SOUTHWEST FISHERIES SCIENCE CENTER

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INTERANNUAL VARIABILITY IN DOLPHIN HABITATS AND ABUNDANCES ESTIMATED FROM TUNA VESSEL SIGHTINGS IN THE EASTERN TROPICAL PACIFIC, 1975-1989

By

Paul C. Fiedler and Stephen B. Reilly

ADMINISTRATIVE REPORT LJ-91-35

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ABSTRACT

The results of a canonical correspondence analysis (CCA) of data from research vessel surveys of the eastern tropical Pacific, consisting of dolphin school sightings and concurrent environmental variables, were applied to time series of estimated dolphin abundances from tuna vessel sightings. Habitat quality was calulated from historical bathythermograph data using CCA ordination results. For spotted and eastern spinner dolphins, annual abundance estimates or interannual changes in those estimates are significantly correlated with habitat quality. This effect is at least partly due to expansion of high quality habitat beyond the geographic ranges assumed for the abundance estimate. We discuss ways that environmental data could be used to reduce error in dolphin abundance estimates.

INTRODUCTION

The eastern tropical Pacific Ocean (ETP) supports a diverse and abundant cetacean fauna that has attracted scientific, governmental, and popular interest since the late 1960's, when it became clear that large numbers of dolphins were being killed in tuna purse seine operations (Perrin 1969). After 17 years of monitoring effort by observers on tuna vessels and 5 consecutive years of effort by research vessels, we are now assessing results: can we detect statistically significant trends in a times series of species or stock abundance estimates that are subject to considerable sampling error plus the effects of environmental variability on abundance and distribution?

Reilly and Fiedler (1991) showed that sighting rates of dolphin species on research surveys are related to concurrently measured environmental variables. The data were collected for the NMFS Monitoring of Porpoise Stocks (MOPS) program during August-November in 1986 through 1990 (Gerrodette and Wade 1990). We focus on dolphin species affected by the tuna fishery: spotted dolphin (*Stenella attenuata*), the "whitebelly" form and "eastern" subspecies of spinner dolphin (*S. longirostris*, Perrin 1990), common dolphin (*Delphinus delphis*), and striped dolphin (*S. coeruleoalba*). Reilly and Fiedler (1991) used a robust and efficient multivariate technique, canonical correspondence analysis, to examine relationships between spatial distributions of dolphin species and environmental variables.

Canonical correspondence analysis (CCA) has been developed and used in ecological applications only in the last few years (ter Braak 1986). CCA estimates unimodal (Gaussian) responses of species along canonical axes which are linear combinations of observed environmental variables. In general, the response is observed abundance or probability of occurrence. For this study, the observed response is encounter rate, equal to number of sightings or schools per unit of sighting effort (trackline distance). Encounter rate is a rough measure of relative abundance, since the final abundance estimate also depends on school size and effective track width. We assume that this response, at a site in time and space, reflects the proximity of environmental conditions at that site to the species optimal habitat or niche. The estimated response may also include error caused by behavioral responses to the environment that affect the detectability of schools. For this study, we use the response as an index of habitat quality, *H*, which is equal to the abundance expected at a site, based on local environmental conditions, divided by the mean abundance in the study area.

We use archived bathythermograph data to quantify variability of surface temperature, thermocline depth, and thermocline strength in the MOPS study area since 1975. These variables were shown to be important in explaining variations in encounter rates in the MOPS surveys (Reilly and Fiedler 1991). Other important variables (salinity and chlorophyll concentration) have not been routinely observed with sufficient frequency to be used in this historical analysis.

The best available time series of target species abundance estimates are derived from tuna vessel observer data (Anganuzzi and Buckland 1989, Anganuzzi et al. 1991). These are yearly estimates of stocks of spotted, spinner, and common dolphins within stock boundaries covered by the MOPS survey area (the so-called SOPS boundaries, Au et al. 1979). We ask one simple question in this study: Are changes in these estimates related to environmental variability? In this 15-year record of populations with very low growth rates (Reilly and Barlow 1986), we can detect short-term sampling effects but not long-term effects on population size. We then discuss ways to use the habitat variability results from CCA to improve estimates of dolphin species abundance from tuna vessel or research vessel data.

METHODS

Seasonal fields of surface temperature, thermocline depth, and thermocline thickness for the period 1975-1989 were derived from a bathythermograph data base described by Fiedler (1991). Thermocline depth is defined as the depth of the 20°C isotherm. Thermocline thickness is defined as the difference between the 20°C and 15°C isotherm depths. See Fiedler (1991) for details on sources and quality control of the data.

Data were objectively gridded by seasons (December-February, March-May, June-August, September-November from 1975 through 1989) on a 2-degree latitude-longitude grid from 20S to 30N latitude and from the coast out to 160W longitude. At each grid point, the mean of at least 20 observations within 2 degrees or more was calculated. The range of observations around a grid point was increased in increments of one degree to obtain a minimum sample size of 20 for each mean. Thus, local grid resolution decreases in data-poor regions, generally south of the equator where the maximum radius required was up to 20 degrees. Within the MOPS area, sufficient observations were available within 4 degrees of 61% of the gridpoints and within 10 degrees of 95% of the gridpoints. We converted observations to anomalies (deviations from the seasonal climatology) before gridding to reduce the magnitude of spatial variability of the observations and the resultant error at grid points far from observations. This minimizes bias caused by interpolation over or extrapolation into large data gaps.

Relationships between dolphin species abundances and environmental variables were analyzed using canonical correspondence analysis (CCA, Ter Braak 1986). CCA is a constrained ordination technique that directly estimates ordination axes as linear combinations of observed environmental variables. The advantages of CCA for multivariate species-environment analyses and details of the method are presented in Reilly and Fiedler (1991).

CCA was performed as described in Reilly and Fiedler (1991), except that sightings of mixed spotted and spinner schools were not treated separately, but were counted as sightings of both component species. The results of the CCA of 5 species and 3 environmental variables observed during 1986-1990 MOPS research surveys are summarized in the species-environment biplot (Fig. 1), with additional information in Tables 1 and 2. The eigenvalues of the three canonical axes were 0.296, 0.074, and 0.001. The first two axes explain 99.7% of the species-environment variance accounted for by all three axes. Therefore, the third axis has not been used. The first two axes explain 20.5% of the total variance of species encounter rates (Table 3).

Habitat quality for species i (H_i) at a gridpoint was calculated from the Gaussian responses fit to the two dominant canonical axes by CCA. The response to each environmental axis was calculated as follows:

$$H_{ij} = 1/t_{ij} \exp(-0.5*((x_j-u_{ij})/t_{ij})^2)$$

where,

x_j = the site (gridpoint) score on environmental axis *j*

u_{ij} = the species *i* score (optimum) on axis *j*

t_{ij} = the tolerance (standard deviation) of species *i* on axis *j*

The H_{i1} and H_{i2} responses derived for the present application are illustrated in Figure 2. In this figure, the values are scaled so that the mean of H_{ij} is 1.0 over a range of ±2 units (standard deviations) on the canonical axis. The means (optima) of a species distribution on the two canonical axes are equal to the species scores in the ordination biplot (Fig. 1). Habitat quality, H_i, was calculated as $(H_{i1}H_{i2})^{\frac{1}{2}}$, with H_{ij} scaled so that the mean value is 1.0 during 1975-1989.

Annual point estimates of abundance were provided by Anganuzzi (1991, pers. comm.) for pooled stocks: spotted dolphins include northern and southern offshore spotted dolphins, whitebelly spinner dolphins include northern and southern whitebelly spinner dolphins, and common dolphins include northern, central, and southern common dolphins. No estimates were made for striped dolphins, which are sighted infrequently by tuna vessel observers.

RESULTS

Positive scores on canonical axis 1 indicate cool surface temperature and a shallow, weak thermocline (Table 1). These are characteristic of the productive "cool upwelling" habitat that we identified with the first axis in the complete CCA (Reilly and Fiedler 1991). This habitat is found in the equatorial and eastern boundary current (Peru and California Currents) waters of the ETP. It is also present seasonally in the region of the Costa Rica Dome at 10N, 90W (Fiedler 1991). Positive scores on canonical axis 2 indicate warm surface temperature and a shallow thermocline (Table 1). These are characteristics of the "coastal tropical" habitat of Reilly and Fiedler (1991). This habitat is centered in the warmest tropical surface water of the ETP, along the coast of Mexico south of Baja California.

