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Estimates of Low Frequency Volume Scattering off the Oregon-Washington Coast

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ABSTRACT

Estimates are made of low frequency volume scattering using average numbers of animals for the shelf break and offshore waters off the Oregon-Washington coast. Animal densities were derived from fisheries assessments and surveys of marine mammals. Target strengths were based on resonant models of fish with swimbladders and in situ measurements of mammals. Average volume reverberation levels of -60 dB at 100 Hz, and -44 dB at 1000 Hz are expected at both offshore and shelf-break locations during summer nights (July - September). These levels will decline by about 7 dB by day. During winter (January - March) scattering will be low at offshore sites, less than -90 dB at 100 Hz and -60 dB at 1000 Hz but will remain high at the shelf break, near -61 dB at 100 Hz to -48 dB near 1000 Hz. Spring and fall are transitional between winter and summer, and hence, will have volume reverberation levels between those of summer and winter. A model of school encounter suggests that when schools of pomfret jack mackerel, anchovy, and rockfish are present they will be sufficiently widespread to appear as average reverberation levels. Schools of albacore, coho, and chinook salmon will be sufficiently rare and compact so as to cause discrete echoes.

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INTRODUCTION

The performance of long range low frequency active sonar systems can be limited by scattering from marine organisms. Resonance scattering from the swimbladders of relatively high numbers of large widely dispersed fish can produce high levels of volume reverberation and fish schools, or pods of marine mammals can cause clutter or discrete echoes that can interfere with target detection. Volume reverberation, clutter, or discrete echoes are also potential sources of confusion in any active acoustic experiment. The goal of this paper is to reduce any possible confusion for experiments or operations conducted off the Oregon-Washington coast by estimating low frequency biological scattering in shelf waters and offshore.

Models predicting volume scattering were applied to biological data obtained from fisheries agencies and published literature. Biological data include estimates of the occurrence and abundance of all large fishes and mammals in the region. Average volume reverberation levels were calculated based on models of swimbladder resonance and in situ measurements. All species under consideration aggregate to some degree. The importance of patchiness or aggregation producing clutter or discrete echoes was evaluated by first estimating the frequency of occurrence of schools or pods of different species in an area surrounding the experimental sites and then calculating the target strengths of the schools and pods.

Analyses are for animals encountered at the shelf break at the 200-m isobath at latitudes between 45 and 48°N and for offshore waters typical of the limit of the 200 mile U.S. Exclusive Economic Zone (EEZ) at latitudes of 45 to 50°N. This area includes several strong oceanographic features, which encompass both seasonal changes and strong spatial gradients, that occur between the continental shelf and the open ocean. Volume scattering characteristics are expected to change rapidly in accordance with these changes in oceanography. This paper addresses these expected changes in scattering.

OCEANOGRAPHY

The eastern North Pacific at latitudes 40 to 50°N is dominated by the eastward flow of water toward the North American coast and is bounded by two major gyral systems, the cyclonic Alaskan gyre north, the anticyclonic central Pacific gyre south, of this eastward flow (Fig. 1). The Alaskan gyre includes the subarctic current and the the Alaska current. The central Pacific gyre includes the west-wind drift and the California current. Between 40 and 50°N a "transition" between cool subarctic waters and warmer waters of the central Pacific gyre occurs. This transition zone moves north in summer and south in winter. In contrast to the subarctic, waters which are of low salinity with a permanent halocline between 100 and 200 m, the transition zone waters are unstable and have rapid latitudinal temperature and salinity changes.

The oceanography of the eastern North Pacific has a strong influence on the oceanography of the North American continental shelf and slope (Ware and McFarlane, 1989). Two major oceanographic regions are recognized: the coastal upwelling domain and the coastal downwelling domain (Fig. 1). The coastal upwelling domain is characterized by a northwesterly wind flow and offshore Ekman upwelling in the summer that brings intermediate depth cold water onto the continental margin. The coastal downwelling domain is dominated by the poleward flow of the Alaskan current that induces downwelling throughout much of the region.

The study area is situated at the northern end of the coastal upwelling domain. In summer months the region is dominated by coastal upwelling, high productivity, and high fish biomass. In the fall, wind patterns switch to a southerly flow and upwelling ceases. Many fish species are seasonal

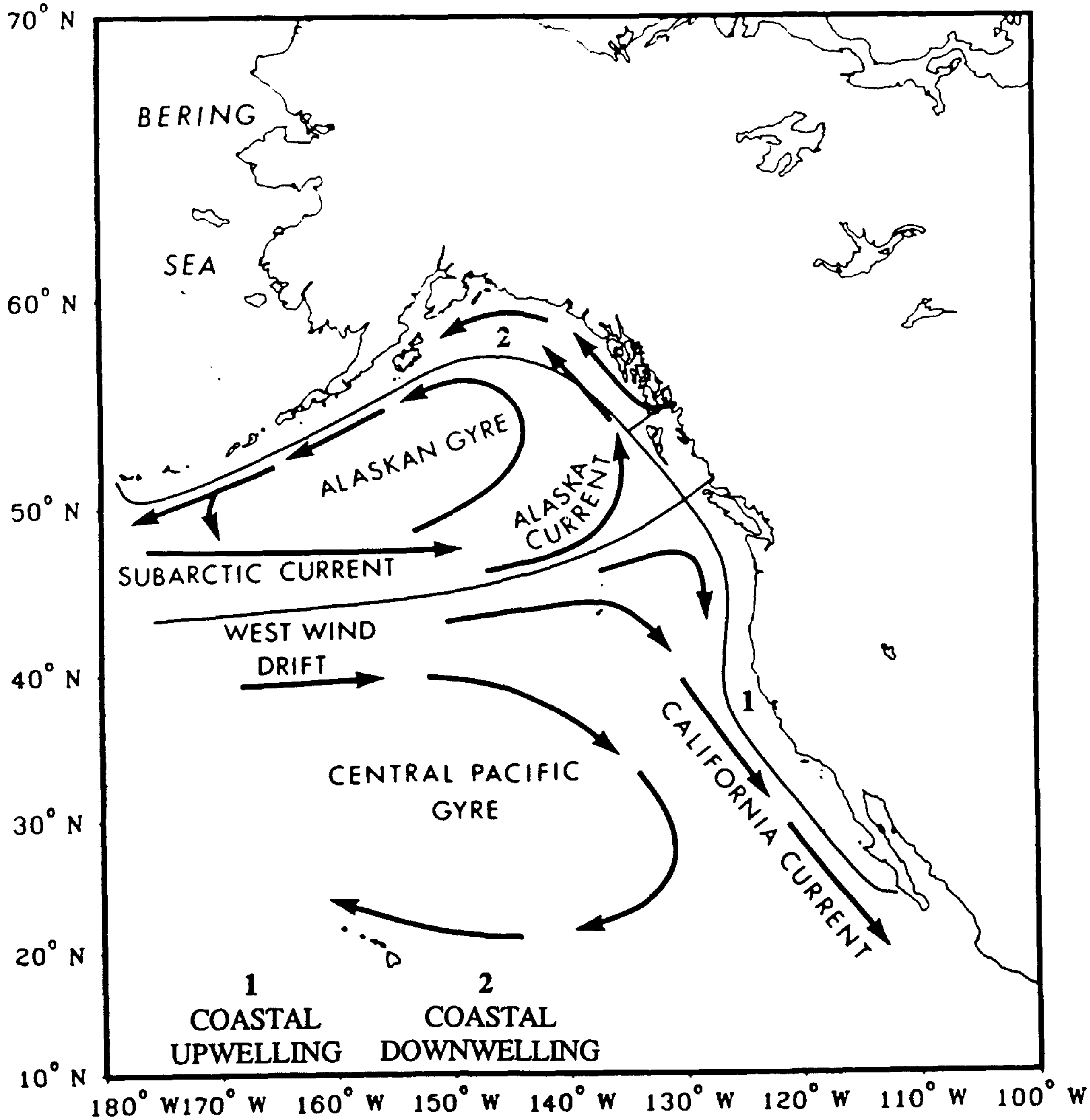

Figure 1. Oceanography of the northeast Pacific (after Ware and McFarlane, 1989).

migrants, spending their summers in the productive waters of Oregon and Washington and their winter months in the warmer waters off California and Baja California. Sea surface temperatures near the Oregon-Washington coast range from 17° C in summer to 8° C in winter, (Fig. 2). Offshore water temperatures tend to lag behind the inshore water temperatures by about one month such that offshore waters are cooler in the spring and warmer in fall. This paper considers four oceanographic seasons: (1) spring, April - June, a period of increasing temperatures; (2) summer, July - September, a period of maximum temperatures; (3) fall, October - December, a period of decreasing temperatures, and (4) winter, January - March, a period of minimum temperatures.

Highest biological activity is associated with the interaction of ocean currents with offshore banks and ridges. At the outer edge of the continental shelf is a southward flowing shelf-break current. Near the coast is a northward flowing coastal current. Both currents produce enhanced mixing wherever they encounter changes in topography associated with submarine canyons or offshore banks. For example, tidal exchange through the Strait of Juan de Fuca, the Vancouver Island coastal current, and the shelf-break current generate the Tully eddy which in turn impinges on La Perouse Bank, a site of enhanced biological activity (Healy et al., 1990). This area has been noted as a region of an abundance of euphausiids that are believed to attract large numbers of predatory fish (Simard and Mackas, 1989). Plumes from the Columbia River and Strait of Juan de Fuca frequently extend to the edge of the continental shelf and because of their higher nutrient concentrations, also result in enhanced biological activity (Pearcy and Fisher, 1990; Healy et al., 1990). For these reasons, the outer banks and ridges at the depth of the shelf break (100 to 200 m) off Oregon and Washington are often preferred habitat for many Pacific coast fishes.

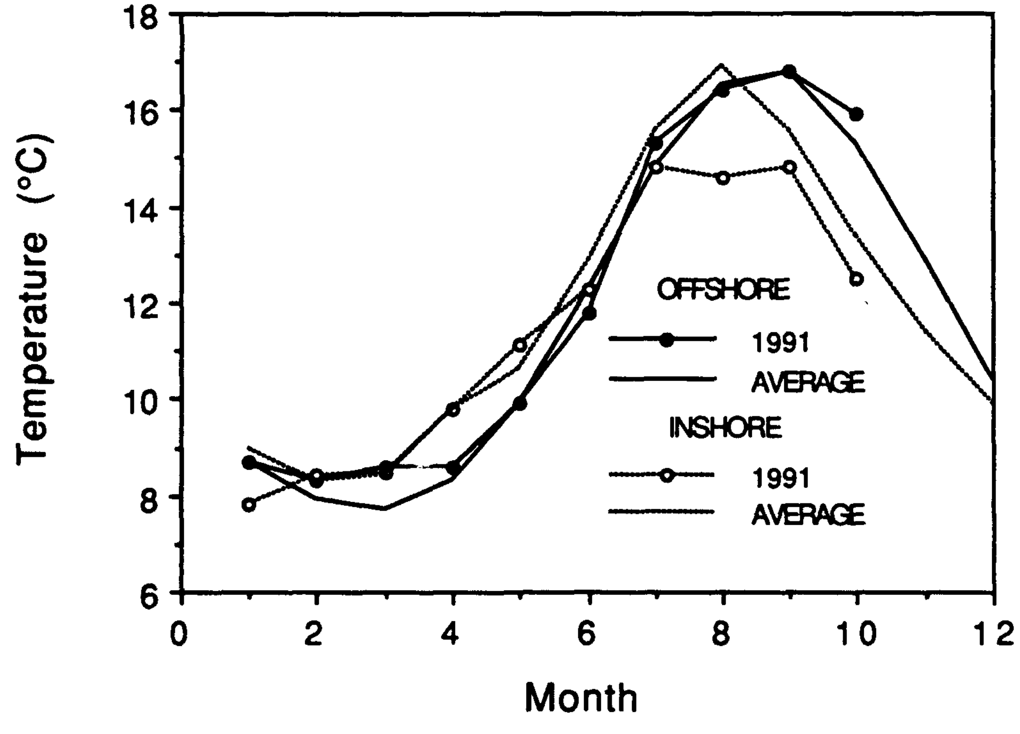

Figure 2. Mean monthly sea surface temperature for the shelf (46° N 125° W) and offshore (46° N 130° W) areas from data in Anonymous (1991a).

ACOUSTIC DATA

Integrated scattering strengths of the water column above 1000 m at frequencies mostly above 800 Hz were available for several stations within an area between 40 and 50° N and from the coast out to 140° W. Information was available from several sources: the Canadian Defense Research Establishment Atlantic (O. Z. Bluy, DREA, Dartmouth, Nova Scotia, unpublished data, 1978); Canadian Defense Research Establishment Pacific (DREP) as reported in Scrimger and Turner (1973) and Turner (1973); and the Naval Oceanographic Office (E. E. Davis, NOO, Stennis Space Center, MS, unpublished data, 1973). Their results are shown for frequencies from 800 Hz to 10,000 Hz (Fig. 3) for all seasons, day and night. Levels range from -40 to -60 dB at 10,000 Hz to about -50 to -70 dB at 800 Hz. When examined on a seasonal basis (not shown in Fig. 3) the data do show a seasonal effect with the lowest levels observed during January and the higher levels in the spring, summer, and fall months. This limited amount of acoustic data will be compared on a seasonal and day-night basis with results from bioacoustic models.

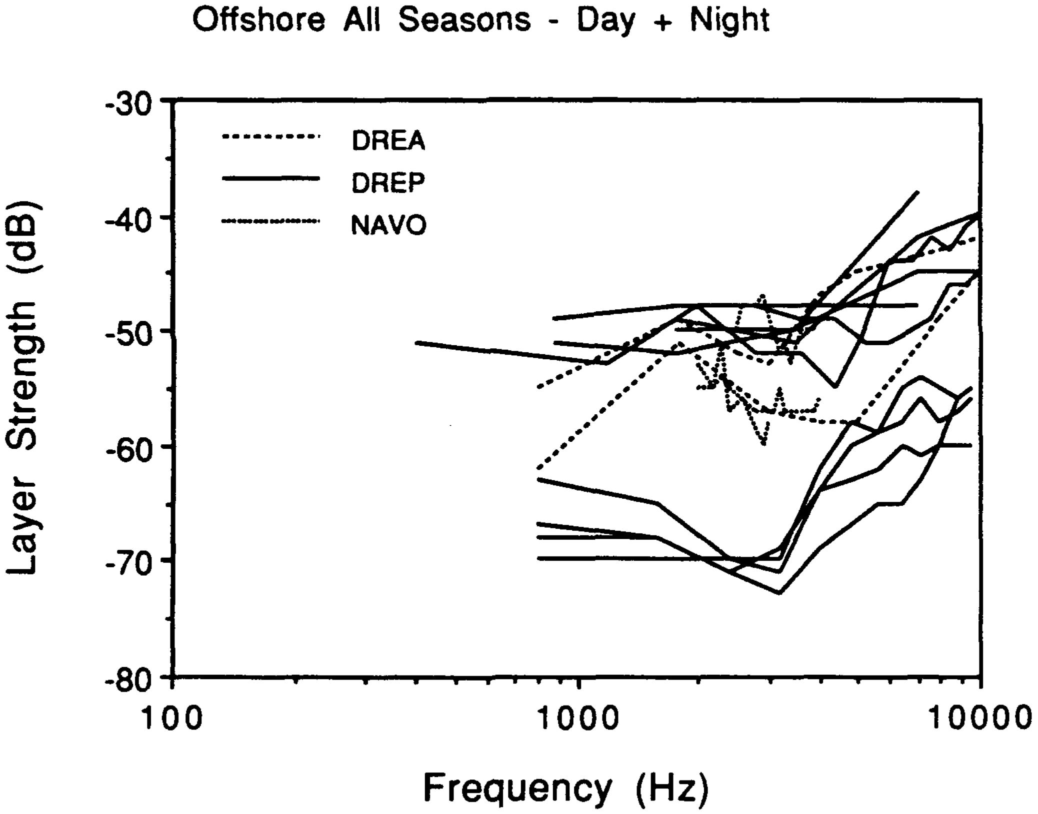

Figure 3. Levels of volume reverberation for waters off Oregon-Washington. DREA, Defence Research Establishment Atlantic; DREP, Defence Research Establishment Pacific; and NAVO, Naval Oceanographic Office, sources described in text.

