Title

An examination of the whistling behavior of small odontocetes and the development of methods for species identification of delphinid whistles

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An Examination of the Whistling Behavior of Small Odontocetes and the Development of Methods for Species Identification of Delphinid Whistles

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in
Oceanography
by
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2006

"If you have the desire for knowledge and the power to
give it physical expression, go out and explore"

Apsley Cherry-Garrard

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ABSTRACT OF THE DISSERTATION

An Examination of the Whistling Behavior of Small Odontocetes and the Development of Methods for Species Identification of Delphinid Whistles

by

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Doctor of Philosophy in Oceanography

University of California, San Diego, 2006

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The distribution and abundance of cetaceans has traditionally been investigated by conducting visual line transect surveys; however, visual detection and identification can be challenging because cetaceans spend much of their lives completely under water. Some limitations inherent to visual surveys may be overcome with the addition of passive acoustic methods. Many cetaceans produce distinctive sounds that propagate well under water and therefore acoustic techniques can be used to detect and identify them. This dissertation advances the role of passive acoustic monitoring during visual surveys by examining the whistling behavior of small odontocetes and developing methods for species identification of delphinid whistles. Chapter one provides an introduction to sounds produced by delphinids and prior research on acoustic species identification. Chapter two examines whistle use by small odontocetes. Data collected during visual and acoustic line transect surveys suggests that species in the eastern tropical Pacific Ocean whistle more frequently than species in the eastern North Pacific Ocean. Seven hypotheses to explain this trend are discussed. Group size seems to be an important factor in the whistling behavior of delphinid schools, however the distribution of whistling vs. non-whistling species does not likely have a simple univariate explanation. Whistling behavior and whistle structure are still largely unknown for many species. This is illustrated in chapter three, which provides the first description of the whistles of a seldom-recorded delphinid species in the Pacific Ocean, *Lagenodelphis hosei.* The remaining chapters focus on acoustic species identification. In chapter four, discriminant function analysis (DFA) and classification and regression tree analysis (CART) are used to classify the whistles of nine delphinid species. Overall, 41% of whistles were correctly classified using DFA and 51% were correctly classified using CART. Chapter five evaluates the effect of recording and analysis bandwidth on acoustic species identification. For the four species included in this chapter, an upper bandwidth limit of at least 24 kHz is necessary for an accurate representation of fundamental whistle contours. Finally, chapter six incorporates the classification techniques and bandwidth extensions discussed in chapters four and five into a software tool for real-time acoustic species identification in the field.

CHAPTER I

Introduction

All cetacean species found in United States waters are protected by the Marine Mammal Protection Act of 1972 (MMPA). Under the 1994 amendments to this Act, the National Marine Fisheries Service (NMFS) is required to prepare regular stock assessments for all cetacean stocks in waters under U.S. jurisdiction. The distribution and abundance of marine mammals has traditionally been investigated by conducting visual line transect surveys (Holt 1987, Jaramillo-Legorreta *et al.* 1999, Carretta *et al.* 2000, Buckland *et al.* 2001, Hammond *et al.* 2002). Visual detection and identification of marine mammals can be challenging during these surveys as cetaceans spend much of their lives completely under water. In addition, shipboard surveys are both labor intensive and costly and are therefore limited in the time span and geographic area that they can cover. Because many cetaceans produce characteristic calls that propagate well under water (Richardson *et al.* 1995), acoustic techniques are becoming increasingly valuable in overcoming the limitations of visual line transect surveys. The addition of towed hydrophone arrays to visual surveys makes it possible to detect groups of animals that would otherwise have been missed by visual observers, and the use of seafloor mounted acoustic recorders makes it possible to collect long time series of data that would be difficult to obtain using shipboard surveys alone.

The addition of acoustic techniques has been shown to increase the rate and distance of cetacean detections during visual surveys (Thomas *et al.* 1986, Leaper *et al.* 1992, Clark and Fristrup 1997, Gordon *et al.* 2000). However, the ability to identify cetaceans to species using acoustic methods varies. Many large whales produce stereotyped calls that are easily recognized (ex. fin whales, *Balaenoptera physalus,* Thompson *et al.* 1992; sperm whales, *Physeter macrocephalus,* Goold and Jones 1995; blue whales, *Balaenoptera musculus,* Stafford *et al.* 1999). In contrast, the vocalizations produced by many delphinid species are highly variable and difficult to classify (Matthews *et al.* 1999, Rendell *et al.* 1999). One of the main objectives of this dissertation research was to explore the potential for acoustic identification of delphinid species based on their whistles.

Sounds produced by delphinids

Odontocete cetaceans produce a considerable diversity of acoustic signals, which have generally been placed into three structural categories. These categories include the short broadband clicks used in echolocation, and two types of sounds thought to play a role in social interactions: rapid repetition rate click trains known as ‘burst pulses’, and tonal, frequency modulated whistles (Popper 1980, Herzing 2000).

Echolocation Clicks

Early biosonar research began with bats. Harvard University researchers Pierce, Griffin, and Galambos were the first to experimentally demonstrate that bats could emit and hear ultrasonic pulses (Pierce and Griffin 1938, Galambos 1941, Galambos 1942). Subsequent research on the emission and detection of ultrasonic sounds by bats paved the way for the discovery of echolocation in dolphins. The first evidence that dolphins may use echolocation to detect objects came from experiments showing that dolphins could hear ultrasonic frequencies up to 50 kHz. Based on these results, it was postulated that dolphins might also produce ultrasonic sounds and use them as sonar signals (Kellogg and Kohler 1952). Evidence supporting the use of echolocation signals by dolphins was gathered throughout the 1950's (Schevill and Lawrence 1953, Wood 1953, Kellogg 1958), and the first definitive evidence of echolocation in dolphins was provided by Norris *et al.* (1961).

Echolocation click trains are composed of forward projecting sound pulses of high intensity and frequency. Each click resembles an exponentially damped sinusoidal wave with a rapid rise time and short duration, ranging from approximately 50 µs (ex. bottlenose dolphins, *Tursiops truncatus*, Au 1980) to 400 µs (ex. Dall's porpoises, *Phocoenoides dalli*, Hatakeyama and Soeda 1990). Peak frequencies of echolocation clicks vary from tens of kilohertz (ex. rough-toothed dolphins, *Steno bredanensis,* Norris and Evans 1966) to well over 100 kHz (ex. bottlenose dolphins, Au 1980; Dall's porpoises, Hatakeyama and Soeda 1990). The number of clicks in a click train and the time interval between clicks can vary from click train to click train (Richardson *et al.* 1995). The inter-click interval does not always remain constant within a click train; it often varies in a cyclical manner, increasing to a peak and then decreasing again (Au 1993). In most cases a dolphin sends out a click, receives the echo, and waits for a specific lag time before sending out another click. It is assumed that dolphins use this lag time to process incoming echoes (Au 1993). Bottlenose dolphin sonar signals tend to have lag times ranging from 19 ms to 45 ms, except at very small target ranges of less than approximately 0.4 m, where lag time can decrease to 2.5 ms (Evans and Powell 1967, Morozov *et al.* 1972, Au 1993).

Dolphins can vary the amplitude of their sonar signals over a large dynamic range. For example, bottlenose dolphins have been found to produce click trains with peak-to-peak source levels as low as 150-160 dB re 1μPa and as high as 230 dB re 1μPa (Evans 1973, Au *et al.* 1974). A typical click train begins with low amplitude clicks, rises to a peak, and decreases at the end, but many variations in this pattern do occur. The amplitude of sonar signals is influenced by factors such as background noise, target strength, and target range (Au 1993).

Delphinid sonar signals are emitted in a narrow, forward projecting beam (Evans *et al.* 1964, Norris and Evans 1966, Au *et al.* 1986). Au *et al.* (1986) determined that, in captive bottlenose dolphins, echolocation signals are projected at an angle of 5° above the dolphin's head in the vertical plane and directly ahead of the dolphin parallel to its longitudinal axis in the horizontal plane. The 3 dB beamwidth of these sonar signals is approximately 10° in both the vertical and horizontal planes (Au 1980). Waveforms and frequency spectra of clicks detected at hydrophones placed in vertical and horizontal arrays around the head of a bottlenose dolphin show that signals become progressively more distorted as the angle to the hydrophone departs from the major beam axis (Au 1980). This positional bias makes echolocation clicks recorded from free-ranging animals difficult to study.

Burst Pulses

Burst pulse signals are broadband click trains with very short inter-click intervals. The individual clicks within burst pulses resemble echolocation clicks both in bandwidth and waveform, suggesting that they may also be highly directional signals (Lammers *et al*. 2003). Some of these vocalizations have little or no energy in the human audible range and burst pulses with energy extending up to 130 kHz have been recorded from free ranging spinner dolphins (*Stenella longirostris*) and spotted dolphins (*S. frontalis*, Lammers *et al.* 2003). In contrast to echolocation click trains, burst pulses take on a tonal quality to human ears because the clicks are repeated at such high rates that the rate itself, rather than the individual clicks, is audible (Watkins 1967, Herzing 2000). These sounds have been qualitatively described in the literature using terms such as buzzes, creaks, pops, and squeals (Caldwell and Caldwell 1967, dos Santos *et al*. 1990, Herzing 1996). It is thought that they play a role in social interactions, although they may also function in echolocation tasks.

Due mainly to technological restrictions, most studies investigating delphinid vocalizations have been limited in bandwidth to the human-audible range (below 20 kHz). As a result, descriptions of burst pulses have largely been qualitative (Busnel and Dziedzic 1966, Caldwell and Caldwell 1967, Caldwell and Caldwell 1971), and quantitative descriptions are limited (Overstrom 1983, Herzing 1988, Herzing 1996

McCowan and Reiss 1995, Van Parijs and Corkeron 2001). Full bandwidth descriptions of burst pulse vocalizations are rare (Dawson 1991, Lammers *et al.* 2003). This focus on the human-audible frequency range has led some to the unsubstantiated belief that, in most odontocete species, whistles are the primary mode of communication and clicks are used primarily, if not solely, in target discrimination and ranging tasks (Popper 1980, Morris 1986, Dawson 1991). This hypothesis implies that non-whistling species do not communicate acoustically. Herman and Tavolga (1980) suggested that whistling species live in large groups and forage communally, while non-whistling species are more solitary. However, these differences between whistling and non-whistling species do not always hold true. For example, both bottlenose dolphins and Hector's dolphins (*Cephalorhynchus hectori*) are coastal species generally found in small groups characterized by fluid social affiliations. Despite these similarities, bottlenose dolphins whistle extensively and Hector's dolphins do not whistle at all (Dawson 1991). There are several other odontocetes that produce only pulsed sounds, including phocoenids, other *Cephalorhynchus* species, and sperm whales (Watkins 1980, Evans and Awbrey 1988, Dawson 1991). If these animals communicate vocally, then they must do so using pulsed signals.

Burst pulse vocalizations have been associated with social communication (Popper 1980, Overstrom 1983, Herzing 1988, Lammers *et al.* 2006). The hypothesis that burst pulses are social signals is based on two main observations: 1) burst pulses have often been recorded during periods of high social activity (Caldwell and Caldwell 1967, Overstrom 1983, McCowan and Reiss 1995, Herzing 1996), and 2) they have extremely short inter-click intervals (0.5 – 10 ms, Lammers *et al.* 2004). It is assumed that when echolocating, dolphins process incoming echoes before emitting another click. Because of the assumed need of dolphins to process each echo, it has been hypothesized that burst pulses could not be used during echolocation (Gish 1979, Herman and Tavolga 1980, Popper 1980, Herzing 1988). It is possible, however, that dolphins process more than one echo at a time (Au 1993). Echolocating dolphins have been observed to substantially increase their pulse repetition rate as they approach a target (Evans and Powell 1967, Au 1993) and therefore some burst pulses may simply be echolocation click trains emitted at very close range. The assignment of click trains to mutually exclusive communication or echolocation categories based on inter-click interval may or may not match their uses by dolphins. Because of the uncertainty surrounding the functional categorization of click trains, it is necessary to examine the production of all pulsed sounds within their behavioral contexts rather than categorizing first and then analyzing them separately.

Whistles

Because many whistles have fundamental frequencies below 20 kHz and can be recorded using standard audio equipment, they are the most commonly studied type of delphinid vocalization. Whistles are continuous, narrow-band, frequency modulated signals that often have harmonic components. The fundamental frequency of most whistles ranges from 2 kHz to 30 kHz, although whistles with fundamentals extending to almost 30 kHz have been reported for several species (Lammers *et al.*

2003, Oswald *et al.* 2004). Whistles range in duration from several tenths of a second to several seconds (Tyack and Clark 2000).

Many delphinid species that produce whistles are gregarious and live in large groups, and their whistles are thought to function in social communication (Janik and Slater 1998, Herzing 2000, Janik 2000). Exactly how whistles are used in communication is a much-discussed topic in the literature. Several specific functions of whistles are suggested by the "signature whistle hypothesis". Caldwell and Caldwell (1965) first coined the term "signature whistle" when they observed captive bottlenose dolphins producing individually distinctive and, in certain acoustic features, stereotyped whistles. The signature whistle hypothesis proposes that dolphins use these whistles in order to broadcast their identity and location to other members of their social group (Caldwell *et al.* 1990). Bottlenose dolphins have been observed to mimic the signature whistles of other dolphins within a group (Caldwell and Caldwell 1972, Tyack 1986), leading to the hypothesis that these whistles may be used to establish and maintain contact between individuals, particularly mother/calf pairs (Sayigh *et al.* 1990, Smolker *et al.* 1993). Potential signature whistles have been recorded from bottlenose dolphins, dusky dolphins (*Lagenorhynchus obscurus*), *Stenella* species, *Lagenorhynchus* species, long-finned pilot whales (*Globicephala melaena*), tucuxi (*Sotalia fluviatilis*), and Amazon river dolphins (*Inia geoffrensis*) (Caldwell and Caldwell 1965, Caldwell and Caldwell 1971, Caldwell *et al.* 1973, Caldwell *et al.* 1990, Steiner 1981, Wang *et al.* 1995). This hypothesis however, is a topic of considerable debate (McCowan and Reiss 1995, McCowan and Reiss 2001).

Species identification using whistles

A complex social system is a hallmark of many cetacean species, and is an adaptation that is carried to the highest degree among delphinids. The maintenance of these social systems depends on a well-developed communication system (Gish 1979, Popper 1980). In particular, because many delphinid species are very social and highly mobile, they require mechanisms for maintaining and re-establishing contact with conspecifics (Tyack and Clark 2000). This is especially important in situations such as mating, foraging, and aggressive interactions. Many delphinid species have distinguishing body types or coloration patterns, but in murky water or at distance these visual cues are not likely to be useful because light propagates poorly under water. Sound, however, travels long distances under water and can therefore be an effective means of communicating species identification (Tyack and Clark 2000).

Vocalizations are the primary cue by which parents and offspring of several species, including adelie penguins (*Pygoscelis adeliae*, Falls 1982), Mexican free-tailed bats (*Tadarida brasiliensis mexicana*, Balcombe and McCracken 1992), and vervet monkeys (*Cercopithecus aethiops*, Cheney and Seyfarth 1980) recognize one another. In playback experiments involving Galapagos fur seals (*Arctocephalus galapagoenis*) and subantarctic fur seals (*A. tropicalis*), mothers and pups responded positively to recordings of each other's calls but not to those of strangers (Trillmich 1981, Roux and Jouventin 1987). If vocalizations carry individual-specific information, it seems probable that they carry species-specific information as well.

Marine mammals produce a wide variety of sounds, and variation in the characteristics of their calls makes some species easy to identify. For example, the low frequency pulses of fin whales and broadband clicks of sperm whales are distinctive and characteristic of those species (Thompson *et al.* 1992, Goold and Jones 1995). The vocalizations produced by delphinids, however, are more variable and less distinctive than those produced by other cetaceans. Because of the directional nature of delphinid clicks and the distortion that occurs when they are recorded off axis, using these signals to identify species may prove problematic. Whistles, however, are relatively omni-directional and propagate further than clicks. In addition, the continuous, frequency modulated nature of whistles gives them the potential to carry more species-specific information than pulsed vocalizations.

Time and frequency characteristics measured from spectrograms have been used to classify delphinid whistles to species in several studies (Steiner 1981, Fristrup and Watkins 1993, Wang *et al.* 1995, Matthews *et al.* 1999, Rendell *et al.* 1999). Correct classification scores obtained in these studies are given in Table 1.1. To facilitate comparisons among studies, Steiner (1981), Wang *et al.* (1995), Matthews *et al.* (1999), and Rendell *et al.* (1999) used similar classification techniques and reported similar spectrographic measurements (Table 1.1). As an alternative approach, Fristrup and Watkins (1993) devised a number of statistical measures to resolve the many acoustic features used to describe sounds. Correct classification scores obtained in these whistle classification studies have been significantly greater than expected by chance alone, suggesting that delphinid species can be identified based on characteristics of their whistles.

Dissertation Outline

The main objectives of this dissertation are to explore the whistling behavior of odontocetes and to test the hypothesis that delphinids can be identified to species based on characteristics of their whistles. The first objective is addressed in chapters two and three. Chapter two: ‘To whistle or not to whistle? Geographic variation in the whistling behavior of small odontocetes’ investigates patterns in the geographic distribution of whistling vs. non-whistling species of small odontocetes in the central and eastern Pacific Ocean. Data are presented that suggest that whistle use by odontocetes varies geographically, and seven hypotheses that may explain why species in the eastern tropical Pacific Ocean whistle more frequently than species in the eastern North Pacific Ocean are discussed. Whistling behavior and characteristics of whistles are still largely unknown for many species. This is illustrated in chapter three: ‘First description of whistles of Pacific Fraser’s dolphins, *Lagenodelphis hosei*’, which provides a description of the whistles of a seldom-recorded delphinid species. The remaining chapters address the second objective of this dissertation: to test the hypothesis that delphinid species can be identified based on characteristics of their whistles. In chapter four: ‘Acoustic identification of nine delphinid species in the eastern tropical Pacific ocean’, multivariate discriminant function analysis (DFA) and classification tree analysis (CART) are used to classify the whistles of nine delphinid species. Chapter five: ‘The effect of recording and analysis bandwidth on acoustic identification of delphinid species’ is a broadband analysis of the whistles of four delphinid species in the eastern tropical Pacific Ocean. This chapter explores the extent to which the recording and analysis of ultrasonic frequencies can improve correct classification scores such as those obtained in chapter four. The classification techniques and bandwidth extensions discussed in chapters four and five are incorporated into a software tool for real-time acoustic species identification in chapter six: ‘ROCCA: A new tool for real-time species identification of delphinid whistles’. Matlab code for ROCCA is provided in Appendix 6.A. All chapters have been written and are presented as individual manuscripts with acknowledgement to the co-authors in the study. There may therefore be some redundancy in their introduction and methods sections.

Table 1.1. Species included, variables measured, classification algorithms used, percent of vocalizations correctly classified and number of vocalizations analyzed in marine mammal acoustic species identification studies.

Study	**Species**	**Variables**	**Classification technique**	**Overall correct classification**	**# Vocalizations**
Steiner 1981	*Tursiops truncatus, Globicephala melaena, Lagenorhynchus acutus, Stenella plagiodon, S. longirostris*	beginning, end, minimum, and maximum frequencies, duration, number of inflection points	Discriminant Function Analysis	69%	6733
Fristrup and Watkins 1993	53 species including mysticetes, odontocetes and pinnipeds	91 variables	Linear classifier Tree based classifier	50% 66%	2104
Wang *et al.* 1995	*Inia geoffrensis, Tursiops truncatus, Lagenorhynchus obscurus, Stenella longirostris, S. frontalis, S. attenuata, Sotalia fluviatilis*	beginning, end, minimum and maximum frequencies, duration, number of inflection points, slope of beginning and ending sweep, presence/absence of harmonics, break in contour	Discriminant Function Analysis	65%	4667
Matthews *et al.* 1999	9 odontocete species and 1 mysticete species	beginning, end, minimum, and maximum frequency, duration	Discriminant Function Analysis	28%	515
Rendell *et al.* 1999	*Pseudorca crassidens, Globicephala macrorhynchus, G. melas, Grampus griseus, Lagenorhynchus albirostris*	beginning, end, minimum and maximum frequencies, duration, number of inflection points	Discriminant Function Analysis	55%	5348

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CHAPTER II

To Whistle Or Not To Whistle? Geographic Variation in the Whistling Behavior of Small Odontocetes

Abstract

Whistles are used by odontocetes to varying degrees. During a visual and acoustic survey of dolphin abundance in the eastern tropical Pacific Ocean (ETP), whistles were heard from 66% of single species schools and 98% of mixed species schools. In contrast, whistles were heard from 24% of single species schools and 23% of mixed species schools during a survey of temperate waters off the western United States. The most common species encountered in the ETP were *Stenella coeruleoalba, S. attenuata,* and *Tursiops truncatus,* all of which whistled frequently. The most common species encountered in the temperate study area were *Delphinus delphis, Phocoenoides dalli, Lissodelphis borealis,* and *Phocoena phocoena,* only one of which whistled. Why do dolphins living in the ETP whistle more than those living in colder waters farther north? Seven hypotheses are explored: 1) predator avoidance, 2) group size, 3) school composition, 4) communication distance, 5) behavior state, 6) temporal variation, and 7) anatomical differences. Multivariate logistic regression with whistling as the dependent variable and group size, school composition, time of day, presence of a rostrum, and study area as dependent variables showed that all variables were significant ($p < 0.001$). Explanation of the aggregation of whistling

species in the tropical study area and non-whistling species in the temperate study area is likely found in some combination of the hypotheses discussed.

Introduction

Odontocete cetaceans produce a considerable diversity of acoustic signals, which have generally been placed into three distinct categories: echolocation clicks, burst pulse sounds, and whistles. Echolocation clicks are short, broadband pulses with peak frequencies that vary from tens of kilohertz (ex. *Steno bredanensis,* Norris and Evans 1966) to well over 100 kHz (ex. *Tursiops truncatus,* Au 1980; *Phocoenoides dalli*, Hatakeyama and Soeda 1990). These clicks have a rapid rise time and short duration, ranging from approximately 50 μs (ex. *T. truncatus*, Au 1980) to 400 μs (ex. *P. dalli*, Hatakeyama and Soeda 1990). Echolocation clicks generally occur in trains containing few to hundreds of clicks and are used for navigation and object detection and discrimination (Au 1993). Burst pulse signals are broadband click trains with very short inter-click intervals. These sounds take on a tonal quality to human ears because the clicks are repeated at such high rates that the rate itself, rather than the individual clicks, is audible (Watkins 1967, Herzing 2000). Burst pulses have been qualitatively described using many terms such as buzzes, creaks, pops, and squeals (Caldwell and Caldwell 1967, dos Santos *et al*. 1990, Herzing 1996). It is thought that these signals play a role in social interactions, although they may also function in echolocation tasks. Echolocation click trains and burst pulses lie on a continuum relative to their click repetition rates. While they are perceived as different sounds by humans, it is not known at what rate dolphins perceive individual clicks and if click trains and burst pulses are functionally different to dolphins (Murray *et al.* 1998, Herzing 2000). Whistles are continuous, narrowband, frequency modulated signals that often have harmonic components. They range in duration from several tenths of a second to several seconds (Tyack and Clark 2000). The fundamental frequency of most whistles ranges from 2-20 kHz, although whistles with fundamentals extending to almost 30 kHz have been reported for several species (Lammers *et al.* 2003, Oswald *et al.* 2004). Whistles are believed to function as social signals (Janik and Slater 1998, Herzing 2000, Lammers *et al.* 2003).

Because many whistles have fundamental frequencies below 20 kHz and can be recorded using standard audio equipment, studies examining social communication have focused on these signals rather than higher frequency burst pulses. This emphasis has lead to the assumption that whistles are the primary social signals for odontocetes. However, several species, including members of the families Kogiidae, Physeteridae, and Phocoenidae and of the subfamily Cephalorhynchinae, produce whistles infrequently or not at all (Watkins and Wartzok 1985, Tyack 1986). These species are thought to communicate exclusively through pulsed sounds (Herman and Tavolga 1980, Dawson 1991).

When phylogenetic relationships among species that whistle frequently and those that whistle infrequently or not at all are examined, two possible scenarios emerge: 1) whistles may have evolved independently twice; once in *Berardius* and once in delphinoids and river dolphins with secondary losses in *Cephalorhynchus* spp.

(including some *Lagenorhynchus* spp.) and *Phocoenidae*, 2) whistles may have evolved once in the common ancestor of *Ziphiids*, river dolphins, and delphinoids with secondary losses in *Cephalorhynchus, Phocoenidae*, and beaked whales (Figure 2.1, May-Collado and Agnarsson 2006, May-Collado *et al.* submitted). What pressures drove the evolution and secondary losses of whistling behavior? Answers may be found by examining the geographic distribution of whistling versus non-whistling species. In this paper we present data that suggest that whistle use by odontocetes varies geographically, and discuss seven hypotheses that may explain why species in the eastern tropical Pacific Ocean whistle more frequently than species in the eastern North Pacific Ocean.

Methods

Acoustic recordings were made during two shipboard line-transect surveys conducted by the Southwest Fisheries Science Center (NOAA, NMFS). The Stenella Abundance Research (STAR) survey took place in the eastern Tropical Pacific Ocean from 28 July to 9 December 2000. The study area extended from the United States/Mexico border southward to the territorial waters of Peru, and from the continental shores of the Americas west to the longitude of Hawaii (Figure 2.2). This will be referred to as the tropical study area in this paper. The Oregon, California, and Washington marine mammal survey (ORCAWALE) took place in the eastern north Pacific from 30 July to 8 December 2001. The study area extended from the U.S. western coasts of Washington, Oregon, and California, out to a distance of approximately 300 nautical miles (Figure 2.3). This will be referred to as the temperate study area in this paper. During both surveys, a team of three experienced biologists actively searched for marine mammals using two sets of 25x150 binoculars and by naked eye. When cetaceans were sighted, they were approached for species identification and group size estimation. Group size was estimated independently by each observer. Group sizes reported here are simple arithmetic averages of the observers' best estimate for each group.

Cetacean vocalizations were monitored and recorded using a towed hydrophone array. The array was towed 200 m behind the research vessel at a depth of approximately 4-6 m during daylight hours. Two arrays built by Sonatech Inc., Santa Barbara, CA were used during both surveys: a five-element array (flat frequency response ±4 dB from 2 kHz to 45 kHz at –132 dB re 1 v/µPa after internal amplification), and a three-element array (flat frequency response ±3 dB from 2 kHz to 120 kHz at –164 dB re 1 v/µPa after internal amplification). Signals from both arrays were sent through a Mackie CR1604-VLZ mixer for equalization and were recorded using a Tascam DA-38 eight-channel digital recorder (48 kHz sampling rate). Recordings were also made directly to computer hard drive via an analog-to-digital conversion card (National Instruments BNC-2110 and DAQCard-6062E) using a 200 kHz sampling rate.

An acoustic technician monitored signals from two hydrophones in the array using a stereo headset and real-time scrolling spectrographic software (ISHMAEL, Mellinger 2001). Whaltrak, a mapping program with a GPS-interface automatically logged time and position every 5 minutes while the array was being monitored. A time stamped comment noting acoustic activity was entered into Whaltrak on five-minute intervals. The types of vocalizations detected (if any) were noted and the number and relative intensity of whistles heard were both rated on a scale from 1-5 (low to high).

Confirmation that the vocalizations detected were produced by the sighted dolphin schools was obtained by comparing the angle and distance of acoustic detections with the location of the sighting. Bearing angles were determined using phone-pair cross-correlation algorithms in ISHMAEL and distance was determined by examining the convergence of bearing angles plotted on Whaltrak. Acoustic detection distance was defined as the greatest distance at which the vocalizing dolphins could be successfully localized.

Results

During the tropical survey, 17,337 km of trackline were surveyed visually and 9,274 km were surveyed acoustically (Figure 2.2). There were 420 sightings of delphinid schools during this survey. A total of 224 of these schools were encountered while the hydrophone array was in the water.

