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Abstract

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Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks

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The spectral and temporal properties of echolocation clicks and the use of clicks for species classification are investigated for five species of free-ranging dolphins found offshore of southern California: short-beaked common (*Delphinus delphis*), long-beaked common (*D. capensis*), Risso's (*Grampus griseus*), Pacific white-sided (*Lagenorhynchus obliquidens*), and bottlenose (*Tursiops truncatus*) dolphins. Spectral properties are compared among the five species and unique spectral peak and notch patterns are described for two species. The spectral peak mean values from Pacific white-sided dolphin clicks are 22.2, 26.6, 33.7, and 37.3 kHz and from Risso's dolphins are 22.4, 25.5, 30.5, and 38.8 kHz. The spectral notch mean values from Pacific white-sided dolphin clicks are 19.0, 24.5, and 29.7 kHz and from Risso's dolphins are 19.6, 27.7, and 35.9 kHz. Analysis of variance analyses indicate that spectral peaks and notches within the frequency band 24–35 kHz are distinct between the two species and exhibit low variation within each species. *Post hoc* tests divide Pacific white-sided dolphin recordings into two distinct subsets containing different click types, which are hypothesized to represent the different populations that occur within the region. Bottlenose and common dolphin clicks do not show consistent patterns of spectral peaks or notches within the frequency band examined (1–100 kHz). © 2008 Acoustical Society of America.
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I. INTRODUCTION

Accurate classification of recorded calls to species is needed for passive acoustic monitoring of wild cetaceans. Passive acoustic monitoring is increasingly being used for towed hydrophone line transect surveys (Barlow and Taylor, 2005) and for remote, long-term monitoring of populations using autonomous instruments (Mellinger *et al.*, 2004; Sirovic *et al.*, 2004; Oleson *et al.*, 2007; Verfuss *et al.*, 2007). Recent technological advances allow long-term recordings to reach higher bandwidths (Wiggins and Hildebrand, 2007), which prompts research into use of higher frequency calls for species classification. Odontocete species regularly emit high frequency clicks and burst-pulsed calls, in addition to lower frequency whistles (Richardson *et al.*, 1995) and usage of these call types varies with behavioral state, geographic location, and geometric spacing of conspecifics (Jones and Sayigh, 2002; Lammers *et al.*, 2003; Nowacek, 2005). Advances have been made in classifying delphinid whistles to species (Oswald *et al.*, 2003; Oswald *et al.*, 2004), but little work has focused on classifying delphinid burst pulses and clicks to species (Roch *et al.*, 2007), particularly at frequencies greater than 24 kHz. While the clicks of porpoises, sperm whales, and beaked whales are

easily distinguishable from delphinid clicks based on time duration, interclick interval and peak frequency characteristics (Goold and Jones, 1995; Kamminga *et al.*, 1996; Madsen *et al.*, 2005; Zimmer *et al.*, 2005), delphinid clicks thus far have remained unclassifiable at the species level.

Most echolocation click research to date has focused on the performance of sonar systems and only a few studies look for species-specific characteristics. Kamminga *et al.* (1996) showed that four species of porpoises can be distinguished at the subfamily level by time duration and dominant frequency of their clicks. Akamatsu *et al.* (1998) compared peak frequency and duration characteristics of finless porpoise (*Neophocaena phocaenoides*), baiji (*Lipotes vexillifer*), and bottlenose dolphins (*Tursiops truncatus*) and found that finless porpoise can be distinguished from the two dolphins, but show overlap in duration and frequency between the two dolphin species with a tendency toward lower frequencies from baiji and higher frequencies from bottlenose dolphins. Nakamura and Akamatsu (2003) compared clicks from six captive odontocete species and found that harbor porpoise (*Phocoena phocoena*) and false killer whale (*Pseudorca crassidens*) clicks are distinguishable from four species of dolphin clicks based on click duration and peak frequency. The clicks of baiji, short-beaked common (*Delphinus delphis*), bottlenose, and Pacific white-sided (*Lagenorhynchus obliquidens*) dolphins cannot be distinguished from each

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TABLE I. Published click characteristics of common, Risso's, Pacific white-sided and bottlenose dolphins.

	<i>Delphinus spp.</i>	<i>G. griseus</i>	<i>L. obliquidens</i>	<i>T. truncatus</i>		
Recording situation	Captive ^{a,b}	Free ranging ^c	Captive ^{d,e}	Captive ^{a,f,g}	Free ranging ^h	Captive ^d
Duration (μ s)	50–250	30–75	40–100	25–100	10–20	50–80
ICI (ms)	...	...	...	...	0–400+	...
Source level (dB re 1 μ Pa at 1 m)	145–170	202–222	170–215	170	...	228
Peak frequencies (kHz)	23–67	40–110	30–105	50–80 100–120	40–140	110–130
–3 dB bandwidth (kHz)	...	15–85	30–84	9.5–36	...	...
–10 dB bandwidth (kHz)	...	20–125	100	...	...	...
Centroid frequencies (kHz)	...	60–90	50–80	...	...	...
rms bandwidth (kHz)	...	20–30	25	...	...	...

^aFish and Turl (1976).^bEvans (1973).^cMadsen *et al.* (2004).^dAu (1993).^ePhilips *et al.* (2003).^fFahner *et al.* (2003).^gNakamura and Akamatsu (2003).^hAkamatsu *et al.* (1998).

other with these characteristics (Nakamura and Akamatsu, 2003). To our knowledge, distinct species-specific differences have not been documented within delphinid clicks.

As a result of the focus on dolphin sonar system performance, most research effort has been directed at understanding clicks produced on axis. However, on-axis clicks may not accurately represent the full ensemble of clicks that will be acquired during passive acoustic monitoring of free-range odontocetes. Au *et al.* (1978) demonstrated significant distortion in the waveshape and spectral content of clicks as a function of beam angle. They established that off-axis click durations are longer, typically due to multipaths of the initial click pulse, and suggested that the multipaths are due to reflections within the head, from the external environment, or a combination of the two. Internal reflections are dependent on anatomy and may contain additional information; however, thus far, no study has examined whether the distorted spectra from off-axis clicks contain a species-specific signature. Clicks recorded during passive acoustic monitoring surveys will come from animals of unknown acoustic orientation; therefore, detailed spectral descriptions of all recorded clicks are needed for wild dolphins, regardless of orientation.

Five species of dolphins are commonly observed in the waters offshore of southern California. Short-beaked common and long-beaked common (*D. capensis*) dolphins are small dolphins (160–210 and 190–240 cm, respectively) (Heyning and Perrin, 1994), typically sighted in offshore tropical and temperate waters in schools of hundreds to thousands of individuals (Evans, 1974; Polacheck, 1987; Selzer and Payne, 1988; Gaskin, 1992; Gowans and Whitehead, 1995). They were only recently recognized as separate species (Heyning and Perrin, 1994). Pacific white-sided dolphins are small dolphins (230–250 cm) (Walker *et al.*, 1986) endemic to cold temperate North Pacific waters (Leatherwood *et al.*, 1984; Green *et al.*, 1992) and are observed in schools ranging between 10 and 1000 individuals (Leatherwood *et al.*, 1984). The offshore population of bottlenose dolphins consists of medium-sized dolphins (290–310 cm)

(Perrin and Reilly, 1984) that are typically sighted in medium-sized groups (1–30) (Shane, 1994) throughout tropical and temperate waters (Forney and Barlow, 1998). Risso's dolphins (*Grampus griseus*) are larger dolphins (400 cm) typically found in medium-sized groups (10–50) in tropical and temperate waters (Leatherwood *et al.*, 1980; Kruse *et al.*, 1999). Click feature measurements have been published for free-ranging Risso's and bottlenose dolphins and for captive Pacific white-sided, common, Risso's, and bottlenose dolphins (Table I).

This study describes echolocation clicks for five species of dolphins from the southern California region. This is the first study to describe recordings from free-ranging short-beaked common, long-beaked common, and Pacific white-sided dolphins. We describe the spectral content of echolocation clicks with emphasis on spectral peaks and notches and show that two species of dolphins have a unique peak and notch structure. We quantify the intra- and interspecific frequency variations of these peaks and establish that they represent invariant and distinctive features as required for species specificity (Emlen, 1972; Nelson, 1989), thereby demonstrating their value for species classification in passive acoustic monitoring. Finally, we examine long-term autonomous recordings and quantify the number of click bouts that exhibit the described spectral patterns.