SCATTERERS

Several hundred species of fish and marine mammals occur on the Oregon-Washington coast. Of these, only 13 fish species or species groups and 8 species of mammals were found to be potential sources of volume scattering at the shelf break and in offshore waters. The fishes include: several mesopelagic species; northern anchovy, *Engraulis mordax*; Pacific sardine, *Sardinops sagax*; saury, *Cololabis saira*; Pacific herring, *Clupea harengus pallasi*; jack mackerel, *Trachurus symmetricus*, Pacific mackerel, *Scomber japonicus*; albacore, *Thunnus alalunga*; Pacific pomfret, *Brama japonica*; coho salmon, *Oncorhynchus kisutch*; chinook salmon, *Oncorhynchus tshawytscha*; Pacific whiting, *Merluccius productus*; and a number of rockfish species. The marine mammals include: Risso's dolphin, *Grampus griseus*; Pacific white sided dolphin, *Lagenorynchus obliquidens*; northern right whale dolphin, *Lissodelphis borealis*, Dall's porpoise, *Phocoenoides dalli*; humpback whale, *Megaptera novaeangliae*; sperm whale, *Physeter macrocephalus*; Steller sea lion, *Eumetopias jubatus*; and northern fur seal, *Callorhinus ursinus*. Nonswimbladder bearing shark and squid were not included in the analysis because acoustic models of nonresonant objects indicate they would have very weak target strengths at frequencies below 1000 Hz (Stanton, 1989).

Analyses were based on information on the size, behavioral characteristics, and occurrence of fishes and mammals that were obtained from general reference material (Hart, 1973), technical documents and published papers, as well as discussions with fishery and marine mammal scientists. Detailed information was used in the subsequent acoustic modeling. Presentation of all data is beyond the scope of this paper, only a synopsis is given here. For all fish and marine mammals, general characteristics, including geographical distribution, size, temperature preference, and depth range are considered first; estimates of abundance are considered second; and estimates of school size are considered last.

GENERAL CHARACTERISTICS

Fish

Mesopelagic fishes are generally too small for their swimbladders to resonate at low frequencies (those between 10 and 1000 Hz). However, Rayleigh scattering from their swimbladders will produce low volume reverberation levels at these frequencies. Since populations of these fishes are found virtually everywhere over deep oceanic waters, scattering from them can be expected to set the lower bound in instances where larger fishes are not present. Hence, population characteristics of these fishes in the study area are of interest. Mesopelagic fishes are assumed to be present throughout the year.

The size and depth ranges of mesopelagic fishes off Oregon were obtained from midwater trawl surveys (Pearcy, 1977; Pearcy, 1983; and Kalish et al., 1986) conducted from the shelf, shelf break, and slope to about 300 km offshore. The mesopelagic fauna was dominated by *Diaphus theta* (58%), *Stenobrachius leucopsarus* (23%), and *Tarletonbeania crenularis* (10%). These fish range from 10 to 80 mm length and are found from the surface to 600 m at night and 200 to 800 m by day.

Northern anchovy, *Engraulis mordax*, are a small pelagic fish common to warm waters of the west coast. They are more common off southern California than Oregon and Washington. However, appreciable numbers migrate northward along the continental shelf to Oregon and Washington in midsummer. They form compact schools in midwater by day and migrate to near the surface at night. During midsummer, Oregon and Washington anchovy spawn in the highly productive warm waters, 15 to 19° C, especially in the Columbia river plume (Brodeur and Pearcy, 1986). The river plume and large numbers of anchovy may at times be found near the shelf break. Off Oregon, anchovy are mostly between 10 and 15 cm length (Brodeur and Pearcy, 1986).

Two additional small pelagic fish of near-surface-warm waters of 15 to 18° C are Pacific sardine, *Sardinops sagax* and Pacific saury, *Cololabis saira*. Sardine are common off California but also occur off Oregon and Washington during midsummer as a seasonal migrant. They congregate within the Columbia River plume, but are also widespread on the shelf. Saury are common on the shelf. Sardines off Oregon are mostly between 13 and 24 cm length and saury are slightly larger, between 15 and 30 cm length (Brodeur and Pearcy, 1986).

Pacific herring, *Clupea harengus pallasi*, are a cool water pelagic fish abundant on the continental shelf, spawning in shallow water of 3 to 12° C in the spring and remaining on the shelf into the fall. During winter they move offshore to unknown locations, presumably the outer shelf or just beyond. They are considered present during all seasons at the shelf break. Herring are small, ranging from 8 to 34 cm length. They generally occur in large diffuse layers at night, from the surface to 100-m depth. During day they aggregate into compact schools at depths of 50 to 100 m.

Two mackerel-like fishes common to the Pacific coast are jack mackerel, *Trachurus symmetricus*, and Pacific mackerel, *Scomber japonicus*. Both are moderate sized and abundant pelagic fish of the continental shelf and offshore waters. They range in size from 26 to 60 cm length and prefer moderately warm water, between 11 and 17° C for jack mackerel and 14 and 18° C for Pacific mackerel. Jack mackerel tend to occur more in offshore waters, while Pacific mackerel tend to occur more on the shelf. Both are considered spring, summer, and fall residents occurring at midwater depths of 50 to 100 m during day and between the surface and 100 m during night.

Albacore, *Thunnus alalunga*, is a true open ocean fish, common in the Pacific. They may become abundant only during the summer in waters of 14 to 16° C. Albacore aggregate on thermal fronts in offshore waters, feeding on fish and other organisms that accumulate there (Laurs et al., 1984). They can form large schools; purse seiners have caught up to 500,000 fish in one set. Albacore range from 40 to 100 cm length and are common to the upper 100 m of the ocean.

Pacific pomfret, *Brama japonica*, are abundant in warm waters of the North Pacific Ocean. They follow the advance of the 9-10° C isotherm northwards in the summer, but they are most abundant at temperatures > 20° C. Pomfret are presently caught as bycatch in very large numbers by the Japanese squid driftnet fishery (Anonymous, 1991b). At night they occur very close to the surface in the upper 10 m, by day they are presumably in deeper waters 0 to 50 m (D. Ware, Pacific Biological Station, Nanaimo, B.C., pers. comm., 1991).

Two salmonids, coho salmon, *Oncorhynchus kisutch*, and chinook salmon, *Oncorhynchus tshawytscha*, occur throughout the year in appreciable numbers in cool waters (< 16° C), on the continental shelf off Oregon-Washington, but not in the offshore waters. In offshore waters at the latitude of Oregon and Washington, catch statistics indicate salmon are rare (Major et al., 1978). Most salmon become more abundant in more northerly offshore waters. Both coho and chinook spawn in rivers, with juvenile salmon spending several years at sea. Some chinook are resident in coastal waters of Oregon and Washington, others migrate south to northern California (Fisher and Pearcy, 1987). Substantial numbers of coho salmon remain resident in the Oregon-Washington coastal waters (Fisher and Pearcy, 1987). Coho salmon range in size from 40 to 80 cm while chinook salmon range from 25 to 80 cm. Maturing salmon occur at depths from the surface to 40-75 m while at sea (Major et al., 1978) with recent evidence suggesting they may prefer the upper 10 m at night (D. Ware, Pacific Biological Station, Nanaimo, B.C., pers. comm., 1991).

Pacific whiting, *Merluccius productus*, occur at midwater depths on the continental shelf and slope from Baja California to Queen Charlotte Sound. They occur primarily at temperatures > 11° C. Adult whiting spend their winters on spawning grounds between Point Conception and Baja California. They migrate north in the spring and feed in the productive waters along the continental shelf from northern California to Vancouver Island from April to November. In the autumn, whiting migrate south to their wintering area. Whiting are considered present off Oregon and Washington during spring, summer, and fall. At this time they occur in dense feeding aggregations along the shelf break (Stauffer, 1985) and undergo diurnal migrations, apparently in response to the vertical migration of euphausiids, their primary food (Stauffer, 1985; Simard and Mackas, 1989). Whiting are the only west coast fish for which a fisheries acoustic survey is routinely made. Data from these surveys (R. Kieser, Pacific Biological Station, Nanaimo, B.C. unpublished data, 1991) show that whiting appear to congregate in dense schools at depths of 150 to 250 m during the day (Fig. 4a). At night they migrate upwards into a diffuse layer between 100 m and the surface (Fig. 4b). These diffuse layers of whiting can at times extend up to 10 miles seaward from the shelf break (R. Kieser, opp. cit.). Size and abundance data from trawls indicate that at the Oregon-Washington shelf break, the smallest fish are about 41 cm, with a peak in abundance of 45-cm fish and the largest fish at about 54 cm (M. W. Dorn, National Marine Fisheries Service (NMFS), Seattle, Washington, unpublished data, 1991).

Rockfish are the predominant catch in bottom trawls taken in deep water off the Oregon-Washington coast. Sixty-one species of rockfish occur on the North American west coast. Most rockfish inhabit the continental shelf and slope, occurring over bottom depths of 100 to 400 m. Some occur down to 900 m. Ten species frequent deep 184 to 366 m sites in the Oregon-Washington area. Depth and topography appear to be better predictors of occurrence rather than water temperature. Most are benthic by day, within a few meters of bottom, and pelagic by night, from bottom to 100 m above bottom. They are highly patchy in distribution and associate with rocks, pinnacles, and steep bottom slopes (Wilkins, 1986; Richards et al., 1991). They are present throughout the year. Rockfish adults are 30 cm in length with a range of 20 to 60 cm length. Rockfish occur in tight compact schools by day and disperse into more diffuse schools at night (Richards et al., 1991).

Marine Mammals

Although 19 species of marine mammals are present in the coastal and offshore waters of Oregon and Washington, only three species of dolphin, one species of porpoise, two species of large whale, and two species of pinnipeds were considered sufficiently abundant to be potentially significant contributors to volume scattering. All of the information summarized here is from an in-depth study using aircraft and ship observations by Brueggeman (1991) and a review by Leatherwood et al. (1982).

The dolphins include Risso's dolphin, *Grampus griseus*, Pacific white sided dolphin, *Lagenorynchus obliquidens*, northern right whale dolphin, *Lissodelphis borealis*, and Dall's porpoise, *Phocoenoides dalli*. Some are present year round in both offshore and shelf waters with greater numbers in summer than winter. They are all between 2 and 3 m length and occur from the surface to several hundred meters depth.

The two common large whales are humpback whale, *Megaptera novaeangliae*, and sperm whale, *Physeter macrocephalus*. Gray whales, *Eschrichtius robustus*, although common along the Oregon-Washington coast during their spring and fall migrations, occur primarily within several kilometers of the shore. Humpback whales feed on zooplankton near the surface on the continental shelf during spring, summer, and fall. They are absent offshore. They appear to aggregate over topographical features such as Heceta Bank, Grays Canyon, and Astoria Canyon over bottom depths of 50 to 2000 m. Sperm whales are widespread in the pelagic regions of the North Pacific. They breed in lower latitudes during winter and spread north during summer. Sperm whales are present off Oregon and Washington from spring through fall over bottom depths > 200 m. They dive to depths of several thousand meters. Lengths range from 11 to 16 m for humpback whale and 12 to 17 m for sperm whale.

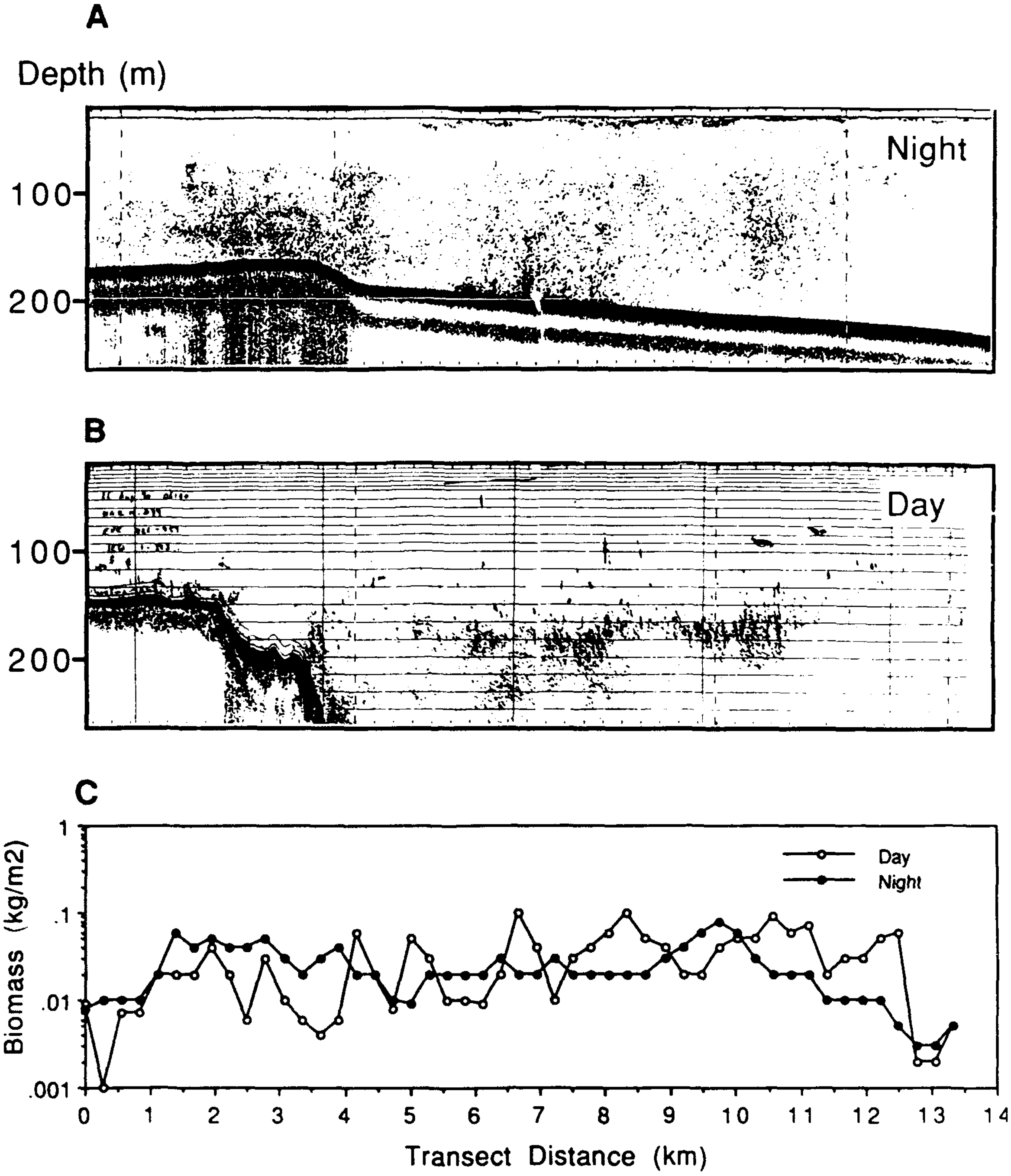

Figure 4. 38 kHz acoustic records of Pacific whiting, *Merluccius productus*, off the west coast of Vancouver Island. Panel A, night (2114-2215 h) echo trace of whiting parallel to the shelf break at 48°30' N 125°20' W. Panel B, day (1145-1239 h) echo trace of whiting perpendicular to the shelf break at 49°55' N 127°50' W. Panel C, biomass of whiting (density using 1 kg/fish) for panels A and B from integration of echo returns (Data courtesy of R. Kieser, Canadian Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, B.C., 1991).