Species habitats, quantified by *H* as derived from climatological values of environmental variables at each gridpoint in the MOPS area (Fiedler 1991), are mapped in Figure 3. These distributions are consistent with stock ranges indicated by the SOPS population boundaries, with the exception of whitebelly spinners. Spatial variations of *H* are similar to patterns in maps of tuna and research vessel sighting records (Perrin et al. 1984), although such maps can give only a rough indication of habitat distribution because the sighting or collection frequencies are not standardized by effort. The distributions of climatological *H* calculated for September-November are significantly correlated with gridded fields of mean (August-November, 1986-1990) MOPS encounter rates as follows: spotted dolphin $r=+0.50$, common dolphin $r=+0.52$, eastern spinner dolphin $r=+0.69$, whitebelly spinner dolphin $r=+0.29$, striped dolphin $r=+0.37$, $p<.01$ for all relationships.

Spotted dolphins are associated with warm, tropical surface water centered on 10N. Moderately high values of *H* (0.8-1.0) are found in equatorial water between 120W and 130W. The Costa Rica Dome (10N, 90W) is a notable gap in favorable habitat. Eastern spinner dolphins are even more tightly associated with warm tropical water. Highest values of *H* are found in the center of the "coastal tropical" habitat off southern Mexico. Whitebelly spinner dolphins are associated with subtropical water to the northwest and southwest of the tropical surface water in the core of the MOPS area. The apparent westward extension of the habitat outside the MOPS area is consistent with the recognition of the "whitebelly" form as a hybrid/intergrade between eastern and pantropical subspecies of spinner dolphins (Perrin 1990). The partial separation of eastern and whitebelly spinner habitats defined by *H* is consistent with the management boundary between the two forms proposed by Perrin et al. (1991): eastern spinners north of 10N and east of 125W, and whitebelly spinners south of 10N or west of 125W.

Common dolphins are associated with cool, upwelling-modified water in three regions: off Baja California, along 10N with a maximum at the Costa Rica Dome, and in equatorial water. These three habitat centers correspond to the northern, central, and southern stocks of common dolphins (Perrin et al. 1984). The offshore *H* maximum along 10N at 120-130W does not correspond to high encounter rates in the MOPS data, but reflects a shoaling of the countercurrent thermocline ridge at that location (Fiedler 1991). Striped dolphins are the most widespread and abundant of the target species. The highest *H* values tend to be in regions between the centers of spotted and eastern spinner habitat in tropical water near the coast of southern Mexico, and northern and southern common dolphin habitat in equatorial water and off Baja California (see also Reilly 1990).

Time series of seasonal values of mean habitat quality, *H*, and annual abundance estimates are plotted in Figure 4. The strongest signal for all species can be attributed to the El Niño events of 1982-83 and 1986-87. *H* increased for spotted and spinner dolphins and decreased for common and striped dolphins during both events. Seasonal variability, indicated by the deviations of the seasonal from the smoothed *H* values, tends to be low for species with large geographic ranges (e.g. striped dolphin) and high for species with more restricted ranges (e.g. eastern spinner dolphin). Seasonal variability of *H* is as great as interannual variability for eastern spinner dolphins.

Annual dolphin abundance estimates, N_t, and interannnual changes in abundance estimates, $N_t - N_{t-1}$, for some species are related to environmental variability as indexed by *H* (Figure 5). Interannual change in spotted dolphin abundance is negatively correlated with *H* ($r=-0.70$, $P=.005$, Table 4). An increase in *H* for spotted dolphins indicates an expansion of favorable habitat to the south of the SOPS population boundary west of 100W (Figure 6a). Annual eastern spinner dolphin abundance is negatively correlated with *H* ($r=-0.56$, $P=.031$, Table 4). An increase in *H* for eastern spinner dolphins indicates an expansion of favorable habitat to the west of the SOPS population boundary (Fig. 6b).

No other species shows a significant linear relationship between N or ΔN and *H*. Common dolphin abundance, however, appears to be maximum at *H* near 1.0 and to drop off at lower or higher values (Fig. 5c). The N_t vs. H_t scatterplots for spotted and whitebelly spinner dolphins suggest similar unimodal relationships. For common dolphins at low values of H, as in early 1983, very little high-quality or favorable habitat is available in the ETP (Fig. 6c). The only favorable habitat with $H>1$ is in equatorial water west of the Galapagos. Half of this favorable habitat is outside the SOPS boundary. At high values of H, as in early 1985, favorable habitat for the central and southern stocks (along 10N and the equator, respectively) expands. Favorable habitat along the equator extends beyond the SOPS boundary. At the same time, favorable habitat for the more abundant northern stock, off Baja California, is reduced.

DISCUSSION

We have detected significant correlation between environmental variability and spotted and eastern spinner dolphin abundances estimated from tuna vessel observer data. The correlation for spotted dolphins is significant only for interannual change in abundance. Differencing of the abundance time series, by calculating year-to-year changes in abundance, eliminates multi-year trends in the series. Anganuzzi and Buckland (1989) found significant 5-year trends in the record of spotted dolphins. They also noted the low 1983 abundance estimate and suggested that it might be explained by dispersal of local concentrations of schools during the strong El Niño. Our results show that spotted dolphin schools may have moved outside the nominal species range as the "coastal tropical" habitat expanded into equatorial water west of 100W during this unusual event.

Eastern spinner dolphin abundance decreases slightly with increasing *H*. As for spotted dolphins, this appears to be the result of dispersal of schools outside the nominal range (SOPS boundaries) used in calculating the abundance estimate. The center of distribution of spotted and, to a greater extent, eastern spinner dolphins is the warm tropical surface water in the core of the ETP. Therefore, the responses of the two populations to environmental variability are similar.

The estimated abundance of common dolphins appears to decrease at values of *H* both above and below normal. The different effects of environmental variability on the habitats of the three stocks of common dolphins appears to complicate the response of the population as a whole. We detected no effect of environmental variability on the abundance estimates of whitebelly spinner dolphins, but the CCA results inadequately define the geographical extent of the habitat of this stock (see Fig. 3).

Reilly and Fiedler (1991) suggested that species habitats defined by axis scores from CCA could be used to improve the precision and accuracy of abundance estimates from research vessel surveys. Precision could be increased by post-stratifying the sighting data based on the spatial distribution of axis scores. Bias could be reduced by using axis scores to quantify the amount of habitat available within a survey area. The present results suggest that this approach could be extended by using species habitat distributions derived from environmental variability along more than one canonical axis. For example, a large area of suitable spotted dolphin habitat existed in equatorial water beyond the SOPS population boundary during 1983, apparently causing a serious underestimate of abundance. Gerrodette et al. (1991) suggest approaches for using fields of *H* to adjust abundance estimates from MOPS research vessel surveys.

We utilized the results of a multi-species CCA for this study. While this approach yields useful information about community structure, as in the separation of eastern and whitebelly spinner habitat, it does not retain the maximum amount of information about any single species for management applications. A similar type of analysis for each individual species or stock might explain more of the variability in abundance and improve the quantification of habitat quality defined by Gaussian responses along dominant environmental gradients. In addition, CCA could be used to account for environmental effects on school size and effective trackline width that cause error in dolphin abundance estimates.

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We thank the dedicated tuna vessel and research vessel observers, oceanographic technicians, and cooperative ship personnel who contributed to the collection of the sighting and environmental data. R. Holland assisted in manipulating the large data sets for this study.

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Table 1. Regression/canonical coefficients for standardized environmental variables on two environmental axes (AX1 and AX2). TEMP = surface temperature, Z20 = thermocline (20°C isotherm) depth, ZD = thermocline thickness (difference between 20°C and 15°C isotherm depths).

	TEMP	Z20	ZD
AX1	-0.501	-0.326	+0.111
AX2	+0.439	-0.486	+0.088

Table 2. Dolphin species optima ±tolerances on the first two CCA canonical axes.

	AX1	AX2
Spotted	-0.53 ±0.57	-0.19 ±0.54
Common	1.68 ±1.16	0.28 ±0.48
Eastern Spinner	-0.84 ±0.49	0.86 ±0.71
Whitebelly Spinner	-0.37 ±0.55	-1.51 ±1.19
Striped	0.24 ±0.69	-0.08 ±0.55

Table 3. Fractions of individual and total species variances explained by CCA. AX1 = canonical axis 1, AX2 = canonical axis 2.