II. MATERIALS AND METHODS

A. Study area and survey platforms

Our study area encompassed the region offshore of southern California extending from 32°42' N, 117°10' W along the coast to 35°5' N, 120°47' W and offshore to 29°51' N, 123°35' W and 33°23' N, 124°19' W (Fig. 1). Recordings were obtained in the southern California neritic and pelagic waters between November 2004 and April 2007 (Fig. 1). Data were analyzed from multiple surveys: California Cooperative of Oceanic Fisheries Investigations (CalCOFI) oceanographic surveys, San Clemente Island (SCI)

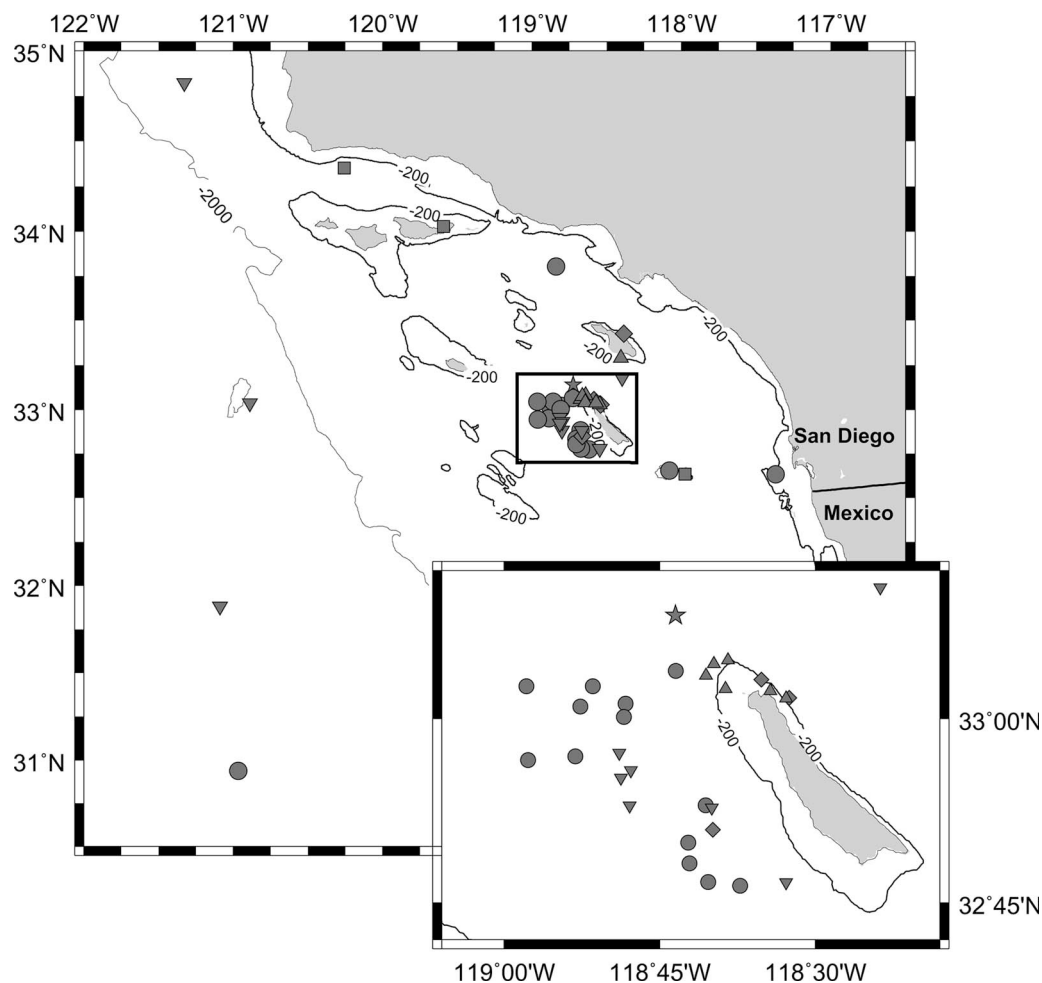


FIG. 1. Map of study area and delphinid recording locations offshore of southern California. Coastline, -200 m, and -2000 m bathymetric contours are represented. The inset expands the cluster of recordings from San Clemente Island area. This cluster represents increased effort, not increased presence. (★) FLIP location represents multiple sightings from Table V. (●) *Delphinus delphis*, (■) *Delphinus capensis*, (◆) *Grampus griseus*, (▼) *Lagenorhynchus obliquidens*, and (▲) *Tursiops truncatus*.

small boat operations, Scripps Institution of Oceanography (SIO) instrumentation servicing cruises on the R/V Robert Gordon Sproul, and Floating Instrument Platform (FLIP, Fisher and Spiess, 1963) moored observations (see Table II for survey and instrumentation details).

The durations of dolphin school recordings obtained from the four studies varied due to differing survey goals. Recording sessions from CalCOFI surveys were typically of

short duration because the ship could not deviate from its course to spend time with detected animals. During SIO instrumentation surveys and SCI field operations, the vessel was held stationary as animals swam past and recordings lasted as long as the animals stayed near the boat. Continuous acoustic recordings were obtained from the moored research platform FLIP, resulting in recording sessions that last the duration that animals were audible at the FLIP hydro-

TABLE II. Survey and instrumentation information. Frequency response and gain of the acoustic instruments are described in detail in the text. Surveys conducted from stationary or drifting platforms are indicated by a blank field under tow distance. Abbreviations: CC: CalCOFI oceanographic survey; SC: southern California instrumentation survey; SCI: San Clemente Island survey; FLIP: FLIP moored observations.

Cruise name	Dates	Platform	Tow distance (m)	Hydrophone depth (m)	Hydrophone type	Circuit board	A/D converter
CC0411	Nov 2004	RV Roger Revelle	...	30	ITC 1042	R100-A	MOTU 896HD
CC0604	Apr 2006	RV New Horizon	270	15–20	SRD HS150	R100-C	MOTU 896HD
SC03	May 2006	RV Gordon Sproul	270	15–20	SRD HS150	R100-C	MOTU 896HD
SCI0608	Aug 2006	RHIB	...	10–30	SRD HS150	R300	Fostex FR2
					ITC 1042	R300	Fostex FR2
FLIP0610	Oct 2006	FLIP	...	30	SRD HS150	R300	MOTU 896HD
SCI0704	Apr 2007	RHIB	...	10–30	SRD HS150	R300	Fostex FR2

phone array. Data from these recordings were used only when the animals were within 1 km of FLIP, as determined by visual observations.

Experienced marine mammal visual observers conducted the visual observation component of this project. Marine mammal detections and species identifications were made by a set number of observers using handheld binoculars, supplemented with 25× binoculars on some platforms. Sighting information included location of group or animal, initial distance and angle from research vessel, group size, presence of calves, and general behavior. Additionally, weather and sea state data were recorded to account for missed animals due to poor sighting conditions. Acoustic recordings from all surveys were used only for schools that were determined to be single species. If an additional species was detected within 3 km, or if this could not be determined due to sea states greater than Beaufort 3, the recording was not used. Following the whistle study of Oswald *et al.* (2003), we consider 3 km a conservative distance for species identification of clicks. Published studies indicate that whistles and echolocation clicks are not detectable beyond about 1 km (Richardson *et al.*, 1995; Philpott *et al.*, 2007), while we find that they are rarely audible beyond 3 km. Differentiation between short-beaked and long-beaked common dolphins is challenging in certain areas off California. In this study, data were used only when the visual identification by species was unambiguous.

B. Acoustic sensors and digitization

The acoustic sensors used on the different surveys consist of a variety of hydrophone and preamplifier configurations (Table II). Two types of omnidirectional, spherical hydrophones were used: ITC 1042 hydrophones (International Transducer Corp., Santa Barbara, CA) and HS150 hydrophones (Sonar Research & Development Ltd., Beverley, UK). These hydrophones exhibit a flat frequency response (± 3 dB) from 1 to 100 kHz. The hydrophones were connected to one of the three custom-built preamplifier and bandpass filter electronic circuit boards: R100A, R100C, and R300. The circuit boards were designed to whiten the ambient ocean noise, which results in a nonlinear frequency response that provides greater gain at higher frequencies where ambient noise levels are lower and sound attenuation is higher. The response increased 20 dB in amplitude from 10 kHz to peak at 90 kHz. The differing frequency responses of the various systems were compensated for during analysis using spectral means subtraction, as described in Sec. II C. Hydrophones and circuit boards were suspended in 2.5–5-cm-diam oil-filled hoses to provide good acoustic coupling to the seawater. Towed hydrophone arrays were weighted with 9 kg of lead wire wrapped around the tow cable ahead of the hydrophone assembly so that the array was towed between 10 and 30 m depth.