Two pinnipeds abundant in shelf and offshore waters are Steller sea lion, *Eumetopias jubatus*, and northern fur seal, *Callorhinus ursinus*. Sea lions and fur seals breed on rookeries during the spring and summer and spend the remainder of the year at sea. Fur seals and sea lions feed on fish and squid and occur from the surface to several hundred meters. On the Oregon-Washington coast, Steller sea lions breed on two rookeries off the southern coast of Oregon. Numbers at sea are low during spring and summer and peak during the fall. Northern fur seals breed on the Pribilof Islands in the Bering Sea and on San Miguel Island, California. They attain their highest abundance off the Oregon-Washington coast in midwinter. They are absent in summer and fall.

ESTIMATES OF ANIMAL DENSITY

Density estimates were obtained from one of three sources: first, samples taken near the Oregon-Washington shelf break; second, regional estimates for the coastal upwelling domain; and third, general estimates for the northeastern Pacific. For estimates within the coastal upwelling domain, most fish occupy a portion, perhaps 10% of the area at any time with a density about 10 times higher than average. However, at the shelf-break densities of fish are expected to decline by about 10 times from those on the shelf; hence, an average of the coastal upwelling domain is probably appropriate at the shelf break. For fish occurring in offshore waters at 200 nmi estimates are obtained from general estimates for the northeastern Pacific.

A single density estimate is determined for each species or group, no attempt is made to estimate transitional densities between seasons and locations. Site and seasonal changes are based on a determination of whether each species is present or absent based on its temperature preference and the average sea surface temperatures for a particular season (Fig. 2). This information was used in combination with each species' known history of occurrence. All species and groups considered, except Pacific pomfret, which are only found at 200 nmi offshore and beyond, are believed to occur at the shelf break. Only four species or groups, mesopelagics, jack mackerel, albacore, and marine mammals are believed to occur at both 200 nmi offshore and the shelf break and are assumed to occur at the same density offshore as at the shelf break. Estimates of average animal density for all fish and marine mammals are given in Table 1.

Fish

The density of mesopelagic fishes was determined from midwater trawls in the slope water approximately 100 km west of Newport, Oregon during September 1981 (Kalish et al., 1986). Average density was approximately 1 ind./m^2 of ocean surface.

Ware and McFarlane (1989) provide a recent review of stock information for anchovy, sardine, herring, jack mackerel, Pacific mackerel, Pacific whiting, coho salmon, and chinook salmon for the coastal upwelling domain. They consider the entire "productive zone" extending from Baja California to the south coast of British Columbia and extending about 220 km offshore. Their estimates of total stock size for each species occurring within the coastal upwelling domain were divided by the total area of this region (480,000 km^2) to give areal estimates of kg/m^2. Their estimates of average fish weights were used to convert kg/m^2 to ind./m^2.

Information on saury and juvenile salmon was obtained from experimental purse seine sets made on the continental shelf and shelf break (Brodeur and Pearcy, 1986; Pearcy and Fisher, 1990). Fish densities were calculated from net catches and a seine area of 20,000 m^2. Only those stations located near the shelf break were included.

Rockfish densities were estimated from a series of bottom trawl surveys conducted in July and August 1986 (Coleman, 1988). Tows were taken during day when most groundfish would be near the bottom. Surface area swept by the trawl was used to calculate average rockfish density.

Table 1. Estimates of animal density and school parameters.

Species	Animal Density (Ind./km^2)	Density in school (Ind./m^2)	School Size (m^2)	Ind. per School	Schools per 100 km x 100 km square
Mesopelagic Fishes	1,000,000	-	-	-	-
Northern anchovy	83,000	1130	177	2×10^5	4150
Pacific sardine	150	526	380	2×10^5	7.5
Pacific saury	500	325	616	2×10^5	25
Pacific herring	2200	0.5	2×10^6	1×10^6	22
Jack mackerel	6700	1	20000	20000	3350
Pacific mackerel	810	1	20000	20000	405
Pacific whiting	3100	0.1	3×10^6	3×10^5	103
Coho salmon	17	0.02	49000	1000	170
Chinook salmon	22	0.02	49000	1000	220
Juvenile salmon	340	-	-	-	-
Rockfish	8000	0.03	8×10^5	27000	2960
Pacific pomfret	5000	0.02	49000	1000	50000
Albacore	100	11.3	707	8000	125
Whales	0.0025	-	-	2	12.5
Other mammals	0.4	-	-	10	400

Because most smaller fish between 6 and 20 cm were poorly sampled by the large mesh size of the trawl (12.7 cm), catches were multiplied by 2 and divided by the swept area to give areal density. Estimates were restricted to tows taken in the 180 to 370 m depth waters off Oregon and Washington that are representative of most of the shelf break.

Estimates for two wide ranging open ocean pelagic species, Pacific pomfret and albacore were obtained from a report in preparation by C. Levenson (Naval Oceanographic and Atmospheric Research Laboratory, Stennis Space Center, MS, pers. comm., 1991). In that report "best estimates" of density were obtained by dividing an estimate of total stock by the habitat area for each month of the year. Habitat area within the northeast Pacific was derived from published seasonal temperature preferences and average sea surface temperature data as augmented by fisheries reports on regions of productive fishing.

Marine Mammals

Brueggeman (1991) gives density estimates for humpback whales, Risso's dolphin, Pacific white-sided dolphin, northern right whale dolphin, and Dall's porpoise. No estimate is given for sperm whales. A rough estimate of sperm whale density was obtained by applying Brueggeman's algorithm for calculating humpback density to their sperm whale sighting data. This estimate could be in error by an order of magnitude; however, no other information is available. These estimates indicate sperm and humpback whales were most abundant in spring, summer and fall seasons, for which a combined estimate for these two large whales was calculated (Table 1). Sperm whales comprised about two-thirds and humpback whales one-third of these combined density estimates. Both whales were considered "not present" in the winter.

Seasonal density maps of Steller sea lion and northern fur seal are given by Brueggeman (1991). Average values of both species were pooled with densities reported for dolphins and porpoise to give average densities of all small mammals of 2 to 3 m length. Densities varied at the shelf break and offshore locations with lower numbers occurring in the winter. Because the estimates of sea lion and fur seal are provisional (Gordon Reetz, Minerals Management Service, Los Angeles, CA, pers comm., 1991), an average value was taken as representative of both locations during all seasons (Table 1).

SCHOOL SIZE

Prediction of school size, density of fish within schools, and number of schools is difficult because of myriad factors that influence fish schooling. All are dependent on fish behavior as influenced by age, spawning, migration, feeding, hydrographic conditions, and the presence of predators (Pitcher, 1986). Fish and marine mammals occur in a range of school, shoal, or pod sizes. Since knowledge of patchiness and schooling for fish and marine mammals is sparse, best estimates of "average" school and pod sizes from the literature were used to calculate the number of such schools and pods of each species or species group occurring within a 100 km by 100 km square (10,000 km^2) surrounding the experimental sites (Table 1).

For most species the school or aggregation characteristics are at best qualitative; quantitative data are almost always lacking. For many species, the estimates used here are approximations based on data from similar species. The exact method of determining school size depends on what data are available. The simplist method used school area. School area was considered the silhouette area of the fish school projected to the water surface, regardless of whether the school was a flat disc or a sphere. Most species are considered as either loose aggregations or schools with the number of individuals within a school based on the number of fish required to fill the school area using an areal estimate of fish density (ind./m^2). An alternative was to assume a school was an oblate spheroid with its volume filled with a volumetric estimate of fish density (ind./m^3). Average school sizes, densities, and numbers are given in Table 1.

Fish

Mesopelagic fishes may sometimes occur in schools. Backus et al. (1968) encountered small schools of *Ceratoscopelus maderensis* in the North Atlantic slope water during the fall of 1967. However, these schools were generally part of larger shoals or layers of mesopelagic fish spread over large areas. Acoustic data (Greenlaw and Pearcy, 1985) suggest mesopelagic fauna occurs as a diffuse layer spread over a large region (40 km or so), with order of magnitude changes in density caused by regional patchiness. Based on this information, mesopelagic fish were considered occurring in layers and not in schools in this study.

Side scan sonar studies of anchovy schools indicate a mean school diameter of 15 m (Smith, 1970). Based on anecdotal information (Radakov, 1973), schools were assumed to be oblate spheroids, with a height to diameter ratio of one-fifth with an average fish of 13-cm length occupying a volume equal to its body length cubed (Pitcher and Partridge, 1979), 200,000 fish would occur in an average school.

Both sardine and saury occur in schools or widely dispersed in large shoals. Quantitative information on schools is lacking. For lack of better information sardine and saury schools are assumed to have sizes and geometries similar to those for anchovy. Average schools of 200,000 fish are estimated to be 380 and 616 m^2, for sardine and saury, respectively.

The sizes and shapes of aggregations of herring are highly variable, ranging from small compact schools of 850 m^2 extent and 67,000 fish to large diffuse shoals of 20 km^2 extent and

97 x 10^6 fish (Buerkle, 1987; Misund and Ovredal, 1988). Shoals of 10^6 fish and 2 km^2 extent were selected as an approximate average size shoal.

Good information on mackerel schools is lacking. Jack mackerel are reported to form loose aggregations with much greater horizontal than vertical extent (MacCall et al., 1980). Information from other mackerel species indicate school size is highly variable, with numbers ranging from 10 to 100,000 individuals (Radakov, 1973). Assuming an intermediate value of 20,000 fish and a loose aggregation of 1 ind./m^2, each school would occupy an area of 20,000 m^2.

Good information on schooling characteristics of albacore is lacking. However, data from a similar species, skipjack tuna, *Katsuwonus pelamis* indicate the modal school size is 8000 fish (Hilborn, 1991). Assuming an oblate spheroid, with a one-fith height to width ratio, and each 70-cm fish occupying a volume equal to its body length cubed (Pitcher and Partridge, 1979), the modal school would extend over about 707 m^2.

Data from driftnets indicate Pacific pomfret occur in large diffuse schools of several hundreds to thousands of fish, at length scales of approximately 250 m (D. Ware, opp. cit.). Based on this information a school of 1000 pomfret was assumed to occur in an oblate spheroid of 250-m diameter and 10-m height with an areal extent of 49,000 m^2. The average areal density within such a school would be 0.02 fish/m^2.

Adult coho and chinook salmon are assumed to have the same school size parameters as pomfret because they appear to have similar statistics of occurrence in driftnets (D. Ware opp. cit.). Juvenile coho and chinook are fairly evenly dispersed on the shelf and apparently do not form large schools and were considered nonschooling fish (Pearcy and Fisher, 1990).

The number and size of whiting and rockfish schools was estimated from fisheries acoustic data obtained from R. Kieser (Pacific Biological Station, Nanaimo, B.C. unpubl. data, 1991) and Richards et al. (1991). Major whiting concentrations off Vancouver Island appear to be about 2 km in diameter, day or night, with a density of about 0.1 ind./m^2 (Fig. 4c) giving about 300,000 fish per school (Table 1). Rockfish schools are approximate oblate spheroids of 50-m height by 1000-m width containing approximately 27,000 fish.

Marine Mammals

Marine mammals occur singly or in small groups. Small average pod size for some species reflects the frequent occurrence of single animals. Dolphins and porpoise occur in pod sizes ranging from single animals to several hundred, with an average of about 10. Observations of average pod size for humpback whale and sperm whale are 1.4 and 1.5 animals, respectively. Sea lions and fur seals usually occur singly but may be found in groups of up to several hundred animals. Values of 2 and 10 animals per pod were used as approximate pod sizes for large whales and other small mammals, respectively.

BIOACOUSTIC MODELING

Individuals

All swimbladder-bearing fish were modeled as resonant scatterers using the model of Love (1978), which assumes an air-filled sphere inside a viscous spherical shell. The resonance frequency (f_o) of a swimbladder of radius r is given by

$$\pi^2 f_o^2 r^2 = P, \qquad (1)$$

where P is the ambient pressure in dynes/cm^2, f_o is in Hz, and r is in cm. The acoustic cross section σ, in cm^2, is

$$\sigma = \frac{4\pi r^2}{\left(\frac{f_o^2}{f^2 H^2} + \left(\frac{f_o^2}{f^2} - 1\right)^2\right)}, \qquad (2)$$

where f is the insonifying frequency in Hz and H is a damping factor.

$$\frac{1}{H} = \frac{2\pi r f^2}{f_o c} + \frac{\xi}{\pi r^2 f_o \rho}, \qquad (3)$$

where c is the speed of sound in water in cm/sec, ρ is the density of fish flesh ($\approx$ 1.05 gm/cm^3) and ξ is the viscosity of fish flesh (taken to be 500 poise).

Swimbladders are not spherical, they more closely resemble prolate spheroids with major-to-minor axis ratios around 5. The resonance frequency of such a spheroid is about 10% higher than for a sphere; this correction factor was taken into account.

There are few measurements of swimbladder sizes. However, one of the primary functions of a swimbladder is to act as a hydrostatic organ, making a fish neutrally buoyant, which requires swimbladder volumes to be about 4 to 5% of fish weight. Ona (1987) has shown that these values can vary in cod, based on their condition. Thus, a distribution of swimbladder volume to fish weight ratios were selected as follows: 10% of the fish have ratios of 0.02, 20% have 0.03, 30% have 0.04, 30% have 0.05, and 10% have 0.06.

Fish size distributions are usually given as length distributions. However, length-weight relations are available for most fish and they can be used to determine swimbladder size directly. The length-weight relations are regression equations, but fish weight can vary significantly with length. Therefore, an approximate normal distribution of weight on length was developed, where 20% of the fish have the mean weight given by the regression equation, 17% are 10% heavier or lighter, 12% are 20% heavier or lighter, 7% are 30% heavier or lighter, and 4% are 40% heavier or lighter.

These distributions provide estimates of swimbladder size distribution for use in the model for those fish whose swimbladder volumes remain constant with depth. This includes all species under consideration except herring and salmon. Herring and salmon swimbladders are open to their digestive tracts. Their swimbladders were assumed to be at equilibrium at 10 m and to compress following Boyle's Law below that depth.