	AX1	AX2	AX1+AX2
Spotted	.191	.000	.191
Common	.321	.004	.325
Eastern Spinner	.169	.089	.258
Whitebelly Spinner	.014	.118	.132
Striped	.037	.002	.039
Total	.164	.041	.205

Table 4. Correlations between dolphin species abundance estimates (N) and habitat quality (*H*) calculated from seasonal fields of environmental variables. N - annual abundance estimates vs. annual mean *H*, ΔN - change in annual abundance estimates vs. mean *H* between mid-years. ** P=.005, * P=.031, all other coefficients are not significantly different from zero.

	N	ΔN
Spotted	-0.13	-0.70**
Common	-0.12	+0.12
Eastern Spinner	-0.56*	+0.30
Whitebelly Spinner	+0.10	-0.25

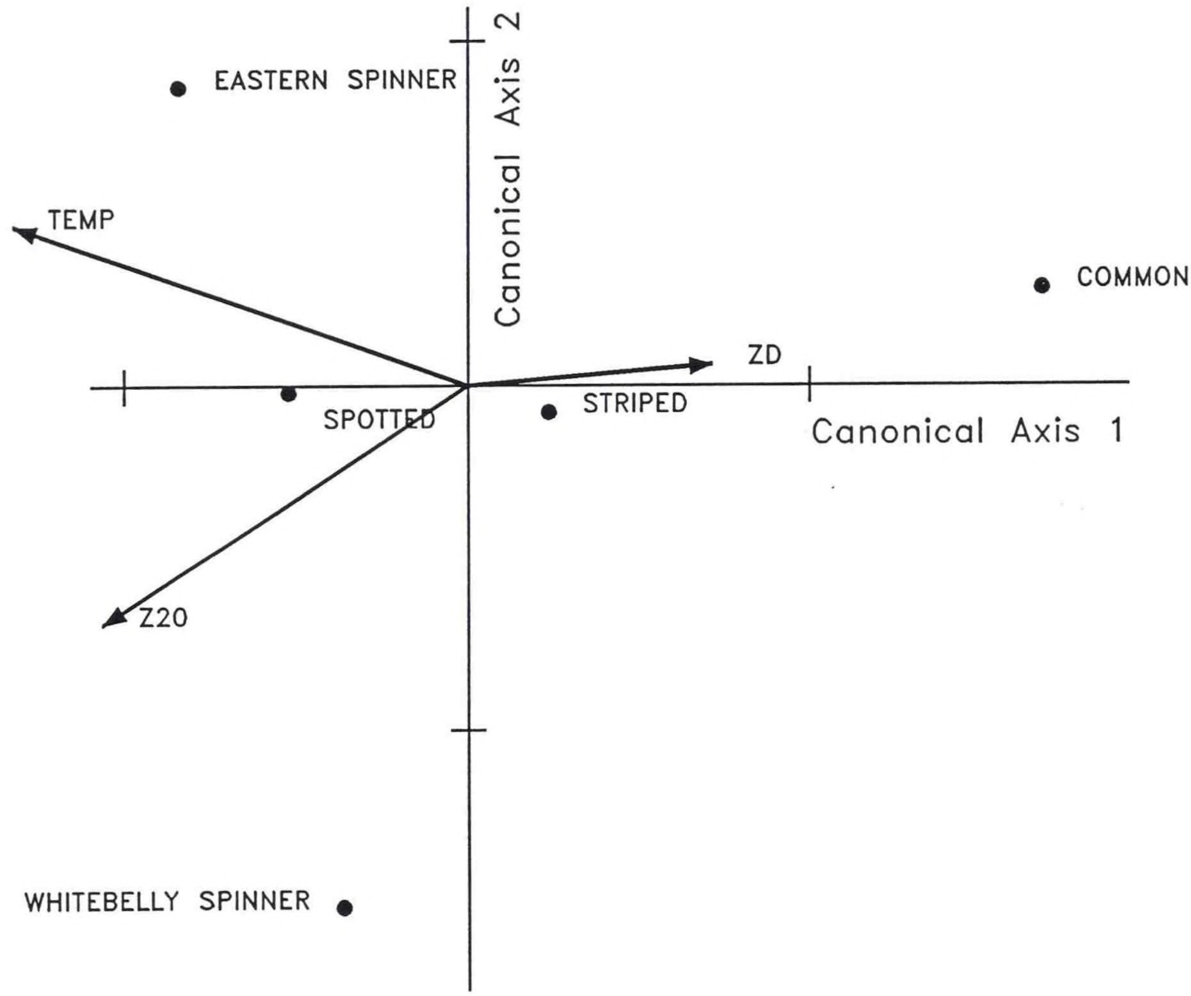


Figure 1. Ordination biplot of first two canonical axes from CCA of species-environment data from 1986-1990 MOPS surveys of the ETP. Points represent species scores (optima) and vectors represent the regression relationships of environmental variables with the canonical axes. TEMP = surface temperature, Z20 = thermocline depth, ZD = thermocline thickness.

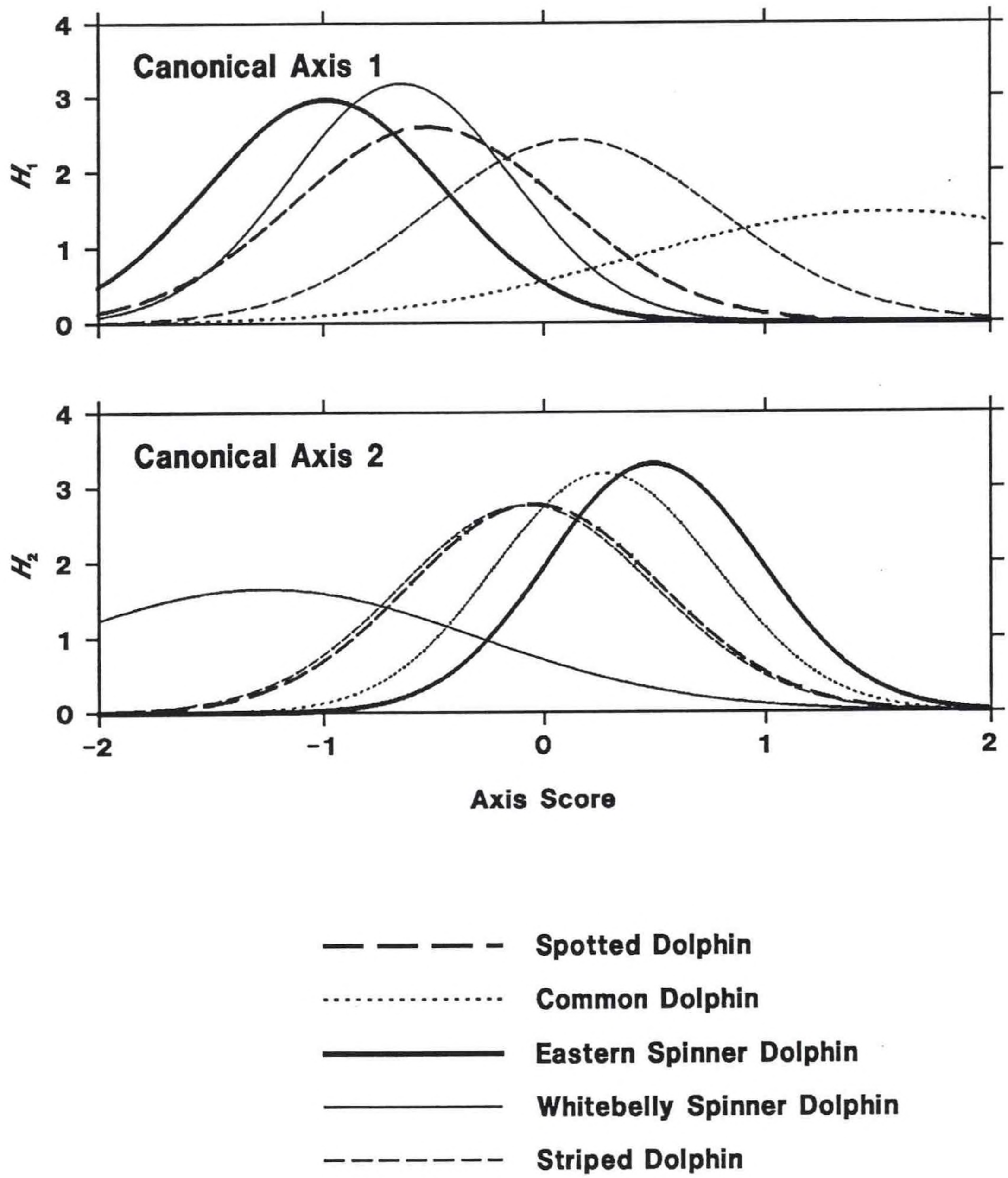


Figure 2. CCA-derived Gaussian distributions of dolphin species habitat quality, *H* (from MOPS 1986-1990 encounter rates), along the first two canonical axes.