The analog signals from the hydrophone circuit boards were converted digitally and recorded with one of the two systems: MOTU audio interface and recording software or a Fostex recorder. The MOTU 896HD firewire audio interface (Mark of the Unicorn, Cambridge, MA) is capable of sam-

pling eight channels at 192 kHz with 24 bit samples. Each channel therefore had a Nyquist frequency of 96 kHz. Gain on the MOTU is adjustable with trim knob controllers and has a light emitting diode readout of the signal amplitude. The knobs were adjusted to minimize clipping while maximizing signal strength and settings were noted. Signals were recorded directly to a computer hard-disk drive using the sound analysis and recording software Ishmael (Mellinger, 2001), with the instrumentation gain set to either -80 or -100 dB. The MOTU/Ishmael system has a flat frequency response (± 0.05 dB) from 1 to 90 kHz. The Fostex FR2 field memory recorder (Fostex America, Foster Electric, USA, Inc., Gardena, CA) is capable of sampling two channels at 192 kHz with 24 bit samples, yielding a Nyquist frequency of 96 kHz, and has a flat frequency response (± 3 dB) from 20 to 80 kHz. Signals were recorded directly to an 8 Gbyte Compact Flash memory card (Transcend Information, Inc., Los Angeles, CA). The recordings were subsequently downloaded onto hard-disk drives.

C. Signal analysis

Signal analysis was performed with customized routines using MATLAB (Mathworks, Natick, MA). Start and end times of clicks were automatically located using a two-step approach. In the first step, a click detection algorithm was implemented on all acoustic data to locate potential click candidates in the frequency domain. Spectra were calculated on 5.33 ms of data using a 1024-point fast fourier transform (FFT) with 50% overlap and a Hann window. Spectral means subtraction was performed on each spectrum by subtracting the mean of the spectral vectors of the surrounding 3 s of data. Individual spectra were selected as click candidates if a minimum percentage of frequency bins exceeded a minimum threshold within the bandwidth range of interest. Values for minimum percentage, threshold, and bandwidth were set as 12.5%, 13 dB, and 15–95 kHz, respectively. For each click candidate, start and end times were defined to be 7.5 ms before and after the click to provide noise for use in spectral means subtraction in the second step. Overlapping click candidates were merged. These automatic detections were subsequently scanned by a trained analyst and false detections and burst-pulse calls were removed. Clicks within burst-pulse calls may exhibit species specificity; however, their analysis is beyond the scope of this study.

In the second step, a finer resolution click detection algorithm was implemented on the data output from step 1 to search for the start and end points of each click in the time domain. To remove any noise caused by water flow around the towed hydrophone, the signal was high-pass filtered with the -3 dB point at 3 kHz using a finite impulse response filter. The Teager energy operator (Kaiser, 1990), a measure which provides nearly instantaneous energy tracking by using only three consecutive signal samples, was calculated for the clicks obtained in the first step. The Teager energy operator of a discrete time signal is defined as

$$\Psi[x(n)] = x^2(n) - x(n+1)x(n-1), \quad (1)$$

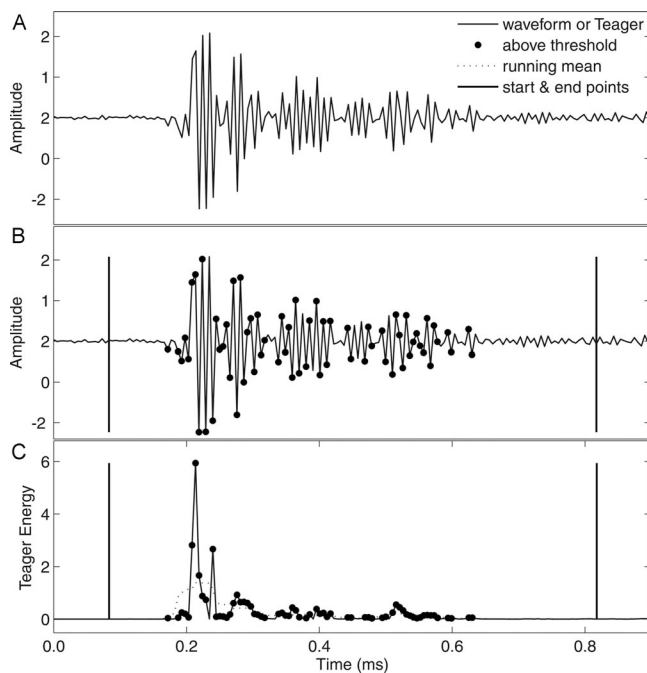


FIG. 2. Example wave form and corresponding Teager energy of a Pacific white-sided dolphin click. Note the reverberations present in the wave form. (A) The click wave form, (B) the click wave form with denotations of click end points and data points above Teager energy noise floor threshold, (C) the Teager energy of the wave form, the running mean of the Teager energy, denotations of click end points, and data points above the noise floor threshold. The solid vertical bars represent the time range of the complete click peak.

where n denotes the sample number. Kandia and Stylianou (2006) demonstrated the utility of the Teager energy operator for detection of sperm whale regular and creak clicks. For each click, a noise floor was defined at the 40th percentile of energy, based on empirical analysis of the data. All points whose Teager energy was 100 times greater than the noise floor were tagged and grouped as belonging to a single click if they were less than 500 μ s apart. If multiple clicks were present, clicks were ranked by maximum Teager energy and the strongest clicks were selected such that one click was chosen per 15 ms of data. Methods for determining the start and end points of symmetric on-axis click wave forms have been developed (Au, 1993); however, clicks obtained from random axis orientations may have distorted asymmetric wave forms, which include reverberations caused by reflections within the head, from the external environment or both (Au *et al.*, 1978) and therefore require a different analysis technique. To obtain the complete click including reverberations, a ten-point running mean of the Teager energy was calculated and start and end points were determined as the first and last points that were three times greater than the noise floor (Fig. 2).

The spectral characteristics of clicks were quantified for the 1.33 ms of data following the start of each click by calculating a 256-point FFT with a Hann window. Noise spectra were calculated from the remaining data, excluding extraneous clicks, and were averaged within each recording session. Spectral means subtraction was performed on each click spectrum by subtracting the mean noise spectrum from the corresponding recording session. Spectral magnitudes were

normalized between 0 and 1, and the means and standard deviations of the normalized click spectra were calculated for each species. Additionally, concatenated spectrograms were created of all clicks analyzed for each species.

D. Click selection and statistical analysis

The original data lack the independence required for statistical analysis because click trains represent multiple clicks from one individual and an individual likely produces multiple click trains over a recording session. To reduce over-representation of an individual's clicks, a two stage process was established to limit the number of clicks and click trains analyzed from each recording session. Click trains were randomly selected from each recording session until either all trains were selected or the number of selected trains was twice the estimated group size. From each sampled click train, a single click was selected at random. Click trains were defined as clicks that were separated by less than 0.5 s; overlapping click trains, although likely to have been produced by different individuals, were grouped as a single train to reduce over-representation.

To examine spectral peak and notch structure and its variability in the frequency domain across clicks, the frequency value of consistent spectral peaks and notches was quantified for clicks of each species. Variability exists among clicks, such that the frequency value of the peaks and notches may vary, the peak or notch may not exist at all, and additional peaks and notches that are not consistent across clicks may exist. To establish and select consistent peaks and notches for statistical analysis while avoiding circularity, clicks were randomly divided into two equal groups, denoted the training and testing data. Training data clicks were used to establish expected frequency ranges for consistent peaks and notches across clicks of a given species. Testing data clicks were used for statistical comparison among species, such that the values of peaks and notches found within the established frequency ranges were quantified and analyzed. Details of the analysis of clicks from the training and testing data follow.

Using the training data clicks to establish the frequency ranges of consistent peaks and notches, a first-order regression-based peak and notch selection algorithm was implemented on the normalized click spectra. To avoid selecting minor peaks or notches, the spectra were smoothed using a five-point window and a threshold was set such that the peak or notch was required to deviate by at least 2 dB. The number of peaks and notches selected per click spectra varied, ranging between 0 and 20 and averaging 8. A histogram was generated from the frequency values of all selected peaks or notches combined across all training data clicks for each species. The histogram was calculated such that each bin was 750 Hz wide to correspond with the FFT frequency resolution. Peak and notch selections existed at all frequencies resulting in "background noise" in the histogram from which consistent peak and notch frequencies needed to be distinguished. To estimate the background noise in each histogram, peaks and notches from each click were randomly reassigned frequency values and a noise estimate histogram was generated. Actual counts of frequency values were com-

pared to estimated background noise counts using a one-tailed z -test (α 0.5) (Zar, 1999) for each species. Peak and notch frequency values were established as consistent if they met three conditions: (1) actual counts were significantly greater than estimated noise counts, (2) the frequency value was greater than 15 kHz (to exclude overlapping whistles), and (3) at least one adjacent frequency value was also consistent. A set of Gaussians is fitted to the peak and notch histograms of each species using Gaussian mixture models (Huang *et al.*, 2001). Frequency means and ranges are established from the mean (μ) and standard deviations ($\pm\sigma$) of the dominant Gaussian for each consistent peak or notch.

