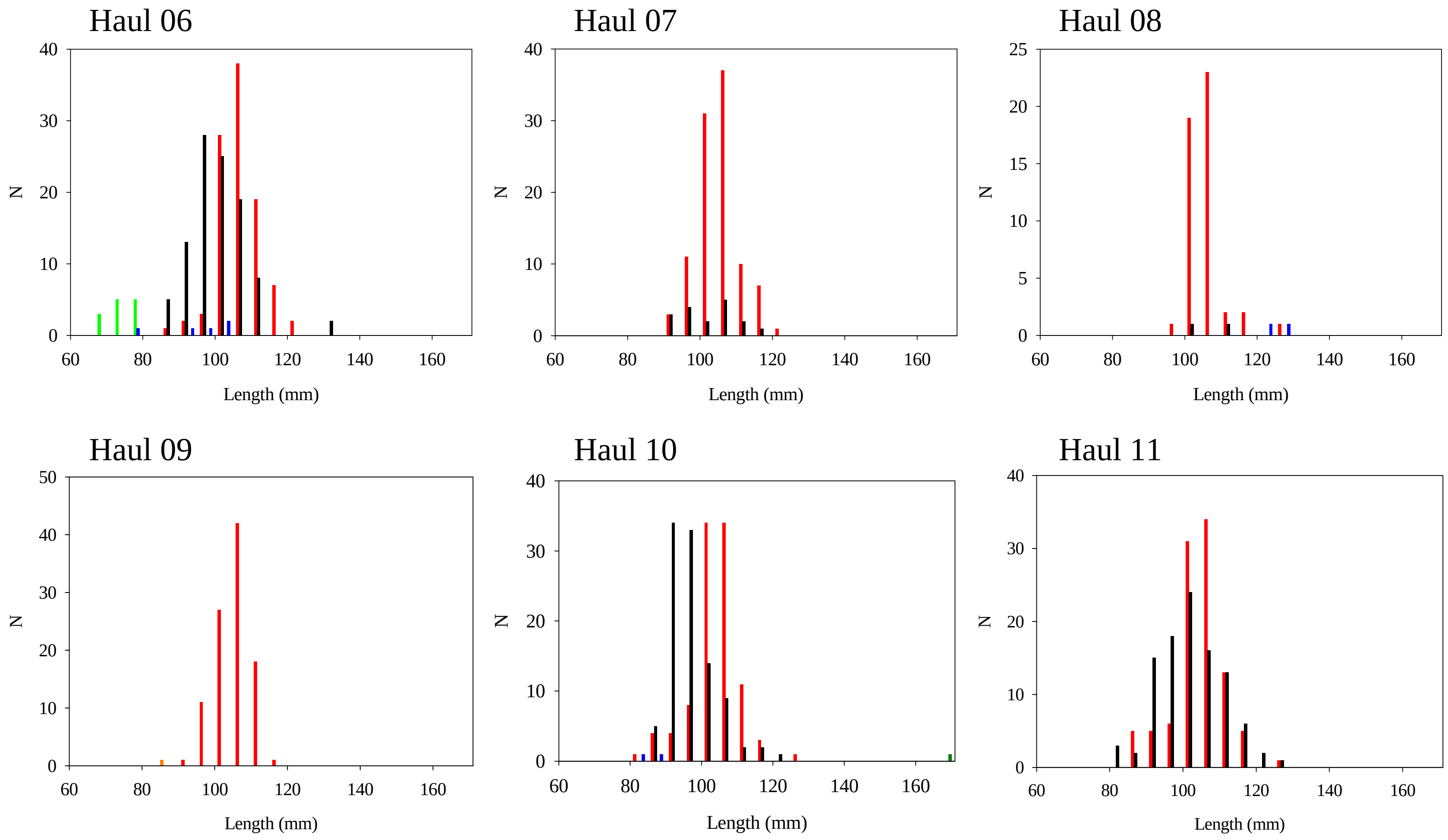
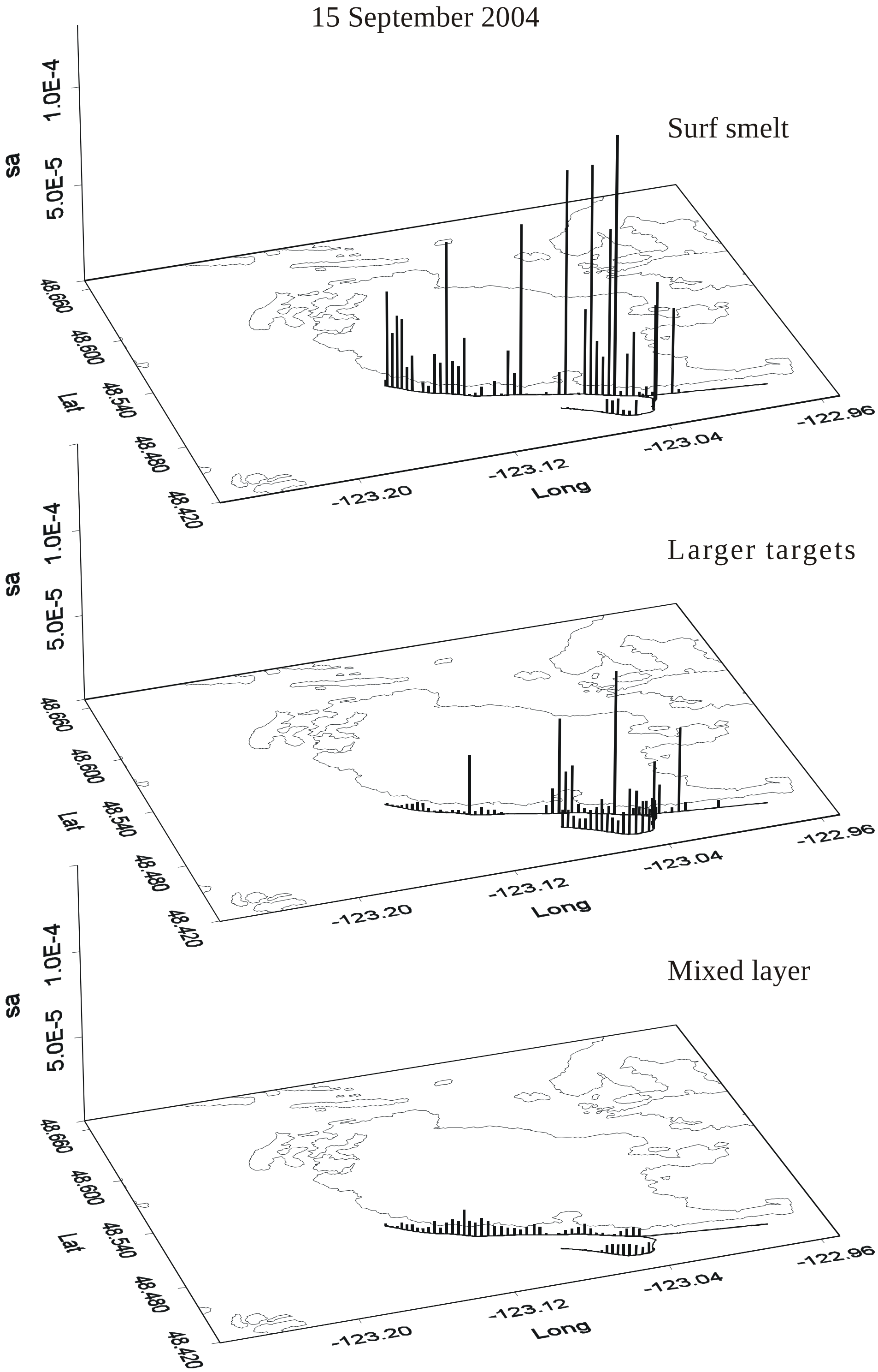