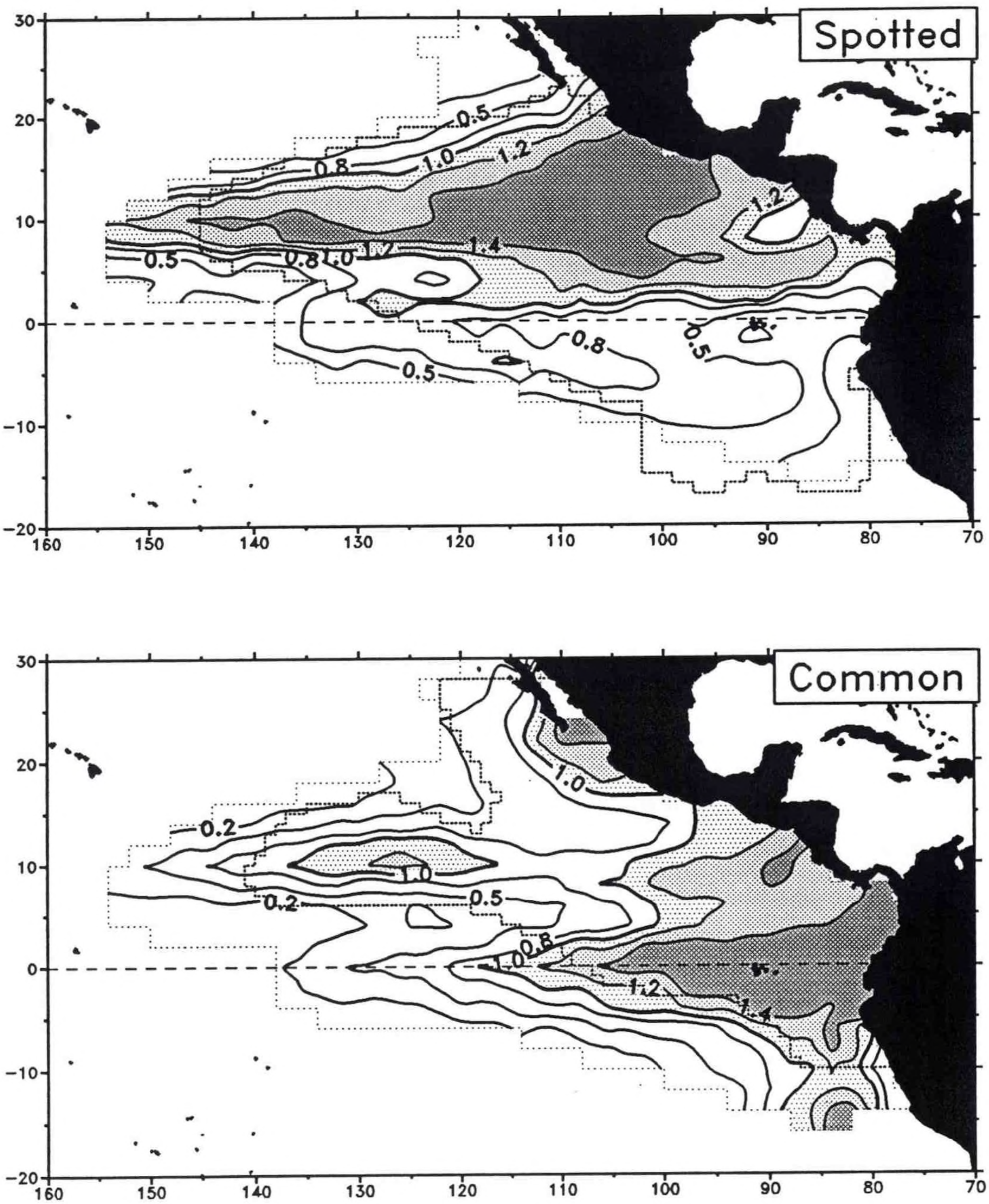


Figure 3a. Mean habitat quality (*H*) for spotted and common dolphins, calculated from climatological fields of surface temperature, thermocline depth, and thermocline thickness in the MOPS area. Heavy dashed lines delimit SOPS population areas used by Anganuzzi and Buckland (1989) and Anganuzzi et al. (1991).

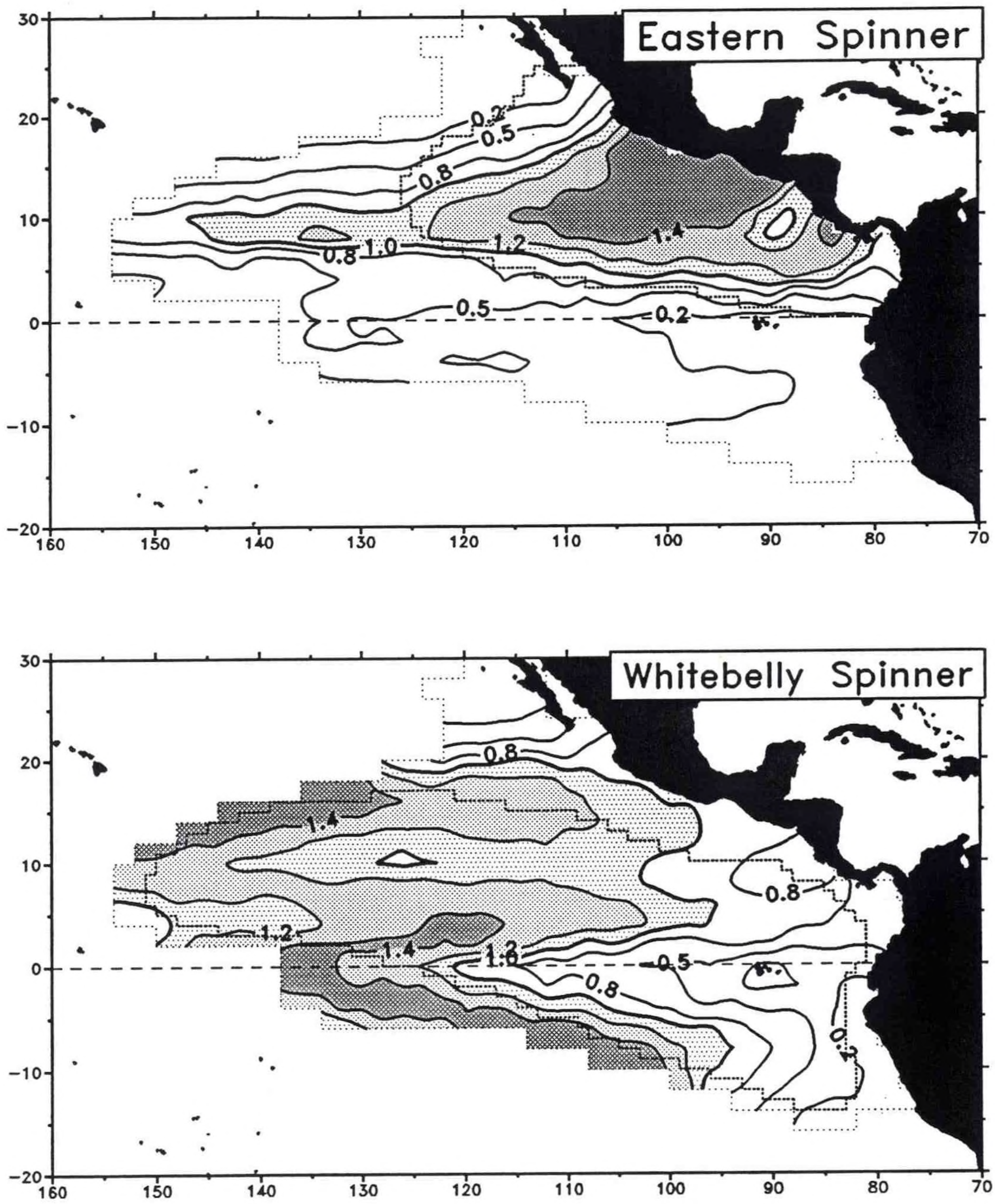


Figure 3b. Mean habitat quality (*H*) for eastern and whitebelly spinner dolphins, as in Fig. 3a.