Using testing data clicks to examine differences in frequency values of peaks and notches among species, peaks and notches were statistically analyzed if they fell within the frequency ranges established using the training data. Peaks and notches from testing data clicks were selected using the peak/notch selection algorithm described above. If any peaks or notches fell within the established frequency ranges, a minimum of one per range was chosen, keeping the peak or notch that was nearest to the mean established from the training data. To examine variability in peak and notch frequencies among and within species, nested analyses of variance (ANOVAs) (Zar, 1999) were performed in SPSS 11.5 (SPSS, Inc., Chicago, IL). For each consistent peak and notch, a nested ANOVA was calculated examining the main effect of species differences in frequency value and the interaction effect of recording session nested within species. Recording session was included to test for effects due to the use of different recording systems among surveys. The nested ANOVA can only determine that differences exist among multiple comparisons; therefore, *post hoc* tests were performed to determine which, if any, recording sessions were different using Tukey's method (Zar, 1999).

To determine whether the spectral properties of clicks could be useful for classifying data from passive acoustic autonomous seafloor recorders, in this case of high-frequency acoustic recording packages (HARPs) (Wiggins and Hildebrand, 2007), 1300 days of data were reviewed for the presence of unique spectral patterns. Long-term spectral averages (LTSAs) (Wiggins and Hildebrand, 2007) were created using the Welch algorithm (Welch, 1967) by coherently averaging 4000 spectra created from 1000-point, 0% overlapped, Hann-windowed data. The resulting LTSAs had resolutions of 100 Hz and 5 s in the frequency and time domains, respectively. LTSAs were manually inspected for click bouts, and bouts containing unique spectral patterns were noted. The total counts of each type of click bout are presented.

III. RESULTS

The total numbers of recording sessions per species included in this analysis were 4 from long-beaked common dolphins, 17 from short-beaked common dolphins, 6 from Risso's dolphins, 22 from Pacific white-sided dolphins, and 7 from bottlenose dolphins (Table III). School sizes ranged between 1 and 500 animals, with the two common dolphin species typically occurring in larger schools than the other three species (Table III). The total number of clicks recorded

per session ranged from 3 to almost 11 000 while the total number of click trains ranged between 1 and 582 (Table III). Example wave forms and spectra are presented for each of the five species described (Fig. 3).

Concatenated spectrograms of the individual clicks and mean spectral plots of clicks for the five dolphin species investigated reveal consistent spectral characteristics for both Pacific white-sided and Risso's dolphins (Fig. 4). Alternating high and low amplitude bands are evident at certain frequencies across the clicks of these two species. These frequency bands appear consistent for the majority of clicks across multiple recording sessions as well as for various hydrophone array configurations. No such pattern is evident for long-beaked common, short-beaked common, or bottlenose dolphins (Fig. 4).

The existence of consistent spectral peaks and notches in only two of the species is reinforced when comparing actual counts of selected peaks or notches to estimated noise counts for frequency values in the training data. Only Pacific white-sided dolphin and Risso's dolphin clicks exhibit frequency values at which the counts of peaks and notches are greater than expected by chance. The remaining three species' clicks did not have significantly greater counts of peaks or notches at any frequency values (Fig. 5). Univariate Gaussian mixture models fit to the peak histograms and notch histograms (Fig. 6) from Pacific white-sided dolphin and Risso's dolphin training data clicks provide estimates of means and standard deviations for each of the consistent peaks and notches (Table IV).

For the two species with spectral peaks and notches, calculations of the percentage of clicks from the testing data that have peaks or notches within the expected frequency ranges show that these consistent peaks and notches occur in the majority of recorded clicks, with percentages ranging between 44% and 89% (Table IV). The two species share similar spectral peaks at mean frequencies 22.2 and 37.3 kHz for Pacific white-sided dolphins and 22.4 and 38.8 kHz for Risso's dolphins. Risso's dolphins have two additional spectral peaks at mean frequencies 25.5 and 30.5 kHz and spectral notches at 19.6, 27.7, and 35.9 kHz, while Pacific white-sided dolphin clicks have spectral peaks at mean frequencies 26.6 and 33.7 kHz, and notches at 19.0, 24.5, and 29.7 kHz (Table IV).

Nested ANOVA analyses indicate that some click variables are distinct both between species and among subsets of recording sessions. Five of the seven frequency peaks and notches are significantly different between Pacific white-sided and Risso's dolphins (Table V). Only the lowest frequency peak and notch are not significantly different. In addition to the distinct separation of five peaks and notches between the two species, four of those five peaks show significant differences among recording sessions within species. Tukey's *post hoc* tests of recording session differences indicate that (1) there are no significant differences among recording sessions of Risso's dolphins and (2) there are significant differences between two distinct subsets of recording sessions of Pacific white-sided dolphins (Table VI). Click peaks and notches are consistent across recording sessions within these Pacific white-sided dolphin subsets, but distinct

TABLE III. Summary of data included in click analysis. Survey platform, numbers of clicks, click trains, and school sizes are presented for each recording of each species. Each recording session represents a new school of dolphins. Abbreviations: Dc: *Delphinus capensis*; Dd: *Delphinus delphis*; Gg: *Grampus griseus*; Lo: *Lagenorhynchus obliquidens*; Tt: *Tursiops truncatus*. CC: CalCOFI oceanographic survey; SC: southern California instrumentation survey; SCI: San Clemente Island survey; FLIP: FLIP moored observations.

Species	Recording	Survey	Clicks	Click trains	School size
Dc	1	CC0411	1256	155	500
	2	CC0604	531	22	45
	3	SC03	2377	198	200
	4	FLIP0610	2338	145	45
Dd	1	CC0604	8	3	60
	2	SC03	192	52	18
	3	SC03	164	30	250
	4	SCI0608	1030	12	230
	5	SCI0608	245	12	175
	6	SCI0608	166	30	225
	7	SCI0608	636	113	320
	8	SCI0608	9	1	180
	9	SCI0608	804	75	430
	10	SCI0608	763	38	30
	11	SCI0608	475	25	85
	12	SCI0608	624	58	7
	13	SCI0608	2269	70	190
	14	SCI0608	455	13	370
	15	SCI0608	3884	48	20
	16	SCI0608	730	26	35
	17	SCI0608	361	25	320
Gg	1	SCI0608	6	1	1
	2	SCI0608	286	24	12
	3	SCI0608	190	45	12
	4	SCI0608	1194	105	40
	5	SCI0608	3	1	18
	6	FLIP0610	2564	446	10
Lo	1	CC0604	224	3	7
	2	CC0604	508	66	4
	3	CC0604	4	1	5
	4	SC03	24	2	10
	5	SCI0608	5961	262	12
	6	SCI0704	333	92	13
	7	SCI0704	1317	145	8
	8	SCI0704	95	26	13
	9	SCI0704	127	18	22
	10	SCI0704	197	17	25
	11	FLIP0610	1409	208	25
	12	FLIP0610	5503	543	50
	13	FLIP0610	3463	358	15
	14	FLIP0610	4761	431	20
	15	FLIP0610	7085	582	20
	16	FLIP0610	916	111	17
	17	FLIP0610	171	56	50
	18	FLIP0610	2688	491	25
	19	FLIP0610	2099	364	40
	20	FLIP0610	10843	544	75
	21	FLIP0610	1075	110	8
	22	FLIP0610	1226	235	50
Tt	1	CC0604	897	32	30
	2	SC03	707	66	30
	3	SCI0608	501	24	18
	4	SCI0608	5959	386	60
	5	SCI0608	687	59	6
	6	SCI0704	120	16	30
	7	SCI0704	205	18	50