Figure 5. Relative acoustic densities (s_a, units $m^2 \cdot m^{-2}$) of the three backscattering layers (Surf smelt, Larger targets, Mixed layer) in the Haro Strait region. Reference values on the vertical axes of plots can differ among days and/or scatter category.



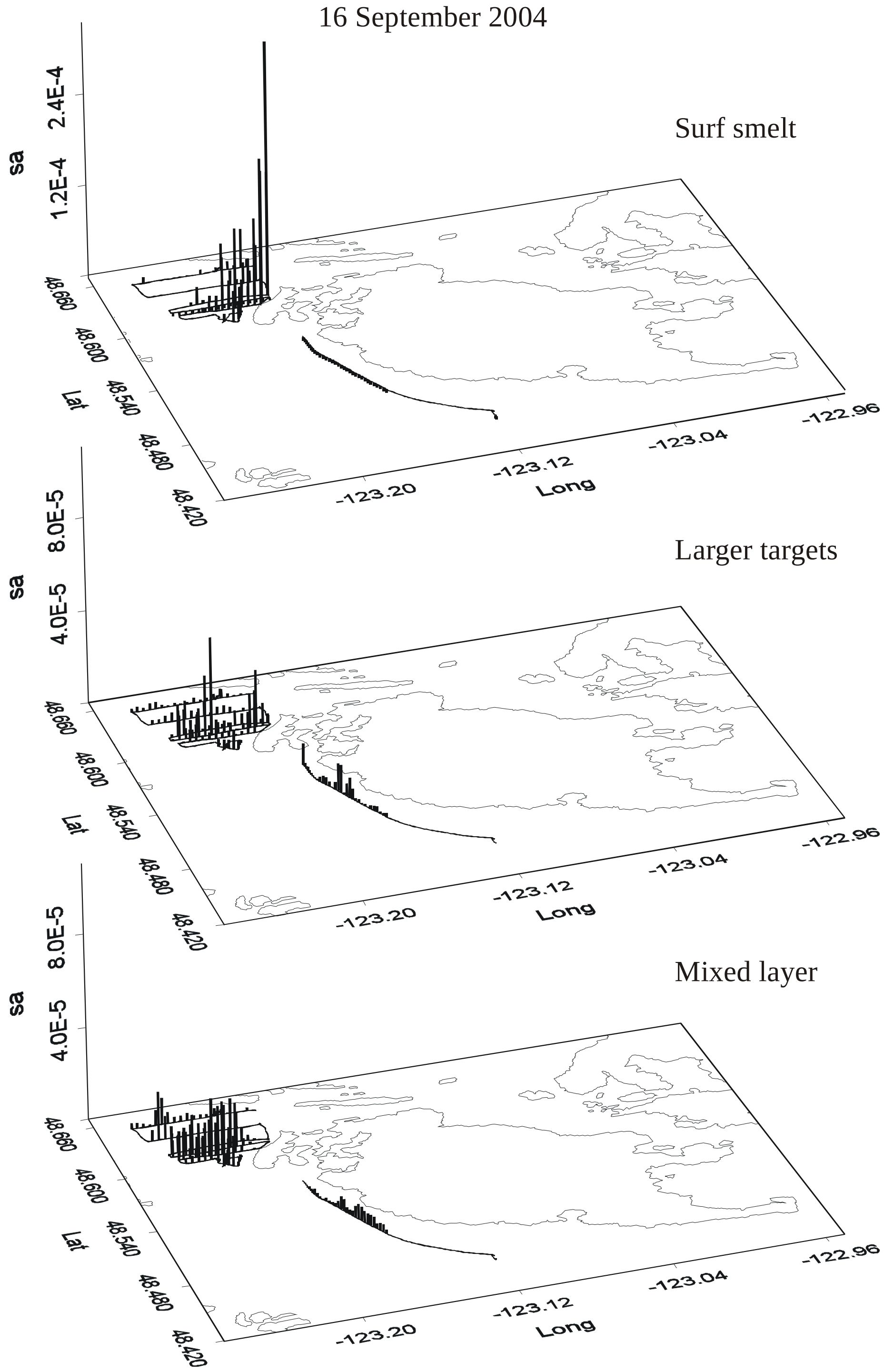
15 September 2004

Surf smelt

Larger targets

Mixed layer

Figure 5 (cont'd).



16 September 2004

Surf smelt

Larger targets

Mixed layer

Figure 5 (cont'd).