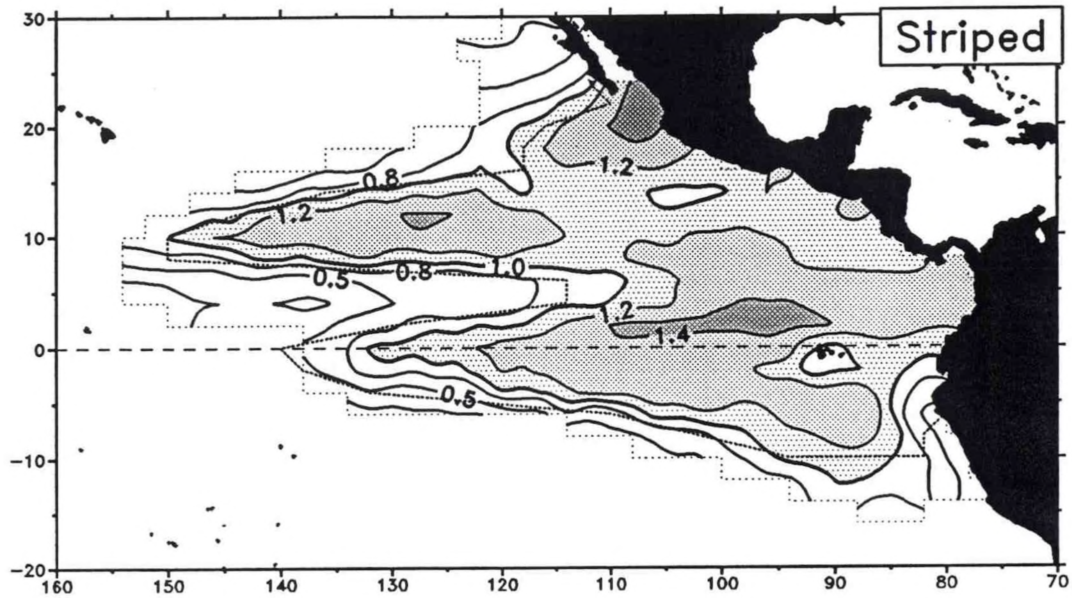


Figure 3c. Mean habitat quality (*H*) for striped dolphins, as in Fig. 3a. Heavy dashed line delimits SOPS population area from Au et al. (1979).

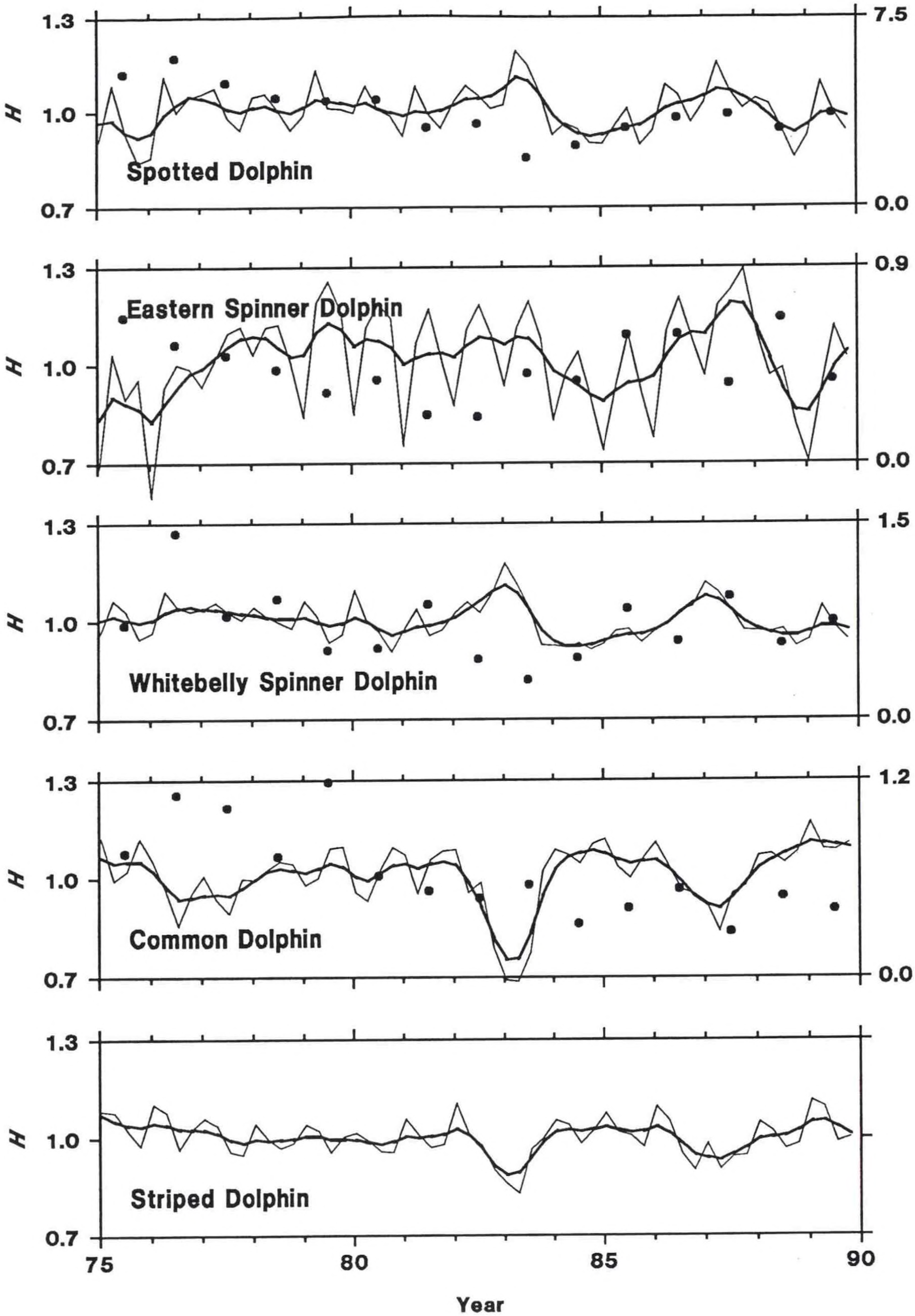
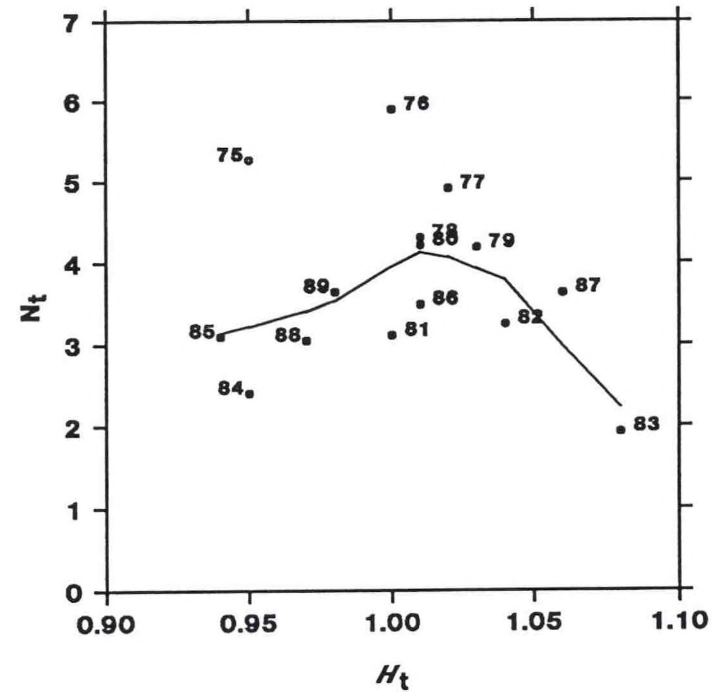


Figure 4. Mean SOPS area habitat quality (*H*) for five dolphin species: seasonal values (thin line) and smoothed values (five-season running mean, thick line). Dots are point estimates of species abundance ($N \times 10^{-6}$).