Visual effort during the temperate survey covered 7,432 km of trackline and acoustic effort covered 8,132 km of trackline (Figure 2.3). There were 337 sightings of delphinid and phocoenid species during this survey, with 219 of those encountered while the hydrophone array was in the water. Only sightings detected while the acoustic team was on effort were included in further analyses.

Tropical visual results

The most commonly sighted species during the tropical survey were striped dolphins (*Stenella coeruleoalba*, 20% of sightings), spotted dolphins (*S. attenuata*, 16% of sightings), and bottlenose dolphins (13% of sightings) (Table 2.1). Most species encountered during this survey were found in mixed species schools at least some of the time, and 16% of sighted schools were mixed species schools. Spinner (*S. longirostris*), bottlenose, and spotted dolphins were the species most commonly sighted in mixed species schools (73%, 48%, and 47% of schools were mixed species, respectively). Mixed species schools were most commonly composed of spinner and spotted dolphins (43% of mixed species schools). Thirty-nine percent of mixed species schools included bottlenose dolphins. Several species were found most often in single species schools. The species and their percentage occurrence in single species schools are: striped dolphins (92%), both short and long-beaked common dolphins (*Delphinus delphis, D. capensis,* 92% and 89%, respectively), Risso's dolphins (*Grampus griseus*, 75%), and rough-toothed dolphins (75%).

Large group sizes (Table 2.1) were common in the tropical study area (mean = 91.4, SD = 178.8). Species with the largest mean group sizes were long-beaked common dolphins (mean = 589.5, SD = 509.3), short-beaked common dolphins (mean = 228.2, SD = 286.1), spinner dolphins (mean = 229.1, SD = 199.5), and spotted dolphins (mean = 180.3, SD = 182.8). Dusky dolphins (*Lagenorhynchus obscurus*) also had a large mean group size (mean = 265.3, SD = 504.8), but this result was skewed by one very large mixed-species school (group size = 1,167). Without this sighting, the mean group size for dusky dolphins was 39.9 (SD = 35.7). Species with the smallest group sizes included pygmy killer whales (*Feresa attenuata,* mean = 14.7, SD = 17.9), rough-toothed dolphins (mean = 21.6, SD = 28.4), and Risso's dolphins (mean = 28.5, SD = 34.4).

Temperate visual results

The most commonly sighted species during the temperate survey were Dall's porpoises (30% of sightings), short-beaked common dolphins (25% of sightings), northern right-whale dolphins (*Lissodelphis borealis*, 11% of sightings), and harbor porpoises (*Phocoena phocoena*, 9% of sightings) (Table 2.1). Mixed species schools were less common in the northern study area compared to the ETP, with mixed species schools comprising only 7% of sightings. Only striped dolphins and bottlenose dolphins were commonly found in mixed species schools (83% and 54% of schools were mixed species, respectively). Mixed species schools were most often composed of bottlenose and Risso's dolphins (26%) or short-beaked common dolphins and striped dolphins (22%). Harbor porpoises, Dall's porpoises, and short-beaked common dolphins occurred largely in single species schools (100%, 99%, and 94% of schools were single species, respectively).

Although not as common as in the tropics, large schools were encountered in the temperate study area. These included long-beaked common dolphins (mean = 452.0, SD = 529.9), short-beaked common dolphins (mean = 137.3, SD = 283.4), and striped dolphins (mean = 329.8, SD = 286.0). Harbor and Dall's porpoises had the smallest mean group sizes (mean = 2.0, SD = 1.0; mean = 3.2, SD = 2.3, respectively).

Pooled visual results

When results from both surveys were pooled, mixed species schools were significantly larger than single species schools (mixed species: n = 90, mean = 165.1, SD = 210.3; single species: n = 667, mean = 57.6, SD = 162.0; *t*-test, $p < 0.001$). Mixed species schools also were significantly larger than single species schools for each cruise individually (*t*-tests, tropical $p < 0.001$, temperate $p = 0.02$, Table 2.1). Overall mean school size was significantly greater in the tropical study area than in the northern study area (*t*-tests, $p < 0.001$, Table 2.1).

Tropical acoustic results

Vocalizations were detected from every dolphin species that was sighted during the tropical survey, with the exception of dusky dolphins and pygmy killer whales. The species most commonly detected acoustically included striped, short-beaked common, bottlenose, spotted, and spinner dolphins. Whistles, burst pulses and echolocation clicks were detected from all vocal species. Whistles were heard during 36% of the 627 hours spent monitoring the array, including 70% of the 224 schools that were encountered while the hydrophone array was in the water. Whistles were detected from 66% of single species schools and 98% of mixed species schools (Table 2.2).

Temperate acoustic results

With the exception of Dall's and harbor porpoises, vocalizations were detected from every small cetacean species that was encountered during the temperate study area. Clicks from these porpoise species are too high in frequency to be detected by our monitoring equipment. Short-beaked common, Risso's, Pacific white-sided (*Lagenorhynchus obliquidens*), and northern right-whale dolphins were the species most commonly detected acoustically. Whistles were not heard from Pacific white-sided or northern right-whale dolphins. Whistles not heard from single species schools of bottlenose or Risso's dolphins, but were heard when these two species were encountered with each other (Table 2.3). It cannot be determined with certainty which species produced those whistles. Whistles were heard during only 13% of the 376 hours spent monitoring the array, and were detected from 23% of the 219 schools that were encountered while the hydrophone array was in the water. Whistles were detected from 24% of single-species schools and 23% of mixed-species schools (Table 2.2).

Pooled acoustic results

The two study areas were pooled and schools of small odontocetes that were encountered while the hydrophone array was being monitored (n = 419) were examined. Mean group size for whistling species (mean = 105.4, SD = 205.9, n = 318) was significantly greater than mean group size for non-whistling species (mean = 4.9, SD = 8.4, n = 125, *t*-test $p < 0.001$). Table 2.3 shows the total number of schools of whistling species that were encountered and the percentage of schools for which whistles were detected for both surveys. Eighteen percent of whistling species and 4% of non-whistling species schools encountered were mixed species schools.

Schools that did not produce whistles while in range of the array were generally small (n = 229, mean = 14.0, SD = 28.3). Seventy one percent of these schools contained 10 or fewer individuals and 91% included 30 or fewer individuals. Schools that did whistle were significantly larger (n = 194, mean = 162.5, SD = 257.4, *t*-test, $p < 0.001$) than those that did not. Only 14% of whistling schools were made up of 10 or fewer individuals and 31% contained 30 or fewer individuals. Sixty percent of the whistling schools contained more than 40 individuals, and every group containing more than 150 individuals whistled (n = 50).

Overall, mean acoustic detection distance was significantly shorter in the temperate study area (2.2 nmi) compared to the tropical study area (3.6 nmi, *t*-test, $p < 0.001$, Table 2.4). For the only species detected acoustically in both study areas (short-beaked common dolphins), mean acoustic detection distance was significantly shorter in the temperate study area (1.7 nmi) compared to the tropical study area (3.3

nmi, *t*-test, $p < 0.001$). For individual species, mean acoustic detection distances ranged from 0.4 nmi for northern right whale dolphins to 3.3 nmi for short-beaked common dolphins (Table 2.4).

Logistic regressions

Univariate logistic regression with whistling as the dependent variable and time of day (morning = sunrise – 10 am, mid-day = 10 am – 2 pm, afternoon = 2 pm – sunset) as the independent variable showed that time of day was significant for both study areas combined ($p = 0.004$). Overall, the number of whistling schools encountered decreased from mid-day to afternoon and the number of non-whistling schools increased from morning to afternoon (Figure 2.4). Temporal patterns in whistling varied among species (Figure 2.5). For short-beaked common dolphins, the number of whistling schools that were encountered decreased with time of day, and the number of non-whistling schools encountered increased with time of day. For striped dolphins, the number of whistling schools encountered remained relatively constant throughout the day, but no non-whistling schools were encountered in the morning. Whistling activity did not vary with time of day for either spotted or bottlenose dolphins. Sample sizes for other whistling species were too small to be included in this analysis. A Generalized Additive Model (logit link function) with whistling as the dependent variable and decimal time as a continuous independent variable showed that time of day was again significant ($p = 0.001$), with whistling being most common in the morning and relatively constant from noon onward (Figure 2.6).

Additional univariate logistic regressions were performed with whistling as the dependent variable and school size, school composition (mixed vs. single species), presence of a pronounced rostrum, and study area as the independent variables. All variables were found to be significant ($p < 0.001$ for all variables).

Multivariate logistic regression with whistling as the dependant variable and school size (log transformed), school composition, time of day (morning, mid-day, afternoon), presence of a pronounced rostrum, and study area as the independent variables showed that all five independent variables were significant when considered together ($p < 0.001$ for all variables).

Discussion

Nearly every delphinid species encountered in the tropical study area produced whistles. The only exceptions were dusky dolphins and pygmy killer whales. Pygmy killer whales were encountered on only one occasion while the array was in the water, and this school was composed of only two animals. Four dusky dolphin schools were encountered during the tropical survey; however, they were all encountered within a 2-hour period. Little time was spent with any of the groups, and it is possible that vocalizations were not detected due to the small window of opportunity available. Both of these species have been observed to produce whistles in other areas (pygmy killer whales in Ecuador: Castro 2004, dusky dolphins in New Zealand: Ding *et al.* 1995, Yin 1999).

In contrast, three of the four species most commonly encountered in the temperate study area (northern right-whale dolphins, harbor porpoises and Dall's porpoises) did not produce whistles. No vocalizations were detected from either harbor or Dall's porpoises. Clicks produced by these species would have been too high in frequency to be detected by our monitoring equipment, and neither of these species are known to produce whistles (Tyack and Clark 2000). Only burst pulses and clicks were heard from northern right-whale dolphins. Whistles recorded in the presence of northern right-whale dolphins have been reported in the literature only once (Leatherwood and Walker 1979). If this species does whistle, it seems to be a rare occurrence (Rankin *et al.* in prep). It has been suggested that species that whistle rarely or not at all may use clicks for both social communication and echolocation (Dawson and Thorpe 1990, Tyack and Clark 2000, Rankin *et al.* in prep). Non-whistling species accounted for approximately 50% of the schools encountered during this survey. The only whistling species that was frequently encountered was the short-beaked common dolphin. Other whistling species, such as bottlenose and striped dolphins, were found in the study area, but accounted for only 5% of the total schools encountered.

Based on the results of these two surveys, it appears that whistling species are much more common in tropical waters, while non-whistling species are more common in cold-temperate waters. In the following sections, we explore seven hypotheses that may explain this difference: 1) predator avoidance, 2) group size, 3) school composition, 4) communication distance, 5) behavior state, 6) temporal variation, and 7) anatomical differences.

Predator avoidance

A major predator of small odontocetes is the killer whale (*Orcinus orca*, Baird and Dill 1995, Barrett-Lennard *et al.* 1996). The diet of transient killer whales in Prince William Sound has been reported to contain a large proportion of Dall's porpoises (38%) and a smaller proportion of harbor porpoises (6%, Herman *et al.* 2005). While killer whales have been reported in both tropical and offshore waters, they are more common at higher latitudes and are found in greatest abundance within 800 km of major continents (Angliss and Lodge 2004, Forney and Wade *in press*). As a result, small odontocetes in the temperate study area are more at risk of killer whale predation than those in the tropical study area.

Szymanski *et al.* (1999) reported that the range of most sensitive hearing for killer whales is 18-42 kHz. Whistles produced by odontocetes range from 5-30 kHz (Lammers *et al.* 2003, Oswald *et al.* 2004), are omni-directional, and propagate well under water. Signals such as these likely serve as acoustic beacons for predators. Therefore, to avoid detection, it would be advantageous for dolphins to produce sounds that attenuate quickly such as directional, high frequency clicks. Most small odontocete species in the temperate study area do not whistle, but produce broadband, pulsed sounds with much of the acoustic energy well above 42 kHz. For example, Dall's porpoises produce clicks with a peak frequency of 135 – 149 kHz (Hatakeyama and Soeda 1990), and harbor porpoises produce clicks with peak frequencies at 1.4 – 2.5 kHz and 110 – 140 kHz (both outside the range of best hearing for killer whales; Kamminga and Wiersma 1981, Hatakeyama and Soeda 1990, Verboom and Kastelein 1995). High frequency clicks are directional and attenuate more quickly than the whistles produced more commonly by species in the tropical study area. High frequency sounds may therefore allow animals to communicate at close range while avoiding detection by predators (Andersen and Amundin 1976, Tyack and Clark 2000).

Some whistling species are found in the temperate study area, but they are more common in the southern portion of the study area, where killer whales are less common (Barlow 2003, Forney and Wade *in press*). These whistling species are also found in larger schools than non-whistling species, which may offer them more protection against predators (Norris and Schilt 1988).

Group size

Whistles may have many functions within schools of dolphins, including: identification of family members or familiar associates, assembly of dispersed animals, and group coordination during foraging, flight and travel. Whistles are relatively omni-directional and propagate over greater distances than echolocation clicks or burst pulses. They may have frequency dependant directional qualities that could provide cues as to the location and direction of movement of whistling animals

(Lammers and Au 2003). This set of characteristics suggests that whistles are well suited to function as long distance communicative signals and may be used more frequently by species that travel in large schools.

Lammers *et al.* (2006) found that, in schools of free-ranging Hawaiian spinner dolphins, whistles were typically produced by dolphins spaced widely apart, suggesting that whistles play a role in maintaining contact between animals in a dispersed group. Herman and Tavolga (1980) reported a general trend that large-school, communal foraging cetacean species whistle, while more solitary species do not. For example, harbor porpoises, Heaviside's dolphins (*Cephalorhynchus heavisidii*), and finless porpoises (*Neophocaena phocaenoides*) do not whistle and are found alone or in small groups of a few animals. Whistling species such as *Stenella* species and bottlenose dolphins are often found in large groups. This is an imperfect relationship, as both *Stenella* species and bottlenose dolphins are also found in small groups, and northern-right whale dolphins can be found in very large groups, but it does seem to be a general trend worth investigating. Support for this hypothesis can be found in other groups of animals, such as canid species. Kleiman (1967) reported that communal living and hunting canids have more complex communication systems than solitary species.

In the tropical and temperate study areas, mean group size of whistling species was significantly larger than non-whistling species (*t*-tests, $p < 0.001$). Groups that did not produce whistles while in range of the array were generally small, with most containing 30 or fewer individuals. In contrast, groups that did whistle tended to be large, containing more than 40 individuals. In addition, overall mean group size was significantly greater in the tropical than in the temperate study area (*t*-test, $p < 0.001$). The larger group sizes in the tropics may explain why whistles were heard more often in that study area. The observed trends support the hypothesis that whistling behavior is related to group size.

It is important to note, however, that the hydrophone array may have detected whistles from larger groups more frequently than from smaller groups simply because of the number of animals present. If each dolphin whistles even only occasionally, the number of whistles produced should increase with group size, thus increasing the probability of a whistle being detected while the array is in acoustic range of the school. Also, there is a greater probability that at least some of the individuals in a larger group will be in a whistling behavior state when encountered. Finally, a larger group may be dispersed over a larger area. If this is the case, the hydrophones may be in acoustic range of the group for a longer period of time, thereby increasing the probability of detecting a whistle (Stienessen 1998).

School composition

Whistles have been shown to contain species-specific information (Steiner 1981, Ding *et al.* 1995, Oswald *et al*. 2003) and therefore may be important for recognition of conspecifics in mixed species schools. If this is the case, we expect whistling species to be found in mixed schools more often than non-whistling species. For the two study areas combined, whistling species were more than 4 times as likely to be found in mixed schools than were non-whistling species. However, only 18% of whistling species schools were mixed. If school composition has influenced the development of whistling behavior, we would expect a greater proportion of whistling species schools to be mixed species schools. In addition, while whistles were detected slightly more often from mixed species schools than single species schools (Table 2.2, Table 2.3); this difference was not large enough to provide strong support for the hypothesis that whistles are used more often in mixed species schools. Finally, mixed species schools were significantly larger than single species schools (t-test, $p < 0.001$). It is possible that whistles were heard from mixed species schools more often because of the school size effects discussed above. Further research into whistling rates within schools may help to elucidate the effect of school composition on whistling behavior.

Communication distance

Narrowband, frequency-modulated signals such as whistles have advantages for communication because they allow both frequency and amplitude modulation for encoding information. Amplitude modulation may be degraded, altered, or masked by reverberation and heterogeneities in the environment, leaving frequency modulation as the best carrier of information over longer ranges. At short range, random amplitude fluctuations are less likely to interfere with signals, allowing amplitude modulation to be used for encoding information (Wiley and Richards 1978). Broadband pulsed sounds may be especially useful for short range communication because they are directional and therefore easy to localize. If frequency modulation is used to encode information over long distances and amplitude modulation is used to encode information at short distances, then species that communicate over longer distances should whistle and species that communicate over short distances should produce clicks.

Based on acoustic detection distances during our surveys, whistling species appear to have the ability to communicate over longer distances than non-whistling species. Mean acoustic detection distances for whistling species ranged from 0.6 nmi for killer whales to 3.3 nmi for short-beaked common dolphins. Mean acoustic detection distances for non-whistling species ranged from 0.4 nmi for northern right whale dolphins to 0.6 nmi for Pacific white-sided dolphins (Table 2.4). As previously discussed, whistling species tend to be found in larger groups. These groups are often quite spread out, thus creating a need for relatively long-range communication.

Differences in detection distances were not only due to the types of sounds being produced, but were also likely influenced by the sound channel through which the signals traveled. For example, short-beaked common dolphins occurred and whistled frequently in both study areas. Mean acoustic detection distance for this species was significantly shorter in the temperate study area compared to the tropical study area (t-test, $p < 0.001$, Table 2.4). This difference may be a result of surface ducting in some parts of the tropical study area (Oswald *et al.* 2004*b*).

Behavior state

Certain behavioral states, such as allomaternal behavior, defense from predators, and cooperative feeding require the maintenance of associations among individuals. Whistles may provide the vehicle for maintaining such associations and may be less important during other behavior states. Rasmussen and Miller (2002) report that whistles were heard from white-beaked dolphins (*Lagenorhynchus albirostris*) when they were socially active, but never when they were feeding, traveling, or resting. Spinner dolphins are nearly silent when resting and become very vocal when traveling or feeding (Norris *et al.* 1994). Increased whistling rates during feeding have been observed for both pilot whales and common dolphins (Dreher and Evans 1964, Busnel and Dziedzic 1966). It is possible that the dolphins in the tropical study area spend more time in, and/or were encountered more often while in vocally active behavior states. It was not possible to explore this hypothesis, as behavioral data were not available for the temperate survey and the sample size available for the tropical survey was not sufficient for statistical analysis. Further behavioral data collection would be a valuable addition to future surveys.

Temporal variation

Whistle production may be affected by seasonality. Jacobs *et al.* (1993) found that bottlenose dolphins in the Newport River Estuary, North Carolina produced more vocalizations per unit time during the fall than during the summer. Behavioral analyses showed that these dolphins spent the greatest proportion of their time feeding in the fall and socializing in the summer. Both the tropical and temperate surveys discussed here occurred between July and December. It is possible that species in the northern study area whistle more often during certain times of the year, such as mating or calving seasons, and that those seasons did not overlap with our surveys.

Whistle production may also be a function of time of day. Norris *et al.* (1994) report that Hawaiian spinner dolphins are quiet during the day when resting in protected bays and whistling increases as the dolphins travel to deeper waters to forage late in the day. Whistles are abundant when the dolphins are feeding offshore at night (Norris *et al.* 1994). Stienessen (1998) found that dolphins in the Gulf of Mexico were more vocal at night than during the day and that the type of vocalization produced varied with time of day. For example, Atlantic spotted dolphins (*Stenella frontalis*) produced a higher proportion of whistles during the day and a higher proportion of pulsed sounds at night. The opposite was found to be true for clymene dolphins (*S. clymene*). Evans and Awbrey (1988) reported diurnal differences in vocalizations recorded from common dolphins. During the day whistles, click trains and squeals were heard, whereas click trains predominated at night.

Nighttime recordings were not made during the tropical or temperate surveys, but it was possible to examine vocal activity as a function of time of day for daylight hours. Overall, the number of whistling schools encountered decreased significantly from morning to afternoon (univariate logistic regression $p = 0.004$, GAM $p = 0.001$, Figures 2.4 and 2.6). Although sample sizes were small, whistling behavior patterns seemed to vary by species (Figure 2.5). These results suggest that, for at least some species, time of day did influence whether or not whistles were heard during these surveys.

It is possible that fewer whistles were heard in the temperate study area because those species whistle more at night than during the day. Small odontocetes such as harbor and Dall’s porpoises have a large surface area to volume ratio and therefore lose a great deal of energy to radiation and conduction when living in cold water. In order to maintain a thick blubber layer and high metabolic rate for thermoregulation, these animals must eat a large amount of food per day relative to their body weight (Kastelein *et al*. 1997). As their diet consists mainly of smoothed rayed fish such as gadoids and clupeoids (Kastelein *et al*. 1997), harbor porpoises may spend the daylight hours foraging using echolocation clicks and vision and use social signals more at night. In contrast, species such as spotted dolphins feed primarily at night on organisms associated with the deep scattering layer (Robertson and Chivers 1997, Baird *et al.* 2001). These species may therefore use social signals more during the day.

Anatomical differences

It is generally accepted that odontocetes produce sounds in the nasal passages of their foreheads (Ridgway *et al*. 1980, Amundin and Andersen 1983, Cranford *et al*. 1997, Cranford 2000). Although sound production has been shown to occur at the ‘phonic lips’ or ‘monkey lips’ in the nasal passages, the exact mechanism of sound production is not completely understood (Cranford 2000). Several odontocete species have been reported to whistle and click simultaneously, which may indicate different generation mechanisms for these two types of sounds (Cranford 2000). Whistle production appears to require greater nasal air pressure compared to click generation and may therefore require a different mechanism (Ridgway and Carder 1988, Cranford 2000).

These observations suggest that whether or not a species whistles may be a function of anatomical differences such as the degree of symmetry in the head and the presence or absence of a beak. Skull geometry and the structure of the air sac system and melon are distinctive between whistling delphinids and non-whistling phocoenids (Cranford 1988, Amundin and Cranford 1990, Cranford *et al.* 1996). Delphinid skulls and soft anatomy are highly asymmetric, whereas phocoenid heads are relatively symmetrical. It has been proposed that the degree of asymmetry is related to variability of sounds produced (Cranford *et al.* 1996). For example, CT scans show that there is less skull asymmetry in Pacific white-sided dolphins compared to bottlenose dolphins (Rasmussen and Miller 2002). Pacific white-sided dolphins do not whistle often while bottlenose dolphins commonly produce highly variable whistles.

A noticeable anatomical difference between many whistling and non-whistling species is the presence of a beak. Whistling species generally have pronounced beaks, while most non-whistling species do not. This trend was evident in the tropical and temperate study areas. Species commonly seen in the tropics and not in the temperate study area included spotted, spinner, and rough-toothed dolphins, all of which have distinct rostrums and whistle often. Dall's porpoises, harbor porpoises, and northern right whale dolphins were commonly observed in the temperate study area, but not the tropical study area; all three of these species lack a definite beak and do not whistle. Perhaps skull morphology affects the ability to produce or energetic cost-effectiveness of producing whistles. Conversely, the tendency to whistle may be a phylogenetic trait that is just casually correlated with the presence of a beak.

Conclusions

The aggregation of whistling species in the tropical study area and non-whistling species in the temperate study area does not appear to have a simple, univariate explanation. It is likely due to some combination of the hypotheses presented here and, perhaps, others that have not yet been explored. Multivariate logistic regression with whistling as the dependent variable showed that group size, school composition, presence of a pronounced rostrum, time of day, and study area were all significant ($p < 0.001$, all variables). Larger groups have a greater need for communication among individuals for coordination of activities, and are often spread out, requiring individuals to use signals that will travel larger distances. However, while group size does seem to have a strong effect on whistle production, it is likely correlated with other factors such as school composition, communication distance, and predator avoidance. Mixed species schools tend to be larger than single species schools and individuals within these schools may have a greater need to communicate with conspecifics spread over larger areas. Whistles may be more effective than clicks for communication over these larger areas. Whistles may serve as ‘acoustic beacons’ for predators, making whistling a disadvantage in areas where predators are common. The reduction or loss of whistling behavior to avoid detection by predators may also have led to smaller school sizes to compensate for the resulting restriction in communication distance. Further study into these interactions could shed more light onto the question of why some species whistle while others don’t and ultimately lead to a deeper understanding of the functions of whistles in the lives of dolphins.

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Table 2.1. Summary of small odontocete species sighted during marine mammal abundance surveys in a tropical study area and a temperate study area. Number of single species and mixed species schools as well as mean school sizes (with standard deviations in parentheses) are given for each species. Final column for each survey gives the percent of the total number of small odontocete sightings accounted for by each species. Last row gives the overall number of sightings and overall mean group sizes (with standard deviations in parentheses) for each survey. 'Unidentified common dolphin' and 'unidentified pilot whale' refer to schools that could only be identified to the genus level.

	Tropical						**Temperate**					
Species	**# single species schools**	**# mixed species schools**	**single species school size**	**mixed species school size**	**overall school size**	**% total sightings**	**# single species schools**	**# mixed species schools**	**single species school size**	**mixed species school size**	**overall school size**	**% total sightings**
Long-beaked common dolphin	8	1	517.4 *(492.9)*	1,167.0	589.5 *(509.3)*	2.1	1	1	825.0	77.0	452.0 *(528.9)*	0.6
Short-beaked common dolphin	36	3	288.5 *(297.1)*	284.0 *(103.5)*	288.2 *(286.1)*	9.3	80	5	97.2 *(170.9)*	671.6 *(732.3)*	137.3 *(283.4)*	25.2
Unidentified common dolphin	1	0	80.0	n/a	80.0	0.2	4	0	20.2 *(14.0)*	n/a	20.2 *(14.0)*	1.2
Risso's dolphin	21	7	15.4 *(26.5)*	67.7 *(24.4)*	28.5 *(34.4)*	6.7	20	8	13.4 *(8.4)*	36.1 *(29.2)*	19.8 *(19.5)*	8.3
Unidentified pilot whale	4	6	10.6 *(4.9)*	64.3 *(65.4)*	42.8 *(56.2)*	2.4	1	0	3.0	n/a	n/a	0.3
Short-finned pilot whale	18	10	20.2 *(13.1)*	58.4 *(32.8)*	33.8 *(28.5)*	6.7	0	0	n/a	n/a	n/a	0.0
Killer whale	4	3	6.8 *(6.8)*	64.4 *(58.6)*	31.5 *(46.0)*	1.7	7	0	5.9 *(2.6)*	n/a	5.9 *(2.6)*	2.1

Table 2.1 cont’d

	Tropical						**Temperate**					
Species	**# single species schools**	**# mixed species schools**	**single species school size**	**mixed species school size**	**overall school size**	**% total sightings**	**# single species schools**	**# mixed species schools**	**single species school size**	**mixed species school size**	**overall school size**	**% total sightings**
Striped dolphin	77	7	44.8 *(39.5)*	170.7 *(123.2)*	55.3 *(61.3)*	20.0	1	5	29	389.9 *(274.1)*	329.8 *(286.0)*	1.8
Bottlenose dolphin	29	27	29.2 *(70.3)*	61.7 *(38.6)*	44.9 *(59.1)*	13.3	5	6	14.8 *(7.1)*	28.9 *(28.7)*	22.5 *(22.1)*	3.2
unidentified dolphin species	94	6	11.9 *(17.1)*	52.1 *(40.4)*	14.3 *(21.2)*	23.8	19	0	6.6 *(4.8)*	n/a	6.6 *(4.8)*	5.6
Dusky dolphin	4	1	39.9 *(35.7)*	1,167.0	265.3 *(504.8)*	1.2	0	0	n/a	n/a	n/a	0.0
Pygmy killer whale	2	0	14.7 *(17.9)*	n/a	14.7 *(17.9)*	0.5	0	0	n/a	n/a	n/a	0.0
False killer whale	3	2	30.1 *(17.2)*	60.5 *(20.5)*	42.3 *(23.0)*	1.2	0	0	n/a	n/a	n/a	0.0
Pantropical spotted dolphin	35	31	105.9 *(117.8)*	261.9 *(207.0)*	180.3 *(182.8)*	15.7	0	0	n/a	n/a	n/a	0.0
Rough-toothed dolphin	6	2	12.2 *(10.8)*	49.9 *(54.3)*	21.6 *(28.4)*	1.9	0	0	n/a	n/a	n/a	0.0

Table 2.1 cont’d

	Tropical						**Temperate**					
Species	**# single species schools**	**# mixed species schools**	**single species school size**	**mixed species school size**	**overall school size**	**% total sightings**	**# single species schools**	**# mixed species schools**	**single species school size**	**mixed species school size**	**overall school size**	**% total sightings**
Spinner dolphin	11	30	123.0 *(131.8)*	267.9 *(207.5)*	229.0 *(199.5)*	9.8	0	0	n/a	n/a	n/a	0.0
Pacific white-sided dolphin	0	0	n/a	n/a	n/a	0.0	16	7	8.7 *(10.4)*	85.3 *(46.1)*	31.7 *(43.9)*	6.8
Northern right-whale dolphin	0	0	n/a	n/a	n/a	0.0	28	8	14.9 *(16.0)*	78.8 *(45.5)*	27.7 *(35.2)*	10.7
Dall’s porpoise	0	0	n/a	n/a	n/a	0.0	101	0	3.2 *(2.3)*	n/a	3.2 *(2.3)*	30.0
Harbor porpoise	0	0	n/a	n/a	n/a	0.0	31	0	2.0 *(1.0)*	n/a	2.0 *(1.0)*	9.2
Totals	353	67	74.6 *(166.2)*	182.0 *(215.2)*	91.4 *(178.8)*		314	23	38.6 *(155.3)*	116.9 *(191.9)*	43.9 *(159.0)*	

Table 2.2. Number of mixed and single species schools that were encountered while the towed hydrophone array was being monitored and percent of each for which whistles were detected in the tropical study area, in the temperate study area, and for both study areas combined.

	single species		**mixed species**	
Study area	**n**	**% whistling**	**n**	**% whistling**
Tropical	169	66	55	98
Temperate	204	24	15	23
Both	373	42	70	81

Table 2.3. Number of schools of whistling species encountered while the towed hydrophone array was being monitored and the percentage of schools for which whistles were detected in the tropical and temperate study areas.