17 September 2004

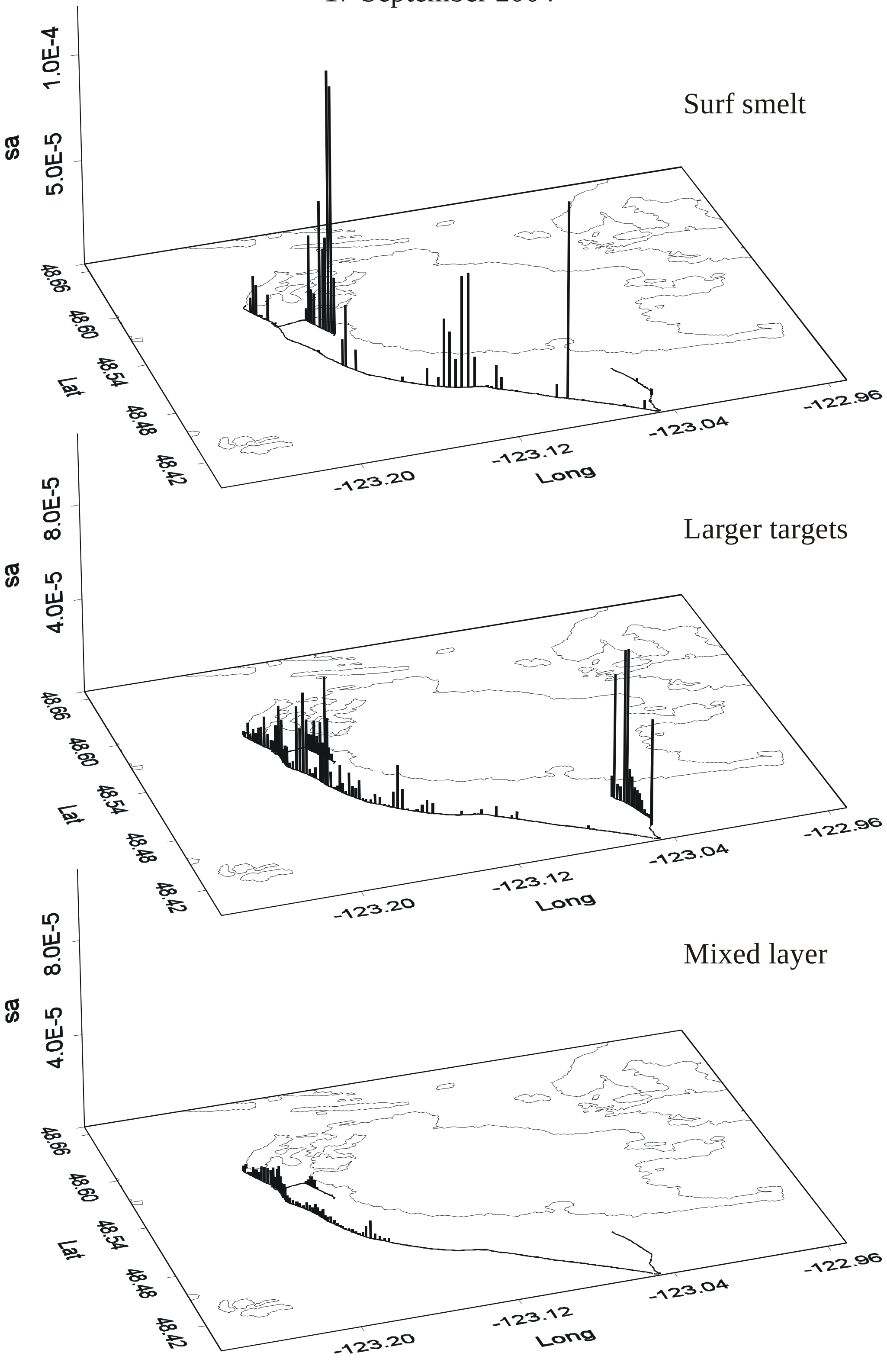


Figure 5 (cont'd).