Because of their large size, marine mammals can be considered as geometric scatterers over the frequency range at which their body lengths (L), are greater than the acoustic wavelength (λ). Rough approximations of side-aspect-target strength were made based on actual target strength measurements of live whales (Dunn, 1969; Love, 1973; Levenson, 1974). These were adjusted to the average length of the most common species, porpoise (2 to 3 m), and large whales (10 m) to give target strengths of -15 and 0 dB, respectively. For $L < \lambda$, Rayleigh scattering is assumed, with target strengths decreasing from the above levels at a rate of 12 dB per octave below $L = \lambda$.

Uniform Layers

Volume scattering strengths of a layer of animals were calculated based on the assumption that all of the animals were uniformly distributed at average areal densities. The average layer strength (S_L) of each species or species group is

$$S_L = TS_i + 10 \log N \,, \qquad (4)$$

where TS_i is the target strength of an individual at a given frequency,

$$TS_i = 10 \log \frac{\sigma}{4\pi} \,, \qquad (5)$$

and N is species abundance in ind./m^2. Results are reported as the total average layer strengths calculated as the exponential sum of the average layer strengths of all species present.

Schools and Pods

Estimates of pod and school densities given in Table 1 were used to calculate the probability of encountering a biological target within a detection area of 100 km^2 (10^8 m^2). Encounter probabilities were determined from an equation of random search (Koopman, 1956), where the probability of encountering a single target P_1, on a single ping,

$$P_1 = \frac{A_d + A_s}{A_o} \,, \qquad (6)$$

when searching operating area A_o, with detection area A_d, and school size A_s. A_d of 10^8 m^2 is 10 times larger than the largest fish schools (Table 1). Thus, A_s is negligible for most calculations.

The probability of encountering at least one of m targets is

$$P_m = 1 - (1 - P_1)^m \,, \qquad (7)$$

where each chance of encountering a target is assumed to occur independently and randomly.

No models exist for estimating target strengths of schools of fish near swimbladder resonance. Love (1981) has developed a model that gives realistic estimates of target strengths in the geometric region well above resonance. This model assumes that the target strength of a school of fish (TS_s),

$$TS_s = TS_i + 10 \log F_i \,, \qquad (8)$$

where F_i is the number of fish insonified when multiple scattering and attenuation through the school are taken into account. The model shows that essentially all fish in small loose schools are insonified and that as the schools get larger and denser, proportionately fewer fish are insonified. Present calculations assume,

$$TS_s = TS_i + 10 \log F_s \, , \qquad (9)$$

where F_s is the number of fish in the school. Although this equation overestimates school target strengths for large schools such as herring and whiting, it provides an upper limit that is adequate for present purposes.

Pods of marine mammals are usually loosely aggregated. Therefore, the above equation should provide a good estimate of pod target strengths.

RESULTS

Volume Reverberation

Volume reverberation is examined in several ways. First, it is considered independent of site or season to show the level and frequency dependence contributed by each species or group. For ease of presentation, scatterers are divided into two groups, major and minor scatterers. Second, results are averaged across species and are examined for site and seasonal effects. Detailed site and seasonal results for each species or group are given in Appendix 1.

Figure 5 shows night and day layer strengths for the major scatterers. These are species that contribute significantly to total scattering in any season or location. They are either of large size, such as the salmonids, or of high abundance, such as anchovy and mesopelagics, or of both large size and high abundance, such as the mackerels. Ten species or groups contribute appreciably to volume reverberation below 1000 Hz. Most fish are expected to migrate from the upper 0 to 100 m of the mixed layer at night to the lower 50 to 100 m of the mixed layer during the day, resulting in a shift in the day curves to higher frequencies.

Minor scatterers contribute at least 20 dB less to volume reverberation than the major scatterers (Fig. 6a). Minor scatterers include small fishes of low abundance and whales and other mammals that occur rarely. Because whales and other mammals have been modeled as non-resonant geometric scatterers they contribute little to average volume reverberation at low frequency. Like the major scatterers, the resonance frequencies of the minor fish scatterers shift upward at day (Fig. 6b).

Figure 7a shows the layer strengths for the shelf break at night where most fish considered are likely to occur in the upper 100 m of these relatively warm productive waters during summer. Maximum volume reverberation levels are expected, near -60 dB at 100 Hz, and -44 dB at 1000 Hz. In Figure 7a, species names are placed to the lower right of the point on the curve where each species contributes most to volume reverberation. For example, chinook and coho salmon contribute most at 70 to 100 Hz. Juvenile salmon are only important scatterers during the winter when they contribute to scattering near 300 Hz. Six species: albacore, jack mackerel, Pacific mackerel, whiting, coho salmon, and chinook salmon contribute most.

During spring and fall, water temperatures are lower on the shelf break and warm water fish such as albacore (and minor scatterers such as anchovy, sardine, and saury) are expected to be absent. Because Pacific mackerel and jack mackerel still remain during the fall and presumably arrive early in the spring, average volume reverberation levels are expected to be close to the summer values (Fig. 7a). At some time during spring or fall the remaining summer species, jack mackerel, Pacific

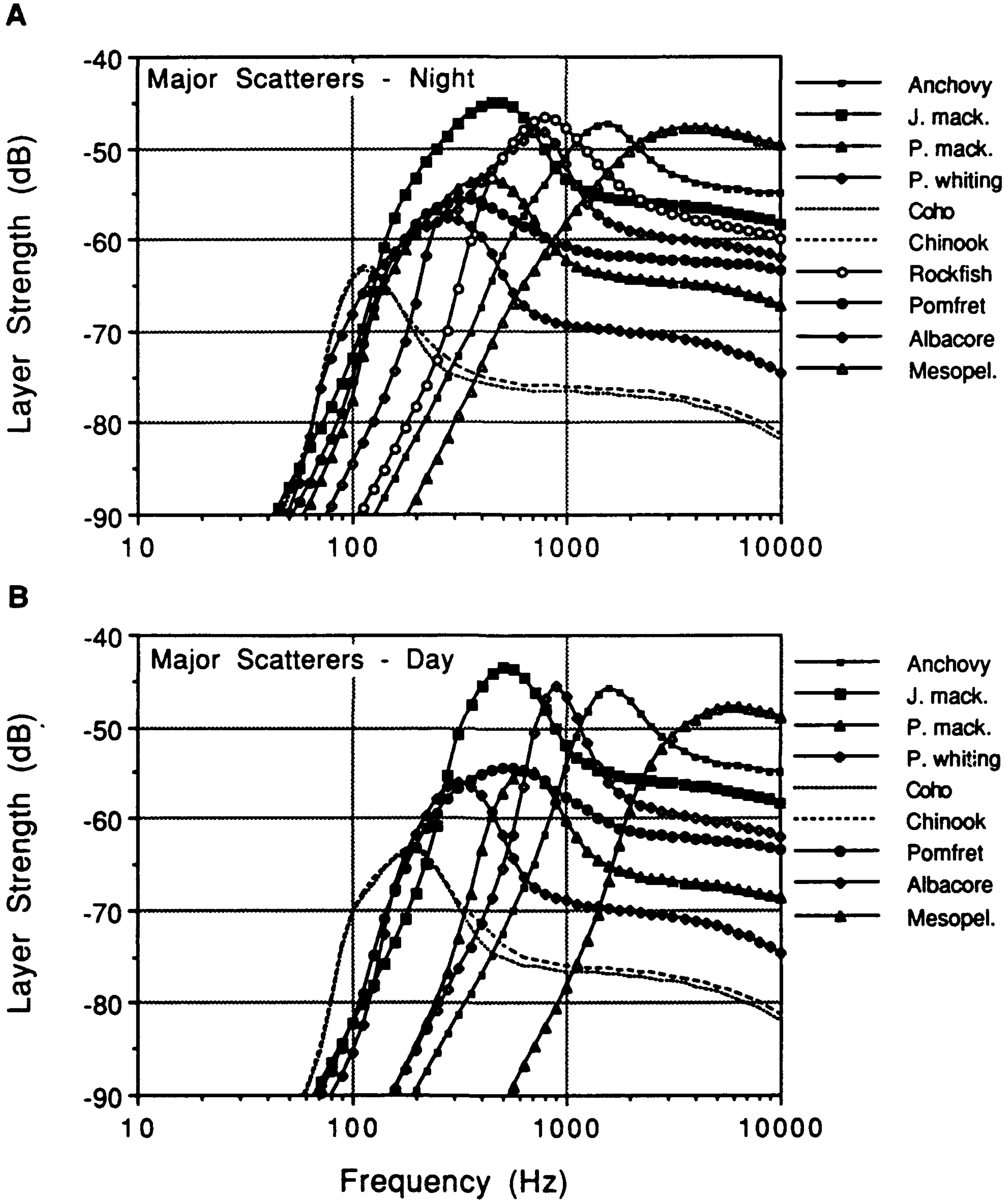

Figure 5. Predicted layer strengths for major scatterers during night (A) and day (B) based on average densities of fish and marine mammals.

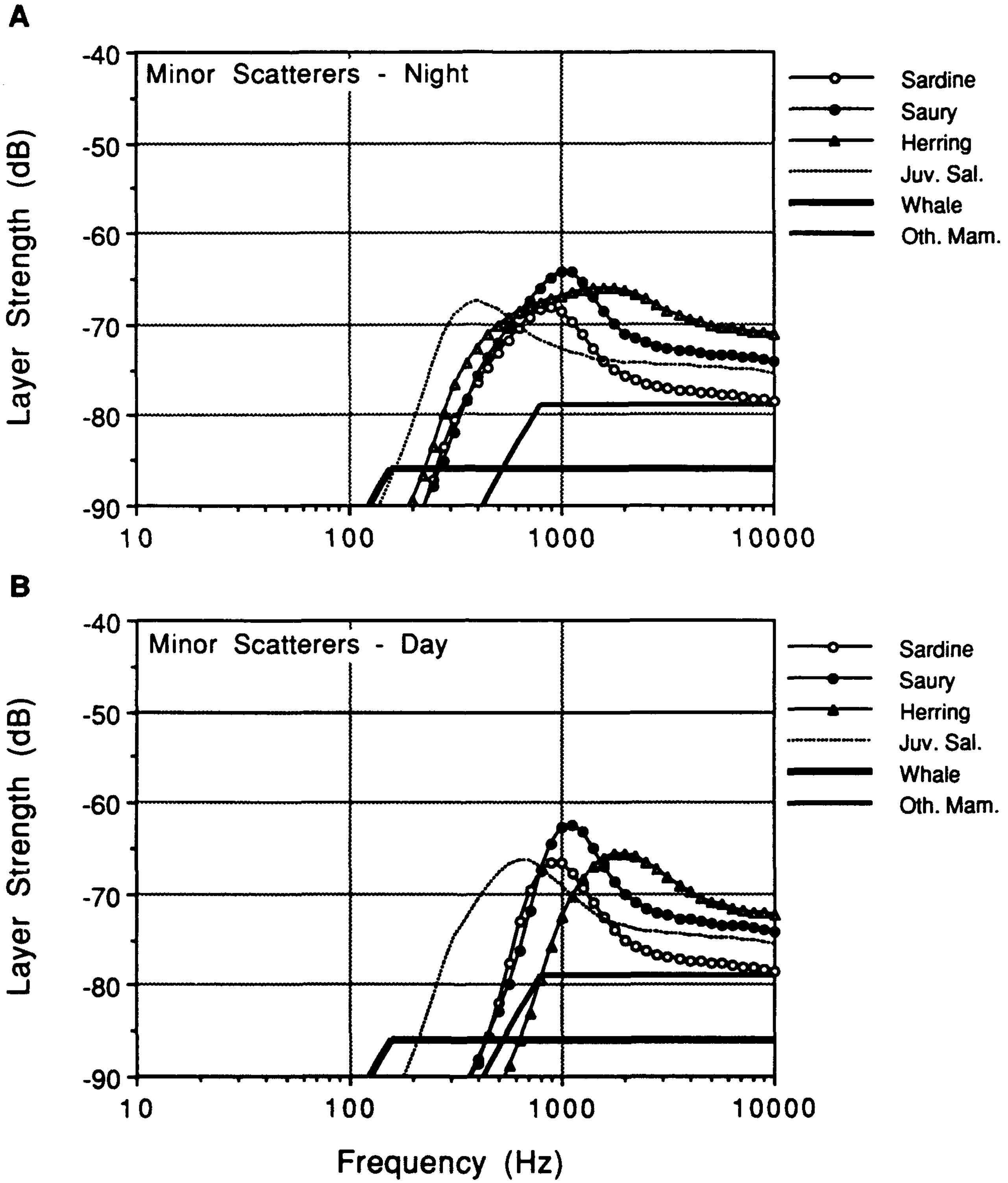

Figure 6. Predicted layer strengths for minor scatterers during night (A) and day (B).

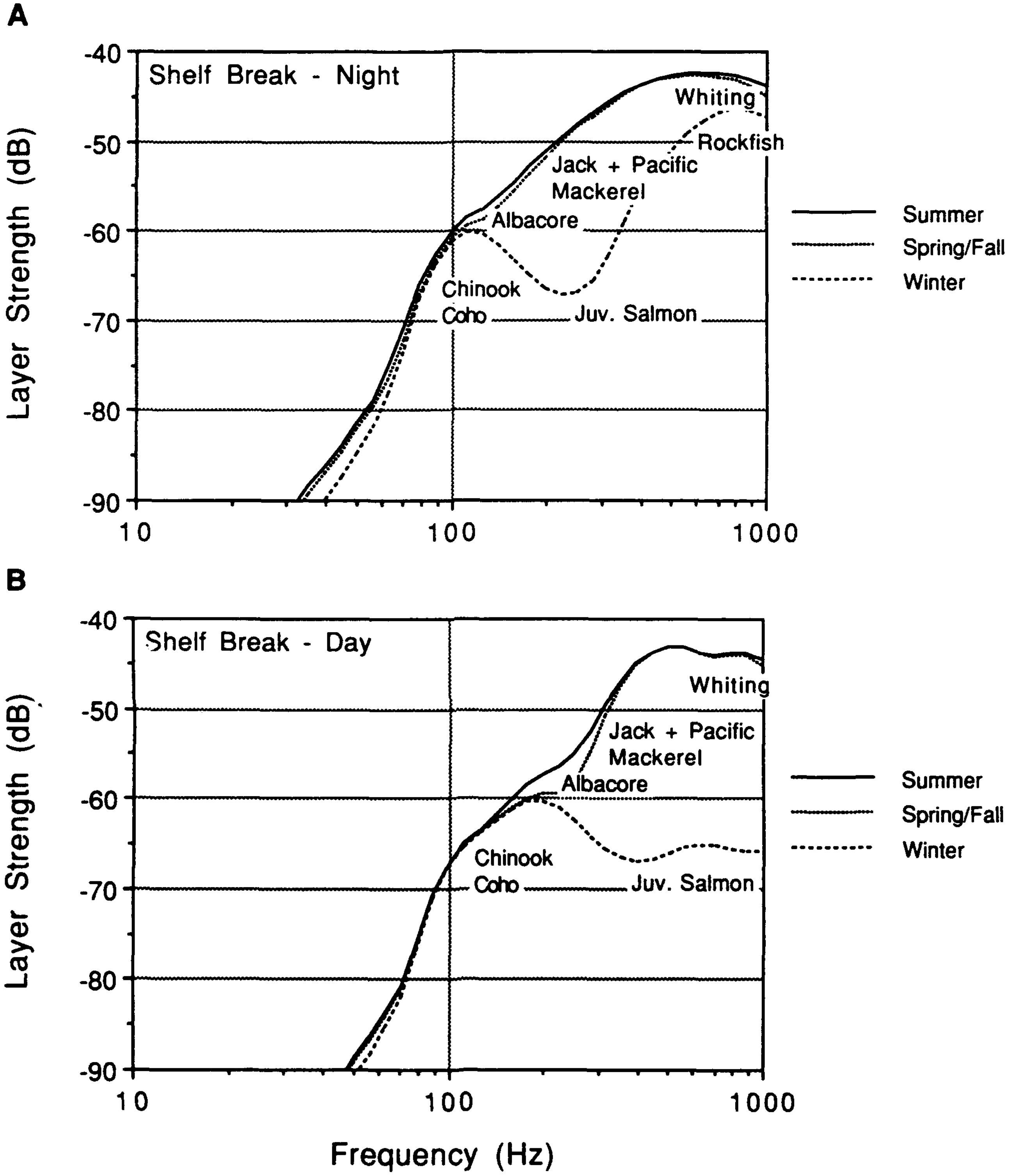

Figure 7. Predicted layer strengths at the shelf break during night (A) and day (B). The frequency and season at which various scatterers make an important contribution to average levels are indicated.

mackerel, and whiting either return to/or leave the Oregon-Washington shelf break. Exact estimates of the timing of these migrations are difficult to obtain because they are dependent on temperature preferences of the fish and complex behavioral patterns keyed on other environmental conditions such as the abundance of food.