	Tropical		**Temperate**	
Species	**n**	**% whistling**	**n**	**% whistling**
Single species schools				
Long-beaked common dolphin	2	100	1	100
Short-beaked common dolphin	24	92	51	84
Risso's dolphin	13	23	15	0
Short-finned pilot whale	11	45	0	n/a
Pacific white-sided dolphin	0	n/a	6	0
Dusky dolphin	2	0	0	n/a
Pantropical spotted dolphin	8	62	0	n/a
Spinner dolphin	6	83	0	n/a
Striped dolphin	45	75	0	n/a
Rough-toothed dolphin	4	50	0	n/a
Bottlenose dolphin	14	78	4	0
Northern right-whale dolphin	0	n/a	20	0
Mixed species schools				
Long-beaked common and dusky dolphins	1	100	0	n/a
Short-beaked common and striped dolphins	3	100	2	100
Bottlenose and Risso's dolphins	4	100	2	50
Bottlenose dolphin and short-finned pilot whale	6	100	0	n/a
Bottlenose and rough-toothed dolphins	1	100	0	n/a
Bottlenose and striped dolphins	1	100	0	n/a
Pantropical spotted and spinner dolphins	18	100	0	n/a
Striped and Risso's dolphins	1	100	0	n/a
Striped and spinner dolphins	1	100	0	n/a
Pacific white-sided and Northern right-whale dolphins	0	n/a	5	0
Risso's and Northern right-whale dolphins	0	n/a	2	0

Table 2.4. Acoustic detection distances (mean and standard deviation) for species encountered in the tropical and temperate study areas. Data are separated by study area for the only species acoustically detected in both study areas (short-beaked common dolphin). Overall mean and standard deviation are given for each study area and for both study areas combined.

Species	**Mean**	**St Dev**
Pantropical spotted dolphin	1.69	1.13
Spinner dolphin	2.9	2.09
Striped dolphin	2.76	1.63
Rough-toothed dolphin	1.36	1.21
Short-finned pilot whale	3.22	1.23
Killer whale	0.62	0.18
Bottlenose dolphin	1.71	1.63
Risso's dolphin	1.3	0.57
Pacific white-sided dolphin	0.64	0.82
Northern right-whale dolphin	0.44	0.68
Long-beaked common dolphin	2.25	0.12
Short-beaked common dolphin		
temperate	1.67	1.54
tropical	3.29	1.86
Overall temperate	2.16	1.84
Overall tropical	3.61	1.91
Overall	3.26	3.95

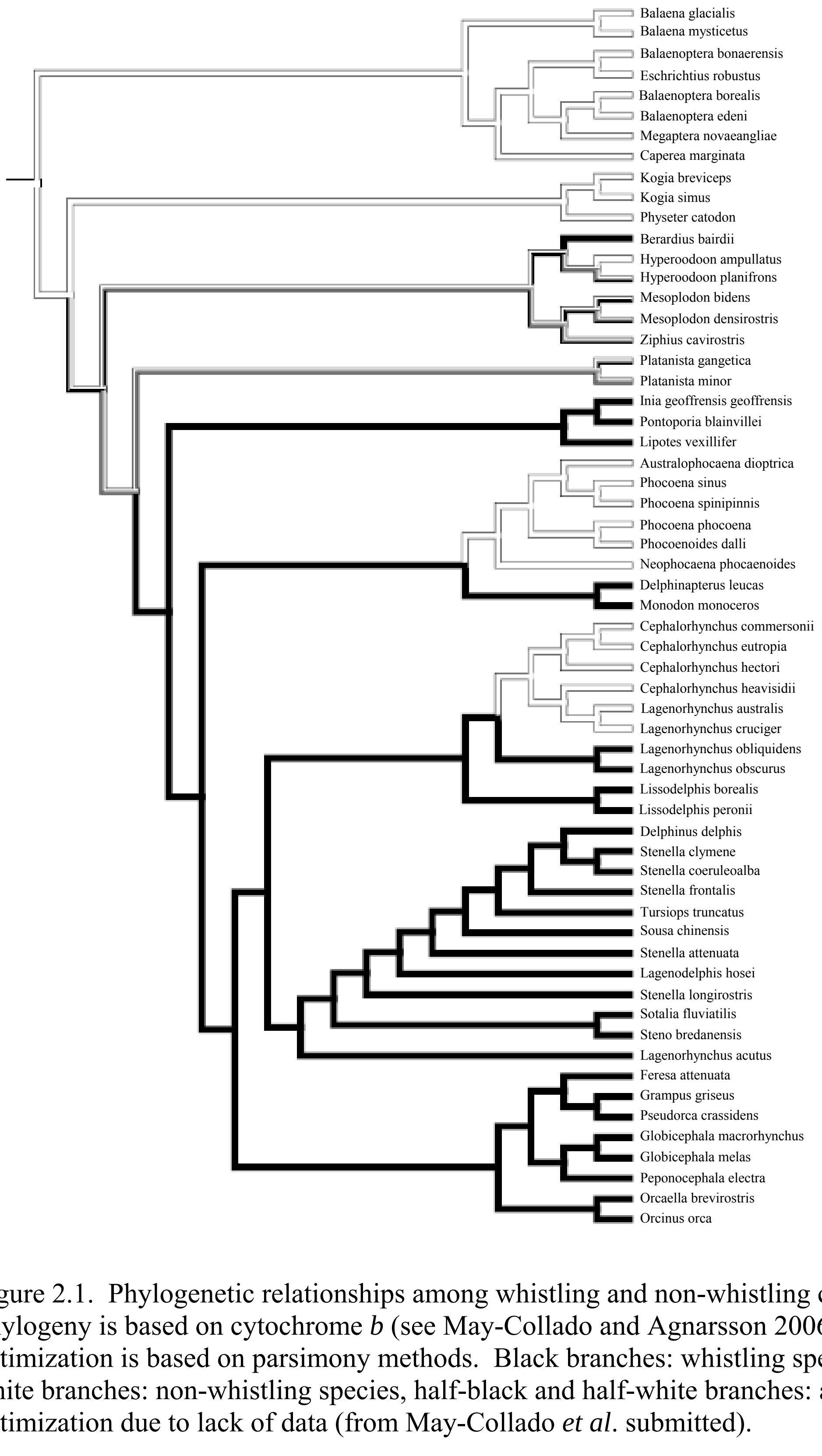

Figure 2.1. Phylogenetic relationships among whistling and non-whistling cetaceans. Phylogeny is based on cytochrome *b* (see May-Collado and Agnarsson 2006) and optimization is based on parsimony methods. Black branches: whistling species, white branches: non-whistling species, half-black and half-white branches: ambiguous optimization due to lack of data (from May-Collado *et al*. submitted).

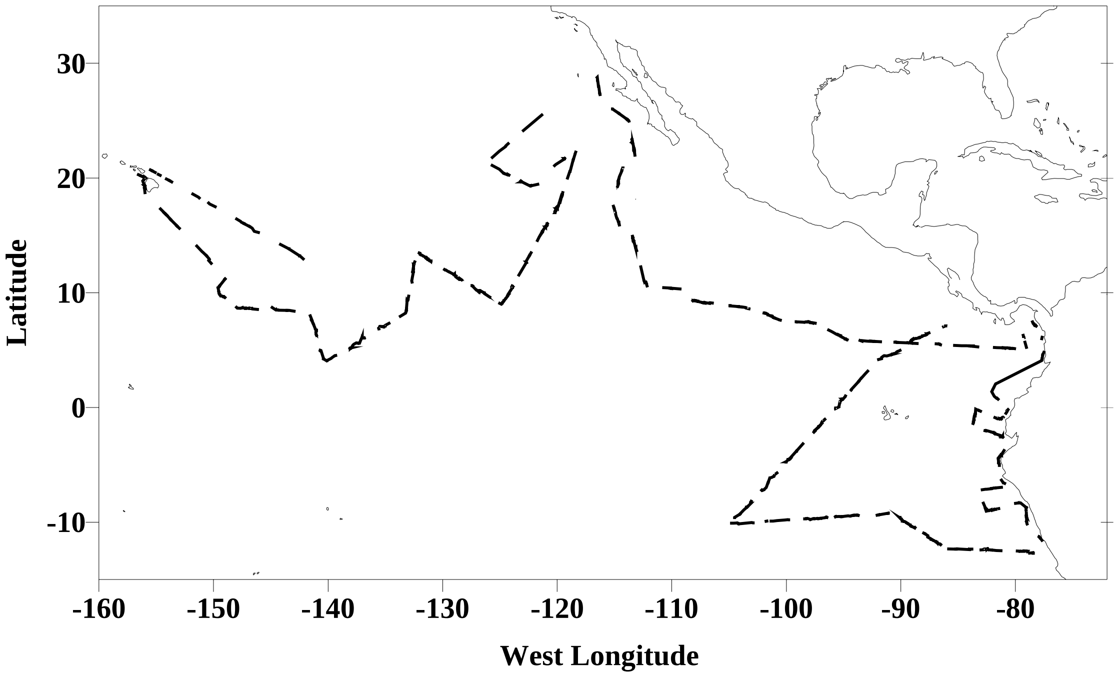

Figure 2.2. Eastern tropical Pacific study area and trackline of acoustic effort for STAR 2000 marine mammal abundance survey.

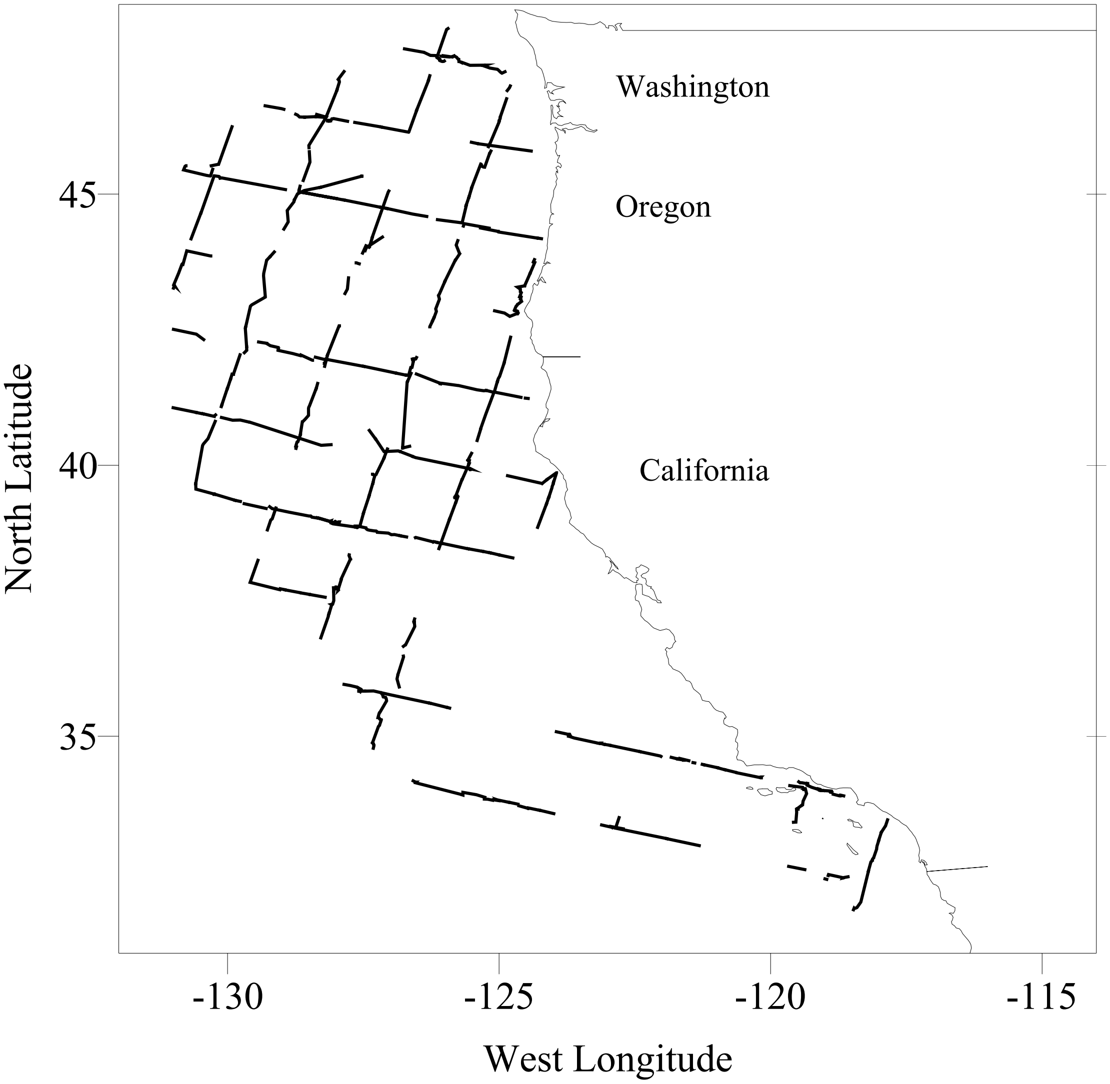

Figure 2.3. Temperate study area and trackline of acoustic effort for ORCAWALE 2001 marine mammal abundance survey.

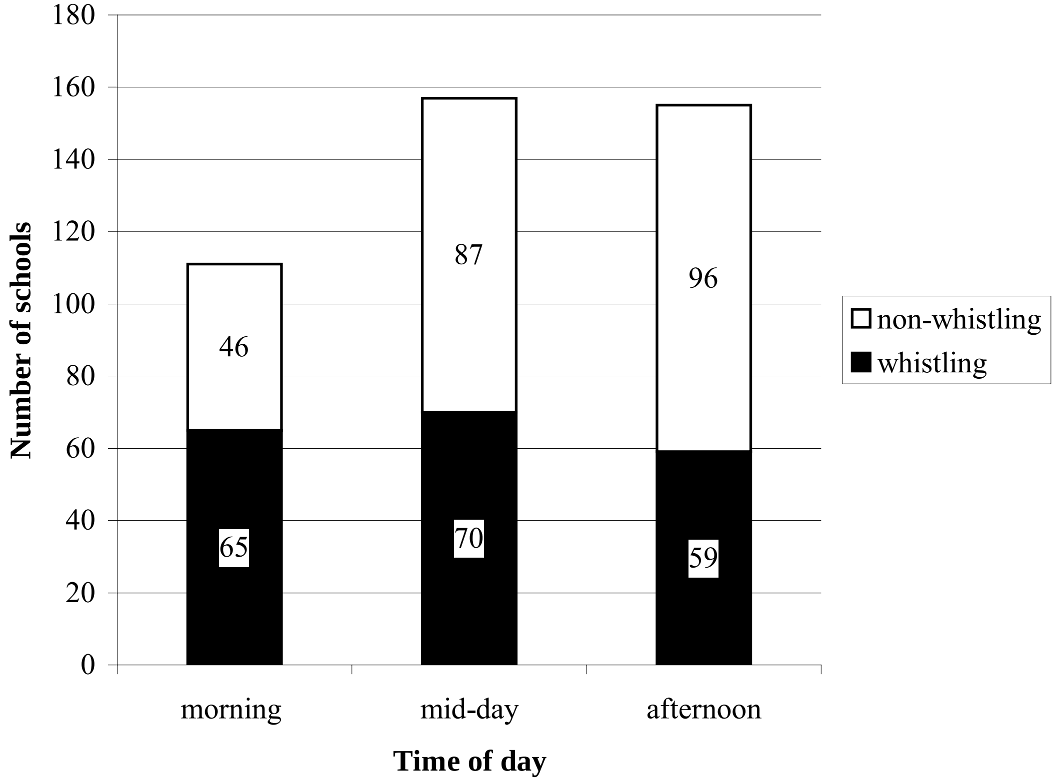

Figure 2.4. Number of whistling and non-whistling schools encountered while the array was being monitored during the STAR and ORCAWALE surveys. Morning = sunrise – 10 am, mid-day = 10 am – 2 pm, afternoon = 2 pm – sunset.

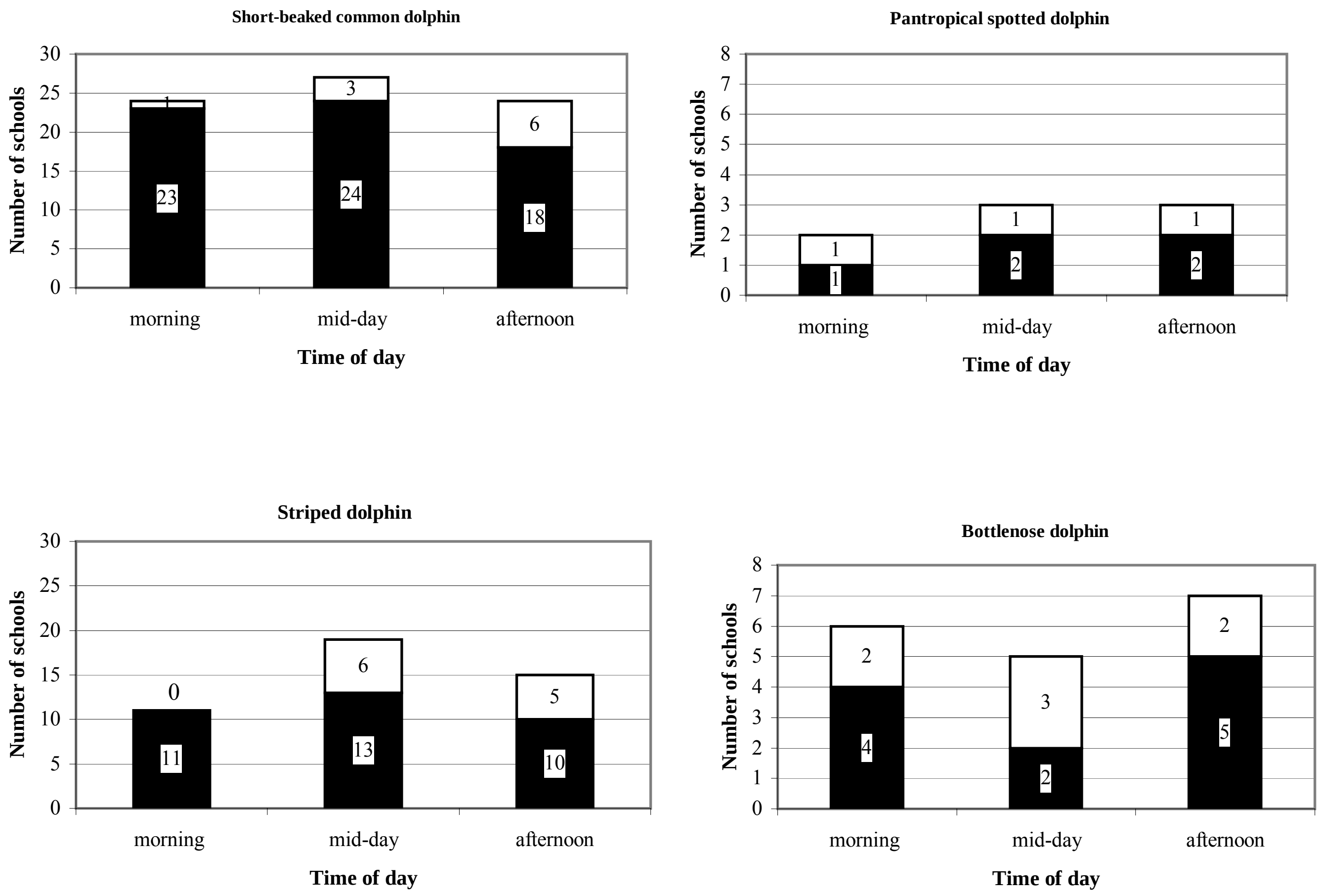

Figure 2.5. Number of whistling and non-whistling schools encountered in the eastern tropical Pacific and northern study areas by species and time of day. Morning = sunrise – 10am, mid-day = 10am – 2pm, afternoon = 2pm – sunset. Black bars represent whistling groups and white bars represent non-whistling groups

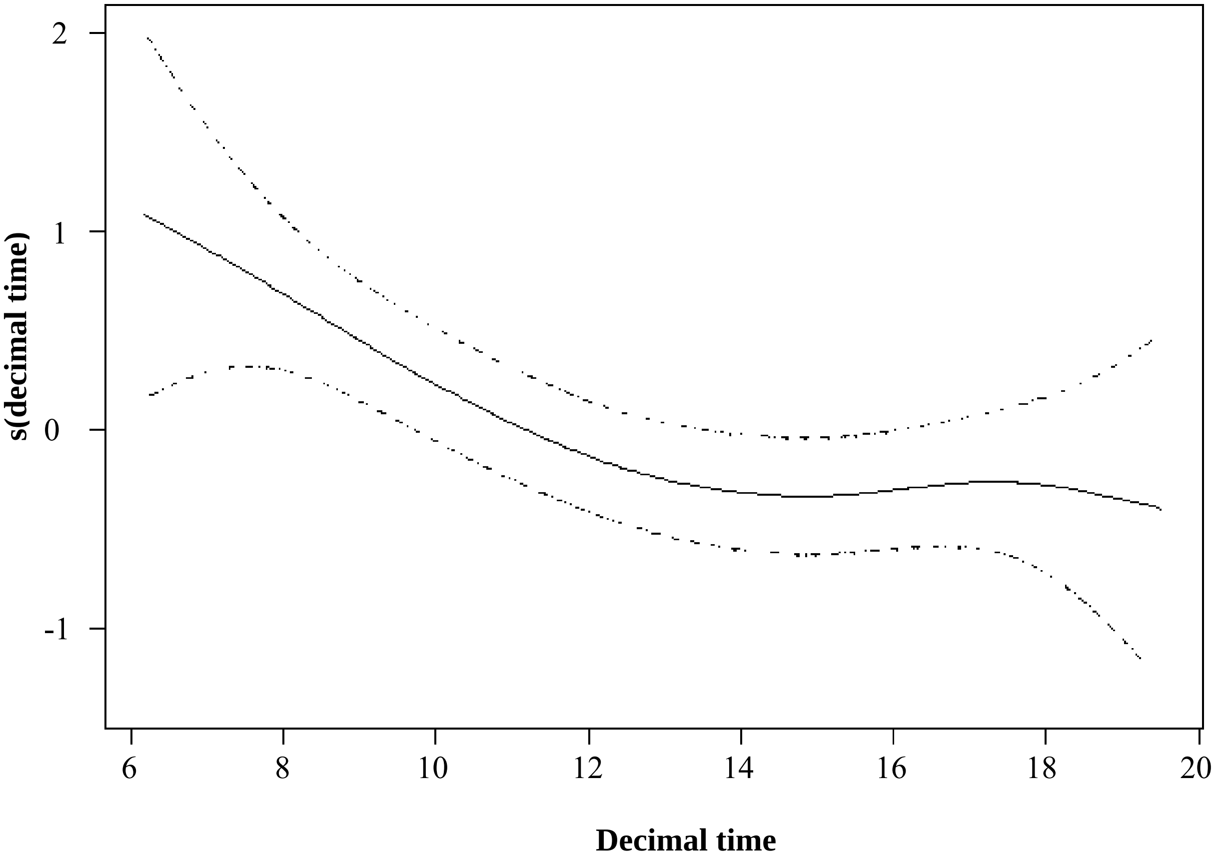

Figure 2.6. Response plot for GAM (logit link function, smoothing spline, three degrees of freedom) with whistling as the dependent variable and decimal time as the continuous independent variable. The solid line is the mean response curve and the dashed lines are the confidence intervals around the mean response. Greater values in this plot represent a greater probability that a group will have been whistling at that time of day.

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CHAPTER III

First Description of Whistles of Pacific Fraser's dolphins, *Lagenodelphis hosei*

Abstract

Acoustic recordings were made in the presence of four single-species schools of Fraser's dolphins, *Lagenodelphis hosei*, during combined acoustic and visual shipboard line-transect cetacean abundance surveys. Recordings were made using a towed hydrophone array and type SSQ-57A sonobuoys. Echolocation clicks were detected during only one recording session and no burst pulses were detected. Whistles were present in all four acoustic detections. Fourteen variables were measured from a total of 60 whistles. The whistles were generally simple, with few inflection points or steps. Whistles ranged in frequency from 6.6 kHz to 23.5 kHz, with durations ranging from 0.06 to 0.93 sec. Whistle characteristics closely match those reported for *L. hosei* recorded in the Gulf of Mexico (Leatherwood *et al*. 1993) and the Caribbean (Watkins *et al*. 1994), although, in general, the Pacific dolphins were less vocally active than the Caribbean dolphins described by Watkins et al. (1994). This difference may be related to the orientation of the hydrophone array relative to the dolphins. It may also be due to behavior, as the Caribbean dolphins were engaged in feeding activities and the Pacific dolphins were fast traveling to evade the approaching vessel.

Introduction

Fraser's dolphins, *Lagenodelphis hosei*, were first described in 1956 based on the skeleton of a stranded animal found in the South China Sea (Perrin *et al*. 1994). Scientific description of the species based on live animals was not made until 1971, when three nearly concurrent sightings of *L. hosei* were made in three locations worldwide (Perrin *et al.* 1973). *Lagenodelphis hosei* is a tropical offshore species, with a distribution ranging from 30ºN to 30ºS in the Pacific, Atlantic, and Indian Oceans (Rice 1998). They are generally found in large schools and are often associated with other species, especially melon-headed whales, *Peponocephala electra* (Au and Perryman 1985).