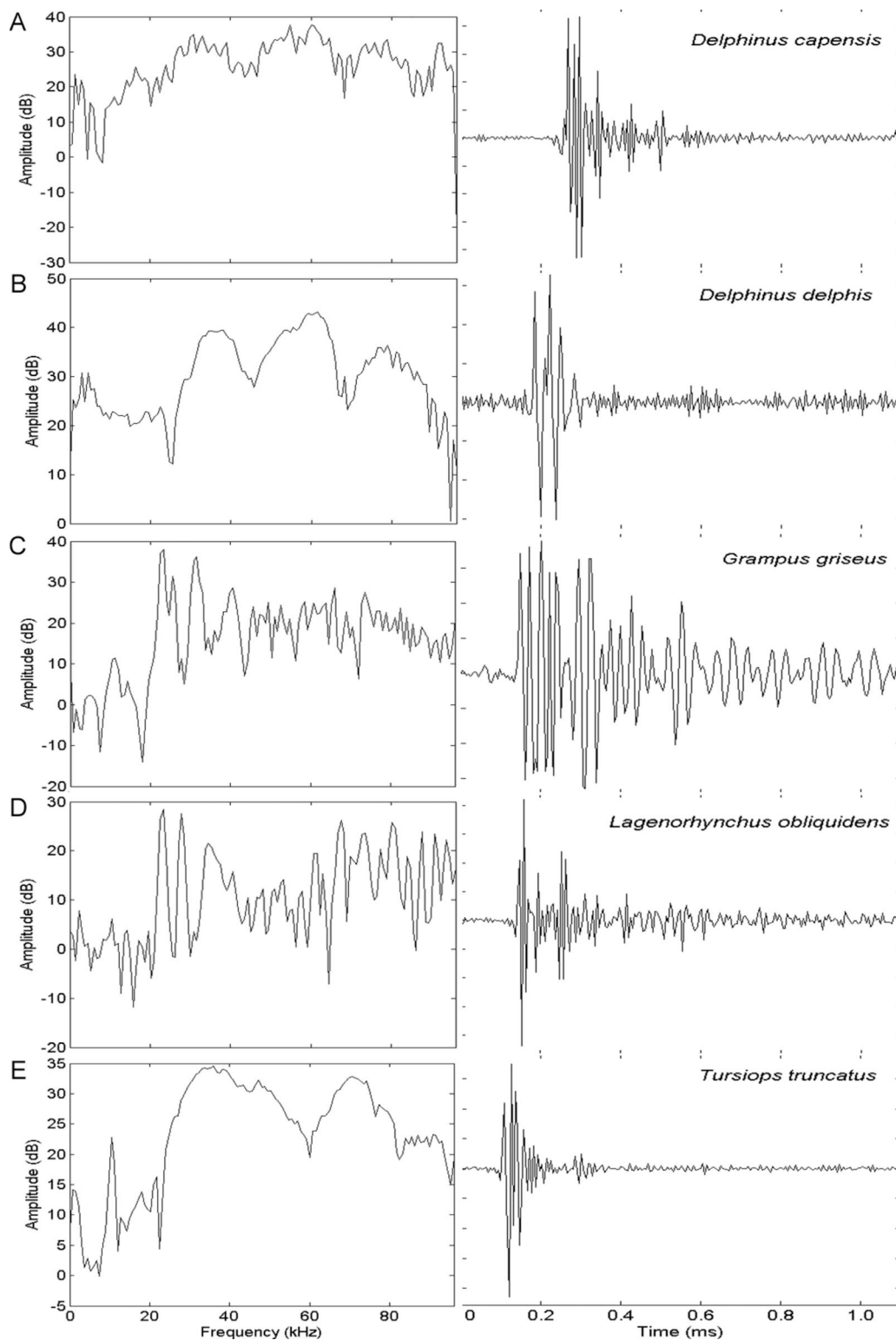


FIG. 3. Example spectra and wave forms for (A) *Delphinus capensis*, (B) *Delphinus delphis*, (C) *Grampus griseus*, (D) *Lagenorhynchus obliquidens*, and (E) *Tursiops truncatus*.

between them. Additionally, these subsets do not differ among surveys with different recording gears: subset A includes sessions from all surveys, including FLIP, while subset B only includes sessions from the FLIP survey. Only two sessions, both recorded from the FLIP survey, are not significantly different from either subset.

To obtain a clearer picture of what these two subsets of Pacific white-sided dolphin recording sessions represent,

concatenated spectrograms and mean click spectra are generated for each subset (Fig. 7). The two subsets appear to represent two distinct click types in which the spectral peaks are more closely spaced in subset B. In particular, the second peak is strikingly different with mean values of 26.1 ± 0.7 and 27.4 ± 0.5 kHz for subsets A and B, respectively. Additionally, inspection of the spectra from the two recording sessions that were not significantly different from either sub-

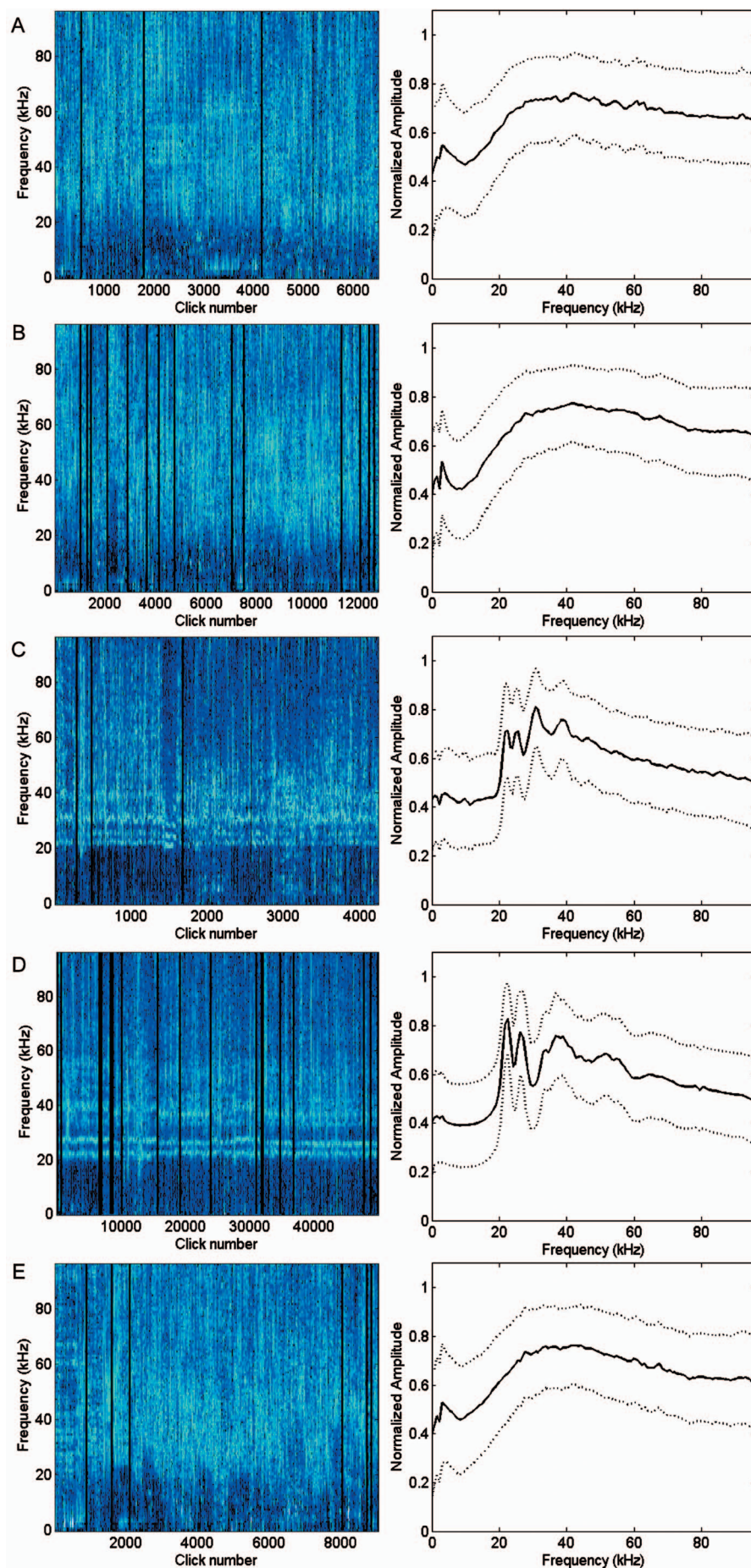


FIG. 4. Concatenated spectrograms and mean normalized spectral plots of complete clicks for each species using Hann-windowed data. (A) *Delphinus delphis*, (B) *Delphinus capensis*, (C) *Grampus griseus*, (D) *Lagenorhynchus obliquidens*, and (E) *Tursiops truncatus*. For the concatenated spectrograms, frequency is plotted on the y-axis. Click number, rather than continuous time, is plotted on the x-axis. The magnitude of the frequency content is represented by the color such that lighter blue represents greater magnitude. Alternating high and low amplitude spectral bands are apparent between 20 and 40 kHz for *G. griseus* and *L. obliquidens*. The black vertical lines in spectrograms represent breaks between recording sessions. For the mean normalized spectral plots, the solid line represents the mean and the dotted lines represent one standard deviation.