During winter, several species tolerant of colder water are expected to remain at the shelf break. The presence of adult and juvenile coho and chinook salmon, as well as rockfish, is expected to maintain levels of volume reverberation near -61 dB at 100 Hz (Fig. 7a). The presence of rockfish over winter will maintain levels near -47 dB at 1000 Hz (Fig. 7a).

Figure 7b shows that for summer, spring, and fall the same effects are expected by day that are expected at night at the shelf break. Resonance peaks will simply shift upward in frequency as most fish occupy greater depths by day. Average volume reverberation in summer will be -67 dB at 100 Hz, and -45 dB at 1000 Hz. However, during winter, rockfish will be on bottom during day and their absence will cause a reduction of volume reverberation at 1000 Hz to levels near -66 dB.

Farther offshore, the fish fauna will differ somewhat from that found at the shelf break. Many shelf species will be absent and Pacific pomfret will become a major component. At night, summertime levels of volume reverberation will be slightly lower than at the shelf break, -66 dB at 100 Hz, and -51 dB at 1000 Hz (Fig. 8a). Maintenance of these high levels offshore will be due to the presence of jack mackerel, pomfret, and albacore. During spring and fall, levels will again depend on the occurrence of seasonal migrants. Pomfret and albacore will leave in late summer, while jack mackerel will remain into late fall. Likewise, in the spring, jack mackerel will arrive first, followed later by pomfret and albacore as water temperatures rise. During winter, only mesopelagics, fur seals, sea lions, and some porpoise are expected in the area, giving extremely low levels of volume reverberation. During day for all seasons, curves shift to higher frequencies as the fish are found lower in the water column (Fig. 8b). For summer, spring, and fall, levels will be near -80 dB at 100 Hz, and -51 dB at 1000 Hz. Levels will be extremely low during winter.

Comparison with Acoustic Data

Figures 9 and 10 show a comparison of volume reverberation estimates at the offshore site with column strength data shown in Figure 3. Comparison of spring, summer, and fall model estimates for night with measurements made at night for the same seasons show reasonable agreement (Fig. 9a). Overall levels agree between model estimates and measurements; however, the shapes of the curves differ. Measured data generally vary much more with frequency than the model results. Similar results were obtained when comparing spring, summer, and fall model estimates for day with measurements taken during day (Fig. 9b).

During winter, model results deviate substantially from measurements taken during both night and day (Figs. 10a and 10b). Assumptions about the density and depth distribution of mesopelagic fishes may be erroneous. To match the model curve to the measured rise in scattering between 3000 Hz and 5000 Hz the mesopelagic fish would need to remain at depth during winter nights. To achieve the appropriate scattering level, mesopelagic densities would need to be reduced to approximately one-fith to one-tenth the assumed density of 1 ind./m^2. At frequencies near 1000 Hz, a peak in the measurements also suggest the occurrence of large swimbladder bearing fish, possibly salmon.

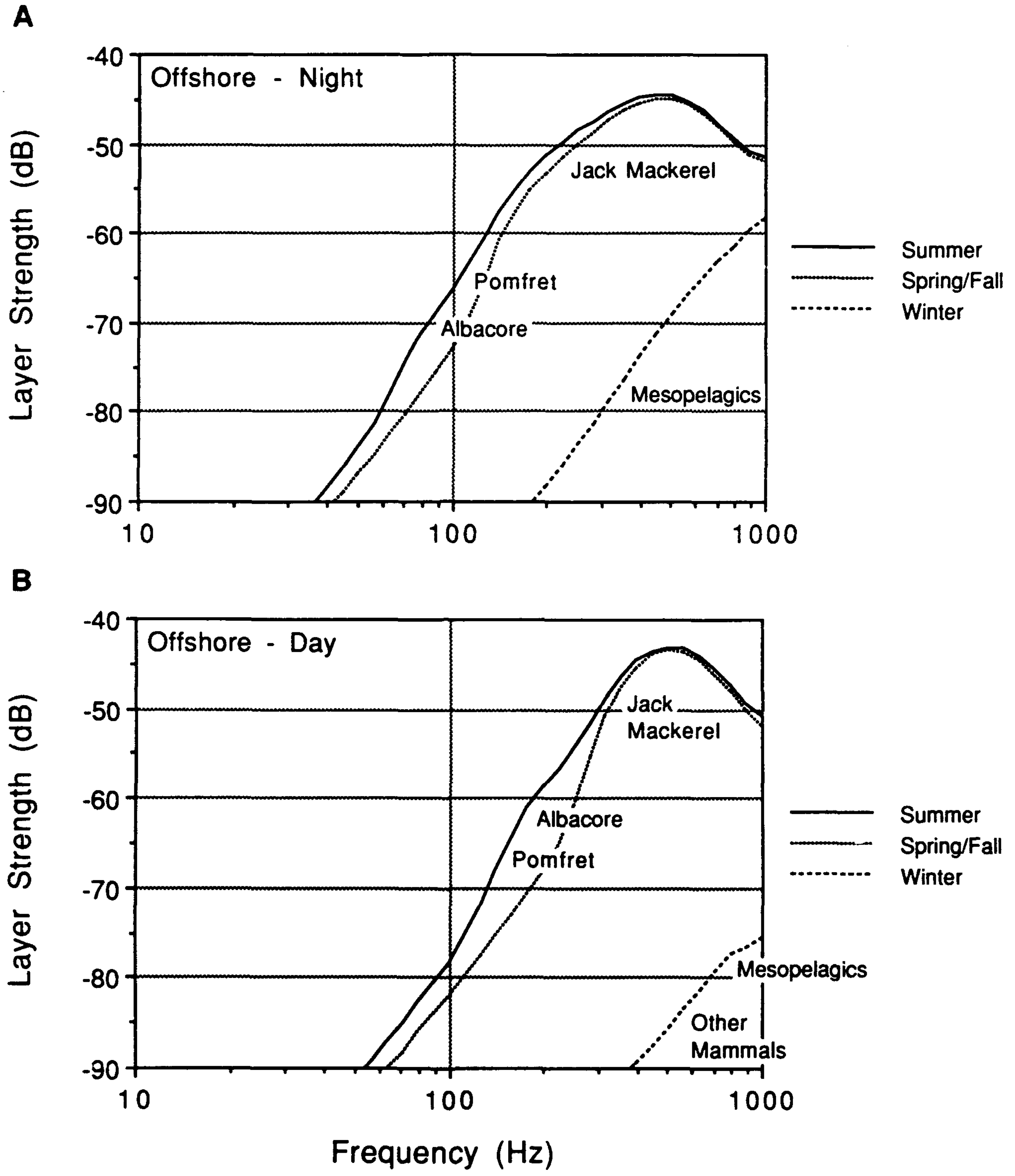

Figure 8. Predicted layer strengths offshore during night (A) and day (B).

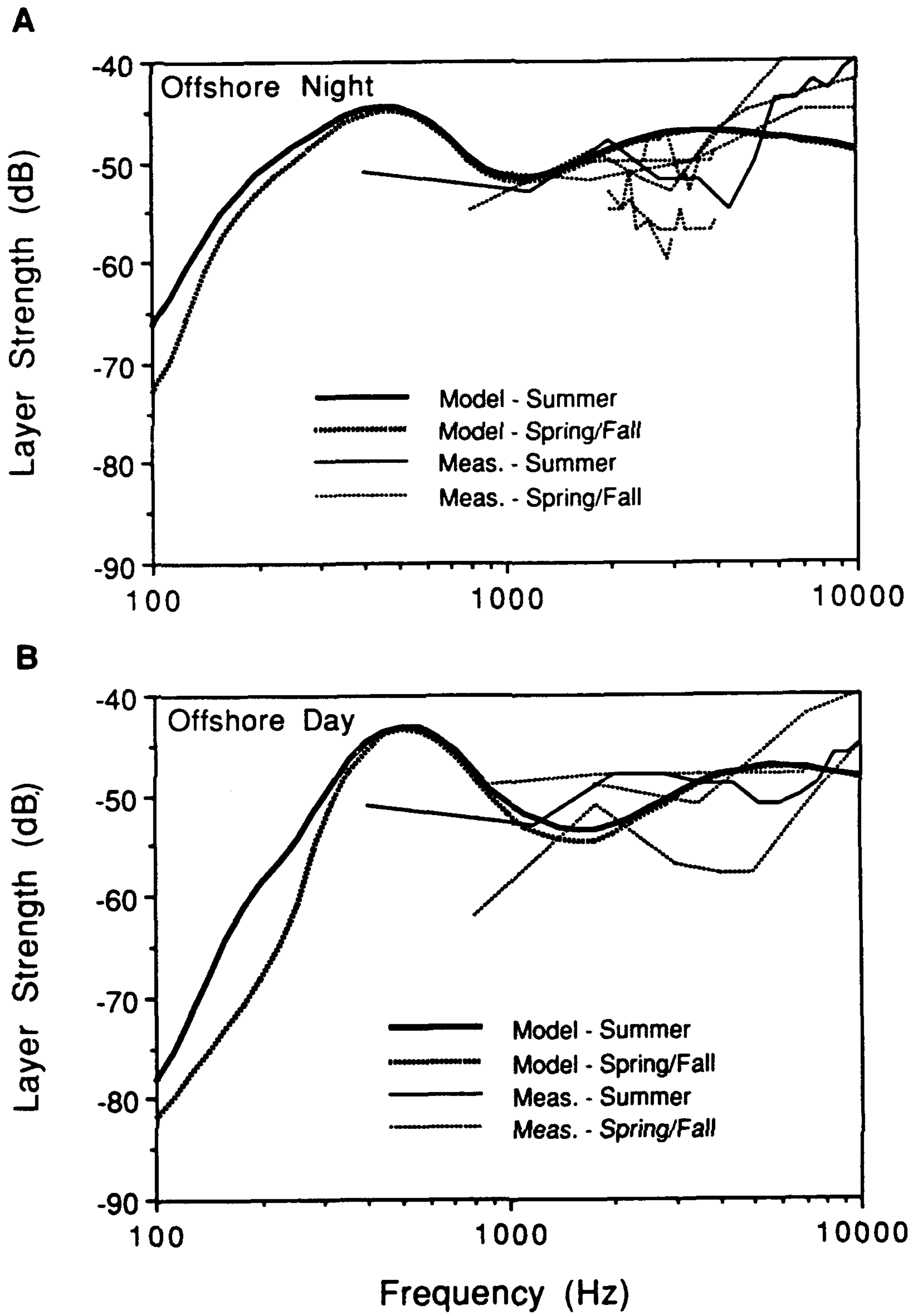

Figure 9. Comparison of model estimates and measurements of volume reverberation for summer, spring, and fall at the offshore location during night (A) and day (B) (sources within text).

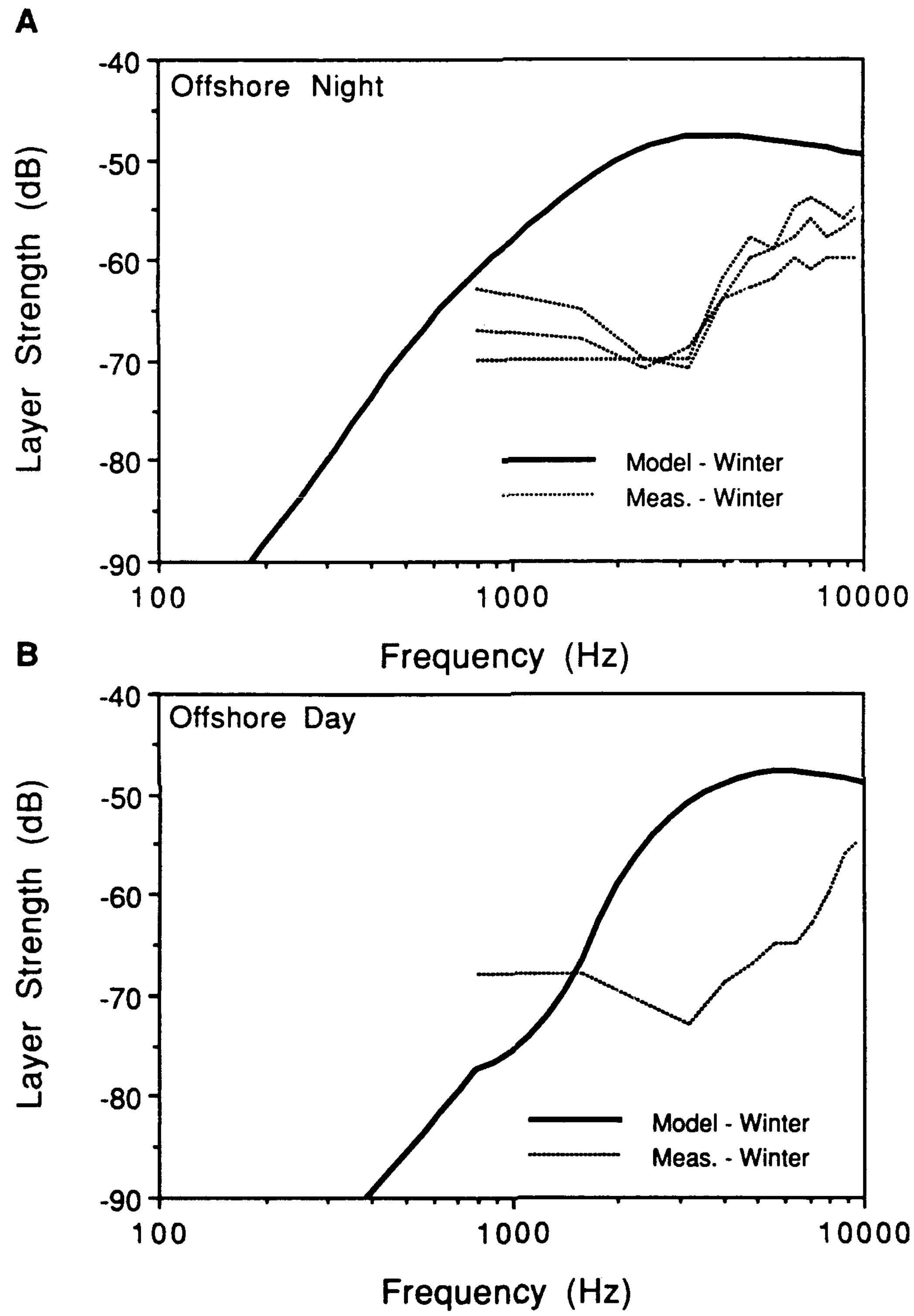

Figure 10. Comparison of model estimates and measurements of volume reverberation for winter at the offshore location during night (A) and day (B) (sources within text).