Few published reports of observations of free-ranging *L. hosei* exist (Jefferson and Leatherwood 1994, Perrin *et al*. 1994), and information on their vocalizations is rarer still. Vocalizations of *L. hosei* have been described based on one recording made in the Gulf of Mexico in 1992 (Leatherwood *et al*. 1993) and two recordings made in the Caribbean in 1991(Watkins *et al*. 1994). The eight whistles recorded from *L. hosei* in the Gulf of Mexico were found to be either short duration (0.2 sec) whistles centered at approximately 12 kHz, or longer whistles (0.4-0.5 sec) centered between 7 kHz and 14 kHz (Leatherwood *et al.* 1993). The 166 whistles analyzed from the Caribbean detections had fundamental frequencies between 4.3 kHz and 24 kHz and an average duration of 0.77sec (Watkins *et al*. 1994). Watkins *et al*. (1994) also noted that the production of one whistle often lead to the production of other whistles, such that most recordings contained overlapping sequences of whistles. Many of the whistles were repeated in stereotyped fashion, and an increase in surface behavior was often associated with an increase in whistle production (Watkins *et al*. 1994). Echolocation clicks were detected during the Gulf of Mexico recording; however, the limited bandwidth of their recordings precluded examination of these sounds (Leatherwood *et al*. 1993). Click trains associated with echolocation were detected during both Caribbean recordings, where animals were observed herding large schools of fish (Watkins *et al*. 1994). No burst pulses were reported in either study.

Leatherwood *et al*. (1993) and Watkins *et al*. (1994) both describe sounds produced by Atlantic *L. hosei*. To our knowledge, there have been no published descriptions of the vocalizations of Pacific *L. hosei*. This paper provides a description of the whistles produced by *L. hosei* recorded from four single-species schools in the central and eastern tropical Pacific Ocean.

Methods

Recordings were made during three different shipboard line-transect surveys in the tropical Pacific Ocean conducted by the Southwest Fisheries Science Center (NOAA, NMFS). The Stenella Population Assessment and Monitoring (SPAM 1998) and Stenella Abundance Research (STAR 2003) surveys were designed to study cetacean populations impacted by the tuna purse-seine fishery in the eastern tropical Pacific Ocean (ETP). The Pacific Islands Cetacean Ecosystem Assessment Survey (PICEAS 2005) was focused on cetacean populations surrounding Johnston and Palmyra Atolls, 800 nmi south of the Hawaiian Islands. During all surveys, a team of three experienced biologists actively searched for marine mammals using two sets of 25x150 binoculars and near-field observation by naked eye. When cetaceans were sighted, they were approached for species identification and group size estimation. Cetacean vocalizations were monitored and recorded using a towed hydrophone array and U.S. Navy surplus type SSQ-57A sonobuoys. The array was towed 200 m behind the research vessel at a depth of approximately 4-6 m during all daylight hours on all three surveys. Characteristics of the three arrays used during these surveys are given in Table 3.1. During the SPAM survey, signals were recorded onto digital audio tape (DAT) using Sony TCD-D7 and TCD-D8 DAT recorders (sampling rate = 48 kHz). During the STAR and PICEAS surveys, signals from the array were sent through a Mackie CR1604-VLZ mixer for equalization and an Avens Model 4128 bandpass filter for anti-aliasing. The sounds were then recorded directly to a computer hard drive using a 200 kHz sampling rate. Additionally, during the STAR survey, Navy surplus type SSQ-57A sonobuoys (flat frequency response approximately 10 Hz to 20 kHz) were deployed from the ship in close proximity to dolphins. Signals from the sonobuoys were transmitted to the ship via radio frequency, received by an ICOM R100 radio receiver in the acoustics lab, and recorded to a Sony TCD-D7 DAT recorder (sampling rate = 48 kHz).

Only recordings of groups that had been seen and identified by experienced biologists were included in the analysis. To ensure that the whistles being recorded were produced by the dolphins being observed, only whistles that were clearly visible above the background noise in the spectrogram were analyzed. These ‘loud and clear’ whistles were assumed to be produced by the animals being observed close to the ship and not more distant animals that may have been in the area. In addition, with one exception, recordings were only included if there were no other dolphins sighted within at least 3 nmi of the dolphins being observed. An exception was made for one recording session during the PICEAS survey (sighting number 101, Table 3.2). When this recording was made there was a group of *P. electra* in the area. The recording was included in the analysis, however, because during the PICEAS survey, whistles were localized using a beamforming algorithm in the spectrographic software application ISHMAEL (Mellinger 2001). The two species in the area were in very different locations relative to the ship, which made it possible to match the source of the whistles to the location of the *L. hosei* and rule out the possibility that they were produced by the *P. electra*.

Loud and clear whistles that did not overlap extensively with other whistles were chosen for analysis. In order to be of sufficient quality for analysis, the entire whistle contour must be clearly visible on the spectrogram. Whistle contours were extracted and measurements were made using custom matlab software (M. Lammers, J. Oswald). Fourteen variables were measured from each whistle, including: 1) median frequency (kHz), 2) start frequency (kHz), 3) end frequency (kHz), 4) minimum frequency (kHz), 5) maximum frequency (kHz), 6) frequency range (kHz, maximum frequency minus minimum frequency), 7) duration (sec), 8) number of steps (defined as a 10% or greater change in frequency over two contour points), 9) number of inflection points (defined as a change from positive to negative or negative to positive slope), 10) mean slope (kHz/sec), 11) percent upswept (percent of whistle with positive slope), 12) percent downswept (percent of whistle with negative slope), 13) percent flat (percent of whistle with zero slope), and 14) presence/absence of harmonics (binary variable).

Results

A hydrophone array was towed for approximately 17,980 km during the SPAM survey (31 July to 9 December 1998, Figure 3.1), 9,274 km during the STAR survey (7 October to 10 December 2003, Figure 3.1), and 15,183 km during the PICEAS survey (28 June to 12 November 2005, Figure 3.1). Due to weather conditions, the hydrophone array was not deployed on 16-17 October 2003. U. S. Navy sonobuoys were opportunistically deployed on dolphin sightings during this time.

A total of six schools of *L. hosei* were sighted during the three surveys (Table 3.2, Figure 3.1). Of these sightings, four were single-species schools, one was a school composed of *L. hosei* and *P. electra*, and one was a school composed of *L. hosei* and an unidentified dolphin species (possibly *Stenella coeruleoalba*). Recordings were obtained from all four of the single-species schools. Recordings made during SPAM and PICEAS were made using a towed hydrophone array. Recordings made during STAR were made using a sonobuoy. The schools observed were large, ranging from 60 to 475 individual dolphins. All of the schools exhibited evasive behavior when approached by the research vessel. Observations lasted from 35 minutes to 2 hours for each school (Table 3.2).

Relatively few vocalizations were detected during the four single-species recording sessions. Echolocation clicks were detected only during the SPAM 1998 recording session. These clicks had very low signal to noise ratio and thus could not be analyzed. No burst pulses were detected on any of the recordings. A total of 60 whistles were analyzed from the four recording sessions (Table 3.2). Descriptive statistics for these whistles are given in Table 3.3. The whistles were generally simple, with few inflection points or steps. The overall mean slope of the whistles was positive (5.9 kHz/sec, SD = 9.7 kHz/sec), and 40% of whistles had a positive slope for at least 80% of their duration. Only 3.3% of whistles had a negative slope for at least 80% of their duration. Overall, whistles ranged in frequency from 6.6 kHz to 23.5 kHz (mean minimum frequency = 11.0 kHz, SD = 2.3 kHz; mean maximum frequency = 14.9 kHz, SD = 3.4 kHz). The frequency range of individual whistles however, was relatively narrow (mean = 3.9 kHz, SD = 2.3 kHz), and was centered at 13 kHz (±2.7 kHz). Harmonics were present in only 10% of the measured whistles. Some examples of whistles included in the analysis are shown in Figure 3.2.

Discussion

This study represents the first description of the whistles of *L. hosei* in the Pacific Ocean. These whistles closely resemble those recorded in the Caribbean (Watkins *et al*. 1994) and Gulf of Mexico (Leatherwood *et al*. 1993). Mean start (11.9

kHz) and end (13.9 kHz) frequencies of the Pacific ocean whistles were remarkably similar to those reported for the Caribbean by Watkins *et al*. (1994) (mean start frequency = 11.9 kHz, mean end frequency = 13.1 kHz). The whistles recorded during both studies had similar frequency ranges (approximately 5 kHz to 24 kHz), with the Pacific ocean whistles having a slightly higher mean minimum frequency (11 kHz vs. 9 kHz) and a slightly lower mean maximum frequency (14 kHz vs. 17 kHz) than the Caribbean whistles. The Pacific whistles had a slightly shorter mean duration than the Caribbean whistles (0.46 sec vs. 0.77 sec), but were similar in duration to the 0.2 – 0.5 sec reported by Leatherwood *et al*. (1993) for whistles recorded in the Gulf of Mexico.

The major difference between the recordings described by Watkins *et al*. (1994) and those described here is that Watkins *et al*. (1994) reported 'considerable underwater sound production', including many overlapping whistles as well as echolocation clicks. Despite the fact that the research vessel was able to approach to within 500 m of all four schools that were recorded for the current study, most of the recordings contained few whistles. Very few echolocation clicks were detected and both the echolocation clicks and many of the whistles had relatively low signal-to-noise ratio. One of the recordings made during the PICEAS survey (sighting 130, Table 3.2) contained a brief period of high vocal activity which including overlapping whistles but many of these whistles also had relatively low signal-to-noise ratio.

This difference in vocal activity is likely related to two factors. The first is the constant maneuvering of the ship required for the approach and observation of evasive dolphin schools. This maneuvering inevitably keeps the dolphins directly ahead of the bow of the ship for the bulk of the encounter. The towed hydrophone array has decreased sensitivity to sounds forward of the ship due to the sensitivity of the cylindrical hydrophone elements and to masking by ship noise. Therefore, fewer sounds from directly ahead of the ship will be clear enough for detection and measurement. This factor did not affect the recordings made during STAR, as these recordings were made using a sonobuoy. In this case, the sonobuoy was dropped in close proximity to the dolphins and the ship moved away while monitoring signals being detected by the sonobuoy.

A second factor that may explain the observed differences in vocal activity is group behavior. The high level of vocal activity reported by Watkins *et al.* (1994) occurred while the dolphins were driving, circling, and catching fish. There was an observed increase in the production of clicks during fish herding behavior and an increase in whistle production after fish herding behavior. During travel, few whistles or clicks were detected. One of the recordings presented in the current study (PICEAS sighting 130) contained a brief period of relatively high vocal behavior near the beginning of the encounter. At this time, the dolphins were observed to be in a loosely aggregated school and many leaps and splashes were noted. When the ship turned towards the dolphins they changed their behavior to fast travel away from the ship and their vocal activity decreased. This is consistent with Watkins *et al.*'s (1994) observation of an increase in vocal activity with increased surface activity and a decrease in vocal activity during travel. The other three groups that were recorded during the current study were initially traveling or milling and exhibited a marked change in behavior to fast travel away from the ship as the ship changed course to approach them. Fast travel away from the ship appeared to be an effort to evade the ship. The paucity of vocalizations detected in these situations suggests that the dolphins may have perceived an immediate threat and tended towards silence in order to avoid detection. These observations are also consistent with Watkins *et al.*'s (1994) observation of very few vocalizations during travel.

Lagenodelphis hosei is a poorly understood species. Live specimens had not been observed until the 1970s (Perrin *et al.* 1973) and sightings have been rare during cetacean surveys ever since. Despite significant survey effort (over 11 months and 42,000 km), only six groups of *L. hosei* were sighted during the three surveys discussed here. An understanding of the vocalizations produced by species such as *L. hosei* can lead to the ability to acoustically identify this species during shipboard acoustic surveys (Oswald *et al.* 2005, Oswald *et al.* 2003). Acoustic identification of dolphin vocalizations will also allow for an examination of temporal and spatial distribution of species using seafloor-mounted hydrophones. The recordings obtained during these surveys therefore represent an important step forward in the endeavor to gain knowledge about this seldom-observed species. Future studies should include broadband recordings of *L. hosei* in different behavior states and incorporation of their whistle characteristics into acoustic species identification algorithms.

Acknowledgements

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The text of chapter three, in full, has been submitted to the journal Bioacoustics (Oswald, J.N, S. Rankin, and J. Barlow. Submitted. First description of the whistles of Pacific Fraser's dolphins, *Lagenodelphis hosei*). The disseration author was the primary researcher and author and the co-authors listed in this manuscript supervised the research that forms the basis for this chapter

Table 3.1. Characteristics of hydrophone arrays used and sampling rates of recordings made during the SPAM 1998, STAR 2003 and PICEAS 2005 marine mammal abundance surveys. The array used during the PICEAS survey had 4 elements, 3 relatively narrowband and 1 relatively broadband.

Cruise	**# Hydrophone elements**	**Flat frequency response (re 1v/µPa)**	**Manufacturer**	**Sampling rate (kHz)**
SPAM	5	500 Hz to 150 kHz at –163 dB ±3 dB	SonaTech Inc., Santa Barbara	48
STAR	3	500 Hz to 30 kHz at –155 dB ±5 dB	Built in-house	200
PICEAS	3	1 kHz to 40 kHz at –150 dB ±5 dB	Built in-house	200
	1	2 kHz to 150 kHz at –166 dB ±2 dB	Seiche Measurements, Ltd., Devon, UK	200

Table 3.2. Date, location, and group size for all *Lagenodelphis hosei* groups encountered during SPAM 1998, STAR 2003, and PICEAS 2005 marine mammal abundance surveys. Sighting number is the identification number assigned to the encounter. Group size is the mean of the best estimates made by all biologists who observed the encounter. Other species refers to additional species seen in the group. Observation time refers to the amount of time spent observing the school visually and/or acoustically. Recording time refers to the length of acoustic recordings analyzed. Number of whistles refers to the number of whistles that were of sufficient quality to be included in the analysis.

Cruise	**Date**	**Sighting number**	**Latitude**	**Longitude**	**Group size**	**Other species**	**Observation time (minutes)**	**Recording time (minutes)**	**# Whistles**
SPAM	8/16/1998	104	N 01:30.17	W 129:35.37	299	unidentified dolphin species	120	n/a	n/a
	8/19/1998	113	N 06:59.32	W 136:59.10	42	no	73	73	7
	9/6/1998	143	N 05:29.23	W 146:37.59	475	*Peponocephala electra*	43	n/a	n/a
STAR	10/17/03	401	S 09:32.69	W 099:45.22	60	no	65	46	10
PICEAS	8/22/2005	101	N 3:11.14	W 163:47.69	222	no	120	52	15
	8/25/2005	130	N 6:56.41	W 161:07.74	186	no	35	95	28

Table 3.3. Descriptive statistics for variables measured from 60 whistles recorded in the presence of four single species groups of *Lagenodelphis hosei* in the tropical Pacific ocean. 'Flat' was defined as a 1% or less change in slope over two contour points.

	Frequency (kHz)												
	Median	**Start**	**End**	**Min**	**Max**	**Range**	**Duration (sec)**	**# Steps**	**# Inflection points**	**Mean slope (kHz/s)**	**% Up-swept**	**% Down-swept**	**% Flat**
Mean	13.0	11.9	13.9	11.0	14.9	3.9	0.46	0.7	0.8	5.9	67.3	23.7	8.9
Std dev	2.7	2.9	3.5	2.3	3.4	2.3	0.23	1.2	0.7	9.7	30.4	27.9	12.9
Min	7.0	7.5	8.3	6.6	8.3	0.1	0.06	0.0	0.0	-19.8	0.0	0.0	0.0
Max	18.4	18.8	23.5	18.3	23.5	9.6	0.93	8.0	3.0	35.8	100.0	100.0	66.7

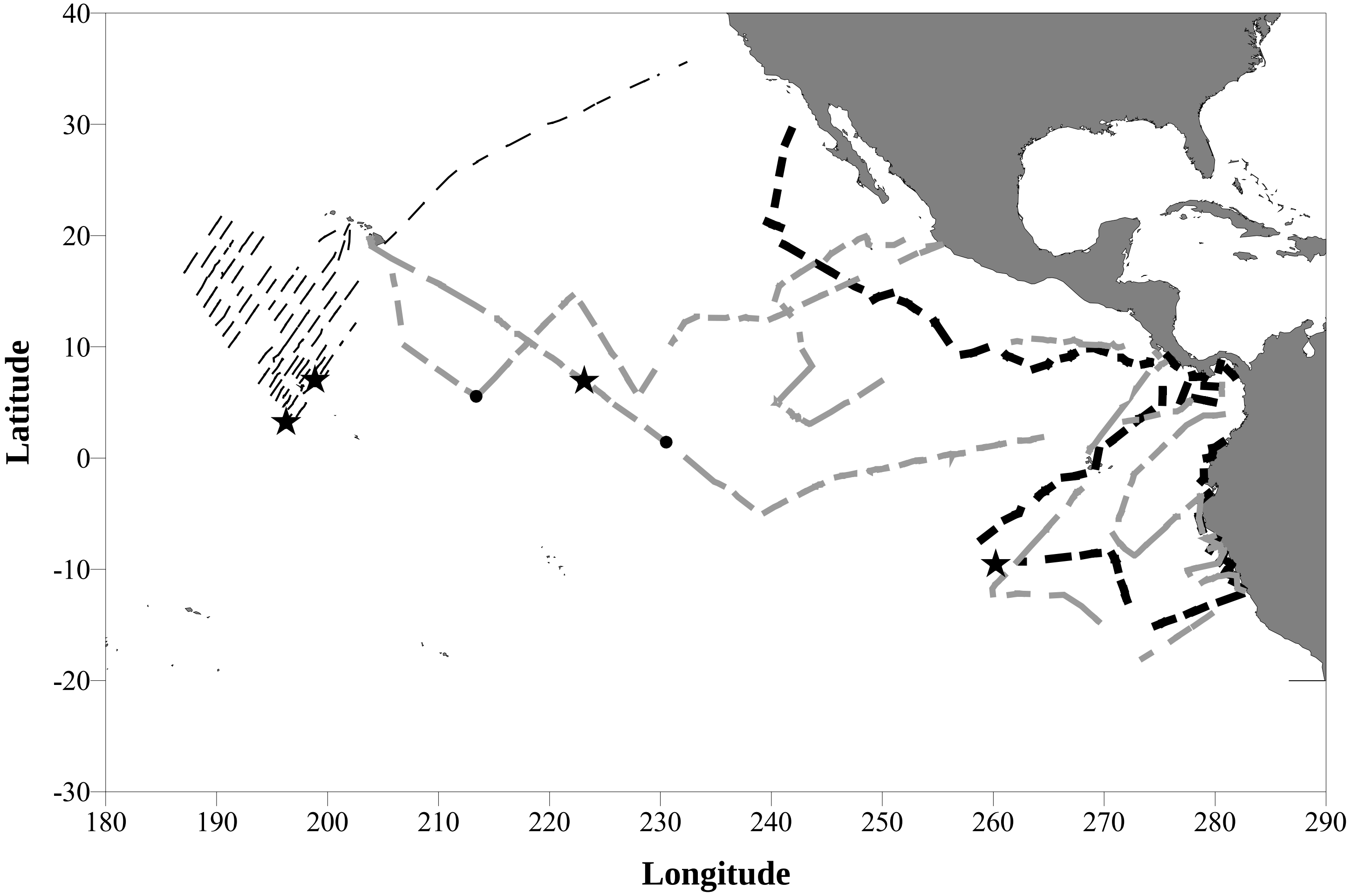

Figure 3.1. Acoustic survey effort for SPAM 1998 (thick gray lines), STAR 2003 (thick black lines) and PICEAS 2005 (thin gray lines). Stars represent visual and acoustic detections of single-species schools of *Lagenodelphis hosei*. Circles represent visual and acoustic detections of mixed-species schools containing *Lagenodelphis hosei*.

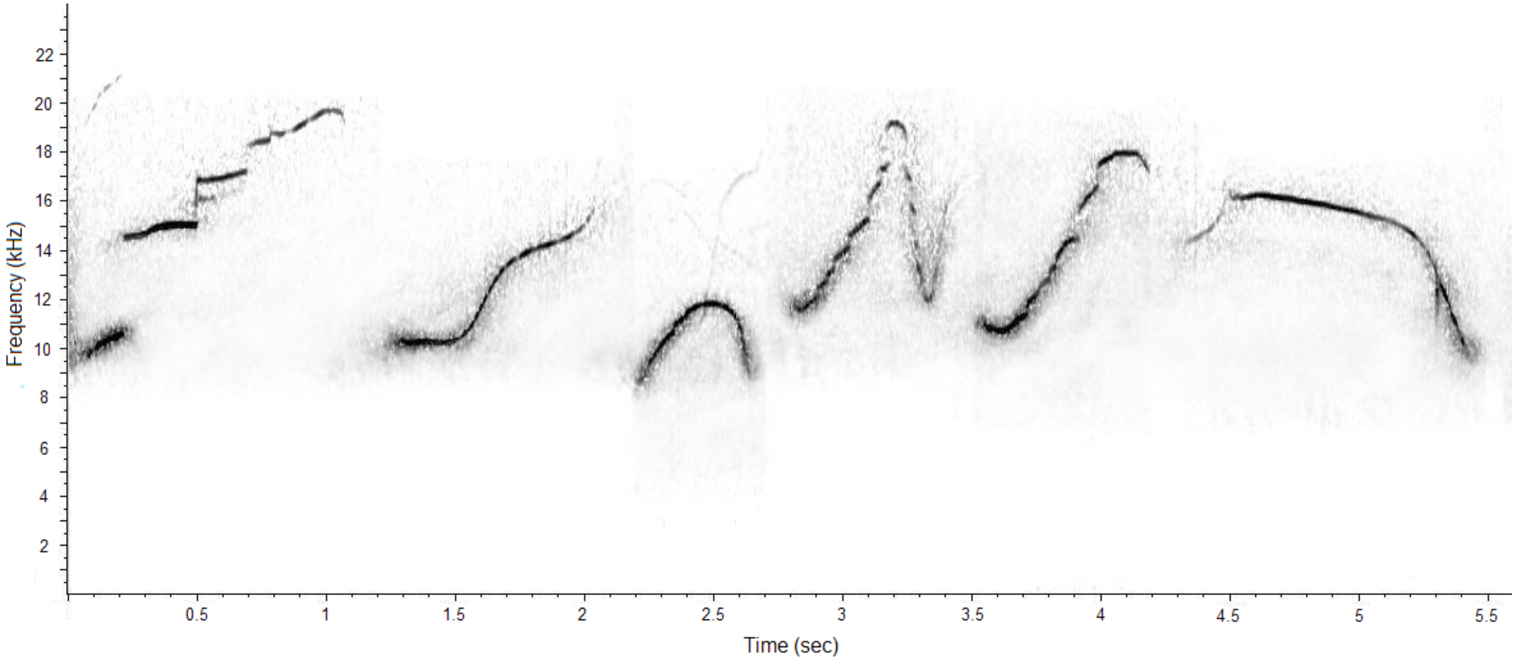

Figure 3.2. Spectrogram of *Lagenodelphis hosei* whistles recorded in the tropical Pacific ocean (512 point FFT, hanning window).

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CHAPTER IV

Acoustic Identification of Nine Delphinid Species in the Eastern Tropical Pacific Ocean

Abstract

Acoustic methods may improve the ability to identify cetacean species during shipboard surveys. Whistles were recorded from nine odontocete species in the eastern tropical Pacific to determine how reliably these vocalizations can be classified to species based on simple spectrographic measurements. Twelve variables were measured from each whistle (n = 908). Parametric multivariate discriminant function analysis (DFA) correctly classified 41.1% of whistles to species. Non-parametric classification and regression tree (CART) analysis resulted in 51.4% correct classification. Striped dolphin whistles were most difficult to classify. Whistles of bottlenose dolphins, false killer and pilot whales were most distinctive. Correct classification scores may be improved by adding prior probabilities that reflect species distribution to classification models, by measuring alternative whistle variables, using alternative classification techniques, and by localizing vocalizing dolphins when collecting data for classification models.

Introduction

Visual detection and identification of cetaceans during shipboard surveys is often constrained by inclement weather, darkness, and animal behavior. Sound propagates long distances in the ocean (Medwin and Clay 1998) and many cetaceans are extremely vocal (Richardson *et al*. 1995). As a result, acoustic techniques can augment visual surveys by providing methods for detection and identification of cetaceans when they are likely to be missed by visual observers. The use of acoustic techniques to compliment visual efforts has increased rates and distances of detection for several cetacean species, including: humpback whales (*Megaptera novaeangliae*, Winn *et al*. 1975), sperm whales (*Physeter macrocephalus*, Leaper 1992), blue and fin whales (*Balaenoptera musculus* and *B. physalus*, Clark and Fristrup 1997), bowhead whales (*Balaena mysticetus*, Clark and Ellison 2000), striped dolphins (*Stenella coeruleoalba*, Gordon *et al*. 2000), and other delphinids (Thomas *et al*. 1986). While the use of acoustic techniques to detect marine mammals is becoming an increasingly common element of shipboard surveys, acoustic species identification has, until recently, received less attention (Steiner 1981, Potter *et al.* 1994, Schultz and Corkeron 1994, Wang *et al.* 1995, Matthews *et al.* 1999, Rendell *et al.* 1999, Mellinger and Clark 2000).

Using multivariate discriminant function analysis, Steiner (1981) correctly classified the whistles of five western North Atlantic odontocete species 70% of the time. Wang *et al*. (1995) correctly classified 65% of the whistles of seven odontocete species from diverse geographic locations. Rendell *et al*. (1999) correctly classified 55% of the whistles of five odontocete species from several geographic locations. In contrast, Matthews *et al*. (1999) examined the potential for acoustic species recognition using published spectrographic measurements for 10 cetacean species (nine odontocetes and one mysticete) and achieved only 28% correct classification.

To facilitate comparisons among studies, Steiner (1981), Wang *et al.* (1995), Rendell *et al*. (1999), and Matthews *et al*. (1999) reported similar spectrographic measurements. These measurements are ones that can be taken quickly and reliably in the field, which is advantageous if the goal is to aid visual observers with real-time species identification. As an alternative approach, Fristrup and Watkins (1993) devised a number of statistical measures to resolve the many acoustic features used to describe sounds. When these measures were taken from the vocalizations of 53 marine mammal species (including mysticetes, odontocetes and pinnipeds) and linear classification techniques were applied, a correct classification score of 50% was obtained. Fristrup and Watkins (1993) also used tree-based classification models, which classified 66% of vocalizations to the correct species.

Correct classification scores obtained in most whistle classification studies have been significantly greater than would be expected by chance alone, suggesting that differences in whistle structures can be used to identify species. However, in most cases whistles were recorded from only a few different groups of animals. As a result, high correct classification scores could be biased by over-sampling groups or individuals and not controlling for group composition or behavioral variation in call types.

With the exception of Steiner (1981), the aforementioned studies classified the vocalizations of species recorded in widely separated geographic locations. The correct classification scores in these studies may therefore be a function of geographic differences as well as inter-species differences. To determine whether acoustic signals can be useful for species identification during marine mammal surveys, many recordings from a single study area should be classified. In this study, two different statistical methods are used to develop classification systems for the tonal whistles of nine odontocete species recorded in the eastern tropical Pacific Ocean (ETP).

Materials and Methods

Data Collection

Acoustic recordings were made from 31 July through 9 December 1998 and from 28 July through 9 December 1999 during a marine mammal survey conducted in the ETP. The study area extended from the United States/Mexico border to the territorial waters of Peru, and from the continental shores of the Americas to the longitude of Hawaii (Figure 4.1). Visual line-transect methods were used to survey all cetaceans encountered in the study area (Kinzey *et al.* 1999).