18 September 2004

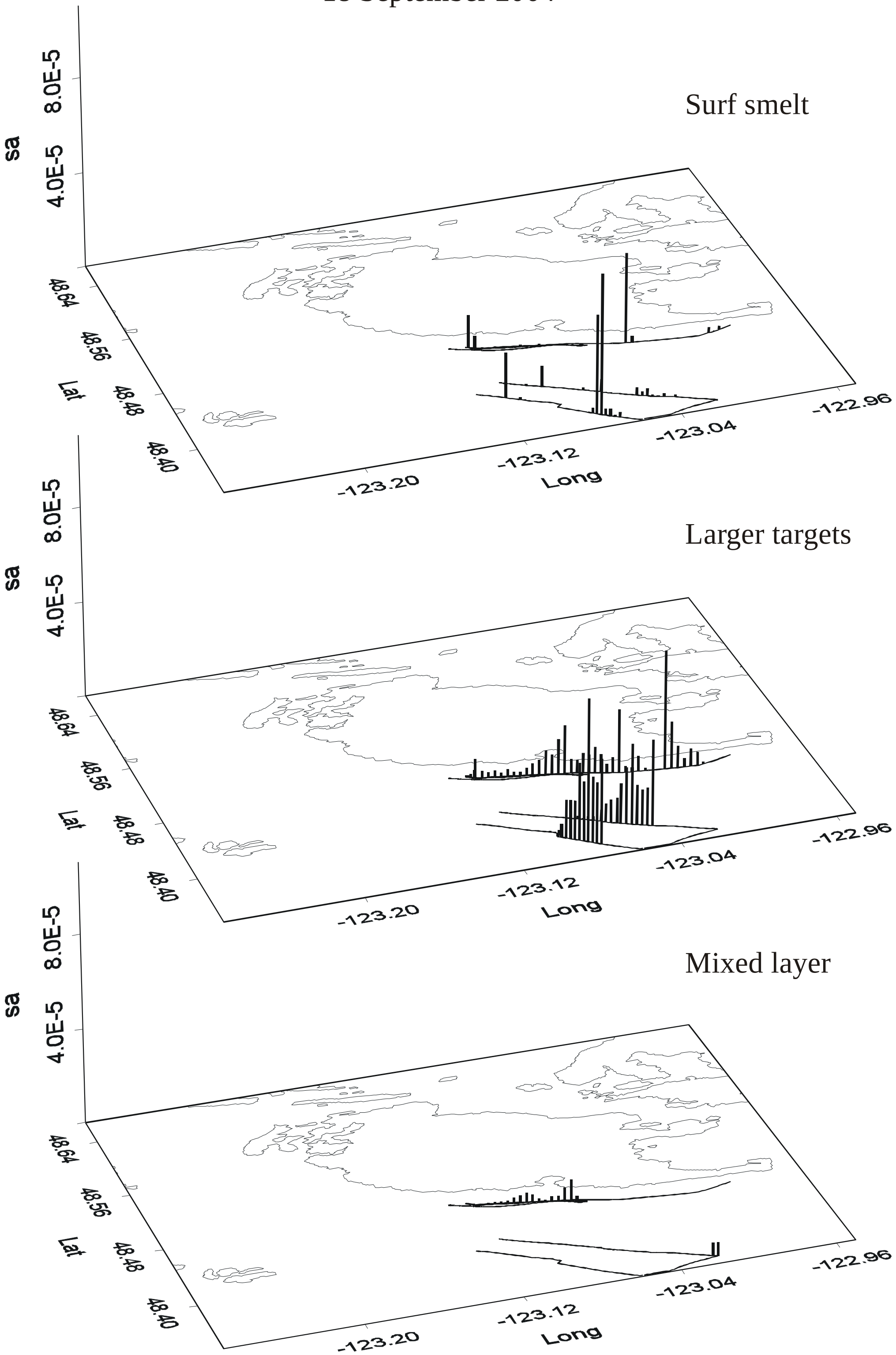
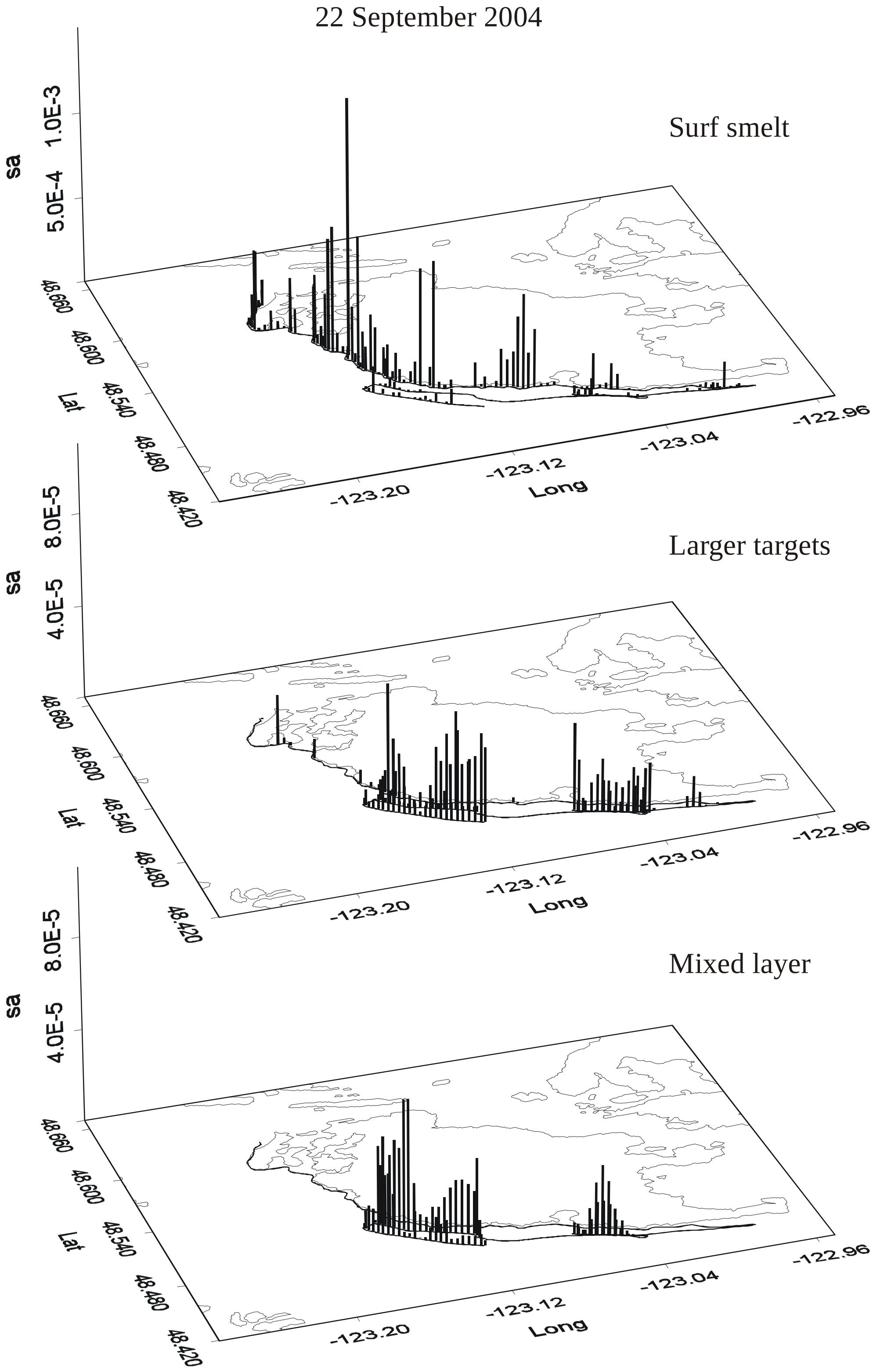
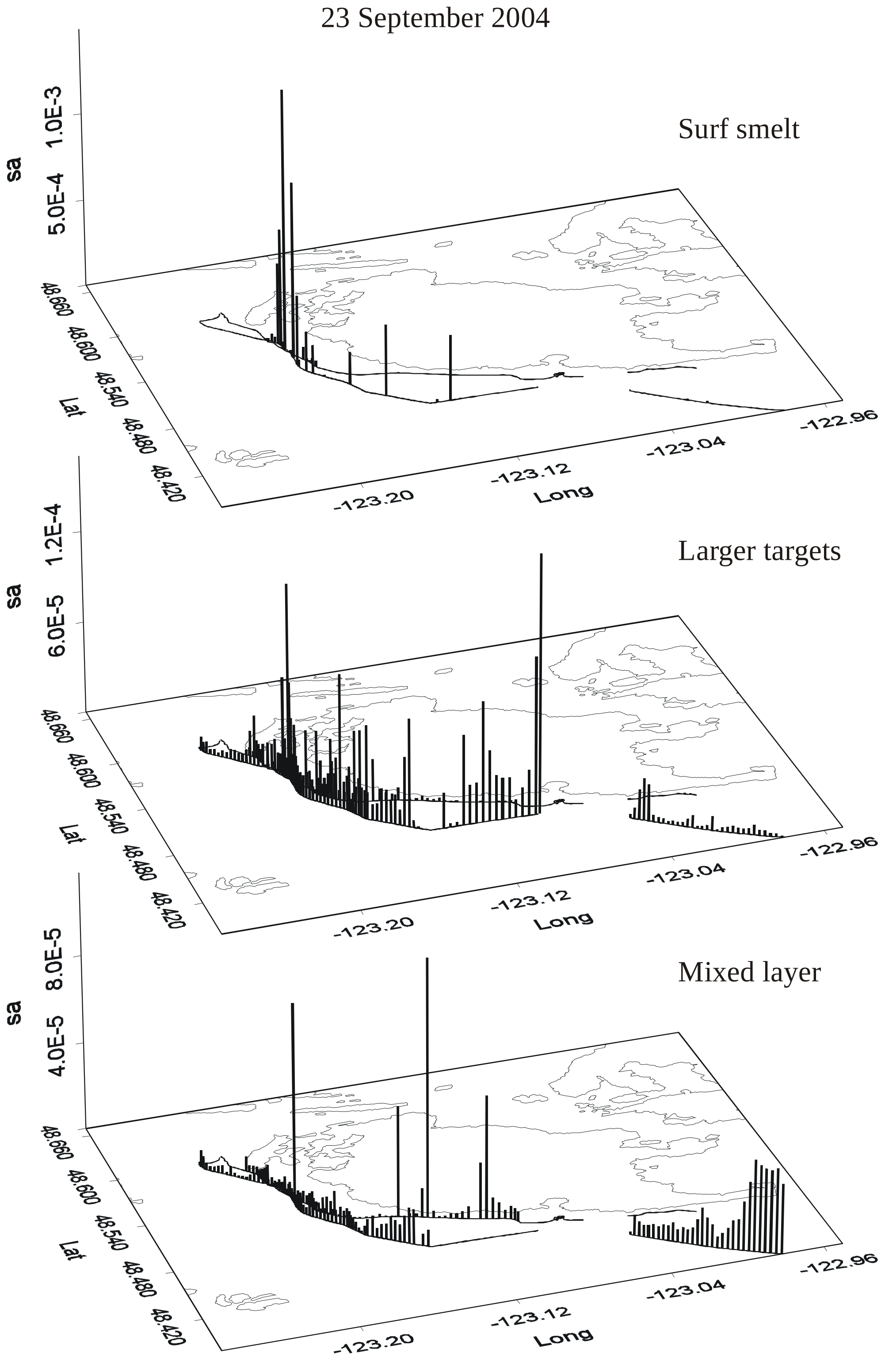


Figure 5 (cont’d).