Clutter and Discrete Echoes

Accurate predictions of clutter and discrete echoes depend on schooling information that is not generally available. Present biological knowledge allows only rough estimates of school and pod numbers and approximations of target strength. Calculations of numbers of schools and pods have been based on all fish or mammals being in "average-size" schools or pods for each species. Target strengths were determined using the individual fish target strength at 100 Hz at night.

Figure 11 shows the results of the target strength calculations for a hypothetical detection area of 10 km x 10 km (100 km^2) determined for the number of schools expected within a hypothetical operating area of 100 km x 100 km (10,000 km^2). Encounter probability is proportional to the number of schools or pods. For a detection area one-tenth this size, or about 3 km x 3 km, encounter probability would shift to the right in Figure 11, such that a probability of 0.01 would occur at 10 schools rather than 1. The calculations only apply when a particular fish species is present at average density within the operating area. Since determining the transition from

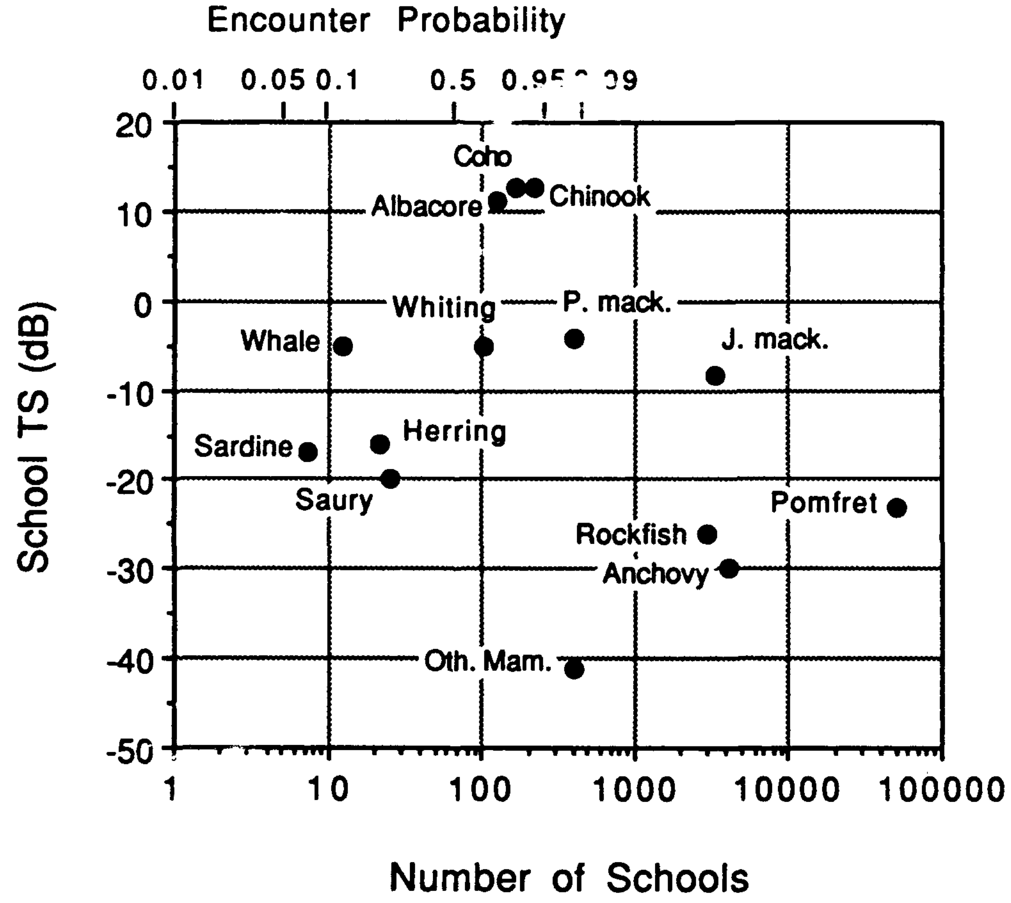

Figure 11. Expected number of fish and marine mammal schools at both the shelf break and offshore areas and their potential school target strength. Data based on individual target strengths at 100 Hz, a detection area of 100 km^2, and an operating area of 10,000 km^2.

reverberation to clutter to discrete echoes is subjective, interpretation of Figure 11 is also subjective. Even under the simple assumption that all fish were in average schools, there is a large spread in target strengths and encounter probabilities (number of schools).

Two effects are notable: (1) pomfret, jack mackerel, rockfish, anchovy, Pacific mackerel are so numerous when they are present that they should produce reverberation; and (2) whales, whiting, albacore and coho and chinook salmon should when present, statistically, produce discrete echoes or clutter. The remaining animals, sardine, herring, saury, and other mammals will be too infrequent and of sufficiently low target strengths so as not to cause reverberation or discrete echoes. These statements are based on average schools and pods; actual distributions of school or pod size and density will further blur the indistinct boundaries between reverberation, clutter, and echoes.

DISCUSSION

The importance of oceanographic features in determining the occurrence of fish must be emphasized. All calculations are based on average densities. Most fish and marine mammals will more likely be associated with unique oceanographic features such as thermal fronts and eddies than with regions of more homogeneous water. Higher than average layer strengths can be expected in unique features and lower than average layer strengths in homogeneous features.

All of the preceding observations are based on the presence or absence of fish based on an assumption of average temperature conditions. Strong seasonal change in volume scattering is expected because of the shift from warm-water species such as pomfret and mackerel dominating the volume scattering in summer-to-cool water year-round residents such as salmon and mesopelagics in winter. The exact timing of this transition is difficult to predict because of year-to-year climatic variability. In Figure 2, recent sea surface temperature data compiled from the National Oceanic and Atmospheric Administration climatic summary (Anonymous, 1991a), are given for offshore and shelf-break locations off the Columbia River. Data indicate that as of October 1991, sea surface temperatures were 1/2 °C warmer than normal offshore and 1/2 °C cooler than normal inshore. Based on these relatively weak temperature anomalies average volume scattering conditions are expected during November 1991.

Caution must be used in applying the predicted volume reverberation levels. Because of the inclement weather occurring during winter in the northeast Pacific, most scientific field observations and commercial fisheries data are restricted to summer months and nearshore waters. Fish populations are also highly variable in distribution and abundance. Unfortunately, the least reliable data are for those species that appear to contribute most to volume reverberation. This is especially true of jack mackerel. This assessment implicates jack mackerel as one of the more important sources of volume reverberation on the west coast. However, jack mackerel data are very poor, no assessments and very little research has been conducted since 1980. The fish population has likely changed in abundance since that time. Presently, the population is considered abundant and underutilized by the fishery (J. Hunter, National Marine Fisheries Service, Southwest Fisheries Center, P.O. Box 271, La Jolla CA, pers comm., 1991). During 1992, an offshore commercial trawl fishery for jack mackerel is expected to commence. At that time, a greater degree of management may be implemented by NMFS and better assessment information may be available. Estimates for other open water pelagic species are also highly speculative, especially those for pomfret and albacore.

Information on fish schools used in the analysis are at best approximations. Actual distributions of individuals, groups, and schools although unknown, are certain to be nonuniform. Fish schools usually occupy some complex distribution of school sizes. The analysis was conducted on "average" or "typical" fish schools. Animals, particularly the fish, are more likely to be concentrated in one or a few areas and absent from others at a given moment. These concentrations will migrate depending on the behavioral characteristics of the particular species. Thus, values higher or lower than the average curves presented can be expected. As animals concentrate in certain areas the layer strength will increase, while in other areas it will decrease: Example A - if 90% of the scatterers occur in 50% of the area, the layer strength in that area will be 2.6 dB higher than that based on average densities, while in the remaining 50% of the area it will be 7 dB lower; Example B - if 95% of the scatterers occur in 10% of the area, the increase will be almost 10 dB, while the decrease in 90% of the area will be 13 dB. Given that several species are generally involved, Example A is possible, while Example B seems extreme. Therefore, it is believed that the "average" limits ± 5 dB of the figures shown provide reasonable working limits on expected volume reverberation.

SUMMARY

Acoustic models were used to estimate low frequency volume scattering from average numbers of animals for the shelf break and offshore waters of the Oregon-Washington coast. Animal densities were derived from fish stock assessments and surveys of marine mammals. Target strengths were based on resonant models of fish with swimbladders and in situ measurements of mammals.

Average volume reverberation levels of -60 dB at 100 Hz, increasing to -44 dB at 1000 Hz are expected at both offshore and shelf-break locations during summer nights (July - September). During day, fish will migrate into deeper water causing the frequency of resonant scattering to shift upward and reverberation levels to decline by about 7 dB. During winter (January - March) scattering during day and night will be extremely low at offshore sites, less than -90 dB at 100 Hz and -60 dB at 1000 Hz and will remain high at the shelf break, near -61 dB at 100 Hz and -48 dB near 1000 Hz. Spring and fall (April-June and October-December) represent transitions in fish densities between winter and summer, and hence, in volume reverberation levels. The timing of these transitions will depend on a particular thermal scenario with warmer or cooler than normal conditions favoring summer-like or winter-like volume reverberation levels, respectively.

A model of school encounter suggests that when schools of pomfret, jack mackerel, anchovy, and rockfish are present, they will be sufficiently widespread to appear as average reverberation levels. Schools of albacore, coho, and chinook salmon will be sufficiently rare and compact so as to cause discrete echoes.

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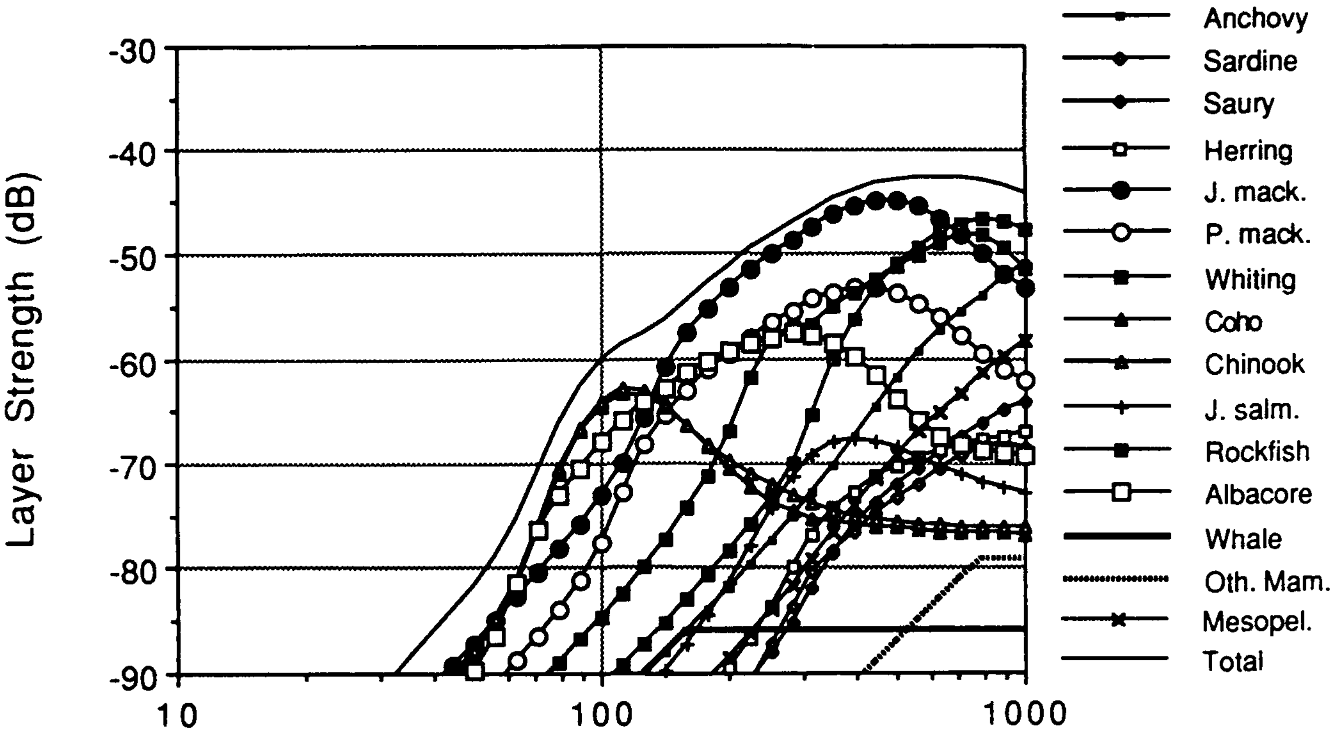
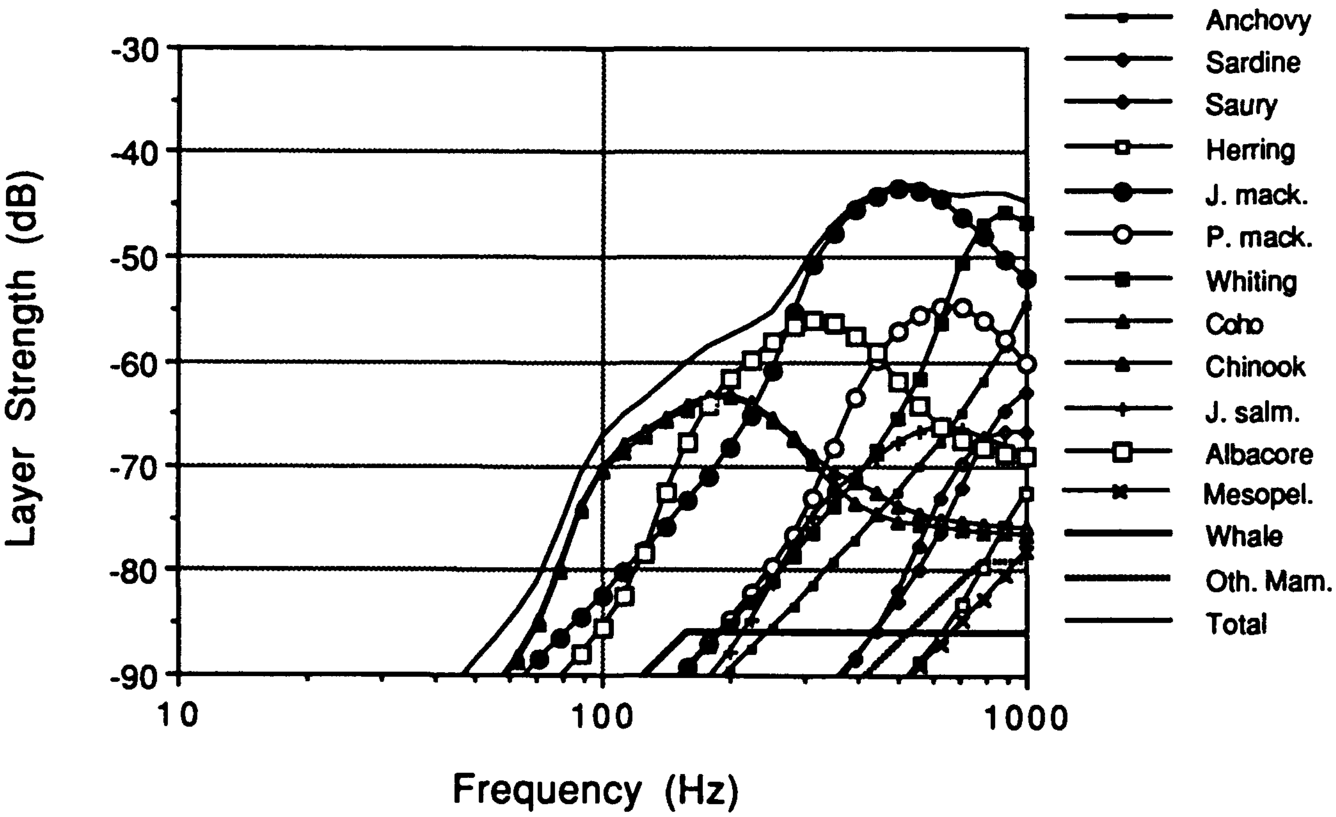
Appendix 1

Model estimates of layer strength by location, season, time of day, and animal group.