During the 1998 survey, a hydrophone array was towed during daylight hours at a depth of 13-20 ft (4-6 m), approximately 656 ft (200 m) behind the 185 ft (56 m) NSF/UNOLS research vessel *Endeavor* while traveling at a speed of 10 kn. The depth of the array was periodically monitored using a Suunto ‘Solution Nitrox’ dive computer. A three element array (SonaTech Inc., flat frequency response ±3 dB from 500 Hz to 150 kHz at –163 dB re 1v/μPa after internal amplification) was used for the majority of the survey. A five-element array (Innovative Transducers Inc., flat frequency response ±3 dB from 32 Hz to 25 kHz at –173 dB re 1v/μPa after internal amplification) was used for approximately one month of the survey. An acoustic technician monitored signals from two hydrophones in the array using a stereo headset and custom-written software that displayed real-time spectrograms from a single channel. Signals were high-pass filtered at 500 Hz – 2 kHz to reduce system, ship, and flow noise and were low-pass filtered at 20 kHz to prevent aliasing. Signals of interest were recorded onto digital audio tape (DAT) using Sony TCD-D7 and TCD-D8 DAT recorders (20 Hz to 22 kHz ± 1 dB).

During the 1999 survey, sonobuoys (type 57A) were deployed when dolphins were sighted. These sonobuoys had a flat frequency response from approximately 2 kHz to 20 kHz, and were deployed at a hydrophone depth setting of either 60 or 90 ft (18 or 27 m). Sonobuoy signals were transmitted to a multi-channel receiver aboard the research vessel (NOAA ships *McArthur* or *David Starr Jordan*) and were recorded onto DAT using Sony TCD-D7 DAT recorders.

Spectrographic Analysis

Recordings of dolphins that had been visually identified to species by experienced marine mammal observers were digitized (44.1 kHz sample rate, 16 bit precision) using a Pentium III dual-processor personal computer and the commercially available software packages *Spectrogram 4.2.8* (R.S. Horne) and *Cool Edit 96* (Syntrillium Corp.). Only recordings of groups that had been observed to contain a single species were digitized. Because it is possible that some recordings identified as "single species" may contain distant faint vocalizations produced by other species in the area, only "loud and clear" whistles were analyzed. Whistles were considered to be "loud and clear" if they were easily detected aurally and by visual inspection of the spectrogram. Richardson *et al*. (1995) suggest that the maximum detection range for many delphinid species is on the order of 1 km (0.54 nmi). To be conservative, recordings made within 3 km (1.62 nmi) of any other sightings were excluded from the analysis. Distance to the next sighting was calculated as the distance between the location of the ship at the beginning of the acoustic recording session and the location of the next group of dolphins when initially sighted (based on angle and reticle measurements read from binoculars). Distance to the previous sighting was calculated as the distance between the location of the ship at the beginning of the acoustic recording session and the location of the previous group of dolphins when last seen.

Spectrograms (512 point FFT, 22 kHz bandwidth) were produced using *Spectrogram 4.2.8* software. Loud and clear tonal whistles that did not overlap extensively with other whistles were randomly chosen for analysis. To avoid oversampling groups or individuals (which can lead to non-independence of data) a maximum of 35 randomly selected whistles were analyzed from each recording session.

Twelve variables were measured from each whistle: 1) beginning frequency (Hz), 2) end frequency (Hz), 3) minimum frequency (Hz), 4) maximum frequency (Hz), 5) duration (msec), 6) slope of the beginning sweep (positive, negative, or zero), 7) slope of the end sweep (positive, negative, or zero), 8) number of inflection points (defined as a change from positive to negative or negative to positive slope), 9) number of steps (defined as a portion of the whistle with zero slope lasting at least 20 ms that separates two portions of similar slope). Similar slope refers to direction, not necessarily magnitude. The angles between the sloped portions and zero slope portion must lie between 90 and 135 degrees), 10) presence/absence of harmonics (a binary variable), 11) off-scale (a binary variable, indicating whether any portion of the whistle extended beyond the 20 kHz upper limit of the spectrogram), and 12) frequency range (Hz; determined by subtracting minimum frequency from maximum frequency). These variables were chosen because they can be easily measured from a spectrogram and to allow comparisons with results of previous studies.

Statistical Analysis

Multivariate discriminant function analysis (DFA) was used to classify whistles within and among species. Prior to running DFA, continuous variables (frequency variables, duration, and number of steps and inflection points) were tested for normality and were square root or log transformed as necessary. Binary and categorical variables were coded as dummy variables. Frequency variables with values above 20 kHz were assigned a value of 22 kHz. Assigning the same value to all off-scale cases reduced the variability of the data, however omitting these cases resulted in lower overall means and a loss of information regarding which portions of the whistles extended beyond 20 kHz.

Discriminant function analysis classified whistles to pre-specified groups based on orthogonal linear functions derived from the measured variables. Some whistles were missing measurements for one or more variables because a portion of the whistle was higher than the maximum recorded frequency of 20 kHz. Whistles that were missing measurements were excluded from the DFA. A series of DFAs was run using the statistical software package SPSS 7.0 (SPSS Inc.). Within each species, the presence of group-specific whistle patterns was examined by using DFA to predict group membership from whistle characters (where a group is defined as a 'recording session' at one time and location). Only recording sessions containing at least three whistles were included in this analysis. Differences among species were examined by using a DFA to predict species from whistle characters.

The jackknife, or cross-validation, method was used to calculate percent correct classification for within-species DFAs. Each whistle was omitted from the total sample and new discriminant functions were calculated for classification of the omitted whistle. A modified jackknife method, omitting entire recording sessions instead of individual whistles, was used to calculate percent correct classification for among-species DFAs. The discriminant functions calculated using this method were created from data independent of the whistles being classified. This helped ensure that whistles were classified based on species-specific characteristics rather than group- or individual-specific characteristics. To evaluate correct classification scores, it is necessary to compare them to what would be expected by chance alone (50% for two species, 33% for three species, 11% for nine species). Chi-square was used to test whether correct classification was significantly greater than expected by chance alone. Statistical significance was evaluated at α=0.05 without corrections for multiple testing.

Tree structured, non-parametric data analysis was performed using CART (Classification And Regression Trees) software (Salford Systems). CART "grows" the largest possible decision tree by separating data into groups (nodes) through a series of binary splits. Each split is based on a value for a single variable, and the criteria used for making splits are known as primary splitting rules. Surrogate splitters are provided at each node. They closely mimic the action of primary splitting rules and can be used in cases when the primary splitting variable is missing. As a result, all with missing values whistles were included in this analysis. Nodes are labeled based on the number of whistles of each species in the node. 'Pure' nodes are nodes that contain the whistles of only one species. Final classification is reached at terminal nodes. When the maximal tree has been grown, CART removes branches and examines the error rates of smaller trees. The smallest tree with the highest predictive accuracy is considered to be the optimal tree. The misclassification rate is estimated using a cross-validation technique similar to the modified jackknife method used in DFA. CART software, however, is not sufficiently flexible to allow the use of encounters as the unit for cross-validation. In CART analysis, data are divided into ten roughly equal subsets, each created by random sampling stratified on the dependent variable. These subsets are the units used in cross validation (Breiman *et al*. 1984, Steinberg and Colla 1995). Because classification tress are built using whistles recorded from the same group and possibly the same individual, percent correct classification of the CART analysis is likely to be exaggerated.

Because CART is a non-parametric technique, it was not necessary to assume normality or transform data. For the reasons cited earlier, off-scale variables were assigned a value of 22 kHz before running the analysis. Initially, a decision tree was constructed using all twelve variables, however; a decision tree requiring fewer variables would increase efficiency in the field. A series of trees were constructed using different subsets of the twelve variables in order to find the smallest subset with acceptable predictive accuracy.

Results

A hydrophone array was towed and monitored for approximately 17,980 km (9,702 nmi) and a total of 38 sonobuoys were deployed. Single species recordings were made of nine species including: spinner dolphins (*Stenella longirostris*), striped dolphins (*S. coeruleoalba*), pantropical spotted dolphins (*S. attenuata*), long-beaked common dolphins (*Delphinus capensis*), short-beaked common dolphins (*D. delphis*), rough-toothed dolphins (*Steno bredanensis*), bottlenose dolphins (*Tursiops truncatus*), short-finned pilot whales (*Globicephala macrorhynchus*), and false killer whales (*Pseudorca crassidens*).

A total of 908 whistles recorded in 62 locations were included in the analysis (Table 4.1, Figure 4.1). Recordings from at least two and up to ten different locations were analyzed for each species. Descriptive statistics for the eight continuous whistle variables are presented in Table 4.2. Number of inflection points and number of steps had the highest coefficients of variation for every species. Of the nine species, short-finned pilot whales and rough-toothed dolphins generally had the highest coefficients of variation for all variables. Whistles of false killer whales have a markedly narrow frequency range and, similar to short-finned pilot whales, relatively few inflection points and steps. In contrast, whistles of pantropical spotted dolphins and bottlenose dolphins contain a relatively large number of steps. Bottlenose dolphins also produce whistles with distinctively long durations and numerous inflection points.

Discriminant Function Analysis

Within-species - The percentage of whistles classified to the correct recording session was significantly greater than expected by chance alone for every species (χ^2 test, $P < 0.05$; Table 4.3). Correct classification compared to chance alone was particularly high for short-finned pilot whales.

Among-species - Overall, 41.1% of whistles were classified to the correct species. Correct classification scores for individual species ranged from 6.7% for striped dolphins to 66.0% for short-finned pilot whales (Table 4.4). Only false killer whales, striped dolphins and short-beaked common dolphins had correct classification scores that were not significantly greater than expected by chance alone (false killer whales: $\chi^2_8 = 0.0$, $P = 1.0$; striped dolphins: $\chi^2_8 = 1.52$, $P = 0.99$; short-beaked common dolphins: $\chi^2_8 = 2.75$, $P = 0.95$). An examination of misclassification scores in Table

4.4 and the plot of group centroids for the first two canonical discriminant functions (Figure 4.2) suggests similarities in whistles among several species. For example, striped dolphin whistles were not accurately classified by the DFA and misclassifications as bottlenose dolphin, short-beaked common dolphin, long-beaked common dolphin, pantropical spotted dolphin, or spinner dolphin were more likely than correct classification. These facts indicate that striped dolphin whistles lie between those five species (as seen on the group centroid plot) and may be more variable than those of the other species.

Classification Trees

Using all 12 variables, the optimal classification tree consisted of 70 terminal nodes and produced an overall correct classification score of 51.4%. In subsequent CART runs, the tree that provided the best trade-off between number of variables and predictive accuracy included seven of the original 12 variables: beginning frequency, end frequency, minimum frequency, maximum frequency, duration, number of inflection points, and number of steps. Using these seven variables resulted in an optimal tree with 66 terminal nodes and a correct classification score of 53.1%. Correct classification scores for individual species ranged from 24.7% for long-beaked common dolphins to 88.4% for false killer whales (Table 4.5). All correct classification scores were significantly greater than the 11% expected by chance alone except for long-beaked common dolphins ($\chi^2_8 = 12.4$, $P = 0.13$). Classification errors followed similar patterns to those in DFA.

The four frequency variables (beginning, end, minimum, maximum) were the most important discriminating variables in the seven variable tree, as judged by their performance as both primary and secondary splitters. Number of inflection points was the least important discriminating variable. Note that the importance of a variable pertains only to that variable's performance in the tree in question and cannot necessarily be generalized to the performance of that variable in any other model.

Discussion

Within-species

The percentage of whistles classified to the correct recording session in within-species comparisons was high for every species (Table 4.3). Our ability, within a species, to correctly associate a whistle with other whistles from the same recording session may indicate geographic variation in whistle patterns; however, it may also be attributable to other sources of variation, such as behavior, group composition, or distinctive individual vocal characteristics. An attempt was made to analyze as many different recording sessions as possible to obtain a representative sample of the vocal repertoire of each species, but behavioral data and group composition were not recorded. It would be valuable to collect such data during future recording sessions in order to determine the relative contributions of social context, geographic separation, and differences among individuals.

Among-species

The results of both DFA and the classification tree suggest that whistles may be useful for the identification of delphinid species during marine mammal surveys. Overall, correct classification of whistles was between 40% and 50% for both types of analyses, much greater than the 11% correct classification expected by chance alone. Whistles of individual species were correctly classified significantly more often than expected by chance alone, with only a few exceptions. At least one of these exceptions is likely due to sample size; the low correct classification score for false killer whales may be due to the fact that there were only two false killer whale encounters in the analysis. Thus, when DFA classification functions were created using the modified jackknife method, they were based on one encounter at a time. Using whistles from only one encounter is not likely to allow a complete representation of the whistle repertoire of a species, especially if that species produces whistles containing pod specific characteristics. Future collection of false killer whale whistles in the eastern tropical Pacific will allow an examination of pod- and species-specific characteristics for this species.

Similarity in overall correct classification scores from a parametric statistical method (DFA) and a non-parametric method (CART) supports the use of either technique for species identification. One beneficial feature of CART is that surrogate splitters are available at each node so whistles can be classified even if primary splitting variables are missing. Surrogate splitters closely mimic the actions of primary splitters so there is little, if any, loss in accuracy when surrogate splitters are used (Breiman *et al.* 1984). A classification tree also provides an intuitive diagrammatic representation of the classification process. It displays patterns in the data that may not be apparent using techniques such as DFA. A disadvantage to using CART is that the software is not flexible enough to allow the use of encounters as the unit for cross-validation. As a result, percent correct classification of the CART analysis is likely to be exaggerated.

Based on the seven variable classification tree and the 12-variable DFA, false killer whales, pilot whales, and bottlenose dolphins have the most distinctive whistles. These three species lie apart from the others on the plot of group centroids (Figure 4.2), and have a small number of relatively pure terminal nodes in the decision tree (Figure 4.3), resulting in high correct classification scores (Table 4.5). The species with the lowest correct classification scores (short-beaked common, long-beaked common, and spinner dolphins) cluster together on the plot of group centroids (Figure 4.2), and have many terminal nodes that are generally not very pure.

Although our results show that dolphin whistles contain species-specific information, our correct classification scores are much lower than the usual standards applied to visual identification (i.e. near certainty). Additional research is needed before whistle classification can be used routinely as a field identification tool. We note, however, that the task of classifying species from a single whistle is a difficult challenge. It might be analogous to asking a visual observer to determine species from a single random surfacing of a single individual. It may prove to be an easier task to determine species from the collection of all whistles recorded during an encounter.

A potential method for increasing the probability of correctly identifying whistles in the field is the use of classification models that take species distribution into account. In the current DFA and CART models, each whistle was assigned to species without considering whether that species is common, rare, or even absent in the specific area where the whistle was recorded. Some species are more common in the study area than others and their distributions are not uniform across these waters. Long-beaked common dolphins were seen only in coastal waters during the 1998 survey, while short-beaked common dolphins ranged much further offshore (Kinzey *et al.* 1999). Wade and Gerrodette (1993) observed that pantropical spotted and spinner dolphins were most abundant in the warm tropical waters of the eastern tropical Pacific, short-beaked common dolphins were most abundant in cold upwelling-modified waters, and striped dolphins were most abundant where the other three species were not. To take species distribution into account, the study area should be divided into strata and classification models built using prior probabilities based on sighting frequencies in each stratum.

Lower than desired correct classification scores may also be a result of the variables measured. The twelve variables used in this study were chosen due to their compatibility with previous work, allowing for comparisons among studies. They are variables that can be measured relatively easily and reliably in the field and do not require extensive training of operators. These variables, however, do not provide a complete representation of dolphin whistles. Additionally, it is difficult to make biological interpretations based on these variables, as they are simply a representation of the way humans perceive whistles and may not reflect whistle characters actually utilized by dolphins. Measuring additional or alternative variables (such as frequency at intervals along a whistle) may provide a more accurate representation of whistles and lead to higher correct classification scores.

The fact that the variables in this study are measured by human operators reduces the need for special programs or hardware; however, it introduces an element of subjectivity to the measurements. It can also create a bottleneck when there are large volumes of data to analyze, and may make the measurement of additional or alternative variables difficult. An automated feature extraction system could be implemented in order to reduce subjectivity and make the measurement of additional variables more feasible.

The use of alternative classification methods, such as artificial neural networks, may be another way to increase the accuracy of whistle classification. Artificial neural networks operate in a non-linear, self-organizing way and therefore may be able to detect differences among species that would be missed by other statistical methods (Deecke *et al.*1999). Artificial neural networks have been successfully utilized to recognize the calls of bowhead whales (Potter *et al*. 1994) and to measure the similarity of discrete calls of killer whales (Deecke *et al.* 1999).

Another consideration that must be taken into account before the classification system can be used in the field is that it currently includes only 9 of the 16 delphinid species encountered in the ETP (Kinzey *et al*. 2000). Adding the missing species (Risso's dolphins, *Grampus griseus*; killer whales, *Orcinus orca;* pygmy killer whales, *Feresa attenuata*; dusky dolphins, *Lagenorhynchus obscurus*; Pacific white-sided dolphins, *L. obliquidens*; Fraser's dolphins, *L. hosei*; and melon-headed whales, *Peponocephala electra*) will make the system complete and ensure that every whistle has a chance of being correctly classified. It is important to note, however, that adding species is likely to decrease correct classification because the structure of the DFA and classification tree will change as variable space becomes more crowded.

Not every school encountered is a single species school. During the 1998 and 1999 surveys, 11% and 12% of all sightings were mixed species schools (Kinzey *et al.* 1999, Kinzey *et al.* 2000). Mixed species schools present a challenge because it is difficult to determine whether whistles have been classified as multiple species due to classification errors or due to the actual presence of multiple species in the group being recorded. Knowledge of which species commonly associate with each other will help with these decisions. For example, mixed schools composed of spinner and spotted dolphins were the most commonly sighted mixed species schools during both the 1998 and 1999 surveys (30% and 43% of the mixed species schools, respectively, Kinzey *et al.* 1999, Kinzey *et al.* 2000). If whistles are being classified as spinner dolphins and spotted dolphins consistently during a sighting, it is likely to be a mixed school. Whistles from known mixed species schools should be run through the classification system and confusion matrices for these schools compared to confusion matrices for single species schools. Perhaps patterns exist that would aid in discerning actual mixed species schools from classification errors.

There are two additional issues that must be addressed when developing a classification system based on whistles recorded at sea. The first is the statistical assumption of independent data. Using a towed array, it is currently not possible to precisely locate individual animals that are being recorded. Therefore, it is not possible to ensure that each whistle included in the analysis is produced by a different individual. We attempted to avoid over-sampling groups or individuals by randomly selecting a small subsample of whistles from each recording session, and by analyzing as many different recording sessions as possible for each species.

The second obstacle inherent to recording animals at sea is ensuring that each recording session included in the analysis contains only whistles produced by a single species. If a group is detected both acoustically and visually, it can usually be identified as a single species school by experienced marine mammal observers, but whistles of other species present in the area may also be detected by the array. Recent observations suggest that whistles can be heard at distances much greater than 3 km (1.6 nmi) (Janik 2000), and hence, it is possible that the recordings used in our analysis may include vocalizations produced species other than those seen by the visual observers.

The ability to localize dolphins detected using a towed hydrophone array could aid in the resolution of both issues. Differences in the arrival times of sperm whale clicks at two hydrophones in a towed array have been used to estimate bearing angles to vocalizing animals in order to track them during dives (Leaper 1992). Miller and Tyack (1998) used frequency domain beamforming techniques to localize individual killer whales detected using a small towed array. Thode *et al.* (2000) obtained bearing angles to whistling dolphins using a three-element towed array and frequency domain beamforming techniques. These bearings were not precise enough to allow the identification of individual animals. Beamforming techniques may, however, be used to reduce over-sampling individuals. Whistles originating from widely spaced bearing angles at similar times are likely to have been produced by different individuals. Including such whistles in the analysis would ensure that a wider cross section of the school is sampled. Similarly, determining the location of vocalizing dolphins makes it possible to discern whether whistles are being produced by the school seen and identified by visual observers or by some other school in the area. This will reduce the chance of mislabeling recordings and should result in a more accurate classification system. Localization techniques are currently being further developed and tested for use during future acoustic surveys.

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Table 4.1. Number of recording sessions and whistles analyzed for each species. Different recording sessions are separated by time and geographic location.

Species	**# recording sessions**	**# whistles**
Bottlenose dolphin	7	157
Short-beaked common dolphin	7	88
False killer whale	2	69
Pantropical spotted dolphin	7	97
Long-beaked common dolphin	6	73
Short-finned pilot whale	10	153
Rough-toothed dolphin	5	68
Striped dolphin	10	91
Spinner dolphin	8	112
Total	**62**	**908**

Table 4.2. Means, standard deviations, and coefficients of variation for measured whistle variables. All frequency measurements are expressed in kHz and time measurements are expressed in seconds.

	Beginning freq.	**End freq.**	**Min freq.**	**Max freq.**	**Freq. range**	**Duration**	**# inflection pts**	**# Steps**
Bottlenose dolphin								
Mean	11.2	9.0	7.4	17.2	10.0	1.4	3.7	3.1
SD	4.6	3.7	2.2	3.1	3.5	0.7	3.0	4.3
CV	3.3	3.2	2.3	1.4	2.8	4.4	6.5	11.1
Short-beaked common dolphin								
Mean	9.8	11.4	7.4	13.6	6.3	0.8	1.2	1.0
SD	3.9	3.9	2.3	3.4	3.3	0.4	1.3	1.6
CV	4.2	3.6	3.3	2.7	5.6	5.3	11.7	16.9
False killer whale								
Mean	5.2	5.8	4.7	6.1	1.4	0.4	0.5	0.1
SD	2.2	1.5	1.2	1.5	1.3	0.2	0.7	0.3
CV	5.4	2.9	3.2	2.9	10.9	7.3	17.1	43.4
Pantropical spotted dolphin								
Mean	9.5	15.3	8.2	18.7	10.6	0.9	1.9	4.3
SD	2.9	5.2	1.7	3.0	3.3	0.4	1.8	4.5
CV	3.1	3.4	2.1	1.7	3.2	4.5	9.7	10.7
Long-beaked common dolphin								
Mean	10.1	14.1	7.7	15.5	7.9	0.7	1.3	1.5
SD	3.9	4.5	2.2	4.2	4.3	0.4	1.1	2.4
CV	4.5	3.7	3.4	3.2	6.3	7.6	10.0	19.4
Short-finned pilot whale								
Mean	4.4	5.5	3.6	6.1	2.5	0.4	0.7	0.1
SD	3.1	4.3	2.3	4.2	3.2	0.3	0.9	0.4
CV	5.7	6.3	5.0	5.6	10.4	7.5	11.0	25.1
Rough-toothed dolphin								
Mean	6.8	8.5	6.3	9.1	2.8	0.6	1.3	1.3
SD	2.9	3.1	2.5	3.0	2.1	0.4	2.8	1.6
CV	5.2	4.3	4.9	4.1	8.8	9.1	26.3	15.0

Table 4.2 cont'd

	Beginning freq.	End freq.	Min freq.	Max freq.	Freq. range	Duration	# inflection pts	# Steps
Striped dolphin								
Mean	10.2	12.0	8.1	14.8	6.8	0.8	1.9	2.0
SD	3.7	2.8	1.6	3.5	3.7	0.3	2.1	2.5
CV	3.8	2.4	2.1	2.6	5.8	3.8	11.2	13.3
Spinner dolphin								
Mean	10.4	12.4	9.1	13.7	4.6	0.6	1.9	0.7
SD	3.4	3.6	2.5	3.5	3.4	0.4	4.1	1.4
CV	3.1	2.7	2.5	2.4	7.1	6.7	20.8	20.2

Table 4.3. Results of within-species discriminant function analysis (DFA). Only recording sessions containing at least three whistles were included in the analysis. The fourth column lists the percent of whistles classified to the correct recording session in within-species DFAs. The column labelled "chance" lists the correct classification scores that would be expected by chance alone in within-species DFAs. Correct classification was significantly greater than expected by chance alone for every species (χ^2 test, $P < 0.05$).

Species	**# recording sessions**	**# whistles**	**% Correct Classification**	**chance (%)**
Bottlenose dolphin	7	151	36.4	14.3
Short-beaked common dolphin	7	88	47.7	14.3
False killer whale	2	68	91.2	50.0
Pantropical spotted dolphin	5	81	37.5	20.0
Long-beaked common dolphin	5	64	40.9	20.0
Short-finned pilot whale	10	149	41.6	10.0
Rough-toothed dolphin	4	64	64.2	25.0
Striped dolphin	8	87	29.9	12.5
Spinner dolphin	6	107	45.8	16.7
Total	**54**	**859**		

Table 4.4. Results of the among-species discriminant function analyses (DFA) (overall correct classification = 41.1%, *n* = 869). Numbers in parentheses are chi-square *P*-values testing whether the correct classification is greater than expected by chance. Bold-face numbers are percent correct classification scores; others are percentages of whistles classified incorrectly.

Actual Species	**Classified As**								
	Bottlenose dolphin	**Short-beaked common dolphin**	**False killer whale**	**Pantropical spotted dolphin**	**Long-beaked common dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**
Bottlenose dolphin	**64.2** **(< 0.05)**	7.9	2.6	10.6	6.6	0.0	0.7	0.7	6.6
Short-beaked common dolphin	14.8	**17.0** **(< 0.95)***	6.8	9.1	18.2	1.1	6.8	6.8	19.3
False killer whale	1.5	2.9	**17.6** **(1.0)***	0.0	0.0	25.0	50.0	1.5	1.5
Pantropical spotted dolphin	23.2	1.2	0.0	**50.0** **(< 0.05)**	15.9	0.0	3.7	2.4	3.7
Long-beaked common dolphin	4.5	18.2	6.1	12.1	**30.3** **(< 0.05)**	0.0	6.1	6.1	16.7
Short-finned pilot whale	1.3	2.0	19.3	0.0	2.7	**66.0** **(< 0.05)**	4.7	0.0	4.0
Rough-toothed dolphin	1.5	3.0	22.4	1.5	1.5	10.4	**35.8** **(< 0.05)**	3.0	20.9
Striped dolphin	15.7	14.6	1.1	18.0	16.9	0.0	7.9	**6.7** **(<0.99)***	19.1
Spinner dolphin	6.5	8.3	6.5	0.9	13.0	0.0	13.0	11.1	**40.7** **(< 0.05)**

*not significantly greater than expected by chance alone ($P > 0.05$)

Table 4.5. Results of the 66 terminal node classification tree grown using seven variables (beginning frequency, end frequency, minimum and maximum frequency, duration, number of inflection points, number of steps) (overall correct classification = 53.1%, *n* = 908). Bold-face numbers are percent correct classification scores; others are percentages of whistles classified incorrectly. Numbers in parentheses are chi-square *P*-values testing whether the correct classification is greater than expected by chance.