Spotted Dolphin



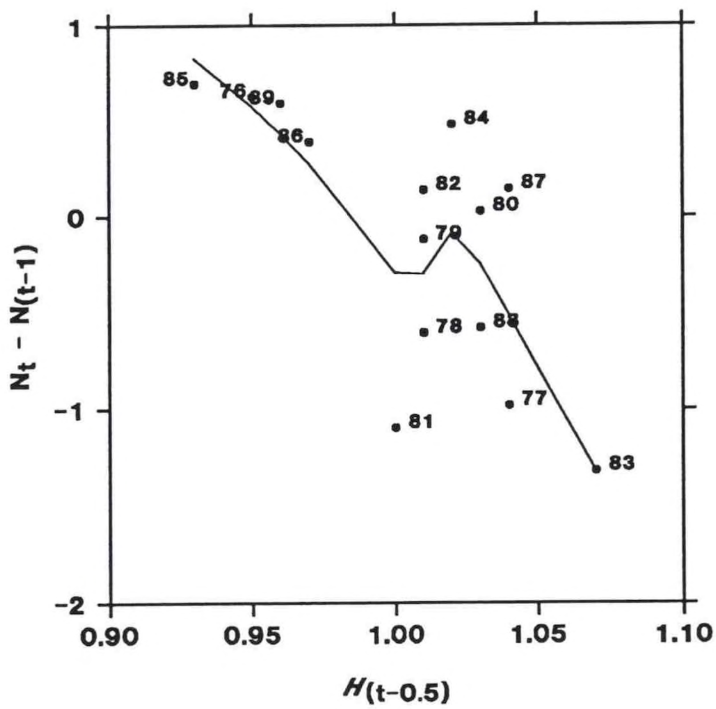


Figure 5a. Abundance-environment relationships for spotted dolphins in the MOPS area: (Top) Annual abundance estimates ($N_t \times 10^{-6}$) vs. annual mean habitat quality (H_t) calculated from CCA results. (Bottom) Interannual change in abundance estimates ($N_t - N_{t-1}$, $\times 10^{-6}$) vs. mean habitat quality from June of year **t-1** through May of year **t** ($H_{t-0.5}$). Thin lines connect lowess-smoothed values (Wilkinson 1990).

Eastern Spinner Dolphin

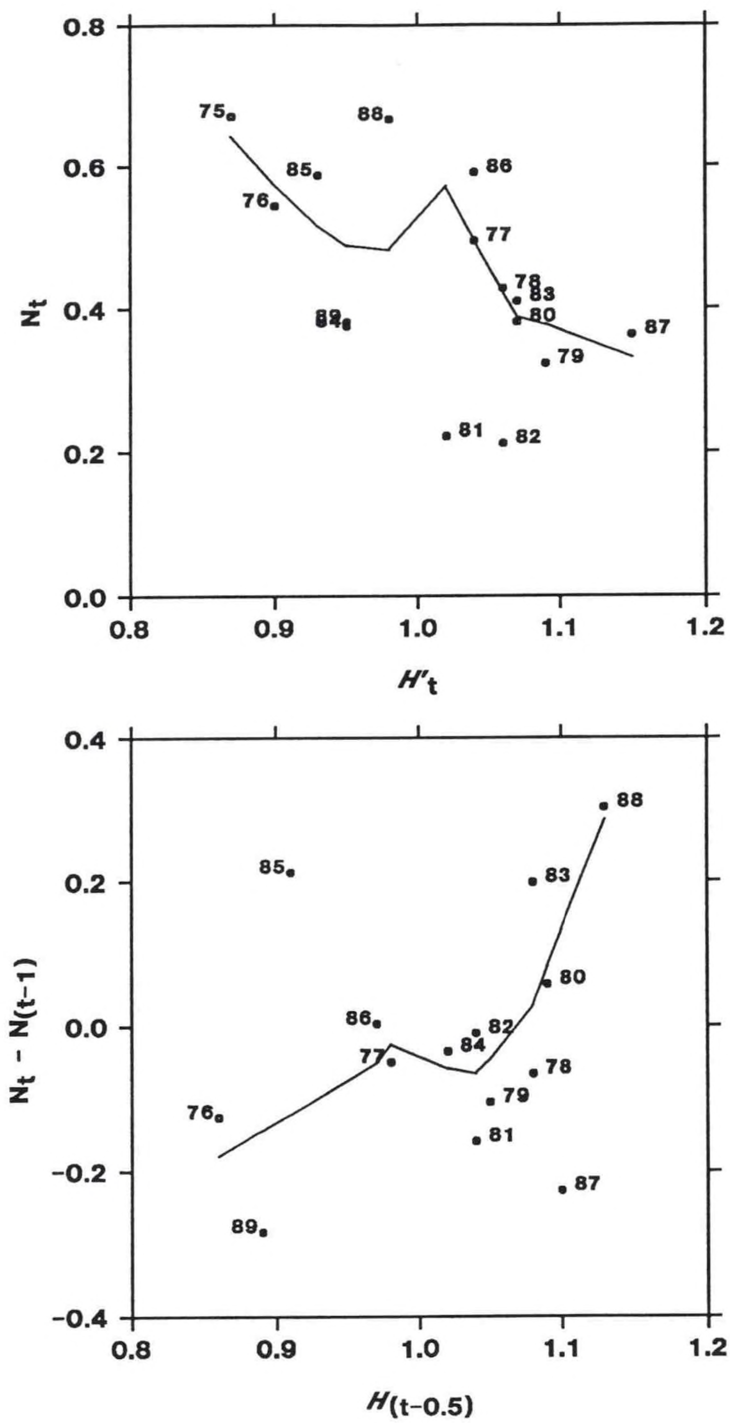


Figure 5b. Abundance-environment relationships for eastern spinner dolphins in the MOPS area, as in Fig. 5a.

Common Dolphin

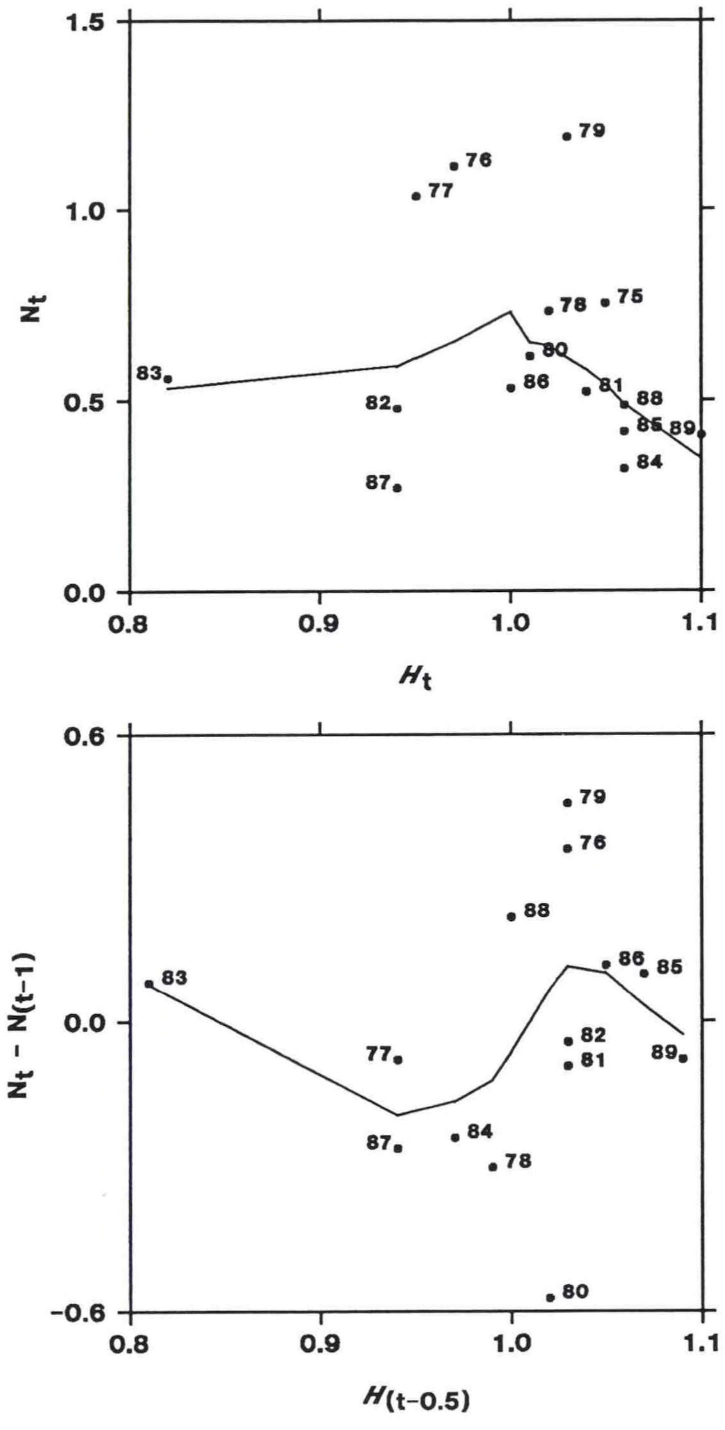


Figure 5c. Abundance-environment relationships for common dolphins in the MOPS area, as in Fig. 5a.