22 September 2004

Figure 5 (cont’d).



23 September 2004

Figure 6. Relative acoustic densities (s_a, units $m^2 \cdot m^{-2}$) of the three backscattering layers (Surf smelt, Larger targets, Mixed layer) from a loop around the San Juan Archipelago. Reference values on the vertical axes of plots differ among scatter categories.

19 -21 September 2004

Surf smelt

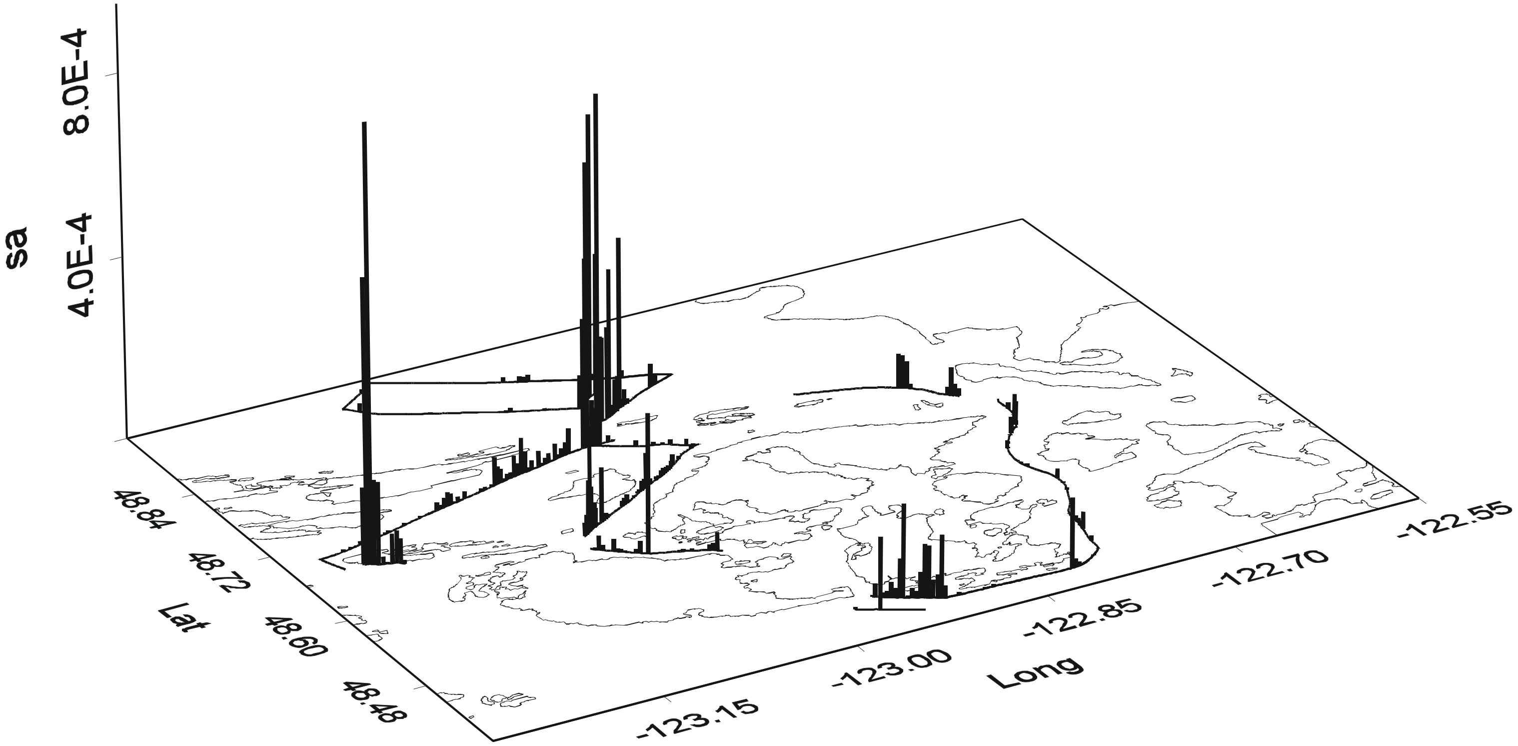


Figure 6 (cont’d).