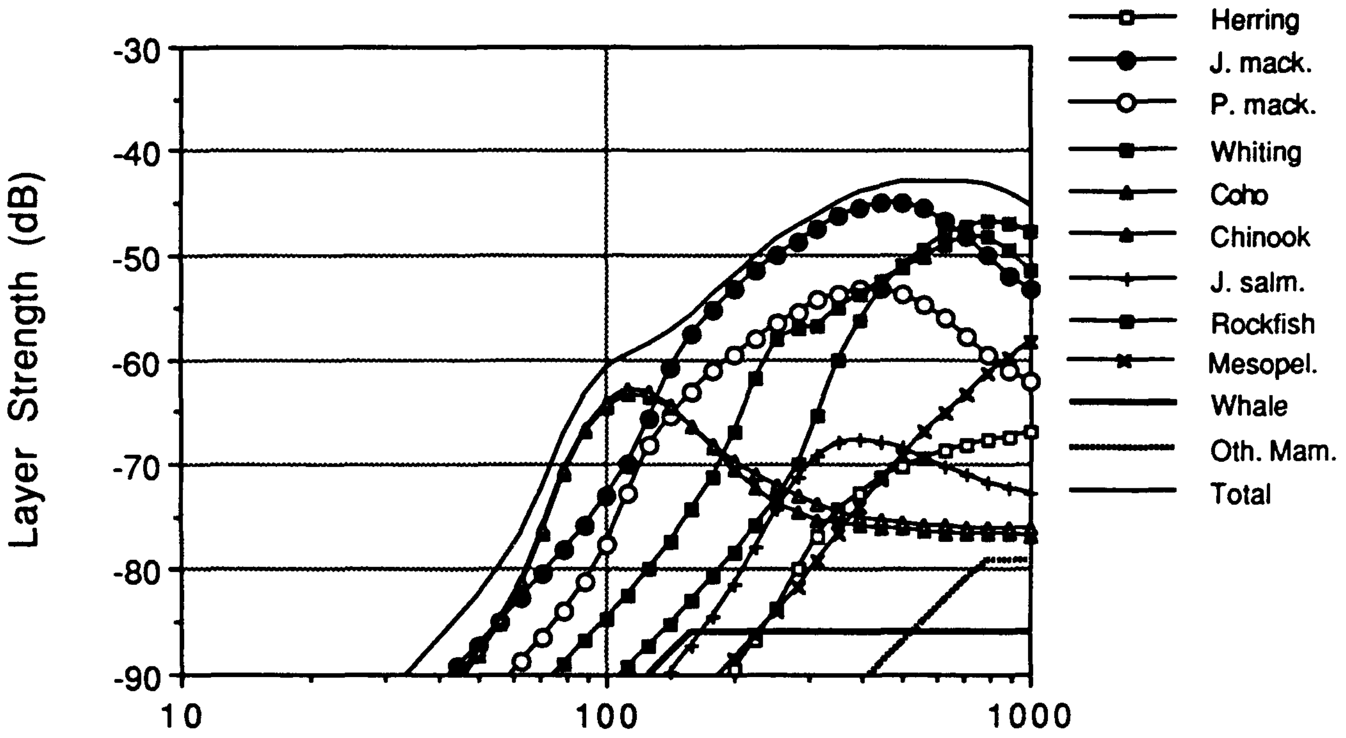
Shelf Break Summer - Night



Shelf Break Summer - Day



Shelf Break Spring/Fall - Night



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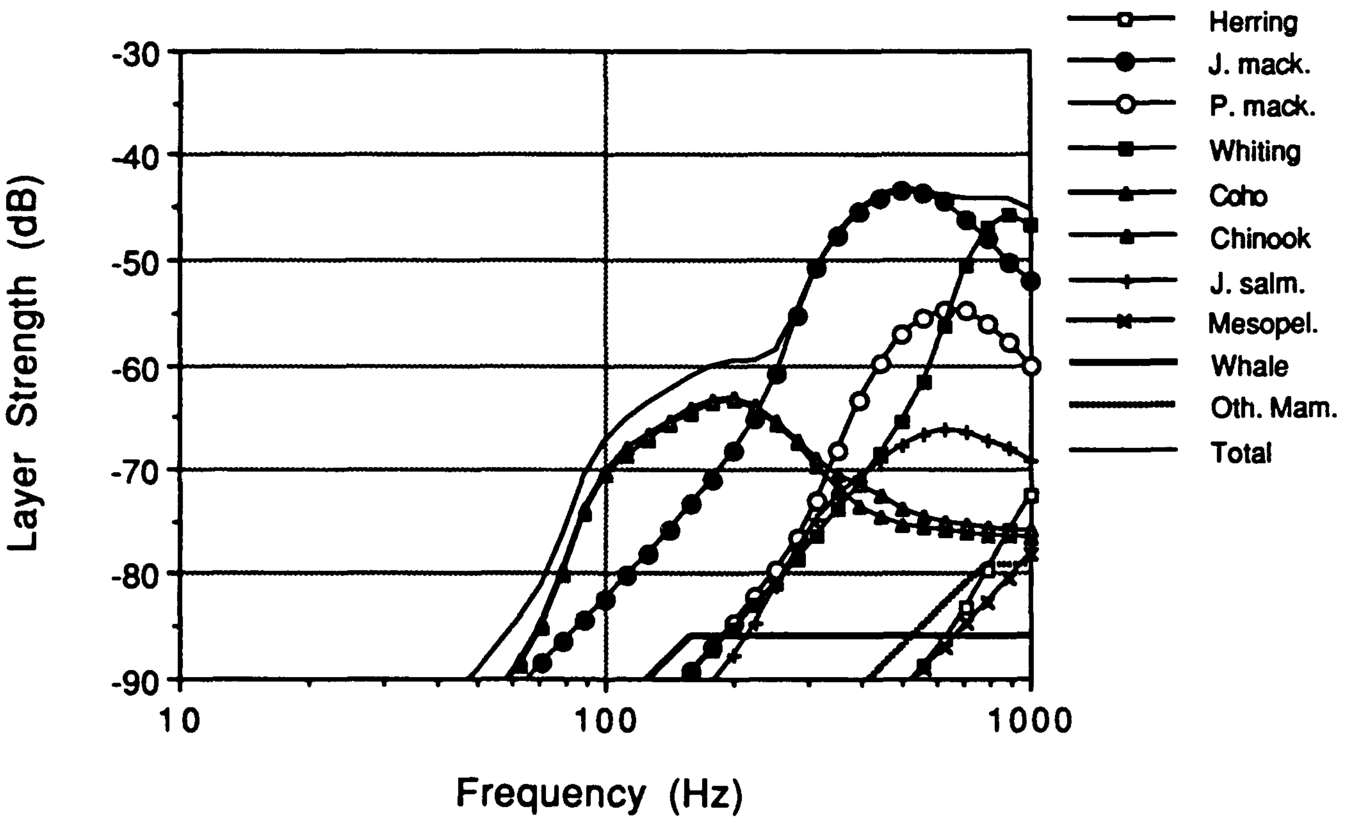

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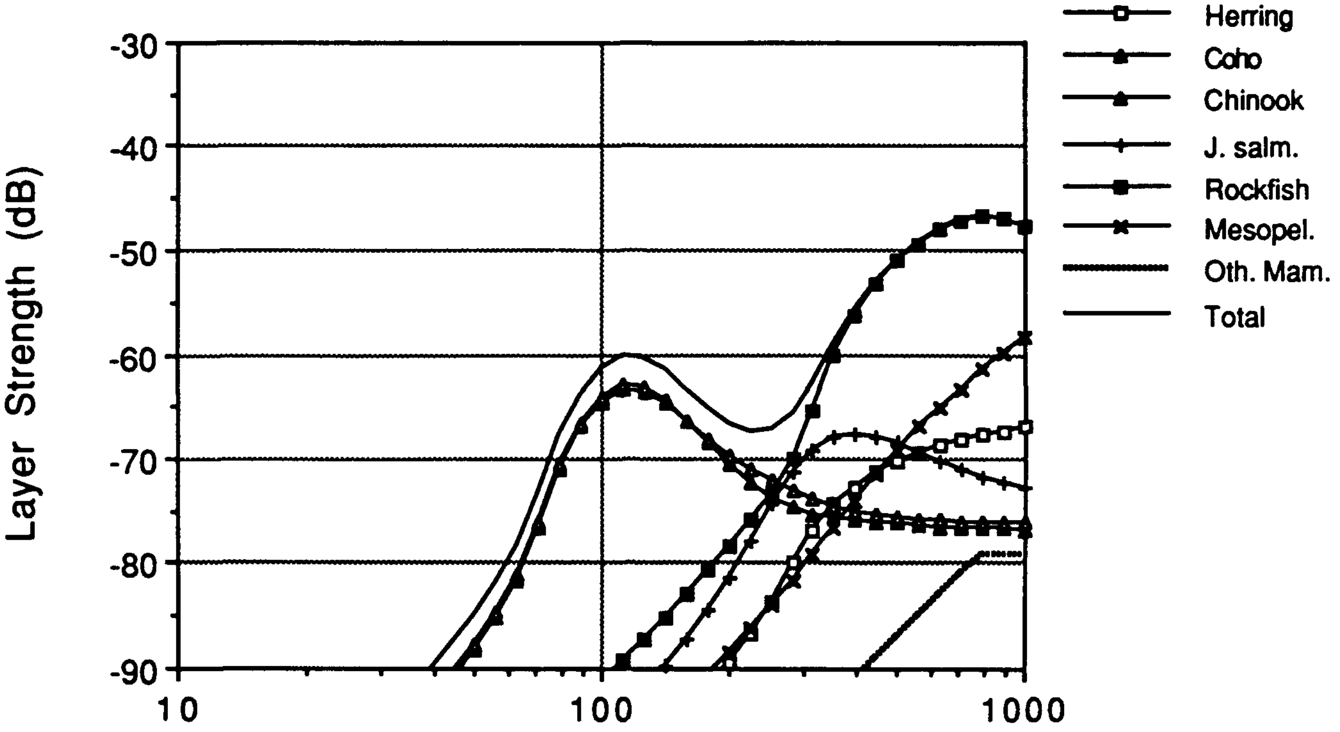
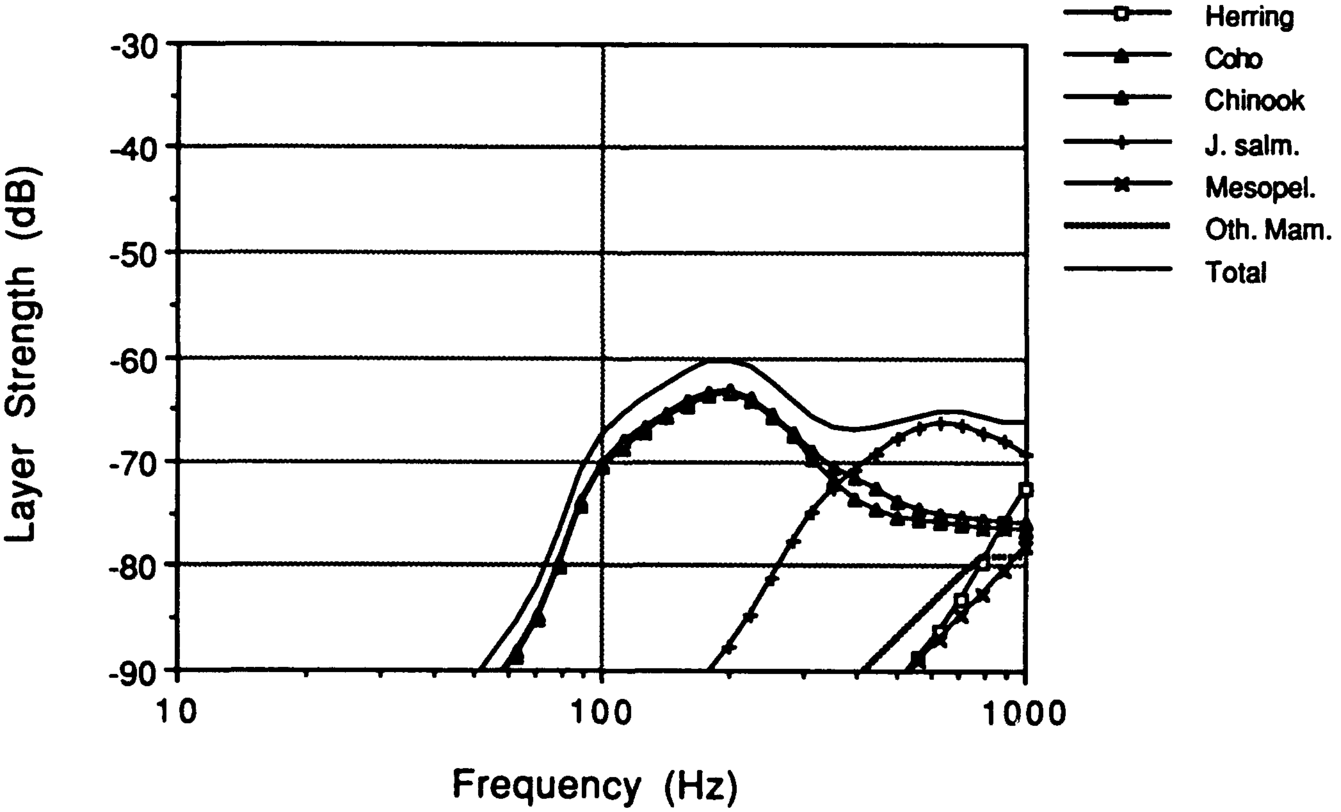
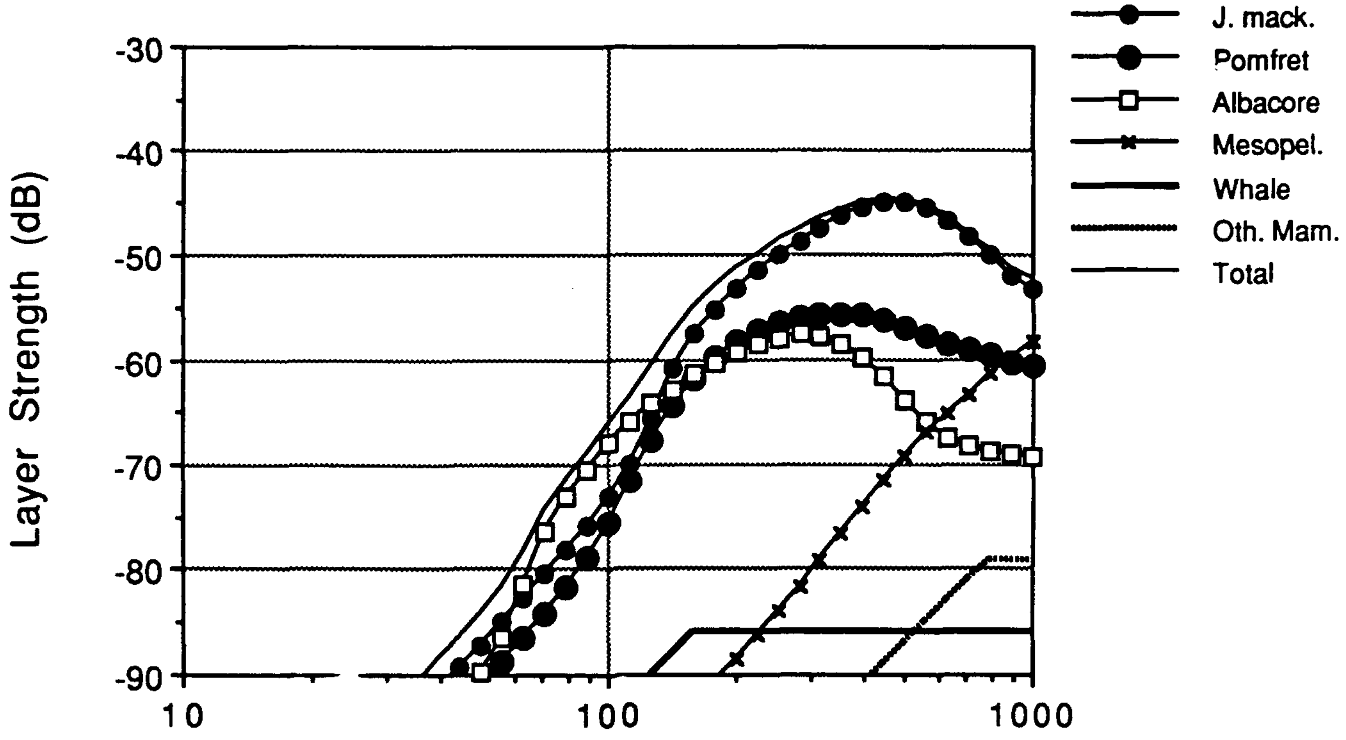