Whitebelly Spinner Dolphin

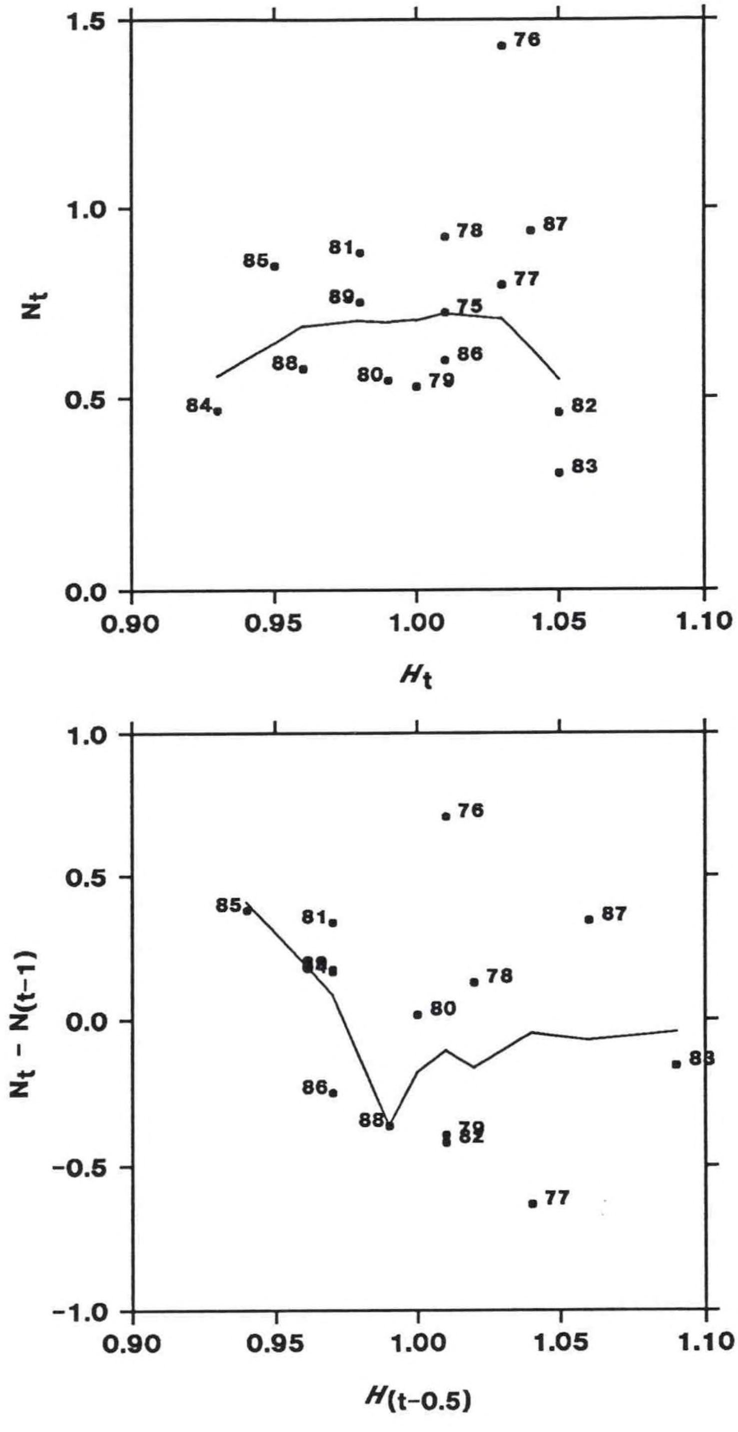


Figure 5d. Abundance-environment relationships for whitebelly spinner dolphins in the MOPS area, as in Fig. 5a.

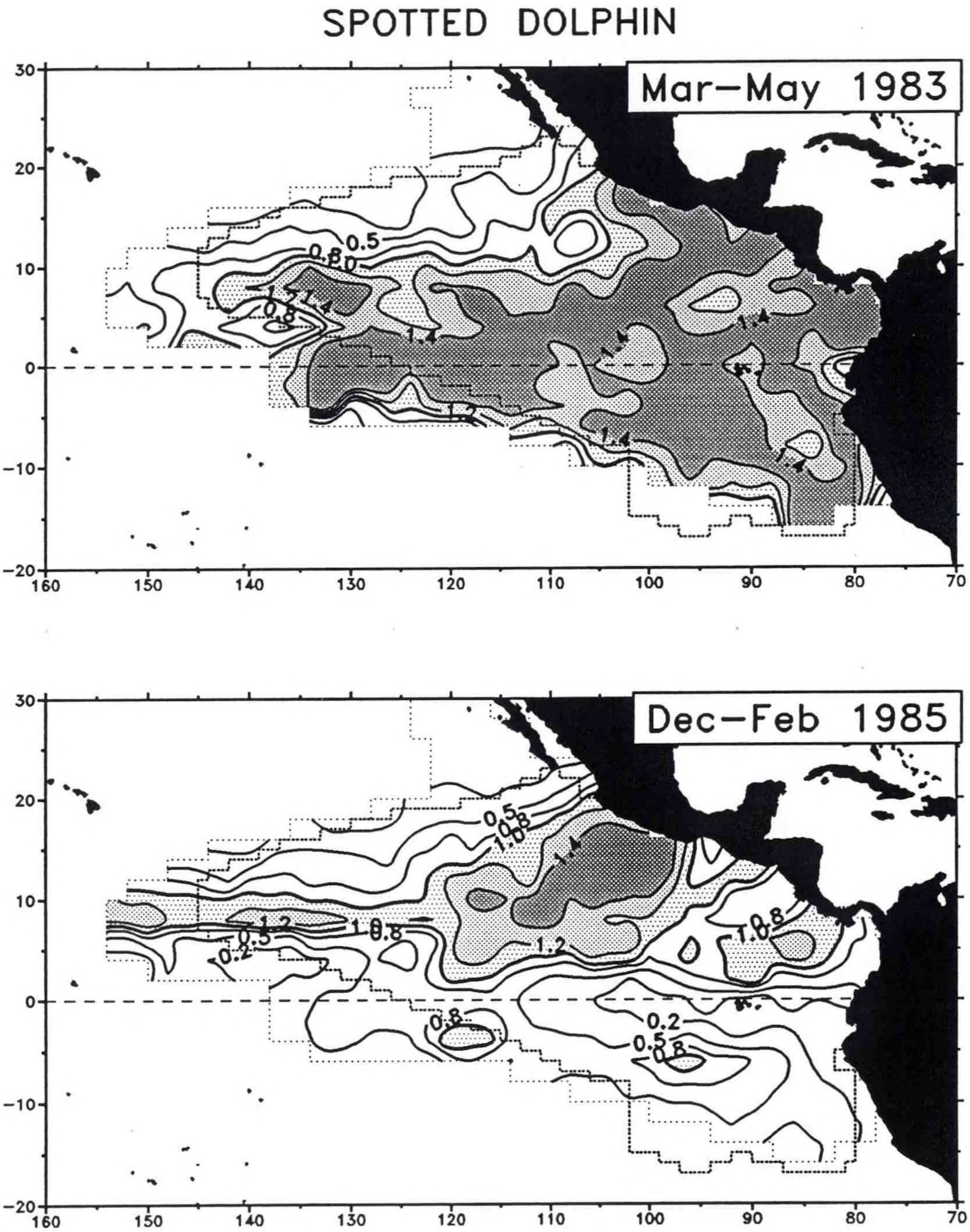


Figure 6a. Spotted dolphin habitat quality (*H*) calculated for extreme seasons: March-May 1983 and December 1984 - February 1985.