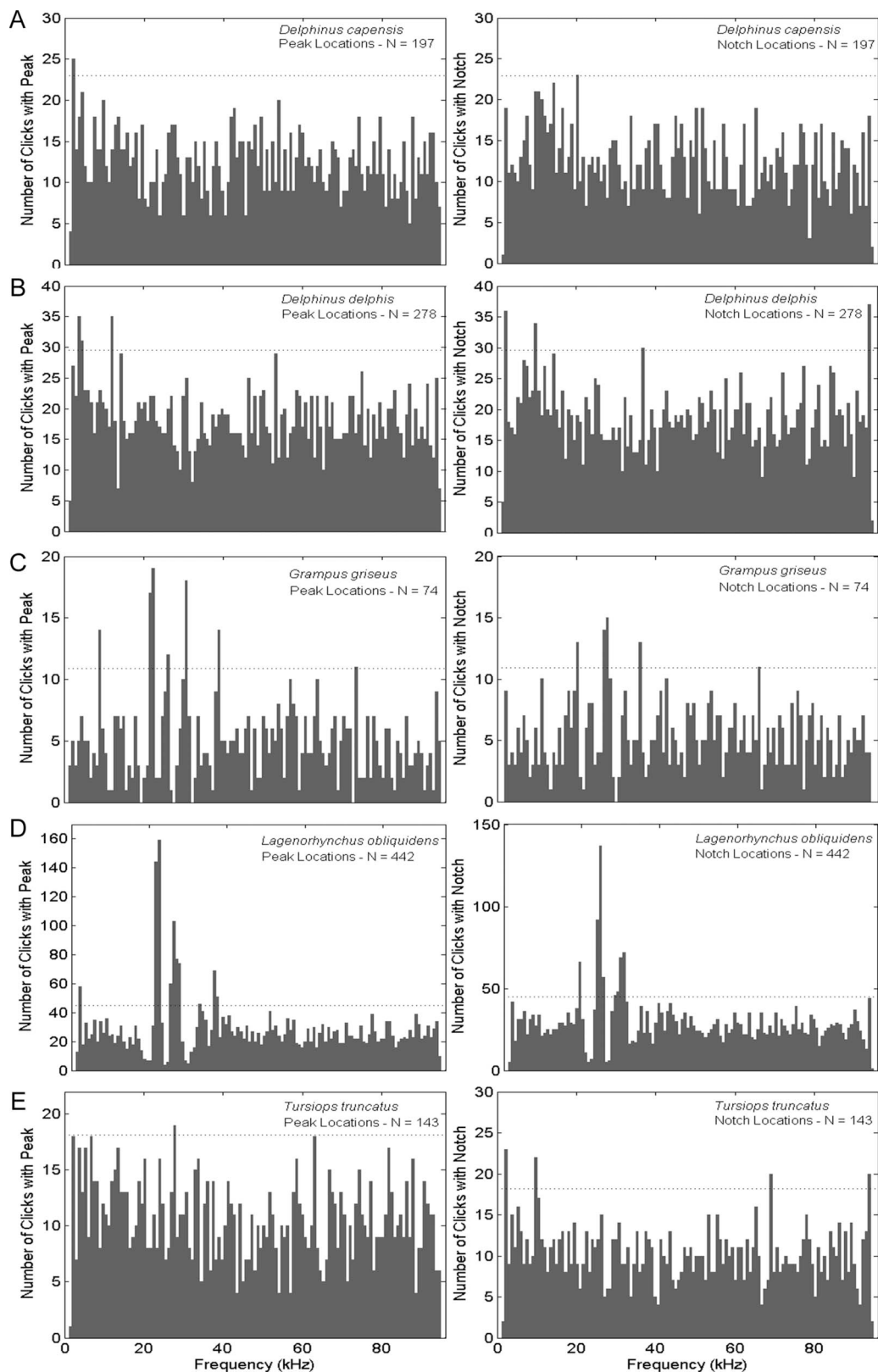


FIG. 5. Histograms of frequency values of spectral peaks (left) and notches (right) for (A) *Delphinus delphis*, (B) *Delphinus capensis*, (C) *Grampus griseus*, (D) *Lagenorhynchus obliquidens*, and (E) *Tursiops truncatus*. Each bar represents one 750 Hz FFT frequency bin. The dotted lines represent the upper boundary of estimated histogram background noise as determined from peak and notch randomization procedure. Groups of bars that rise above this line represent consistent peaks or notches that are analyzed further.

set reveals the presence of both click types rather than clicks with peaks evenly distributed between these frequencies.

Finally, an analysis of 1300 days of long-term autonomous recorder data reveals the presence of hundreds of click

bouts containing the three unique spectral peak and notch patterns found for Risso's and Pacific white-sided dolphins (Fig. 8), as well as click bouts that do not contain consistent spectral peaks and notches and are therefore unidentifiable.

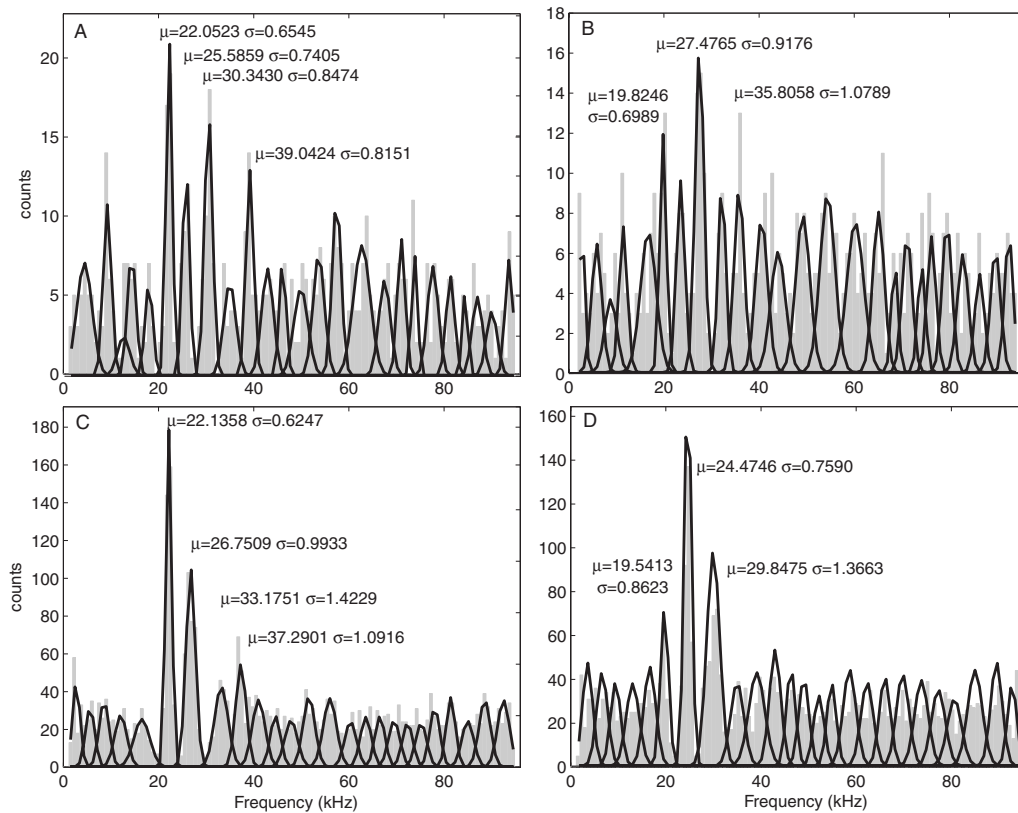


FIG. 6. Univariate Gaussian mixture model fits to spectral peak and notch histograms from the training data set for *Grampus griseus* (A) peaks and (B) notches and *Lagenorhynchus obliquidens* (C) peaks and (D) notches. Each bar represents one 750 Hz FFT frequency bin. Mean and standard deviation estimates of the Gaussian distributions of consistent peaks and notches are noted.

The total numbers of click bouts containing clicks with patterns similar to these four click types are 1769 Risso's dolphin type click bouts, 473 Pacific white-sided dolphin type A click bouts, 337 Pacific white-sided dolphin type B click bouts, and 9210 unidentifiable dolphin click bouts. Click bouts containing mixed Risso's and Pacific white-sided clicks or mixed Pacific white-sided type A and type B clicks occurred in only 14 and 10 bouts, respectively.