19 -21 September 2004

Larger targets

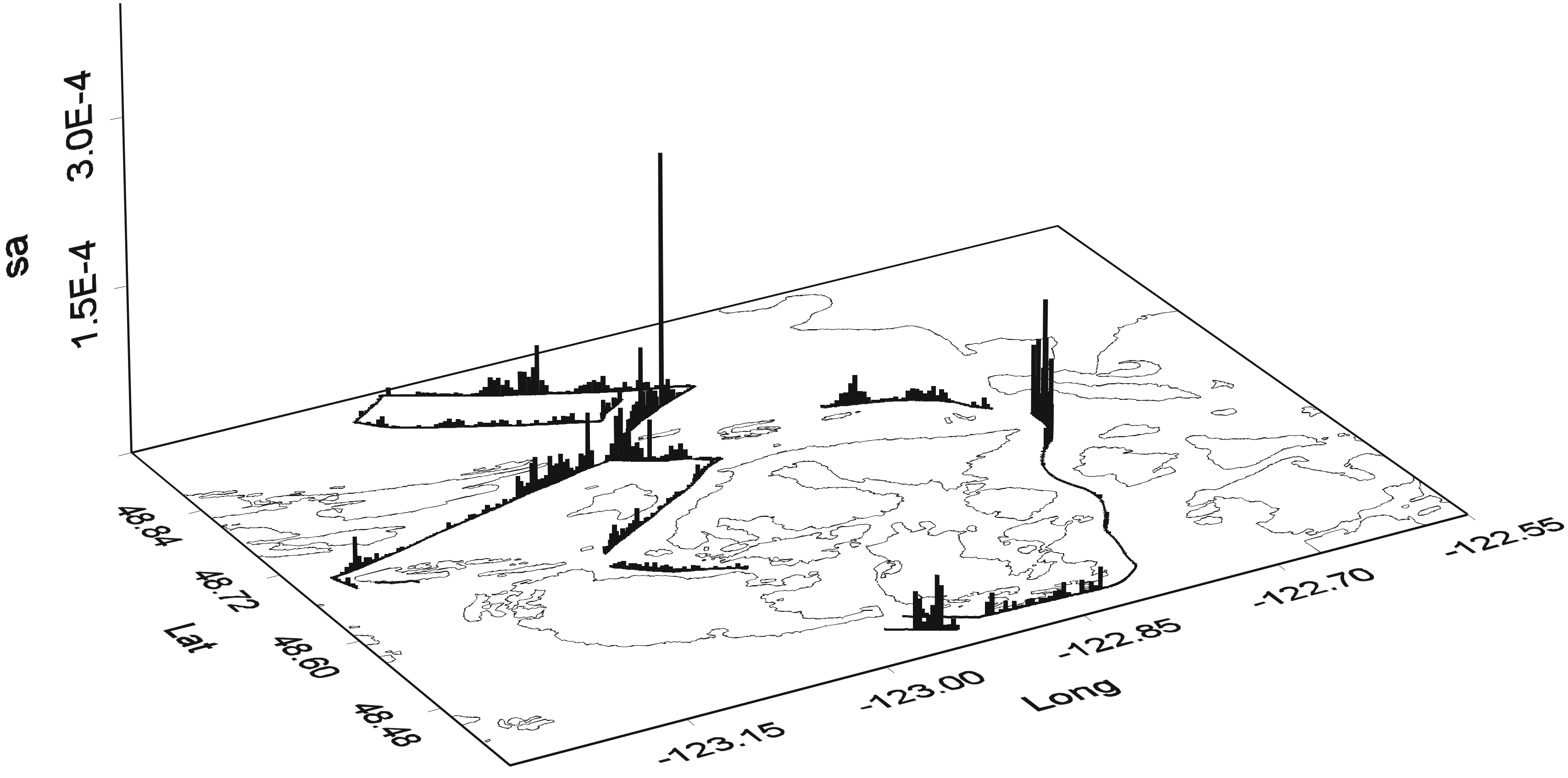


Figure 6 (cont'd).

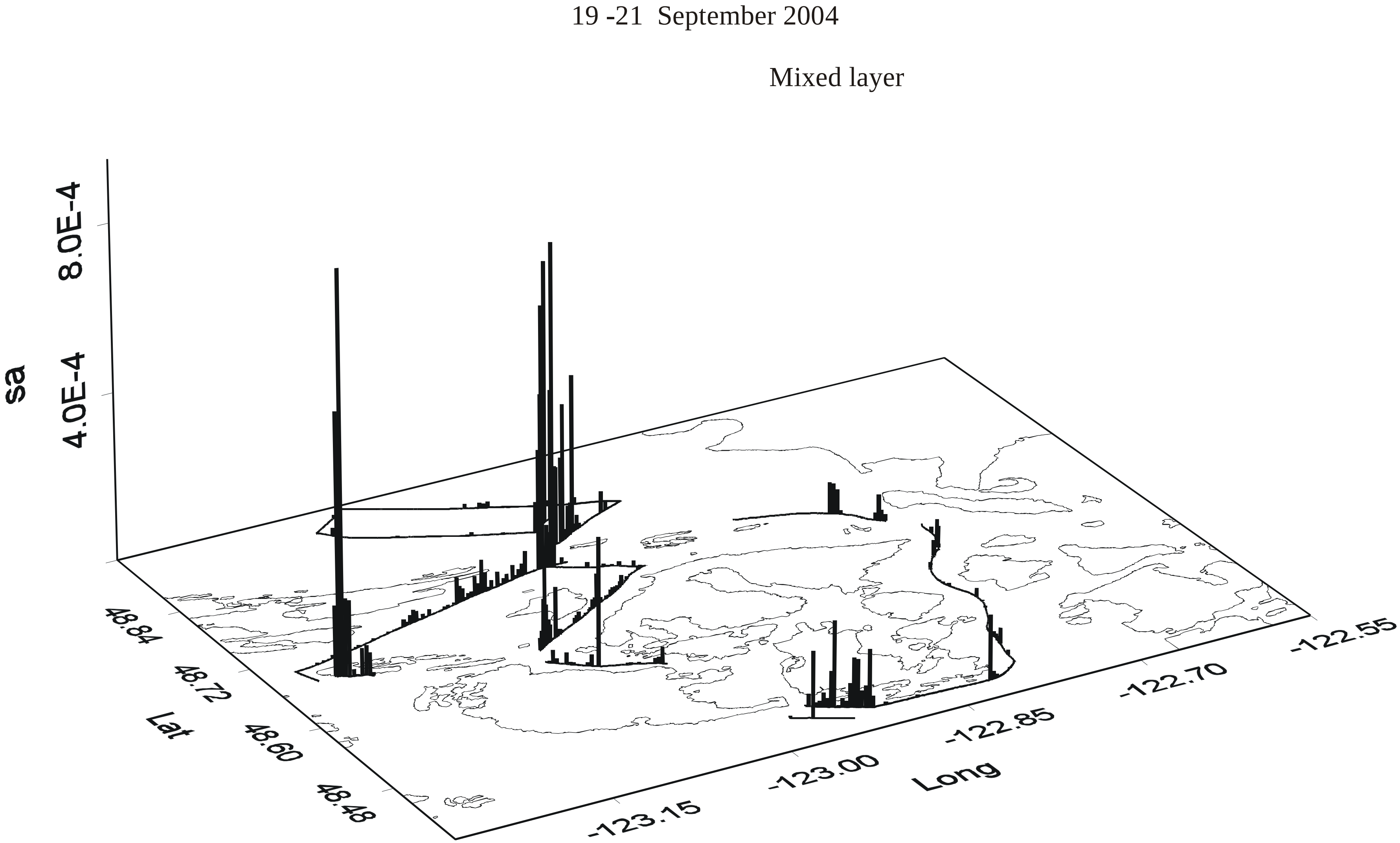


Figure 7. Relative acoustic densities (s_a, units $m^2 \cdot m^{-2}$) of the three backscattering layers (Surf smelt, Larger targets, Mixed layer) obtained during Lagrangian events. Examples of images obtained from the multibeam sonar are provided for each event.