Actual Species	**Classified As**								
	Bottlenose dolphin	**Short-beaked common dolphin**	**False killer whale**	**Pantropical spotted dolphin**	**Long-beaked common dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**
Bottlenose dolphin	**60.3** **(< 0.05)**	7.7	0.6	7.1	7.1	0.6	1.3	11.5	3.8
Short-beaked common dolphin	12.5	**28.4** **(< 0.05)**	5.7	5.7	10.2	2.3	8.0	15.9	11.4
False killer whale	0.0	1.4	**88.4** **(< 0.05)**	0.0	0.0	4.3	2.9	1.4	1.4
Pantropical spotted dolphin	10.3	9.3	0.0	**48.5** **(< 0.05)**	12.4	0.0	2.1	12.4	5.2
Long-beaked common dolphin	5.5	5.5	4.1	19.2	**24.7** **(< 0.2)***	0.0	9.6	20.5	11.0
Short-finned pilot whale	2.0	2.6	11.8	1.3	0.7	**68.0** **(< 0.05)**	7.2	3.3	3.3
Rough-toothed dolphin	2.9	5.9	16.2	0.0	7.4	11.8	**45.6** **(< 0.05)**	4.4	5.9
Striped dolphin	2.2	14.3	1.1	15.4	4.4	1.1	7.7	**40.7** **(< 0.05)**	13.2
Spinner dolphin	7.1	11.6	6.3	8.0	10.7	3.6	7.1	14.3	**31.3** **(< 0.05)**

*not significantly greater than expected by chance alone (*P* > 0.05)

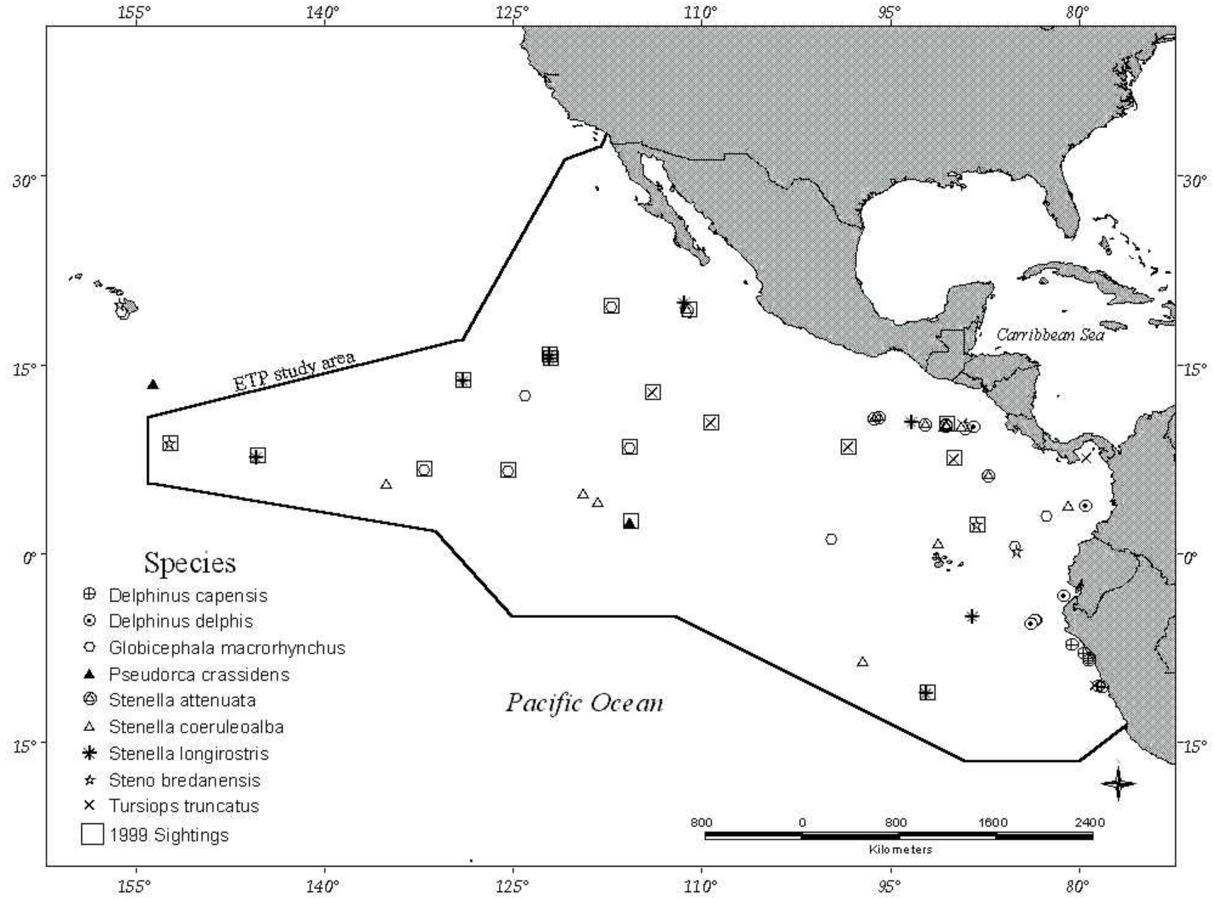

Figure 4.1. Eastern tropical Pacific study area. Locations of all recordings included in the analysis are indicated, with each species represented by a different symbol.

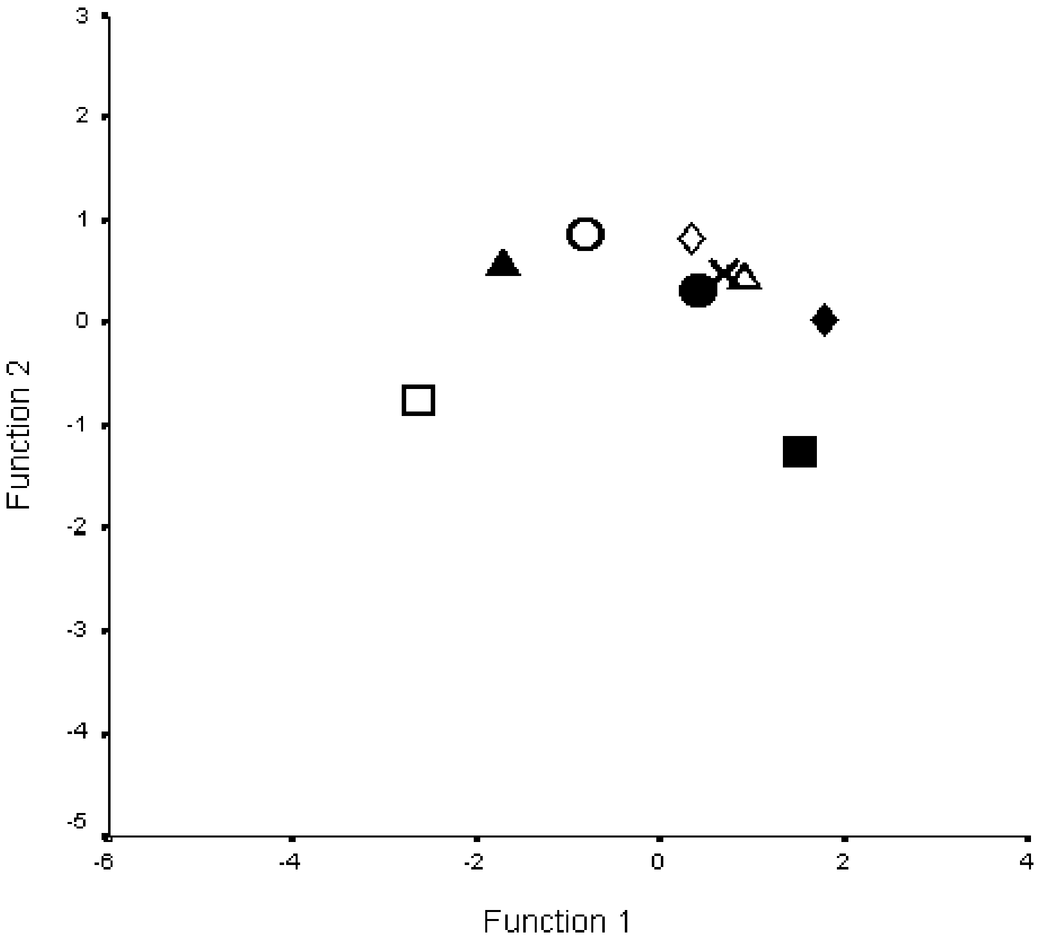

Figure 4.2. Plot of group centroids for the first two canonical discriminant functions in the nine-species comparison. × Long-beaked common dolphin (*Delphinus capensis*), ■ bottlenose dolphin (*Tursiops truncatus*), ● short-beaked common dolphin (*Delphinus delphis*), ▲ false killer whale (*Pseudorca crassidens*), ♦ pantropical spotted dolphin (*Stenella attenuata*), Δ striped dolphin (*S. coeruleoalba*), ◊ spinner dolphin (*S. longirostris*), O rough-toothed dolphin (*Steno bredanensis*), □ short-finned pilot whale (*Globicephala macrorhynchus*).

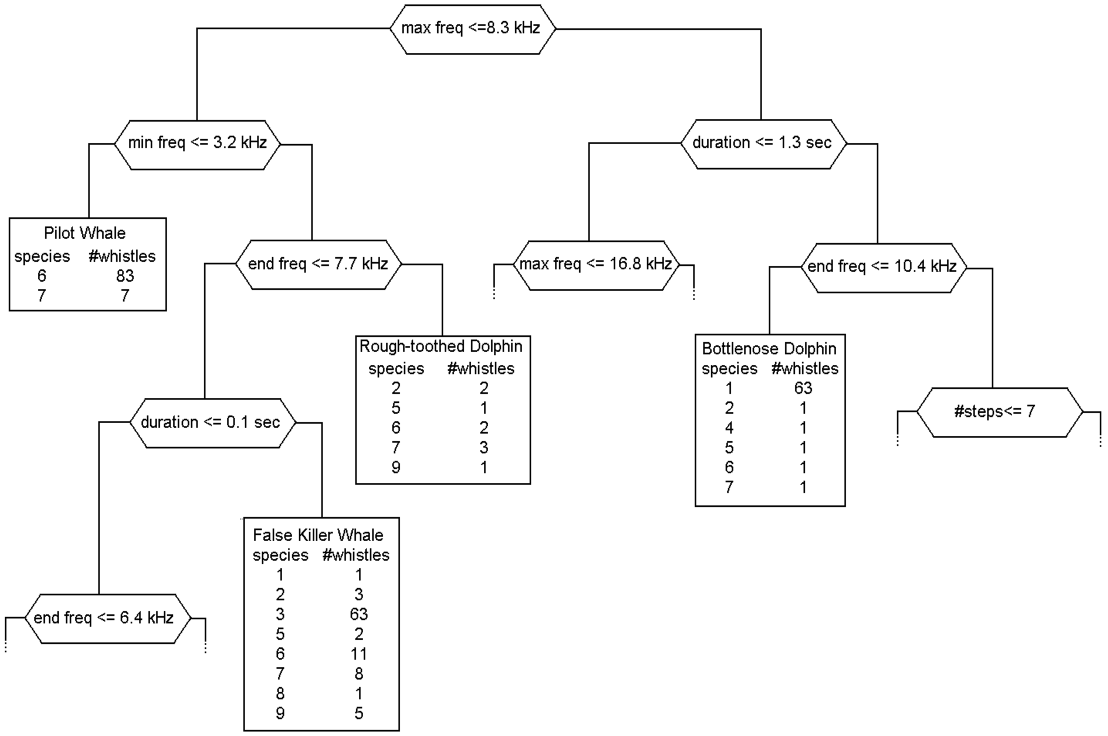

Figure 4.3. Seven variable classification tree constructed using CART software. For brevity, only the initial portion of the 66 terminal node tree is presented. Squares represent terminal nodes and are labeled based on the species with the greatest number of whistles in that node. Species designation is as follows: 1 = bottlenose dolphin (*Tursiops truncatus*), 2 = short-beaked common dolphin (*Delphinus delphis*), 3 = false killer whale (*Pseudorca crassidens*), 4 = pantropical spotted dolphin (*Stenella attenuata*), 5 = long-beaked common dolphin (*D. capensis*), 6 = short-finned pilot whale (*Globicephala macrorhynchus*), 7 = rough-toothed dolphin (*Steno bredanensis*), 8 = striped dolphin (*Stenella coeruleoalba*), 9 = spinner dolphin (*S. longirostris*).

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CHAPTER V

The Effect of Recording and Analysis Bandwidth on Acoustic Identification of Delphinid Species

Abstract

Because many cetacean species produce characteristic calls that propagate well under water, acoustic techniques can be used to detect and identify them. The ability to identify cetaceans to species using acoustic methods varies and may be affected by recording and analysis bandwidth. To examine the effect of bandwidth on species identification, whistles were recorded from four delphinid species (*Delphinus delphis, Stenella attenuata, S. coeruleoalba,* and *S. longirostris*) in the eastern tropical Pacific ocean. Four spectrograms, each with a different upper frequency limit (20 kHz, 24 kHz, 30 kHz, and 40 kHz), were created for each whistle (n = 484). Eight variables (beginning, ending, minimum, and maximum frequency; duration; number of inflection points; number of steps; and presence/absence of harmonics) were measured from the fundamental frequency of each whistle. The whistle repertoires of all four species contained fundamental frequencies extending above 20 kHz. Overall correct classification using discriminant function analysis ranged from 30% for the 20 kHz upper frequency limit data, to 37% for the 40 kHz upper frequency limit data. For the four species included in this study, an upper bandwidth limit of at least 24 kHz is required for an accurate representation of fundamental whistle contours.

Introduction

Shipboard cetacean abundance surveys have traditionally relied on visual line transect methods (Holt 1987, Wade and Gerrodette 1993, Barlow 1995, Jaramillo-Legorreta *et al.* 1999, Carretta *et al.* 2000, Jefferson 2000, Buckland *et al.* 2001, Hammond *et al.* 2002). Visual detection and identification of cetaceans can be challenging as these animals spend most of their lives completely under water. Many cetacean species produce characteristic calls that propagate well under water (Richardson *et al.* 1995), and therefore acoustic techniques can be used to detect and identify them. Because of this, towed hydrophone arrays are becoming increasingly common elements of cetacean abundance surveys (Thomas *et al*. 1986, Leaper *et al.* 1992, Clark and Fristrup 1997, Goold 1998, Norris *et al.* 1999, Gordon *et al*. 2000, Oswald *et al.* 2003).

The ability to identify cetaceans to species using acoustic methods varies. Many large whales, including blue whales (*Balaenoptera musculus*, Thompson *et al.*1996, Stafford *et al.* 1999), fin whales (*Balaenoptera physalus*, Thompson *et al.* 1992), and sperm whales (*Physeter macrocephalus*, Weilgart and Whitehead 1993, Goold and Jones 1995), produce stereotyped calls that are easily recognized. The calls produced by many dolphin species are more variable, making acoustic identification of these species difficult (Oswald *et al.* 2003).

Time and frequency characteristics measured from spectrograms have been used to classify delphinid whistles to species in several studies (Steiner 1981, Wang *et al*. 1995, Matthews *et al*. 1999, Rendell *et al*. 1999, Oswald *et al*. 2003). These studies have had varying degrees of success, ranging from 28% correct classification of 10 species (Matthews *et al*. 1999) to 70% correct classification of 5 species (Steiner 1981). These correct classification scores are significantly higher than expected by chance, but are lower than the usual standards applied to visual identification during shipboard surveys (i.e. near certainty).

The bandwidth with which sounds are recorded and analyzed may have an effect on the ability to classify them to species. Analysis bandwidths vary among studies and are not always reported. Steiner (1981) reported an analysis bandwidth of 0 - 32 kHz, Wang *et al.* (1995) an analysis bandwidth of 0 – 25 kHz, and Oswald *et al.* (2003) an analysis bandwidth of 20 Hz – 20 kHz. These bandwidths may not be sufficient to provide complete, accurate representations of vocal repertoires because ultrasonic frequencies (above 20 kHz) are produced by many odontocete species. Whistles with fundamental frequencies extending into the ultrasonic range have been reported for several delphinid species, including spinner dolphins (*Stenella longirostris*) and Atlantic spotted dolphins (*S. frontalis*, Lammers *et al.* 1997, 2003), and white-beaked dolphins (*Lagenorhynchus albirostris*, Rasmussen and Miller 2002). Thus, classification errors may be due to inaccurate whistle measurements resulting from bandwidth limitations.

The objectives of this study are two-fold: 1) to evaluate the extent to which four delphinid species recorded in the eastern tropical Pacific ocean produce whistles with fundamental frequencies extending into the ultrasonic range, and 2) to examine the effect of increasing bandwidth on acoustic species identification.

Methodology

Recordings were made during the '*Stenella* Abundance Research' (STAR2000) survey conducted in the eastern tropical Pacific ocean from 28 July to 9 December 2000. The study area extended from the United States/Mexico border southward to the territorial waters of Peru, and from the continental shores of the Americas to the longitude of Hawaii (Figure 5.1). Visual line-transect methods were used to survey all cetaceans encountered in the study area (Kinzey *et al.* 2001).

A hydrophone array was towed at a depth of 4-6 m approximately 200 m behind the NOAA ship *McArthur* while traveling at a survey speed of 10 kt. The depth of the array was periodically monitored using a *Suunto Solution Nitrox* dive computer. Two calibrated arrays were used during the survey: 1) a five-element array (flat frequency response ±4 dB from 2 kHz to 45 kHz at -132 dB re 1v/µPa after internal amplification), and 2) a three-element array (flat frequency response ±3 dB from 2 kHz to 120 kHz at -164 dB re 1v/µPa after internal amplification). The three-element array was used during 2 of the 29 recording sessions that were included in the analysis. A total of 17 whistles from these 2 encounters were included in the analysis (*vs.* 467 whistles from 27 recording sessions using the 5-element array). Any differences in sensitivity between the two arrays are therefore not likely to have had a significant effect on the results. Also, the selection of whistles was based on a signal-to-noise ratio, which did not differ between the two arrays. An acoustic technician monitored signals from two hydrophones in the array using a stereo headset and custom-written software that displayed real-time scrolling spectrograms. Recordings were made using custom software that recorded signals directly to computer hard drive via an analog-to-digital conversion card (*Data Translation DT-3809*). Recordings were made using sampling rates between 100 kilo-samples/second and 200 kilo-samples/second. Anti-aliasing filters were applied prior to recording.

Based on sample sizes of acoustic recordings made during the survey, whistles of four delphinid species were chosen for analysis: short-beaked common dolphins, *Delphinus delphis*; pantropical spotted dolphins, *Stenella attenuata*; striped dolphins, *S. coeruleoalba*; and spinner dolphins. Only recordings of groups that had been visually identified to species and observed to contain only one species were included in the analysis. Because it is possible that some recordings identified as "single species" may contain faint vocalizations produced by other species in the area, only "loud and clear" whistles were analyzed. Whistles were considered to be "loud and clear" if they were at least 9 dB louder than background noise.

Richardson *et al.* (1995) suggest that the maximum detection range for many delphinid species is on the order of 1 km. To be conservative, we assumed that whistles detected within 3 km of the array would be of sufficient quality for analysis. To avoid including whistles produced by dolphins other than those being observed and recorded, recordings made within 3 km of any other delphinid groups were excluded from the analysis. Distance was calculated between the location of the ship at the beginning of the recording session in question and the location of the initial sighting of the next group of dolphins encountered (based on angle and reticle measurements read from binoculars). Distance was also calculated between the location of the ship at the beginning of the recording session in question and the location of the previous group of dolphins encountered when they were last seen. Any recording session that occurred within 3 km of either the next or previous sighting was excluded from the analysis.

Fifty percent of the loud and clear whistles recorded during each acoustic encounter were randomly selected for analysis, up to a maximum of 30 whistles per encounter. It was assumed that this degree of subsampling would allow a sufficient sample size to be obtained while minimizing the risk of over-sampling groups or individuals (which can lead to non-independence of data). Overlapping whistles were only included in the data set if each individual whistle contour could be discerned without question.

Four spectrograms (512-point FFT), each with a different upper frequency limit (20 kHz, 24 kHz, 30 kHz, and 40 kHz), were created for each whistle using commercially available sound analysis software, '*SpectraPlus*'. Eight variables were measured from the fundamental frequency of each whistle: 1) beginning frequency (Hz), 2) ending frequency (Hz), 3) minimum frequency (Hz), 4) maximum frequency (Hz), 5) duration (ms), 6) number of inflection points (defined as a change from positive to negative or negative to positive slope), 7) number of steps (defined as a sudden jump in frequency over a short time period), and 8) presence/absence of harmonics (a binary variable).

Following Oswald *et al.* (2003), multivariate discriminant function analysis (DFA) was used to classify whistles to species based on spectrographic measurements.

Prior to running DFA, continuous variables (frequency variables, duration, and number of steps and inflection points) were tested for normality and were square-root or log transformed as necessary. The binary variable (presence/absence of harmonics) was coded as dummy variables. Discriminant function analysis classifies whistles to pre-specified groups based on orthogonal linear functions derived from the measured variables. Some whistles were missing measurements for one or more variables because a portion of the whistle extended beyond the upper bandwidth limit. These whistles were excluded from the DFA, resulting in different sample sizes for the different upper bandwidth limit data sets.

A modified jackknife, or cross-validation, method was used to calculate correct classification scores for DFAs. Each recording session was omitted from the total sample and new discriminant functions were calculated for classification of the omitted whistles. The discriminant functions calculated using this method were therefore created from data independent of the whistles being classified. This helped ensure that whistles were classified based on species-specific characteristics rather than group- or individual-specific characteristics. To evaluate correct classification scores, it is necessary to compare them to what would be expected by chance alone. Chi-square was used to test whether correct classification was significantly greater than expected by chance alone. Statistical significance was evaluated at $\alpha = 0.05$ without corrections for multiple testing.

Results

A total of 484 whistles from 29 different recording sessions were included in the analysis (Table 5.1). Some whistle variables could not be determined if a portion of the fundamental frequency of the whistle extended beyond the upper limit of the analysis bandwidth. These variables were labeled as ‘off-scale’ variables. The percent of whistles with off-scale variables ranged from 11% for striped dolphins to 43% for spotted dolphins when the upper bandwidth limit was 20 kHz (Table 5.1). When the upper bandwidth limit was increased to 24 kHz, the percent of whistles with at least one off-scale variable decreased for every species, ranging from 0% for striped dolphins to 9% for spotted dolphins. An additional 6 kHz increase in upper bandwidth limit reduced the percent of whistles with off-scale variables even further. No whistles had off-scale variables when the upper bandwidth limit was 40 kHz.

Descriptive statistics (means and standard deviations) for all bandwidth limit data are given in Table 5.2. Only maximum and ending frequency showed significant differences with increasing upper bandwidth limit (one-way ANOVA, $\alpha = 0.05$). Maximum and ending frequency increased significantly with increasing upper bandwidth limit in all species except striped dolphins.

Results of the DFAs are given in Tables 5.3 - 5.6. For all bandwidths, both overall percent correct classification (30% - 37%) and percent correct classification of spinner dolphin whistles (37% - 42%) were significantly greater than the 25% expected by chance alone (χ^2 tests; overall, $P < 0.05$; spinner dolphins, $P \leq 0.003$). When the upper bandwidth limit was 20 kHz, percent correct classification was not significantly different than chance for spotted dolphins (23%, χ^2 test, $P = 0.76$) and was significantly less than chance for striped dolphins (16%, χ^2 test, $P = 0.05$). For both species, percent correct classification increased to significantly greater than chance when the upper bandwidth limit was increased to 24 kHz (χ^2 tests; spotted dolphins, 40%, $P = 0.002$; striped dolphins, 36%, $P = 0.01$), and remained significantly greater than chance at all subsequent bandwidths. In contrast, the percent of short-beaked common dolphin whistles that were correctly classified was significantly greater than chance (37%, χ^2 test, $P = 0.003$) when the upper bandwidth limit was 20 kHz and decreased to not significantly different than chance when the upper bandwidth limit was increased to 24 kHz (32%, χ^2 test, $P = 0.06$), 30 kHz (29%, χ^2 test, $P = 0.27$), and 40 kHz (30%, χ^2 test, $P = 0.21$).

Discussion

The production of clicks containing ultrasonic components is common in several dolphin species (Au 1980, Kamminga and Wiersma 1981, Wiersma 1982, Dawson 1991, Au 1993, Lammers *et al.* 2003), and delphinid whistles often have harmonic components that extend well above 20 kHz (Lammers *et al.* 2003). In contrast, the production of whistles with fundamental frequencies extending into the ultrasonic range has been documented for few species (Lammers *et al.* 1997, Au *et al.* 1999, Rasmussen and Miller 2002, Lammers *et al.* 2003). The whistle repertoires of all four species examined in this study contained whistles with fundamental frequencies extending into the ultrasonic range. While all species produced high-frequency whistles, some used high frequencies more often than others. For example, 43% of spotted dolphin whistles had fundamental frequencies that extended beyond 20 kHz, compared to only 11% of striped dolphin whistles (Table 5.1).

The presence of whistles with fundamental frequencies extending beyond the upper limit of the analysis bandwidth can lead to inaccurate representations of whistle contours and have an adverse effect on the ability to classify whistles to species. For example, the spotted dolphin whistle shown in Figure 5.2 has an ending frequency of 39 kHz. When this whistle was analyzed using an upper bandwidth limit of less than 40 kHz, it was impossible to determine not only ending frequency, but also maximum frequency and whistle duration. This whistle also has harmonics that were completely missed when the upper bandwidth limit was less than 30 kHz.

In addition to this loss of information, the presence of off-scale variables can lead to misrepresentations of whistles. The fundamental contour of the striped dolphin whistle shown in Figure 5.3 appears to be entirely below 20 kHz when the upper bandwidth limit is 20 kHz (Figure 5.3a). When the upper bandwidth limit is increased to 24 kHz it becomes apparent that this contour does contain energy above 20 kHz (Figure 5.3b). For this whistle, duration, beginning frequency, and maximum frequency were all underestimated when the upper bandwidth limit was 20 kHz. This whistle also has a harmonic component that was missed when the upper bandwidth limit was 20 kHz.

Overall, for the species in this study, loss of information and misrepresentation had the greatest effect on measurements of maximum and ending frequency. Both variables increased significantly with increasing upper bandwidth limit for every species except striped dolphins (Table 5.2).

Increased accuracy of whistle measurements resulting from increasing bandwidth led to greater overall success in acoustic species identification. Overall correct classification increased from 30% to 37% when the upper bandwidth limit was increased from 20 kHz to 24 kHz, and varied only slightly when bandwidth was increased further (Tables 5.3 – 5.6). More substantial increases were evident in some individual species percent correct classification scores. Percent correct classification of spotted and striped dolphin whistles increased from not significantly different than chance (spotted dolphins) or significantly less than chance (striped dolphins) to significantly greater than chance when the upper bandwidth limit was increased from 20 kHz to 24 kHz. Classification success for both species increased further with subsequent increases in bandwidth, but the most sizeable increases occurred between 20 kHz and 24 kHz.

In contrast, percent correct classification of short-beaked common and spinner dolphin whistles decreased as bandwidth increased. Even with these decreases, classification success for spinner dolphin whistles remained significantly greater than chance at all bandwidths. Percent correct classification of short-beaked common dolphin whistles decreased from significantly greater than chance at 20 kHz upper bandwidth limit to not significantly different than chance at all other upper bandwidth limits. This was an unexpected result as both species had a relatively high percentage of off-scale whistles when the upper bandwidth limit was 20 kHz and relatively low percentages of off-scale whistles at higher upper bandwidth limits. Also, average maximum frequency and average ending frequency increased significantly with increasing bandwidth for both species.

Fewer off-scale whistles and more accurate whistle measurements should lead to more complete representations of whistles at higher upper bandwidth limits. It was expected that this would lead to greater classification success, but as illustrated in the cases of short-beaked common and spinner dolphins, this was not always true. In addition, striped dolphins had the lowest percentage of off-scale whistles when the upper bandwidth limit was 20 kHz and their whistle variables did not change significantly with increasing bandwidth, yet striped dolphin correct classification scores increased markedly with increasing bandwidth. Thus, classification success was not directly related to the percentage of off-scale whistles or changes in mean whistle variables with increasing bandwidth.

To further explore trends in classification success, patterns of misclassification were examined. When the upper bandwidth limit was increased from 20 kHz to 24 kHz, the percent of short-beaked common dolphin whistles that were correctly classified decreased. At the same time, the percent of short-beaked common dolphin whistles that were misclassified as striped dolphins increased (Tables 5.3 and 5.4). It was hypothesized that the additional whistles being misclassified as striped dolphins by the 24 kHz upper bandwidth limit DFA were those that had been excluded from the

20 kHz upper bandwidth limit DFA (recall that whistles with off-scale variables were excluded from the DFA). This hypothesis was rejected because of the 33 short-beaked common dolphin whistles that were missing from the 20 kHz upper bandwidth limit data set, only one was misclassified as a striped dolphin whistle when included in the 24 kHz upper bandwidth limit DFA. Many (n = 15) of the missing short-beaked common dolphin whistles were misclassified as spotted dolphins and one third were correctly classified. This suggests that the observed changes in patterns of classification were not caused directly by the added whistles, but were more likely caused indirectly by the influence of additional whistles on the calculation of discriminant functions. Discriminant functions are orthogonal linear functions derived from the measured variables and will be affected by the relationship of whistle variables to one another as well as the values of the whistle variables themselves. Consequently, when evaluating the benefits of increasing bandwidth, it is not sufficient to examine the percent of off-scale whistle variables or changes in whistle variables with changes in bandwidth for individual species. It is also necessary to consider the ways in which representations of whistles change in relation to whistles of other species.