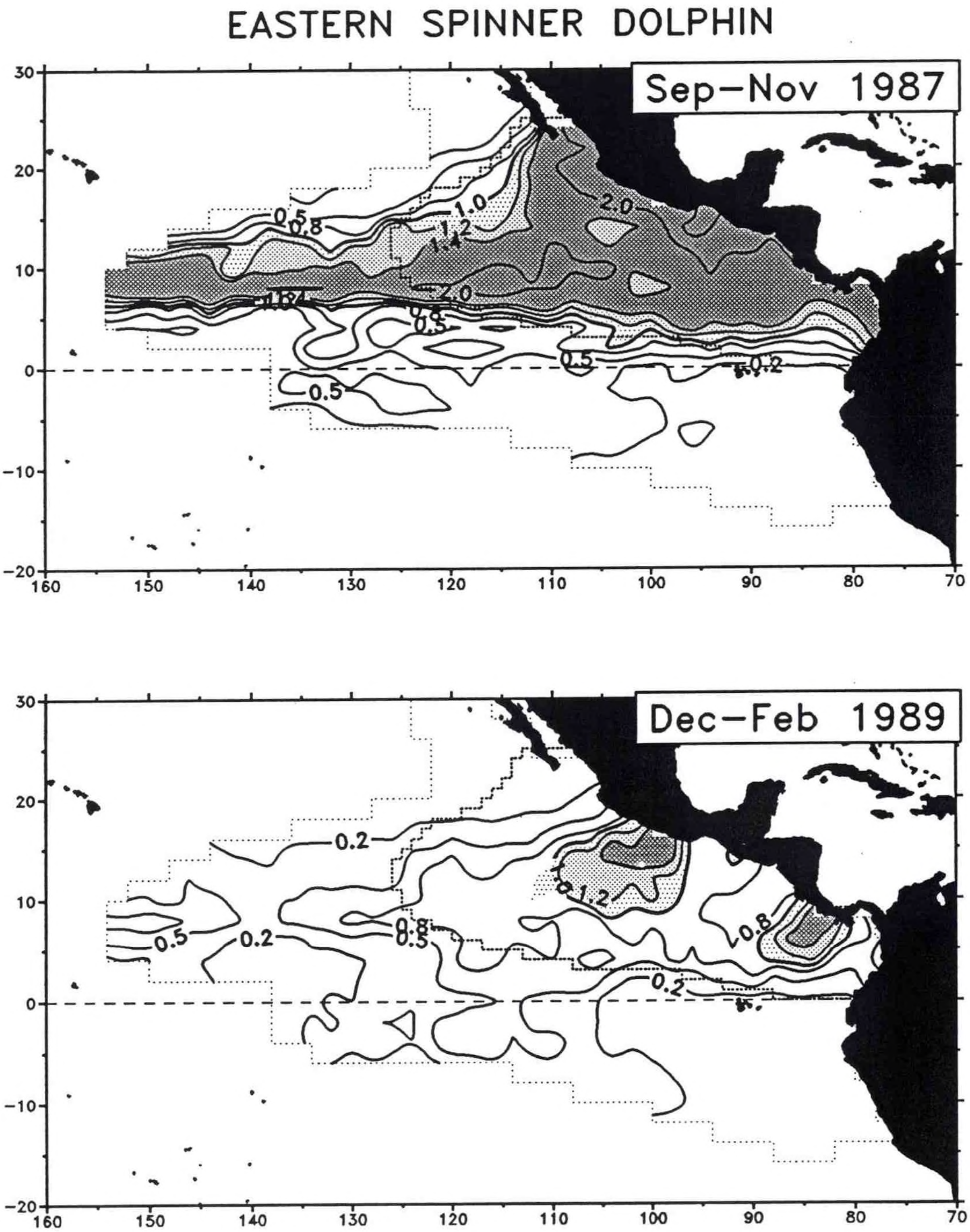


Figure 6b. Eastern spinner dolphin habitat quality (*H*) calculated for extreme seasons: September-November 1987 and December 1988 - February 1989.

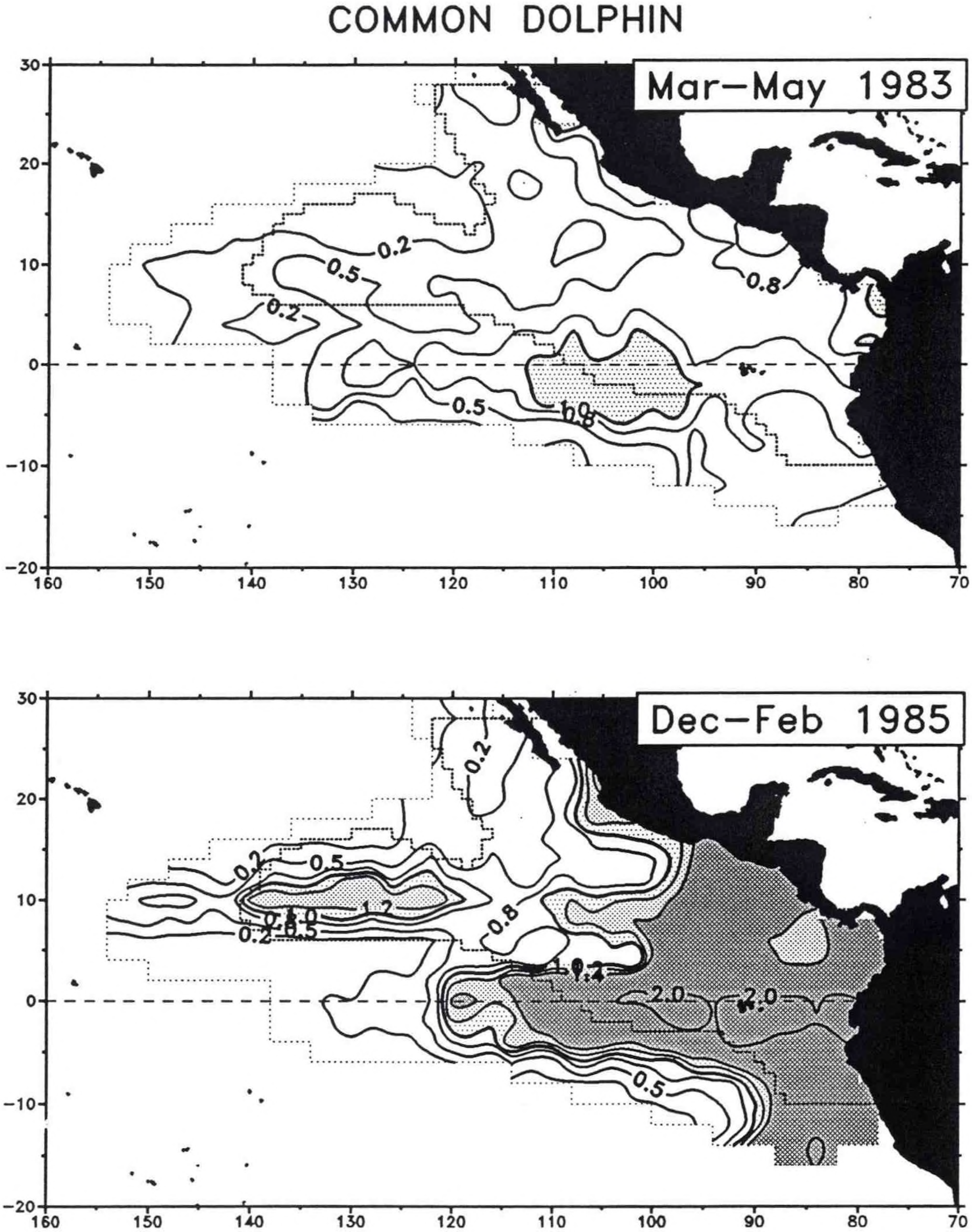


Figure 6c. Common dolphin habitat quality (*H*) calculated for extreme seasons: March-May 1983 and December 1984 - February 1985.