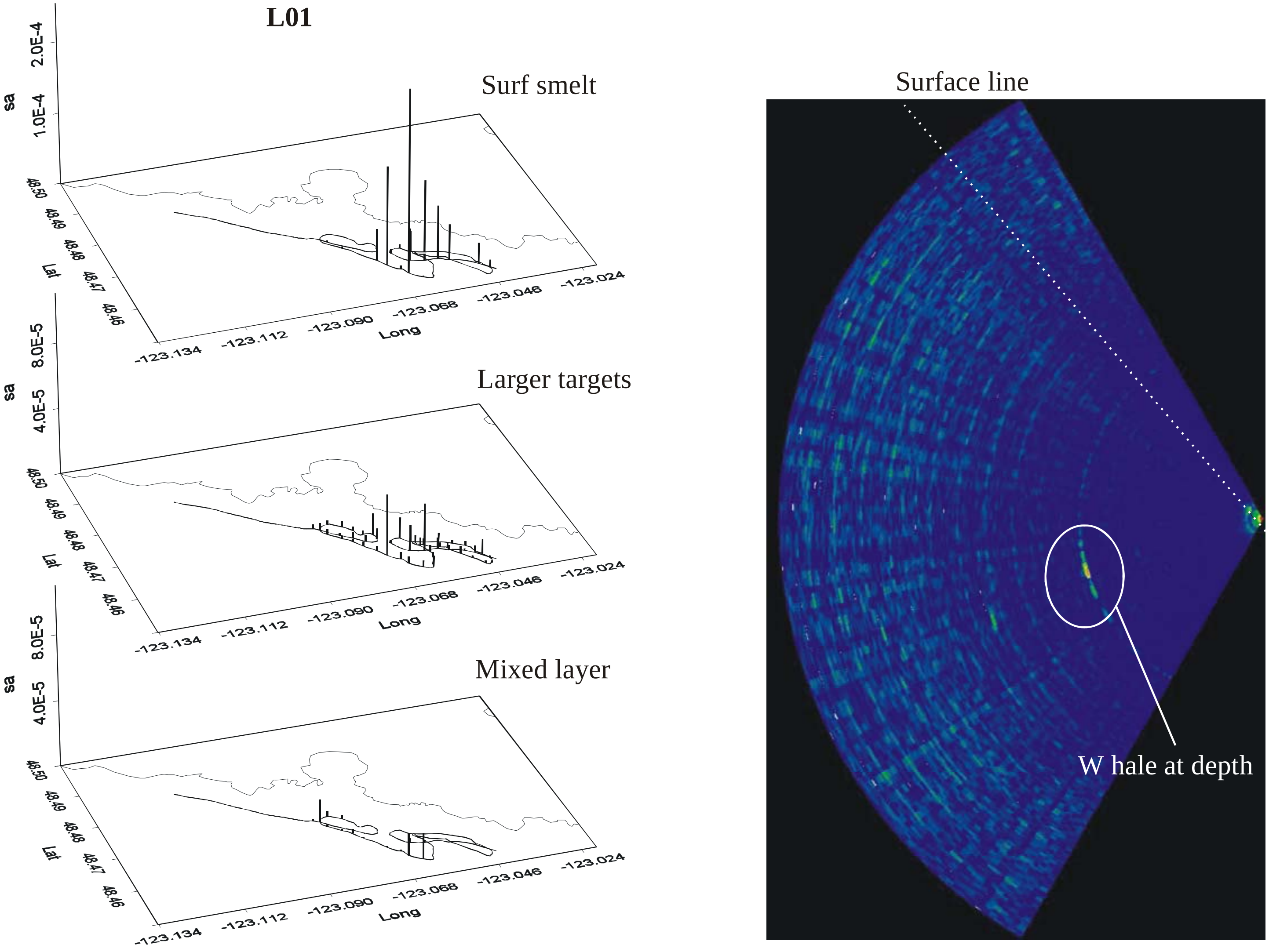


Figure 7 (cont'd).

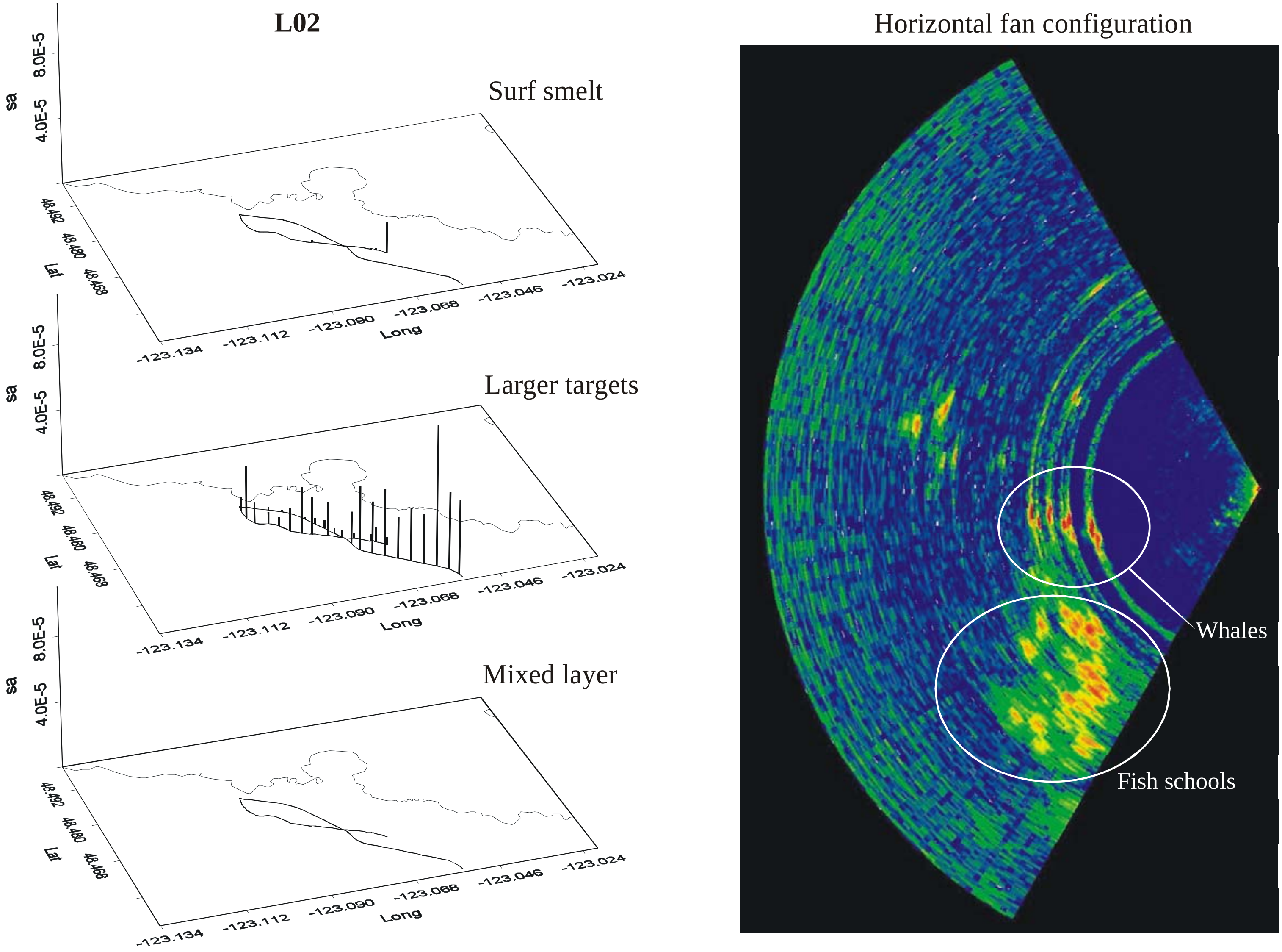


Figure 7 (cont'd).