It is important to note that although percent correct classification of short-beaked common and spinner dolphin whistles did decrease with increasing bandwidth, the decreases (5% for spinner dolphins and 8% for short-beaked common dolphins) were minor compared to the 21% (spotted dolphin) and 26% (striped dolphin) increases in correct classification that were observed.

Even with sufficient bandwidth, classification success was lower than desirable for use as a field identification tool. Classification was based on eight variables that could be measured relatively easily and reliably in the field. These variables, however, do not provide complete representations of whistles and may miss whistle characteristics that carry species-specific information. Fristrup and Watkins (1993) measured variables such as amplitude, median frequency, and mode frequency (frequency corresponding to the largest energy value in the spectrum) from the vocalizations of 53 marine mammal species (including mysticetes, odontocetes, and pinnipeds). They devised a number of statistical measures to quantify the relationships among time, amplitude, and frequency. When tree-based classification models were applied to these variables, 66% of the vocalizations were classified to the correct species. Another approach to whistle classification was taken by Buck and Tyack (1993) and McCowan (1995). In these studies, overall whistle contours were compared rather than specific acoustic parameters. Different variables and approaches such as these could increase the accuracy of delphinid species identification.

Another cause of the lower than desirable correct classification scores could be that classification decisions were based on one whistle at time. This may be analogous to asking a visual observer to determine species from a single random surfacing of a single individual. Determining species based on several whistles may prove more reliable than classifying one whistle at a time.

The results of this study suggest that for the four species included, an upper bandwidth limit of at least 24 kHz is required for an accurate representation of the fundamental frequencies of their whistles and for optimizing the ability of computerized statistical techniques such as DFA to classify these whistles to species. The percentage of off-scale whistles, mean maximum and ending frequencies, and overall percent correct classification scores showed marked differences when upper bandwidth limit was increased from 20 kHz to 24 kHz. Increasing upper bandwidth limit beyond 24 kHz did result in fewer off-scale whistles as well as changes in whistle variables and percent correct classification scores; however, these changes were minor compared to the changes occurring between 20 kHz and 24 kHz.

Many acoustic research projects involve the use of DAT recorders, which typically have the capability to sample at either 44,100 kilo-samples/second or 48,000 kilo-samples/second. The results of this study suggest that the use of DAT recorders is sufficient for examinations of the fundamental frequencies of most dolphin whistles, however care should be taken to sample at 48,000 kilo-samples/second. If alternate equipment is available, advantages can be gained by recording and analyzing dolphin whistles at higher sampling rates.

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Table 5.1. Number of recording sessions and number of whistles included in the analysis (n) for each species. Percentages of whistles containing at least one off-scale variable when measured with an upper bandwidth limit of 20 kHz, 24 kHz, 30 kHz, and 40 kHz are given in the last four columns.

Species	**# recording sessions**	**n**	**20 kHz**	**24 kHz**	**30 kHz**	**40 kHz**
Short-beaked common dolphin	11	163	28%	8%	1%	0%
Spotted dolphin	5	100	43%	9%	3%	0%
Striped dolphin	9	104	11%	0%	0%	0%
Spinner dolphin	4	117	27%	4%	0%	0%

Table 5.2. Descriptive statistics (means, with standard deviations in parentheses underneath) for measured whistle variables. Maximum frequency and ending frequency increased significantly with increasing upper bandwidth limit for all species except striped dolphins (one-way ANOVA, α = 0.05). Significant *P*-values are underlined.

Species	**Upper bandwidth limit (kHz)**	**Beginning frequency (kHz)**	**Ending frequency (kHz)**	**Minimum frequency (kHz)**	**Maximum frequency (kHz)**	**Duration (sec)**	**No. of inflection points**	**No. of steps**
Short-beaked common dolphin	20	11.8 (3.8)	12.4 (4.8)	8.7 (2.3)	15.4 (2.7)	0.68 (0.43)	1.7 (1.5)	1.2 (1.6)
	24	12.3 (4.3)	13.8 (4.8)	8.7 (2.3)	16.7 (3.5)	0.70 (0.42)	1.8 (1.5)	1.2 (1.7)
	30	12.6 (4.7)	14.1 (5.4)	8.6 (2.3)	17.5 (4.4)	0.75 (0.44)	1.8 (1.5)	1.2 (1.8)
	40	12.9 (5.2)	14.1 (5.4)	8.6 (2.3)	17.7 (4.6)	0.75 (0.44)	1.8 (1.5)	1.2 (1.7)
	P	0.31	0.003	0.99	<0.001	0.55	0.84	0.93
Spotted dolphin	20	10.3 (4.4)	13.9 (4.9)	9.0 (3.9)	16.0 (3.6)	0.56 (0.42)	1.1 (1.9)	2.3 (2.6)
	24	10.4 (4.5)	15.6 (5.1)	9.0 (3.9)	18.4 (4.1)	0.60 (0.40)	1.2 (1.8)	2.7 (3.3)
	30	10.4 (4.5)	16.1 (5.6)	9.0 (3.9)	18.9 (4.4)	0.62 (0.40)	1.2 (1.8)	2.8 (3.4)
	40	10.4 (4.5)	16.8 (6.4)	9.0 (3.9)	19.4 (5.2)	0.63 (0.40)	1.2 (1.8)	2.8 (3.4)
	P	0.99	0.01	1.0	<0.001	0.59	0.86	0.77

Table 5.2 cont'd

Species	**Upper bandwidth limit (kHz)**	**Beginning frequency (kHz)**	**Ending frequency (kHz)**	**Minimum frequency (kHz)**	**Maximum frequency (kHz)**	**Duration (sec)**	**No. of inflection points**	**No. of steps**
Striped dolphin	20	10.4 (3.4)	12.5 (3.9)	8.6 (2.1)	15.1 (2.5)	0.61 (0.36)	1.6 (1.8)	1.6 (2.0)
	24	10.6 (3.8)	12.8 (3.5)	8.5 (2.1)	15.9 (3.3)	0.64 (0.37)	1.7 (1.8)	1.7 (2.1)
	30	10.6 (3.8)	12.8 (3.5)	8.5 (2.1)	15.9 (3.3)	0.64 (0.37)	1.7 (1.8)	1.7 (2.1)
	40	10.6 (3.8)	12.8 (3.5)	8.5 (2.1)	15.9 (3.3)	0.64 (0.37)	1.7 (1.8)	1.7 (2.1)
	P	0.97	0.70	0.99	0.17	0.92	0.96	0.94
Spinner dolphin	20	12.8 (3.9)	13.0 (4.9)	10.8 (3.1)	15.8 (3.1)	0.55 (0.46)	1.8 (3.8)	0.87 (1.5)
	24	13.5 (4.5)	14.6 (4.7)	11.1 (3.7)	17.4 (4.0)	0.66 (0.49)	2.0 (3.8)	0.98 (1.7)
	30	13.7 (4.7)	15.0 (5.1)	11.1 (3.7)	17.8 (4.4)	0.67 (0.49)	2.0 (3.8)	0.98 (1.7)
	40	13.7 (4.7)	15.0 (5.1)	11.1 (3.7)	17.8 (4.4)	0.67 (0.49)	2.0 (3.8)	0.98 (1.7)
	P	0.52	0.003	0.87	0.001	0.26	0.73	0.99

Table 5.3. Classification results of discriminant function analysis for the 20 kHz upper bandwidth limit data. Percentage of whistles correctly classified for each species is in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and *P*-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 30% of whistles were classified to the correct species. This is significantly greater ($P = 0.02$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	*P*	n
Short-beaked common dolphin	**37%**	16%	20%	27%	0.003	118
Spotted dolphin	21%	**23%**	32%	24%	0.76	56
Striped dolphin	24%	32%	**16%**	28%	0.05	93
Spinner dolphin	19%	19%	21%	**42%**	<0.001	85

Table 5.4. Classification results of discriminant function analysis for the 24 kHz upper bandwidth limit data. Percentage of whistles correctly classified for each species is in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and *P*-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 37% of whistles were classified to the correct species. This is significantly greater ($P < 0.001$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	*P*	n
Short-beaked common dolphin	**32%**	19%	30%	19%	0.06	150
Spotted dolphin	15%	**40%**	25%	20%	0.002	91
Striped dolphin	22%	23%	**36%**	19%	0.01	104
Spinner dolphin	19%	15%	24%	**42%**	<0.001	112

Table 5.5. Classification results of discriminant function analysis for the 30 kHz upper bandwidth limit data. Percentage of whistles correctly classified for each species is in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and *P*-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 36% of whistles were classified to the correct species. This is significantly greater ($P < 0.001$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	*P*	n
Short-beaked common dolphin	**29%**	20%	31%	20%	0.27	161
Spotted dolphin	13%	**<u>42%</u>**	25%	20%	<0.001	96
Striped dolphin	19%	21%	**<u>40%</u>**	20%	<0.001	104
Spinner dolphin	21%	15%	27%	**<u>37%</u>**	0.003	117

Table 5.6. Classification results of discriminant function analysis for the 40 kHz upper bandwidth limit data. Percentage of whistles correctly classified for each species is in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and *P*-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 37% of whistles were classified to the correct species. This is significantly greater ($P < 0.001$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	*P*	n
Short-beaked common dolphin	**30%**	20%	31%	19%	0.21	163
Spotted dolphin	13%	**<u>44%</u>**	23%	20%	<0.001	100
Striped dolphin	19%	19%	**<u>42%</u>**	20%	<0.001	104
Spinner dolphin	20%	16%	26%	**<u>38%</u>**	0.001	117

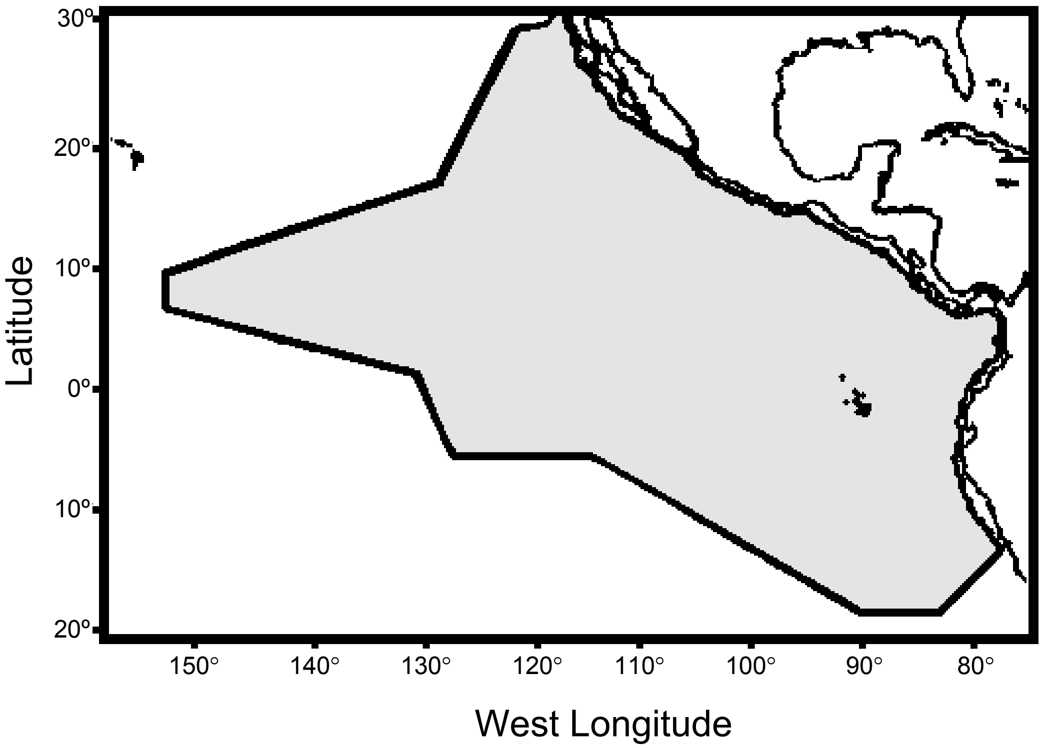


Figure 5.1. Eastern tropical Pacific ocean study area for '*Stenella* Abundance Research' (STAR 2000) survey.

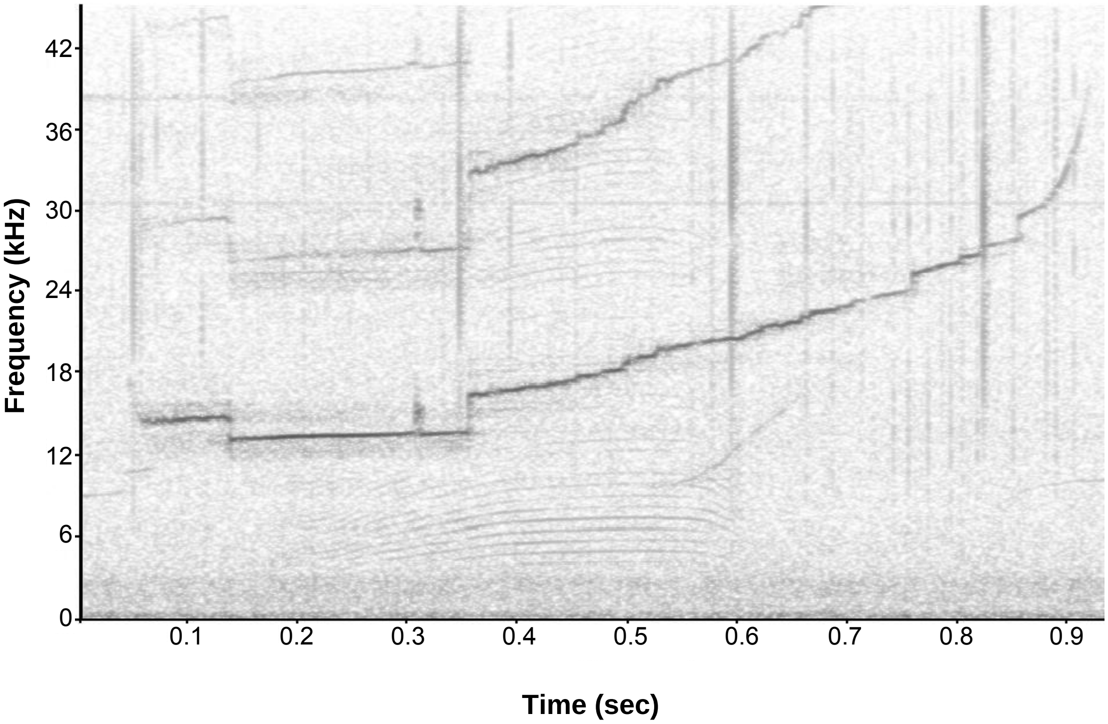
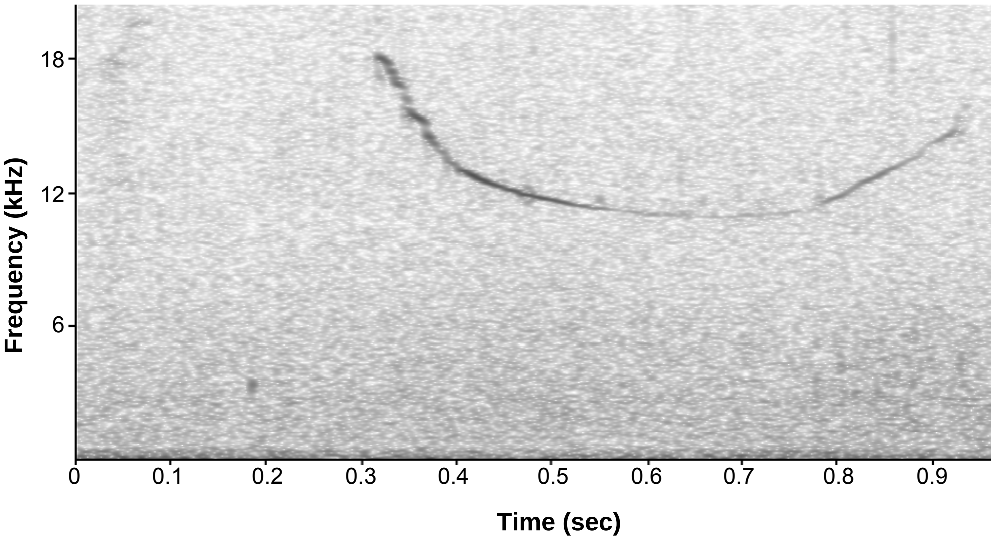


Figure 5.2. Spotted dolphin whistle (512 point FFT). Maximum frequency, ending frequency, and duration were impossible to measure when the whistle was analyzed using an upper bandwidth limit less than 40 kHz. Harmonics were completely missed when the upper bandwidth limit was less than 30 kHz.

a)



b)

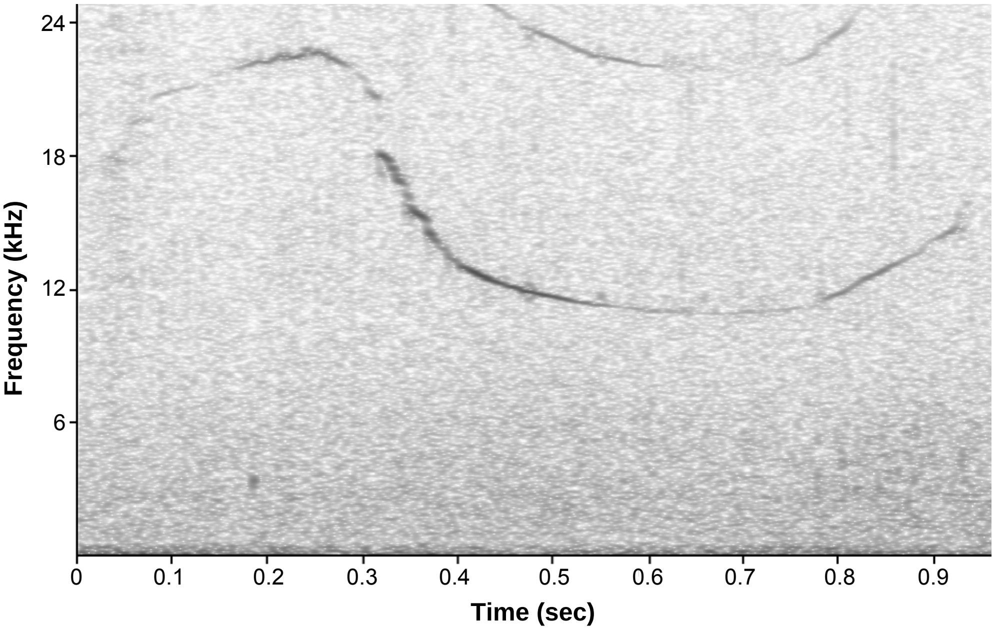


Figure 5.3. Striped dolphin whistle (512 point FFT). a) Upper bandwidth limit = 20 kHz. b) Upper bandwidth limit = 24 kHz. Beginning frequency, maximum frequency, and duration were underestimated and harmonic was missed when the whistle was analyzed using an upper bandwidth limit less than 24 kHz.

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CHAPTER VI

ROCCA: A New Tool for Real-Time Species Identification of Delphinid Whistles

Abstract

Acoustic species identification studies generally focus on post-processing of field recordings to develop classification algorithms. The ability to identify delphinid vocalizations in real-time would be an asset during shipboard surveys. A new automated system, Real-time Odontocete Call Classification Algorithm (ROCCA), has been developed to allow real-time acoustic species identification in the field. This Matlab-based tool automatically extracts 10 variables (beginning, end, minimum and maximum frequencies, duration, slope of the beginning and end sweep, number of inflection points, number of steps, and presence/absence of harmonics) from whistles that are manually selected from a real-time scrolling spectrograph (ISHMAEL software) and runs classification and regression tree analysis (CART) and discriminant function analysis (DFA) to identify whistles to species. Schools of dolphins are classified based on running tallies of individual whistle classifications. Overall, 46% of schools were correctly classified for seven species and one genus (*Tursiops truncatus, Stenella attenuata, S. longirostris, S. coeruleoalba, Steno bredanensis, Delphinus* species, *Pseudorca crassidens,* and *Globicephala macrorhynchus*). This new tool provides a method for identifying schools that are difficult to approach and observe, allows species distribution data to be collected when visual efforts are

compromised, reduces the bottleneck of post-cruise analysis, and is valuable for processing data collected using sea-floor mounted acoustic recorders.

Introduction

Acoustic techniques have been used to monitor populations of a variety of species, ranging from birds (Mills 1995, Chesmore 2001), bats (Vaughan *et al.* 1997, Parsons and Jones 2000), and fallow deer (Reby *et al.* 1997) to insects such as crickets and grasshoppers (Chesmore 2001). Increasingly, acoustic techniques are being used to monitor marine mammal populations (Leaper *et al.* 1992, Clark *et al.* 1996, Stafford *et al.* 1998, Gordon *et al.* 2000, van Parijs *et al.* 2002, Wang *et al.* 2005). Many cetaceans produce distinctive sounds and acoustic techniques can therefore be used to detect not only the presence of cetaceans, but also species identity. Several species of large whales produce stereotyped calls that are easily recognized (Thompson *et al.* 1992, Goold and Jones 1995, Thompson *et al.* 1996), but the whistles produced by many delphinid species are highly variable and overlap in frequency characteristics, making them more challenging to identify.

Delphinid species identification studies have generally focused on post-processing of field recordings to develop classification algorithms (Steiner 1981, Wang *et al.* 1995, Matthews *et al.* 1999, Rendell *et al.* 1999 Oswald *et al.* 2003). Correct classification scores obtained in these studies are generally significantly greater than expected by chance alone, suggesting that whistles can be used to identify delphinid species. While post-processing provides valuable information, the ability to identify vocalizations to species in real time would be a great asset during shipboard marine mammal abundance surveys. Traditionally during these surveys, a team of visual observers searches for marine mammals and then directs the ship towards them for school size estimation and species identification (Wade and Gerrodette 1993, Barlow 1995). Recently, methods have been developed to tow a hydrophone array behind the ship when conducting a standard visual survey (Fristrup and Clark 1997, Barlow 2005). While the addition of acoustic techniques has been shown to increase rates and distances of detection (Leaper *et al.* 1992, Clark and Fristrup 1997, Gordon *et al.* 2000, Barlow and Taylor 2005), real-time acoustic species identification would provide several further advantages. This capability would allow the acoustic team to aid visual observers with the identification of groups that are difficult to approach and observe due to factors such as animal behavior, inclement weather, and reduced visibility. In addition, because marine mammals spend much of their lives under water, schools are often detected acoustically but not visually (Barlow and Taylor 2005). Due to time and logistical constraints it is frequently not possible to acoustically track and locate every acoustic detection for school size estimation. The ability to identify schools that are heard and not seen would allow for more efficient use of valuable ship time by concentrating on species of particular importance. Finally, real-time acoustic species identification can reduce the bottleneck of post-cruise data analysis.

Until now, a method for real time acoustic identification of delphinid whistles has not been available. In this paper we present a new software tool that has been developed for this task: Real-time Odontocete Call Classification Algorithm (ROCCA). ROCCA is a matlab-based tool that extracts, measures and classifies whistles to species in real-time.

Methodology

Data collection

Acoustic recordings were made during six shipboard marine mammal abundance surveys conducted by the Southwest Fisheries Science Center (NOAA, NMFS). Each four-month survey occurred between the months of July and December. Four of the surveys took place in the eastern tropical Pacific Ocean: Stenella Population and Abundance Monitoring (SPAM) 1998, and Stenella Abundance Research (STAR) 1999, 2000, and 2003. This study area extended from the United States/Mexico border southward to the territorial waters of Peru, and from the continental shores of the Americas west to the longitude of Hawaii (Figure 6.1). The Hawai'ian Islands Cetacean and Ecosystem Assessment Survey (HICEAS 2002) study area covered the waters within the 200 nmi Exclusive Economic Zone (EEZ) around the Hawai'ian Island chain from the island of Hawai'i in the southeast to Kure Atoll in the northwest (Figure 6.1). The Pacific Islands Cetacean Ecosystem Assessment Survey (PICEAS 2005) took place in the US EEZ waters of Palmyra and Johnston Atoll and adjacent waters south of Hawai'i (Figure 6.1).

During all surveys, a team of three experienced visual observers actively searched for marine mammals using two sets of 25x150 binoculars and by naked eye

(Kinzey *et al.* 2001). When cetaceans were sighted, they were approached for species identification and school size estimation. Cetacean vocalizations were monitored and recorded using a towed hydrophone array and Type SSQ-57 sonobuoys. The array was towed 200 m behind the research vessel at a depth of approximately 4-6 m during daylight hours. Table 6.1 gives the frequency response characteristics of the arrays used during the surveys. During the 1998 survey, signals from the array were recorded onto digital audio tape (DAT) using Sony TCD-D7 and TCD-D8 DAT recorders (48 kHz sampling rate). During the 2000 survey and all subsequent surveys, signals from the array were sent through a Mackie CR1604-VLZ mixer for equalization and were recorded directly to computer hard drive via an analog-to-digital conversion card (National Instruments BNC-2110 and DAQCard-6062E) using a 200 kHz sampling rate.

An acoustic technician monitored signals from two hydrophones in the array using a stereo headset and real-time scrolling spectrographic software (ISHMAEL, Mellinger 2001). Whaltrak, a mapping program with a GPS-interface, automatically logged time and position every 5 minutes while the array was being monitored. During the 2000 survey and all subsequent surveys, acoustic detections were localized using ISHMAEL and Whaltrak. Bearing angles were determined using phone-pair cross-correlation algorithms in ISHMAEL and distance was determined by examining the convergence of bearing angles plotted on Whaltrak. Comparisons of the angle and distance to the acoustic detection with the location of the sighting allowed confirmation that the vocalizations detected were produced by the sighted dolphins.

A hydrophone array was not towed during the 1999 survey. Instead, U.S. Navy sonobuoys (type SSQ-57) were deployed in close proximity to dolphin sightings. These sonobuoys had a flat frequency response from approximately 2 kHz to 20 kHz, and were deployed at a hydrophone depth setting of either 18 or 27 m. Sonobuoy signals were transmitted to a multichannel receiver aboard the research vessel and were recorded onto DAT using Sony TCD-D7 DAT recorders.

Spectrographic analysis

Recordings of schools that had been visually identified to species and confirmed to contain only one species were chosen for analysis. Recordings were included only if the school was sighted at least 3 nmi from any other school in the area. This helped to ensure that the whistles analyzed were produced by the school being observed and not another nearby school. This was especially important during the 1998 and 1999 surveys, when acoustic localization techniques were not available.

We randomly selected fifty percent of loud and clear whistles from each recording session, up to a total of 35 whistles per recording session. This level of subsampling was chosen in order to obtain a sufficient sample size while avoiding oversampling of groups or individuals (which can lead to non-independence of data). Overlapping whistles were included only if each individual whistle contour could be discerned without question. Whistles were considered to be ‘loud and clear’ if they were at least 9 dB above ambient noise.

Ten variables were measured from the fundamental contour of each whistle: (1) beginning frequency (kHz), (2) end frequency (kHz), (3) minimum frequency (kHz), (4) maximum frequency (kHz), (5) duration (sec), (6) number of inflection points (defined as a change from positive to negative or negative to positive slope), (7) number of steps (defined as a 10% or greater increase or decrease in frequency over two contour points), (8) slope of the beginning sweep (positive, negative, or zero), (9) slope of the end sweep (positive, negative, or zero), and (10) presence/absence of harmonics (a binary variable). Some whistles from the 1998 and 1999 surveys were missing measurements for one or more variables because a portion of the whistle extended beyond the upper bandwidth limit of the recording equipment. These whistles were excluded from the analysis.