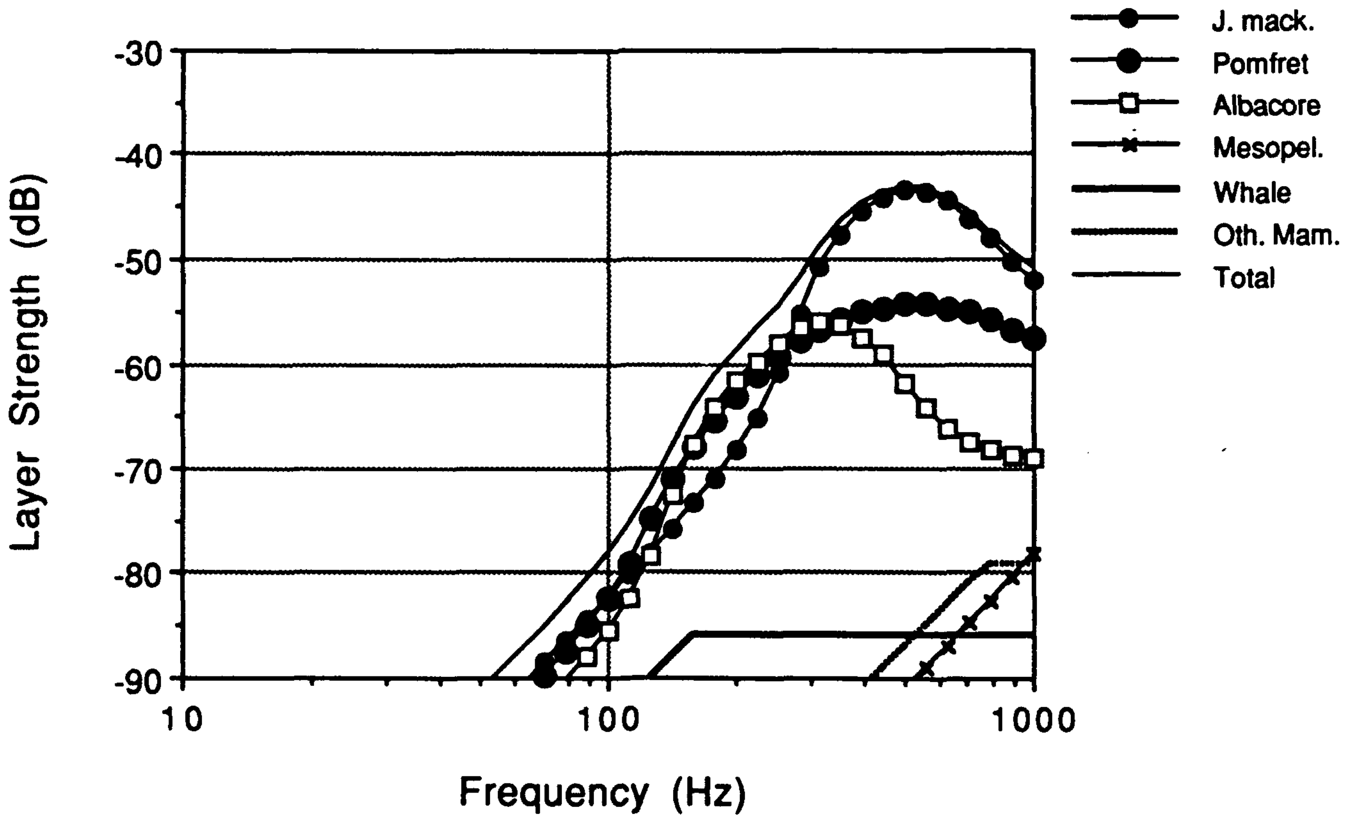
Shelf Break Winter - Day



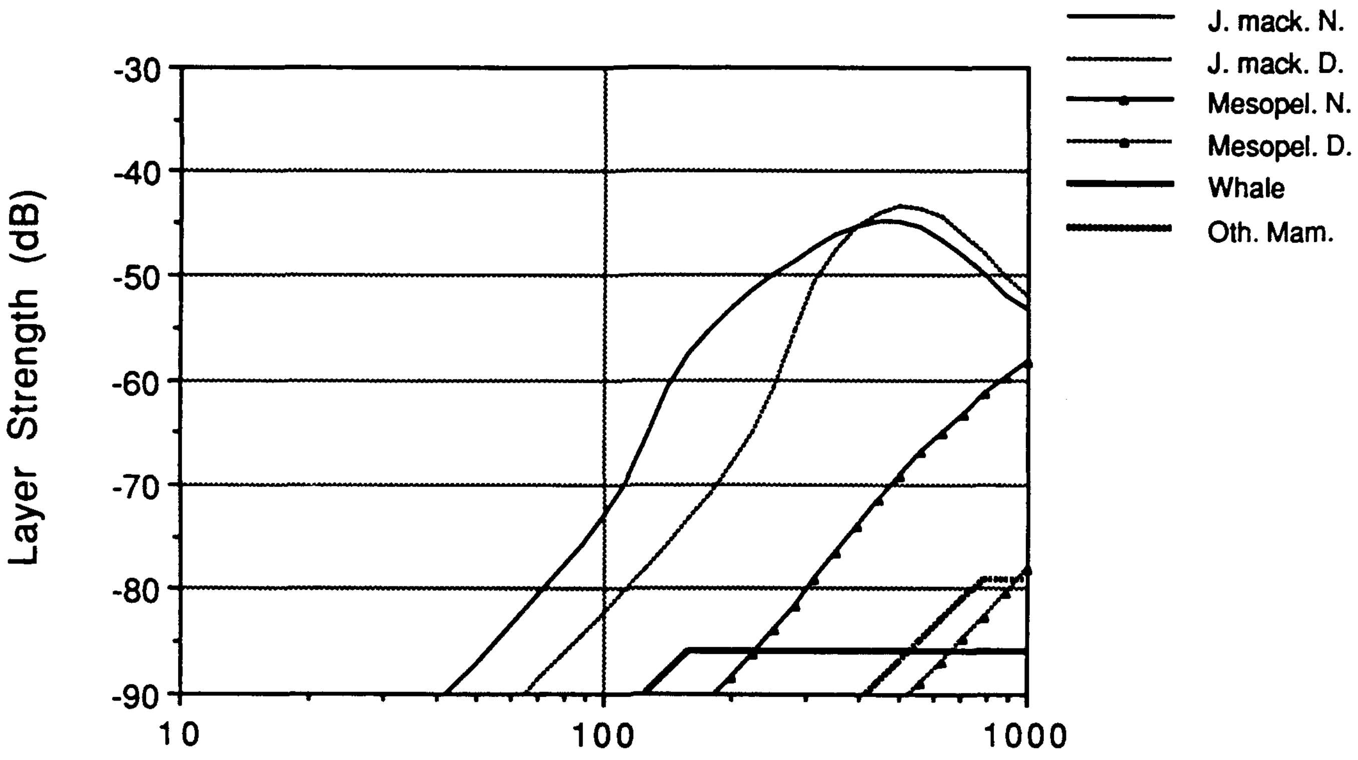
Offshore Summer - Night



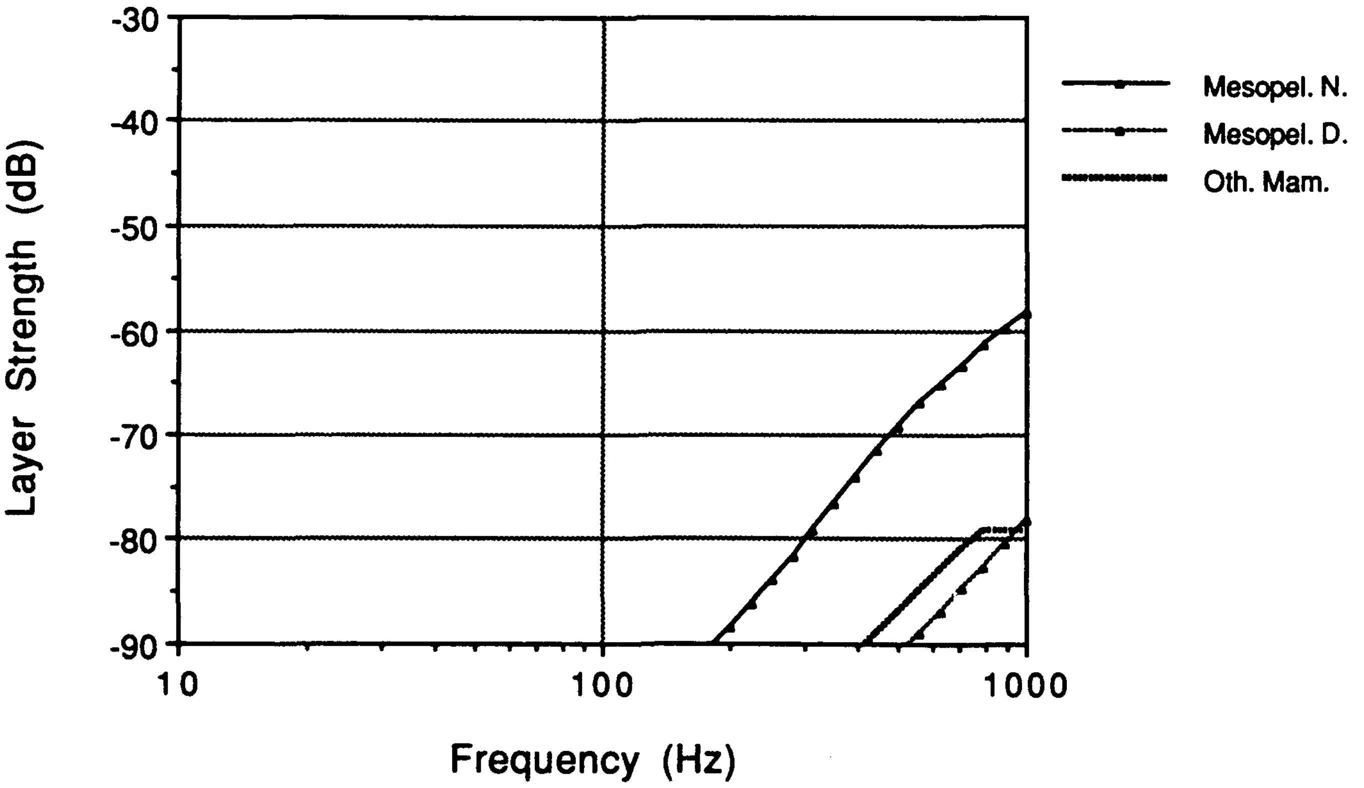
Offshore Summer - Day



Offshore Spring/Fall - Day + Night



Offshore Winter - Day + Night



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Estimates are made of low frequency volume scattering using average numbers of animals for the shelf break and offshore waters off the Oregon-Washington coast. Animal densities were derived from fisheries assessments and surveys of marine mammals. Target strengths were based on resonant models of fish with swimbladders and in situ measurements of mammals. Average volume reverberation levels of -60 dB at 100 Hz, and -44 dB at 100 Hz are expected at both offshore and shelf break locations during summer nights (July - September). These levels will decline by about 7 dB by day. During winter (January - March) scattering will be low at offshore sites, less than -90 dB at 100 Hz and -60 dB at 1000 Hz but will remain high at the shelf break, near -61 dB at 100 Hz to -48 dB near 1000 Hz. Spring and fall are transitional between winter and summer, and hence, will have volume reverberation levels between those of summer and winter. A model of school encounter suggests that when schools of pomfret jack mackerel, anchovy, and rockfish are present they will be sufficiently widespread to appear as average reverberation levels. Schools of albacore, coho, and chinook salmon will be sufficiently rare and compact so as to cause discrete echoes.

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