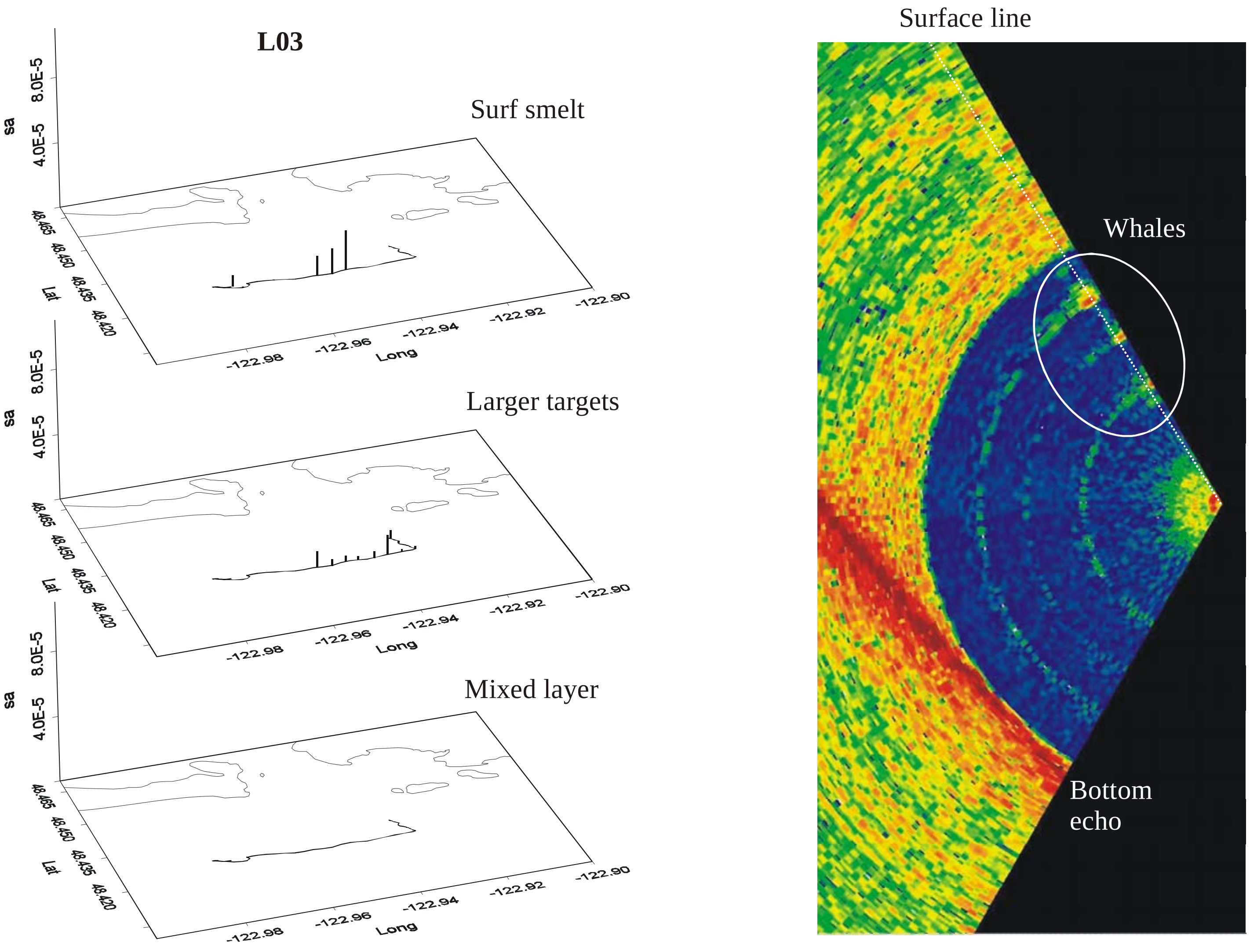


Figure 7 (cont'd).

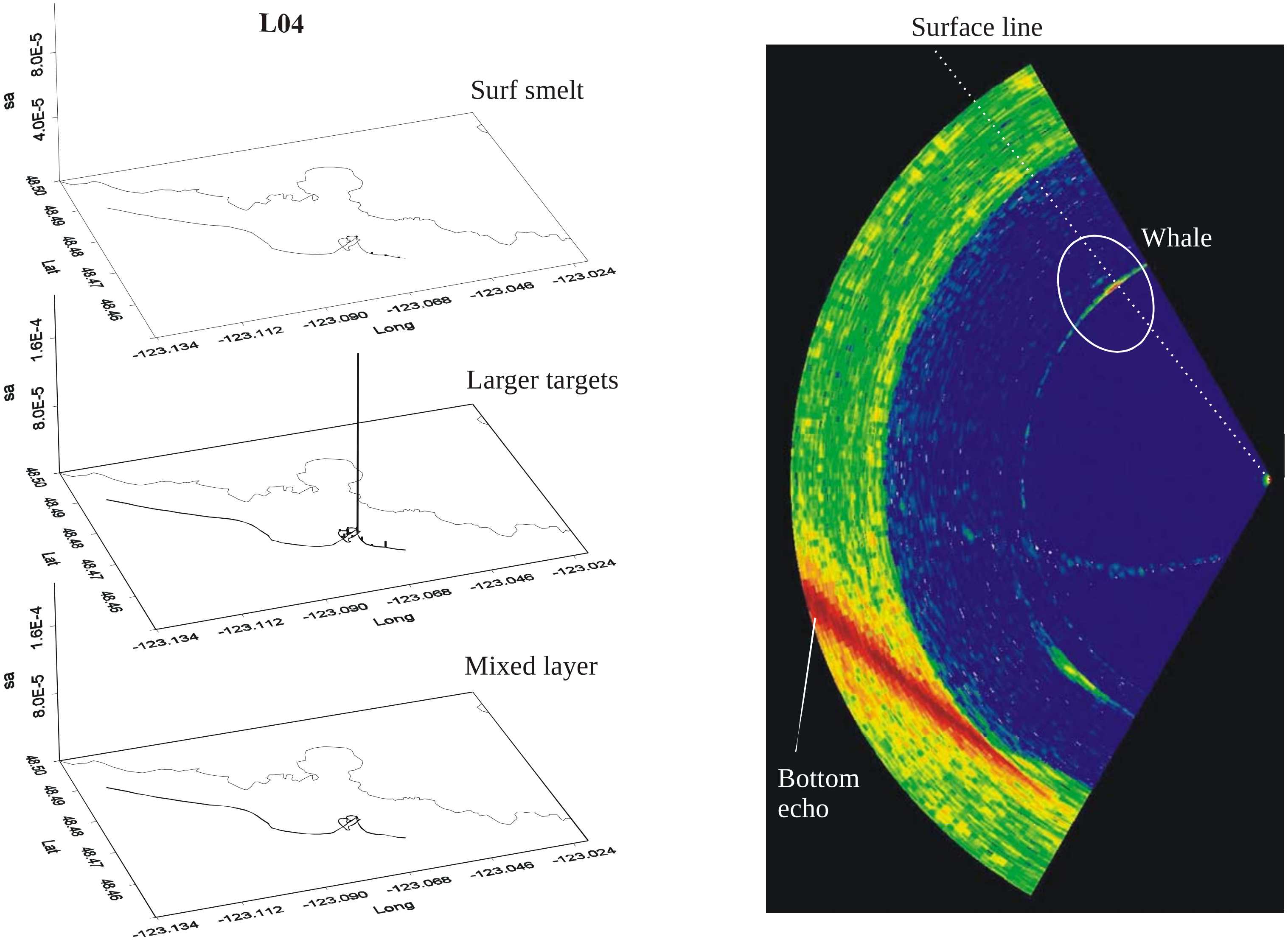


Figure 7 (cont'd).