IV. DISCUSSION

We provide evidence for three levels of classification of echolocation clicks from wild dolphins within the southern California Bight. The first level represents the presence or

absence of click spectral structure: A consistent and distinctive spectral peak and notch pattern is evident for clicks from Risso's and Pacific white-sided dolphins, while no such pattern occurs in the clicks of bottlenose and common dolphins. Therefore, clicks can be separated into two groups—those that contain consistent peaks and notches and those that do not. If this spectral structure is present, bottlenose and common dolphins can be ruled out, and the clicks can be further analyzed at the second level for species-specific differences. However, if this spectral structure is absent, no further distinction can be made until a method to classify these types of clicks is developed.

TABLE IV. Means and standard deviations of local peaks and notches for *Grampus griseus* (Gg) and *Lagenorhynchus obliquidens* (Lo). Means from training data were estimated from Gaussian mixture models. Means from testing data represent frequency variability of the value of the peak or notch used for ANOVA analyses. The percentage of total clicks containing a peak in this frequency range is also presented.

Training data	Peak No.								Notch No.							
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Gg	22.1 (0.7)	25.6 (0.7)	30.3 (0.8)	39.0 (0.8)	19.8 (0.7)	27.5 (0.9)	35.8 (1.1)		19.8 (0.7)	27.5 (0.9)	35.8 (1.1)		19.8 (0.7)	27.5 (0.9)	35.8 (1.1)	
Lo	22.1 (0.6)	26.7 (1.0)	33.1 (1.4)	37.3 (1.1)	19.5 (0.9)	24.5 (0.8)	29.8 (1.4)		19.5 (0.9)	24.5 (0.8)	29.8 (1.4)		19.5 (0.9)	24.5 (0.8)	29.8 (1.4)	
Test data																
Gg	22.4 (0.8)	25.5 (1.0)	30.5 (1.1)	38.8 (1.1)	19.6 (1.3)	27.7 (1.1)	35.9 (1.2)		19.6 (1.3)	27.7 (1.1)	35.9 (1.2)		19.6 (1.3)	27.7 (1.1)	35.9 (1.2)	
% N	72	45	82	48	46	64	54		46	64	54		46	64	54	
Lo	22.2 (0.6)	26.6 (0.9)	33.7 (1.4)	37.3 (1.4)	19.0 (1.1)	24.5 (0.9)	29.7 (1.4)		19.0 (1.1)	24.5 (0.9)	29.7 (1.4)		19.0 (1.1)	24.5 (0.9)	29.7 (1.4)	
% N	89	76	45	62	51	75	66		51	75	66		51	75	66	

TABLE V. Results of nested ANOVAs testing for variation in peaks and notches between species (Pacific white-sided and Risso's dolphins) and among recordings nested within species. Significant differences are indicated by asterisks. ANOVA tests among multiple comparisons, such as among recording sessions, only indicate that significant differences exist, not which sessions were different. See text on *post hoc* analysis for further detail of the differences between recording sessions.

	Species		Recording(Species)	
	F	p	F	p
Peak 1	0.12	0.733	1.84	0.011
Peak 2	11.44	0.002 *	13.58	0.000 *
Peak 3	92.63	0.000 *	1.42	0.106
Peak 4	12.21	0.001 *	2.09	0.003 *
Notch 1	2.46	0.121	1.27	0.189
Notch 2	139.19	0.000 *	3.45	0.000 *
Notch 3	187.99	0.000 *	3.35	0.000 *

At the second level of classification, Risso's dolphins and Pacific white-sided dolphins can be distinguished to species by the frequency values of the spectral peaks and notches. In combination with the other peaks and notches, the presence of a peak or notch at 30 kHz is particularly useful for distinguishing between these two species, as 82% of Risso's dolphin clicks contain a peak while 75% of Pacific white-sided dolphin clicks contain a notch at this frequency. On the other hand, 72% and 89% of clicks from Risso's and Pacific white-sided dolphins, respectively, contain a peak at 22 kHz, which is not significantly different between the two species. If recordings are limited to a 24 kHz Nyquist frequency, as is common to digital audio tape (DAT) recorders and other systems, then only the distinction that one of these

TABLE VI. Subsets of Pacific white-sided dolphin recording sessions as distinguished by Tukey's *post hoc* analyses. While different surveys used different recording gears, subset A includes recordings from all surveys, including FLIP, while subset B only includes recording sessions from FLIP. This suggests that differences between recording sessions are not a function of the differing gear used but rather represent two distinct click types produced consistently within a dolphin school as described in the text. Sessions 13 and 21, also recorded from FLIP, were not significantly different from either subset and visual inspection suggests that they contain both click types.

Subset A		Subset B	
Recording session	Survey	Recording session	Survey
1	CC0604	11	FLIP
2	CC0604	14	FLIP
4	SC03	17	FLIP
5	SCI0608	18	FLIP
6	SCI0704	19	FLIP
7	SCI0704	20	FLIP
8	SCI0704	22	FLIP
9	SCI0704		
10	SCI0704		
12	FLIP		
15	FLIP		
16	FLIP		

two species was present could be made, but not which one. A minimum Nyquist frequency of 40 kHz is needed to classify these clicks at the species level.

Finally, at the third level of classification, Pacific white-sided dolphin clicks can be separated into two click types, types A and B. In combination with the other peaks and notches, a frequency peak near either 26.1 or 27.4 kHz can distinguish these clicks as type B or A, respectively. The significance of these two click types remains unknown, but in 90% of the recording sessions in this study, one click type is prevalent per school of dolphins. Numerous interschool differences could account for the differential use of the two click types including group size, composition, behavior, or prey type. Another hypothesis is that the two click types are population specific, as supported by the presence of two genetically and morphologically distinct populations of Pacific white-sided dolphins whose distributions overlap in the southern California region (Walker *et al.*, 1986; Lux *et al.*, 1997). These populations are morphologically distinguishable by cranial measurements, in particular, the condylobasal length (Walker *et al.*, 1986), a characteristic which could influence the sound production pathway. These populations are not visually distinguishable (Walker *et al.*, 1986), making visual field identification impossible. The ability to distinguish them acoustically could offer insight into differences in the biology of each population. Recordings from other areas in the Eastern North Pacific and field studies incorporating acoustic recording with biopsy sampling could provide additional information for this question.

While several biases in data collection or analysis could account for the differentiation found among these clicks, the authors consider species and subspecies specificities to be the most viable explanation.

Potential bias 1. The use of different recording systems among the surveys included in this analysis could result in differences between click recordings. However, the consistency of the spectral characteristics within a species across surveys compared to the differences between species recorded within the same surveys strengthens the argument that these differences are related to the animals rather the recording instrumentation.

Potential bias 2. The recording of clicks from animals with unknown acoustic orientations could result in aspect-dependent spectral features due to the narrow echolocation beamwidth of dolphins [e.g., Madsen *et al.* (2004) described increasing spectral notch structure with increasing degree off axis within the clicks of Risso's dolphins]. The authors assume that clicks recorded in the wild come from random acoustic orientations since dolphins are highly mobile and typically acoustically scan their environment. Therefore, while aspect-dependent variability may exist, it does not significantly affect the frequency value of spectral peaks and notches, as the variation within species is less than that between species. It is possible that the 15%–20% of clicks that do not contain some of the peaks or notches may be due to aspect dependency. For this reason, it is important that a species or subspecies classification be based on multiple clicks.

Potential bias 3. The use of a relatively long 1.33 ms

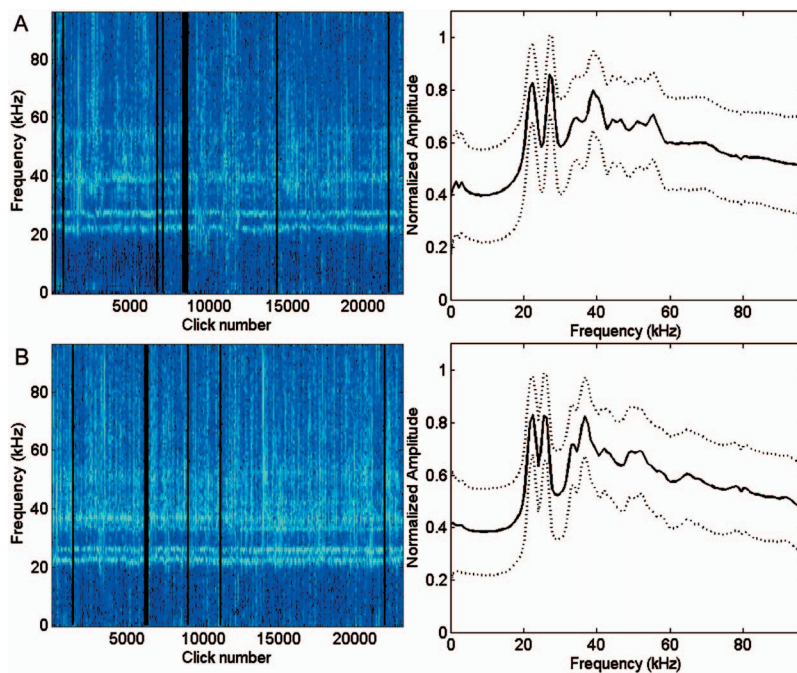


FIG. 7. Concatenated spectrograms and mean spectral plots for (A) subset A and (B) subset B of *Lagenorhynchus obliquidens* clicks using Hann-windowed data. The black vertical lines in spectrograms represent breaks between recording sessions. The consistencies of spectral peaks and notches across recording sessions of each subset are apparent, as are the distinctions between clicks from the two subsets, revealing that *Lagenorhynchus obliquidens* produce two distinct click types.

analysis window to calculate spectra could result in the inclusion of surface reflections whose effect on the spectra remains unknown and could account for the variability between the two click types recorded from Pacific white-sided dolphins. To investigate this potential bias, a subset of Pacific white-sided dolphin clicks from the FLIP survey was examined for the presence of reflections. Of 100 randomly chosen clicks, which included both click types, only 9 clicks exhibited an obvious surface reflection, while 62 clicks clearly did not have a surface reflection within the analysis window. All of these clicks contained spectral peak and notch patterns whose frequency values were not affected by the presence or absence of a reflection. Additionally, it is unlikely that surface reflections from thousands of clicks would exhibit the consistent timing necessary to result in the consistent spec-

tral pattern that we demonstrate, given the expected variability in dolphin depths and distances.

Potential bias 4. The lack of recordings from other species that occur within the southern California Bight means clicks from autonomous recordings cannot definitively be classified to species. While those species, which have been recorded and have different spectral patterns can be excluded it is possible that an unrecorded species could have the exact same spectral pattern. While this will remain unknown until all species have been recorded during concurrent acoustic and visual surveys within this area, the probability of correctly classifying the clicks to species remains high as unrecorded species have low occurrence within this region.

An intriguing question remains as to why some species of dolphins' clicks exhibit these species-specific spectral

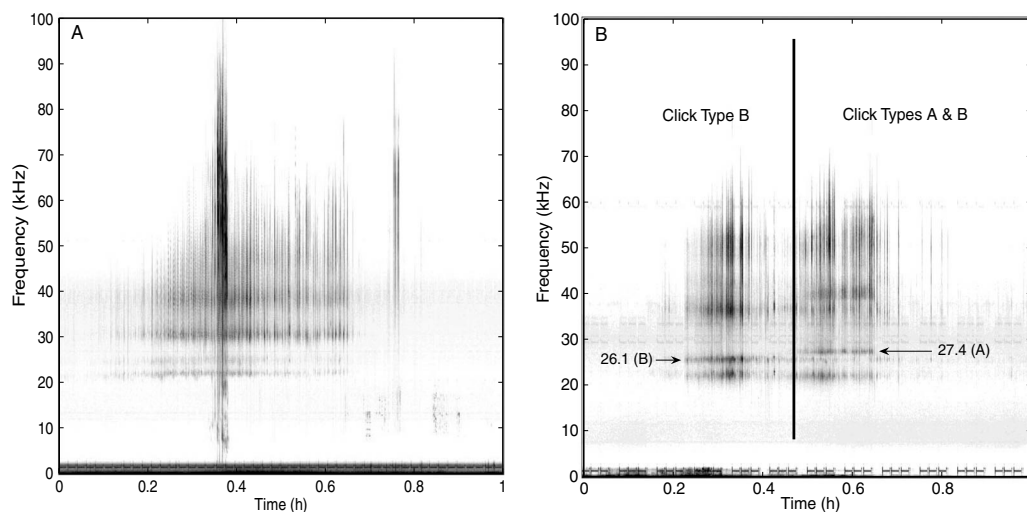


FIG. 8. LTSAs of data from seafloor HARP instruments show echolocation bouts, which exhibit similar spectral peak/notch structure to that found for (A) *Grampus griseus* and (B) *Lagenorhynchus obliquidens*, including both the 26.1 kHz (type B) and 27.4 kHz (type A) clicks. The first half hour has a group producing clicks of type B. In the second half hour, a group begins producing type A clicks while the type B clicks fade out. The vertical line represents the beginning of type A clicks. Each plot shows 1 h of data.

characteristics while others do not. Researchers in the bioacoustics field have speculated many causes for interspecific call differences including phylogenetic constraints, size constraints, morphological differences, prey preferences, niche partitioning, and environmental variability including noise conditions (Dudok van Heel, 1981; Kamminga *et al.*, 1986; Wang *et al.*, 1995; Madsen *et al.*, 2004; Oswald, 2006;). We hypothesize that the morphology of the sound production pathways, including the monkey lip dorsal bursae (MLDB) complex, the melon, airspaces, and skull, is likely to be important. There are several morphological similarities in the sound production pathways between Pacific white-sided and Risso's dolphins that are different from bottlenose and common dolphins. Pacific white-sided and Risso's dolphins have only slightly asymmetrical skulls and MLDB complexes, while bottlenose and common dolphins show strong asymmetry (Cranford *et al.*, 1996). Perhaps the minor asymmetry results in sound production organs producing clicks of similar central frequencies and amplitudes, which result in the interference pattern observed, similar to beat structure for tonal sounds made up of two similar frequencies. Additionally, Pacific white-sided and Risso's dolphins lack an extended rostrum or beak, and both species exhibit protrusions into the melon: A vertical cleft is present on the anterior surface of Risso's dolphin melon (White and Norris, 1978); and a vertical connective tissue column is present in the central melon of Pacific white-sided dolphins (Cranford *et al.*, 1996). These differences could also affect the sound production pathway potentially resulting in the click patterns described in this study.

Autonomous acoustic recording packages have been deployed throughout this region and LTSAs (Wiggins and Hildebrand, 2007) of the data reveal echolocation click bouts exhibiting the same peak and notch structure as described above (Fig. 8). The abundance of occurrences of click bouts from autonomous recordings, which contain the spectral patterns described in this study, demonstrates that these spectral patterns are distinct, repeatable, and useful for classifying Risso's and Pacific white-sided dolphin clicks during passive acoustic monitoring surveys. Ideally, an automated classification scheme could be developed to objectively classify the large amounts of acoustic data collected by these seafloor instruments. Oswald *et al.* (2007) have shown that automated methods can be used to classify dolphin whistles and a classifier, which used all call types produced by dolphins in the 5–24 kHz range, suggests that clicks can be used to automatically classify dolphin recordings (Roch *et al.*, 2007). Additionally, computer learning techniques such as those used by Roch *et al.* (2007) are often able to classify patterns that humans cannot easily distinguish such as those found in bottlenose and common dolphin clicks. Automated classifiers that incorporate higher bandwidth click data (up to 100 kHz) are currently being developed by the authors. The ability to identify dolphin clicks to species will allow researchers to investigate long-term trends in their abundance and distribution patterns using passive acoustic monitoring.

V. CONCLUSIONS

This study is the first to describe a technique for classifying dolphin recordings to species using unique spectral features of echolocation clicks. Clicks can be distinguished at three levels: (1) at the supraspecies level by the presence (Pacific white-sided and Risso's dolphins) or absence (bottlenose and common dolphins) of spectral peaks and notches, (2) at the species level by the frequency values of peaks and notches in Pacific white-sided and Risso's dolphin clicks, and (3) at the subspecies level into two distinct click types of Pacific white-sided dolphins. By extending passive acoustic monitoring equipment to higher frequencies (up to 100 kHz), some delphinid clicks can now be classified to species, which may enable researchers using passive acoustics to study their temporal and spatial distribution and abundance patterns. As the technology behind passive acoustic monitoring continues to advance, even higher frequency sampling could provide recordings from less abundant and elusive species to determine if similar spectral patterns exist. Automatic classification algorithms could be developed to objectively distinguish delphinid species by their clicks, which, along with higher sample rate recordings, may allow all delphinid species to be classified by their clicks. Furthermore, the inclusion of all call types produced by delphinids could potentially strengthen the ability to classify periods of calling to species.

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