Classification Algorithms

Following Oswald *et al.* (2003), classification algorithms were created using multivariate discriminant function analysis (DFA) and classification and regression tree analysis (CART). Discriminant function analysis classifies whistles to prespecified groups based on orthogonal linear functions derived from the ten variables listed above. Mahalanobis distances were calculated for each whistle being classified. The Mahalanobis distance is a measure of the distance in multivariate space of the whistle in question to the group centroid of each species in the analysis. The whistle was classified as the species that it was closest to in multivariate space. Prior to running DFA, continuous variables (frequency variables, duration, and number of steps and inflection points) were tested for normality and transformed as necessary. Classification and regression tree analysis creates decision trees by separating data into groups known as nodes through a series of binary splits. Each split is based on the value of a single variable. Final classification is reached at terminal nodes. Terminal node probabilities reflect the certainty of the classification based on the purity of the node. Because CART is non-parametric, it was not necessary to transform variables for normality.

Two different methods of classification using DFA and CART were evaluated. In the first method, whistles were classified directly to species level. This will be referred to as the 'direct' method for the remainder of this paper. The second method was hierarchical. Whistles were first classified to the broad categories of 'blackfish' or 'delphinid'. The blackfish category consisted of two species: false killer whales (*Pseudorca crassidens*) and short-finned pilot whales (*Globicephala macrorhynchus*). The delphinid category consisted of 5 species and one genus: bottlenose (*Tursiops truncatus*), spotted (*Stenella attenuata*), spinner (*S. longirostris*), striped (*S. coeruleoalba*), rough-toothed (*Steno bredanensis*), and common (*Delphinus spp.*) dolphins. Common dolphin species (*Delphinus delphis* and *D. capensis*) were pooled in this analysis (see Results). Once classified to category, whistles within each category were then classified to species.

A jackknife method was used to calculate correct classification scores for DFA and CART. Six versions of the DFA and CART classification algorithms were created, each omitting all of the whistles from one cruise (one year of sampling).

Whistles were classified using the algorithms that did not include them. In this way, classification algorithms were created from data that were independent of the whistles being classified. This helped ensure that whistles were classified based on species-specific characteristics rather than group- or individual-specific characteristics. Fisher's exact test was used to test whether correct classification scores were significantly greater than expected by chance alone. Statistical significance was evaluated at $\alpha = 0.05$ without corrections for multiple testing.

ROCCA

ROCCA was created using Matlab and interfaces with real-time scrolling spectrograph software, ISHMAEL (Mellinger 2001). ISHMAEL is used to monitor signals detected by the hydrophone array. When a whistle of interest is detected, the user stops the scrolling spectrograph and selects the whistle. A Matlab routine called through ISHMAEL opens a Matlab window and saves the selection as a wav file. ROCCA is then run through the open Matlab window. First, ROCCA automatically extracts the whistle contour from the wav file by stepping through the file one window at a time. The fundamental frequency of the whistle contour is selected based on the peak frequency in each window. A routine within ROCCA ensures that random transient peaks in the spectrum are not mistaken for the fundamental peak frequency. For this study, the Fast Fourier Transform (FFT) window size was set at 1024 points and window overlap was set at 0.25.

When the whistle contour has been extracted, ROCCA automatically measures the ten variables described previously from the fundamental frequency contour of the whistle. The ten variables are then processed using DFA and CART classification algorithms and ROCCA outputs two predicted species, one based on each analysis. As multiple whistles from a single school of dolphins are processed, ROCCA keeps a running tally of species predictions. When all of the whistles from a school have been analyzed, ROCCA classifies the school as the species that the majority of whistles were predicted to be. When DFA and CART results do not agree, the algorithm that resulted in the greatest number of whistles classified as one species is chosen. For example, if DFA classifies 65% of the whistles in a school as bottlenose dolphins and CART classifies 58% of the same whistles as spotted dolphins, the school is classified as bottlenose dolphins. When the same number of whistles is classified as two or more species within DFA or CART, the species with the smallest mean Mahalanobis distance is chosen for DFA and the species with the largest mean terminal node probability is chosen for CART.

As whistles are analyzed, ROCCA creates three text files for each school. One contains the extracted whistle contours (time, frequency, and intensity of the peak frequency in each window). The second contains the 10 whistle variables measured from each whistle in the school. The third contains DFA and CART predicted species, as well as Mahalanobis distances (DFA) and terminal node probabilities (CART) for each whistle in the school.

Matlab code for ROCCA and associated m-files are given in Appendix 6.A.

Results

Single-species acoustic recordings were obtained from nine delphinid species during the six surveys: bottlenose, spotted, spinner, striped, rough-toothed, short-beaked common, and long-beaked common dolphins, false killer whales, and short-finned pilot whales. A total of 2606 whistles from 176 schools were included in the analysis. Table 6.2 lists the number of whistles analyzed for each species and each survey. Descriptive statistics for the seven continuous whistle variables are given in Table 6.3.

When ROCCA was run on all nine species, only 17.8% of short-beaked common dolphin whistles were correctly classified by DFA and 5.7% by CART. Similarly, 6.1% of long-beaked common dolphin whistles were correctly classified by DFA and 2.9% by CART. To explore the possibility that this result was caused by an inability to differentiate between the two *Delphinus* species, a version of ROCCA was created that included only short-beaked and long-beaked common dolphins. Overall correct classification scores in this analysis were not significantly greater than the 50% expected by chance (DFA: 49.7%, $p = 1$, CART: 46.8%, $p = 0.45$). Because the two *Delphinus* species could not be distinguished reliably from one another, they were pooled in further analyses.

When the direct version of ROCCA was run on six species and the pooled *Delphinus* species, DFA correctly classified 33.5% of whistles (Table 6.4) and CART correctly classified 33.6% of whistles (Table 6.5). These correct classification scores are significantly greater than the 12.5% expected by chance ($p < 0.0001$ for both DFA and CART). For individual species, DFA correct classification scores ranged from 14.7% (striped dolphins) to 63.8% (short-finned pilot whales). Correct classification scores were significantly greater than expected by chance for every species except striped dolphins ($p = 0.41$). Correct classification scores for CART ranged from 18.5% (spinner dolphins) to 57.1% (false killer whales). All correct classification scores were significantly greater than chance with the exception of spinner dolphins ($p = 0.07$). Based on the pooled tallies of individual whistle classifications, 43.8% of schools were correctly classified by DFA and CART combined (Table 6.6). Correct classification scores for schools ranged from 31.6% (spinner dolphins) to 73.3% (bottlenose dolphins). Half were significantly greater than chance, with the exceptions being *Delphinus* species ($p = 0.24$), spinner dolphins ($p = 0.23$), spotted dolphins ($p = 0.10$), and striped dolphins ($p = 0.06$).

The hierarchical version of ROCCA resulted in no significant difference in the overall correct classification of either individual whistles or schools compared to the direct version of ROCCA (Table 6.7, Table 6.8, Table 6.9; whistles: DFA $p = 0.23$; CART $p = 0.31$; schools $p = 0.75$). However, several significant differences were found for individual species when the hierarchical version of ROCCA was run. The correct classification of individual whistles increased significantly for false killer whales (DFA, $p < 0.001$) and spotted dolphins (CART, $p = 0.03$) and decreased significantly for striped dolphins (CART, $p < 0.001$). Correct classification scores for individual whistles were significantly greater than chance for every species with the exception of striped dolphins (CART, $p = 0.41$).

The hierarchical version of ROCCA resulted in a significant difference in the correct classification of schools for only one species. Correct classification of *Delphinus* species schools increased significantly from 27.8% to 55.6% (p = 0.03, Table 6.6, Table 6.9). Schools of all species were correctly classified significantly more often than expected by chance, with the exception of short-finned pilot whales (p = 0.06), striped dolphins (p = 0.76), and spinner dolphins (p = 0.96).

To evaluate the effect of combining DFA and CART predictions and basing classification decisions on all whistles analyzed during an encounter rather than on individual whistles, correct classification scores were compared for three approaches 1) classifying one whistle at a time, 2) classifying schools based on tallies of species predictions for DFA and CART individually, and 3) classifying schools based on a combination of DFA and CART predictions. These comparisons were made for both the direct version of ROCCA and the hierarchical version. Correct classification scores and p-values for these comparisons are given in tables 6.10 and 6.11. Basing classification decisions on schools rather than individual whistles for DFA and CART individually resulted in no significant differences in correct classification scores in the direct version of ROCCA. Correct classification of *Delphinus* species increased significantly for both DFA and CART (p = 0.004, p = 0.006, respectively) in the hierarchical version of ROCCA. When classification decisions were based on a combination of DFA and CART predictions, rather than on individual whistles, overall correct classification increased significantly in both versions of ROCCA. Individual species correct classification scores increased significantly for bottlenose dolphins (p

= 0.005 when individual whistles classified by CART), rough-toothed dolphins (p = 0.008 when individual whistles classified by CART) striped dolphins (p = 0.005 when individual whistles classified by DFA), and false killer whales (p = 0.002 when individual whistles classified by DFA) in the direct version of ROCCA, and for bottlenose dolphins (p = 0.002 when individual whistles classified by CART), spotted dolphins (p = 0.04 when individual whistles classified by DFA), false killer whales (p = 0.007 when individual whistles classified by DFA), and *Delphinus* species (p = 0.001 when individual whistles classified by DFA, $p < 0.001$ when individual whistles classified by CART) in the hierarchical version of ROCCA.

Discussion

Traditional visual monitoring techniques during shipboard marine mammal surveys are limited by animal behavior, environmental conditions and logistical constraints. The addition of a passive acoustic component to these surveys provides a method for overcoming these limitations. Real-time acoustic species identification offers an additional tool for identifying schools that are difficult to approach and observe and allows species distribution data to be collected even when visual effort is compromised by factors such as poor visibility, inclement weather and high sea states.

Real-time acoustic species identification is especially valuable during surveys dedicated to specific species. For example, the focus of the PICEAS 2005 survey was to determine the population status of false killer whales in an area of high fishery bycatch in the central tropical Pacific Ocean. Visual detection of these animals was extremely difficult due to animal behavior and high sea states. During the first month of this survey, five schools of false killer whales were encountered. Three of the five schools were detected and located by the acoustic team. Time constraints demanded that the ship deviate from the survey trackline for acoustic detections of this focal species only, and therefore real-time acoustic identification was crucial. The combination of high correct classification scores for the species identity of false killer whale vocalizations, combined with high vocal rates and poor visual detection of this species created a situation in which passive acoustics played an indispensable role. Without real-time species identification, the acoustic detections would not have been investigated and valuable data would have been lost.

In addition to providing assistance to the visual observers, ROCCA has the advantage of reducing the bottleneck of post-cruise analysis. Whistles analyzed in real-time are stored automatically in text files and do not need to be re-analyzed back on land. ROCCA's automated whistle extraction, measurement, and data storage features reduce the time necessary for any post-cruise analysis and make ROCCA valuable for other applications such as processing the voluminous amounts of data collected using seafloor mounted acoustic recorders.

While correct classification scores obtained using ROCCA are not the level of near-certainty that would be optimal for shipboard surveys, results are promising as correct classification scores for the individual whistles of most species were significantly greater than expected by chance. Scores did not reach near certainty due to high within-species variability in whistle variables and a large degree of overlap in the time and frequency variables of many species (Table 6.3). Bottlenose dolphins and false killer whales had the highest correct classification scores, with 80% of schools of both species being correctly identified using the hierarchical version of ROCCA (Table 6.9). Examination of descriptive statistics (Table 6.3) shows that the whistles of these two species are distinctive. Bottlenose dolphin whistles have a longer mean duration and false killer whale whistles have lower mean frequencies compared to most other species in the analysis. However, while few whistles of species other than short-finned pilot whales and rough-toothed dolphins were misclassified as false killer whales, whistles from most species were commonly misclassified as bottlenose dolphins. This suggests a bias within the classification algorithms towards classifying whistles as bottlenose dolphins. This bias does not seem to be related to sample size. If the source of this bias can be found and removed, correct classification scores for other species may be increased.

Correct classification scores were low for spinner and striped dolphins in all analyses. Striped dolphin classification errors were relatively evenly spread across all species except false killer whales, short-finned pilot whales, and rough-toothed dolphins. Similarly, spinner dolphin classification errors were generally evenly spread across all species other than short-finned pilot whales. At least some whistles from all species were misclassified as striped and spinner dolphins; however, these misclassifications were least common for false killer whales and short-finned pilot whales. The whistles of the small delphinid species (bottlenose, spotted, striped, spinner, short-beaked common, and long-beaked common dolphins) had very similar frequency characteristics (Table 6.3). Given the variables that were measured and included in the classification algorithms, the similarities in frequency characteristics likely explain why classification errors were spread over these species.

In order to reduce the effects of high intra- and low inter-species variation, classification decisions were made based on multiple whistles, rather than on one whistle at a time. Classifying overall schools rather than individual whistles resulted in slight increases in correct classification scores, but these were not significant for DFA or CART (Table 6.10, Table 6.11). However, when classification decisions for schools were made based on a combination of DFA and CART results, correct classification increased significantly both overall and for several individual species. These results point not only to the benefit of making classification decisions based on multiple whistles, but also to the benefit of using more than one classification algorithm. Different classification algorithms are sensitive to different characteristics of the data set, and the ability to combine the strengths of more than one algorithm can result in higher classification success.

An additional approach employed to potentially increase classification success was the creation of a hierarchical version of ROCCA. While the hierarchical version did not result in a significant increase in overall correct classification, it did increase slightly, and correct classification of *Delphinid* species schools in particular increased significantly. Additionally, correct classification scores were significantly greater than chance for five of the eight species in the hierarchical version, compared to four of the eight species in the direct version of ROCCA. This approach shows some promise and may produce more significant results with different species categories or a greater number of levels within the hierarchy.

ROCCA performed best when classification decisions were based on multiple whistles classified using the hierarchical method and when decisions made based on a combination of DFA and CART results. This approach resulted in some very high correct classification scores of up to 80% for species such as bottlenose dolphins and false killer whales. A method for further increasing these correct classification scores likely lies in the exploration of additional whistle variables. As previously discussed (Oswald *et al.* 2003), the variables currently included in ROCCA have high intra- and low inter-species variability. Perhaps variables such as slope, the location of steps and inflection points within whistles, and relative intensities of different frequencies would be more effective for separating species. In addition, alternate classification algorithms such as artificial neural networks and hidden Markov models may be better suited to the task of identifying dolphin whistles. Work is currently under way to explore the effect of alternate whistle variables and classification algorithms on correct classification scores. When the optimal set of whistle variables and classification algorithms is assembled, ROCCA will be an even more powerful tool for monitoring marine mammal populations. ROCCA will be valuable not only for real-time species identification during shipboard surveys, but also for analysis of vocalizations recorded using seafloor-mounted hydrophones. While ROCCA has been created for use in the eastern tropical and temperate Pacific Ocean, it can be modified for use in other regions.

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Table 6.1. Frequency response and gain characteristics of hydrophone arrays used during Southwest Fisheries Science Center (NOAA, NMFS) marine mammal abundance surveys. The array used during the PICEAS 2005 survey had 4 elements, 3 relatively narrowband and 1 relatively broadband.

Survey	**Array frequency response**	**# hydrophone elements**
SPAM 1998	500 Hz - 150 kHz ± 3dB at -163 dB re 1v/μPa	3
	32 Hz - 25 kHz ± 3dB at -173 dB re 1v/μPa	5
STAR 2000	2 kHz - 45 kHz ± 4 dB at –132 dB re 1 v/μPa	5
	2 kHz - 120 kHz ± 3 dB at –164 dB re 1 v/μPa	3
HICEAS 2002	500 Hz – 30 kHz ± 5 dB at –155 dB re 1 v/ μPa	2
STAR 2003	500 Hz - 30 kHz ± 5 dB at –155 dB re 1 v/μPa	3
PICEAS 2005	1 kHz to 40 kHz ± 5 dB at –150 dB re 1 v/μPa	3
	2 kHz to 150 kHz ± 2 dB at –166 dB re 1 v/μPa	1

Table 6.2. Number of whistles from each survey analyzed for each species, and the number of schools that those whistles were recorded from.

	1998		**1999**		**2000**		**2002**		**2003**		**2005**		**Total**	
Species	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**
Bottlenose dolphin	78	4	73	3	31	2	5	1	64	3	55	2	306	15
Spotted dolphin	56	6	32	1	103	6	101	5	70	2	37	6	399	26
Spinner dolphin	39	3	69	4	95	6	17	1	21	1	18	4	259	19
Striped dolphin	83	9	0	0	180	15	59	5	25	3	54	6	401	38
Rough-toothed dolphin	21	2	38	2	4	1	86	5	0	0	43	4	192	14
Short-beaked common dolphin	89	7	0	0	154	12	0	0	71	6	0	0	314	25
Long-beaked common dolphin	66	6	0	0	72	3	0	0	36	2	0	0	174	11

Table 6.2 cont'd

	1998		1999		2000		2002		2003		2005		Total	
Species	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**	**# whists**	**# schools**
False killer whale	35	1	34	1	0	0	0	0	35	1	236	7	340	10
Short-finned pilot whale	80	6	70	4	5	1	57	5	0	0	9	2	221	18
Total	547	44	316	15	644	46	325	21	322	18	452	31	2606	176

Table 6.3. Means and standard deviations (in parentheses) for continuous variables measured from whistles. Frequency variables are given in kHz, duration is given in seconds, and number of inflection points and number of steps are count data.

Species	**beginning frequency**	**ending frequency**	**minimum frequency**	**maximum frequency**	**duration**	**# inflect**	**# steps**
Bottlenose dolphin	11.61	10.24	7.92	17.07	1.11	2.85	2.17
	(5.11)	(4.78)	(2.49)	(4.55)	(0.69)	(2.67)	(3.61)
Spotted dolphin	9.92	14.92	8.41	17.99	0.75	1.29	3.06
	(3.94)	(5.66)	(2.39)	(4.69)	(0.38)	(1.45)	(3.84)
Striped dolphin	10.80	12.01	8.48	14.98	0.69	1.84	2.36
	(3.96)	(3.40)	(2.21)	(3.61)	(0.35)	(1.82)	(3.19)
Spinner dolphin	11.85	12.94	9.99	15.09	0.61	1.89	0.83
	(4.42)	(4.33)	(3.18)	(4.57)	(0.42)	(3.53)	(1.64)
Rough-toothed dolphin	7.41	8.33	6.46	9.53	0.64	2.56	1.51
	(3.15)	(2.95)	(2.33)	(2.97)	(0.36)	(3.00)	(1.84)
Short-beaked common dolphin	11.63	12.18	8.30	15.04	0.70	1.64	1.76
	(4.84)	(4.38)	(2.69)	(4.39)	(0.39)	(1.87)	(2.31)
Long-beaked common dolphin	10.87	14.46	8.48	16.21	0.62	1.59	1.74
	(4.89)	(5.12)	(2.70)	(4.94)	(0.34)	(3.29)	(2.19)
False killer whale	5.77	6.27	5.28	6.95	0.44	0.85	0.03
	(1.62)	(1.52)	(1.23)	(1.83)	(0.22)	(0.90)	(0.18)
Short-finned pilot whale	4.40	5.59	3.73	6.39	0.48	0.86	0.21
	(2.72)	(3.60)	(2.04)	(3.89)	(0.35)	(1.58)	(0.81)

Table 6.4. Classification results of discriminant function analysis where whistles are classified directly to species. Percent of whistles correctly classified for each species are in bold. Correct classification scores that are significantly greater (Fisher's exact test, α = 0.05) than the 12.5% expected by chance are marked by an asterisk and *p*-values are given in the last column. The number of whistles included in the analysis for each species (*n*) is given in the second last column. Overall, 33.5% of whistles were classified to the correct species. This is significantly greater ($p < 0.0001$) than expected by chance.

	% Classified as									
Actual species	**Bottlenose dolphin**	**Common dolphin**	**False killer whale**	**Spotted dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**	**n**	**p**
Bottlenose dolphin	**60.8***	9.5	1.0	6.9	1.6	2.6	11.4	6.2	306	<0.001
Common dolphin	27.5	**28.3***	0.2	10.5	1.0	7.4	14.3	10.9	488	<0.001
False killer whale	9.1	3.5	**22.6***	0.0	23.2	35.9	1.5	4.1	340	<0.001
Spotted dolphin	25.8	19.5	0.3	**29.6***	0.5	3.3	12.3	8.8	399	<0.001
Short-finned pilot whale	10.0	7.2	9.0	0.9	**63.8***	3.6	2.7	2.7	221	<0.001
Rough-toothed dolphin	12.5	9.9	4.7	0.0	7.8	**46.9***	9.4	8.9	192	<0.001
Striped dolphin	32.2	19.2	1.2	9.2	0.0	5.0	**14.7**	18.5	401	0.41
Spinner dolphin	22.4	11.6	2.3	10.0	0.4	11.2	17.4	**24.7***	259	<0.001

Table 6.5. Classification results of classification and regression tree analysis where whistles are classified directly to species. Percent of whistles correctly classified for each species are in bold. Correct classification scores that are significantly greater (Fisher's exact test, $\alpha = 0.05$) than the 12.5% expected by chance are marked by an asterisk and *p*-values are given in the last column. The number of whistles included in the analysis for each species (*n*) is given in the second last column. Overall, 33.6% of whistles were classified to the correct species. This is significantly greater ($p < 0.0001$) than expected by chance.

	% Classified as									
Actual species	**Bottlenose dolphin**	**Common dolphin**	**False killer whale**	**Spotted dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**	**n**	**p**
Bottlenose dolphin	**35.9***	18.0	2.0	12.1	1.3	2.6	19.6	8.5	306	<0.001
Common dolphin	10.2	**21.7***	4.3	21.9	0.8	6.1	25.6	9.2	488	<0.001
False killer whale	0.6	7.4	**57.1***	0.3	15.3	11.8	1.2	6.5	340	<0.001
Spotted dolphin	9.3	24.3	2.3	**33.8***	0.3	1.0	23.8	5.3	399	<0.001
Short-finned pilot whale	1.4	5.0	31.2	1.4	**50.7***	4.1	4.1	2.3	221	<0.001
Rough-toothed dolphin	3.1	20.8	20.3	4.7	8.9	**34.4***	5.2	2.6	192	<0.001
Striped dolphin	12.0	22.4	3.2	20.2	0.7	5.2	**26.2***	10.0	401	<0.001
Spinner dolphin	7.7	21.2	6.9	17.8	0.8	6.2	20.8	**18.5**	259	0.07

Table 6.6. Classification results for schools classified based on running tallies of DFA and CART results. Percent of schools correctly classified for each species are in bold. Correct classification scores that are significantly greater (Fisher's exact test, $\alpha = 0.05$) than the 12.5% expected by chance are marked by an asterisk and *p*-values are given in the last column. The number of schools included in the analysis for each species (*n*) is given in the second last column. Overall, 43.8% of schools were classified to the correct species. This is significantly greater ($p < 0.0001$) than expected by chance.

	% Classified as									
Actual species	**Bottlenose dolphin**	**Common dolphin**	**False killer whale**	**Spotted dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**	**n**	**p**
Bottlenose dolphin	**73.3***	0.0	0.0	6.7	6.7	6.7	0.0	6.7	15	0.002
Common dolphin	19.4	**27.8**	2.8	13.9	0.0	5.6	25.0	5.6	36	0.24
False killer whale	10.0	0.0	**70.0***	0.0	10.0	10.0	0.0	0.0	10	0.02
Spotted dolphin	19.2	15.4	3.8	**34.6**	0.0	0.0	15.4	11.5	26	0.1
Short-finned pilot whale	0.0	0.0	27.8	5.6	**61.1***	0.0	0.0	5.6	18	0.004
Rough-toothed dolphin	0.0	14.3	0.0	7.1	7.1	**71.4***	0.0	0.0	14	0.006
Striped dolphin	34.2	10.5	0.0	13.2	0.0	2.6	**34.2**	5.3	38	0.06
Spinner dolphin	10.5	10.5	5.3	10.5	0.0	5.3	26.3	**31.6**	19	0.23

Table 6.7. Classification results of hierarchical discriminant function analysis. Percent of whistles correctly classified for each species are in bold. Correct classification scores that are significantly greater (Fisher's exact test, $\alpha = 0.05$) than the 12.5% expected by chance are marked by an asterisk and *p*-values are given in the last column. The number of whistles included in the analysis for each species (*n*) is given in the second last column. Overall, 35.1% of whistles were classified to the correct species. This is significantly greater ($p < 0.0001$) than expected by chance.

	% Classified as									
Actual species	**Bottlenose dolphin**	**Common dolphin**	**False killer whale**	**Spotted dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**	**n**	**p**
Bottlenose dolphin	**60.8***	10.1	1.0	6.9	1.0	2.6	11.4	6.2	306	<0.001
Common dolphin	27.7	**28.5***	0.8	10.5	1.2	6.6	14.3	10.5	488	<0.001
False killer whale	9.1	3.2	**35.9***	0.0	34.7	10.9	1.8	4.4	340	<0.001
Spotted dolphin	25.8	19.5	0.5	**29.6***	1.3	2.3	12.3	8.8	399	<0.001
Short-finned pilot whale	14.0	8.6	8.6	0.9	**56.1***	4.5	5.0	2.3	221	<0.001
Rough-toothed dolphin	12.5	10.4	8.3	0.0	7.8	**42.7***	9.4	8.9	192	<0.001
Striped dolphin	11.0	23.7	1.7	26.9	0.0	6.0	**20.2***	10.5	401	0.004
Spinner dolphin	22.4	11.6	5.0	10.0	0.4	9.3	17.0	**24.3***	259	<0.001

Table 6.8. Classification results of hierarchical classification and regression tree analysis. Percent of whistles correctly classified for each species are in bold. Correct classification scores that are significantly greater (Fisher's exact test, $\alpha = 0.05$) than the 12.5% expected by chance are marked by an asterisk and *p*-values are given in the last column. The number of whistles included in the analysis for each species (*n*) is given in the second last column. Overall, 35.0% of whistles were classified to the correct species. This is significantly greater ($p < 0.0001$) than expected by chance.

	% Classified as									
Actual species	**Bottlenose dolphin**	**Common dolphin**	**False killer whale**	**Spotted dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**	**n**	**p**
Bottlenose dolphin	**37.9***	21.9	2.6	14.7	0.3	4.2	11.4	6.9	306	<0.001
Common dolphin	15.6	**25.4***	3.7	25.0	0.2	7.4	14.3	8.4	488	<0.001
False killer whale	0.3	7.6	**60.6***	1.2	5.0	7.9	5.0	12.4	340	<0.001
Spotted dolphin	10.3	20.1	2.5	**41.4***	1.0	0.3	19.5	5.0	399	<0.001
Short-finned pilot whale	0.9	5.0	29.0	2.3	**50.2***	7.7	2.3	2.7	221	<0.001
Rough-toothed dolphin	5.7	17.7	13.0	4.2	5.2	**41.7***	8.3	4.2	192	<0.001
Striped dolphin	32.2	19.2	1.5	9.2	0.0	4.7	**14.7**	18.5	401	0.41
Spinner dolphin	17.0	16.2	6.9	11.6	1.2	7.7	19.7	**19.7***	259	0.03

Table 6.9. Classification results for schools classified based on running tallies of hierarchical DFA and CART results. Percent of schools correctly classified for each species are in bold. Correct classification scores that are significantly greater (Fisher's exact test, α = 0.05) than the 12.5% expected by chance are marked by an asterisk and *p*-values are given in the last column. The number of schools included in the analysis for each species (*n*) is given in the second last column. Overall, 46.0% of schools were classified to the correct species. This is significantly greater ($p < 0.0001$) than expected by chance.

	% Classified as									
Actual species	**Bottlenose dolphin**	**Common dolphin**	**False killer whale**	**Spotted dolphin**	**Short-finned pilot whale**	**Rough-toothed dolphin**	**Striped dolphin**	**Spinner dolphin**	**n**	**p**
Bottlenose dolphin	**80.0***	6.7	0.0	0.0	0.0	6.7	0.0	6.7	15	<0.001
Common dolphin	22.2	**55.6***	0.0	13.9	0.0	2.8	5.6	0.0	36	<0.001
False killer whale	10.0	0.0	**80.0***	0.0	0.0	0.0	0.0	10.0	10	0.005
Spotted dolphin	23.1	7.7	3.8	**50.0***	0.0	0.0	7.7	7.7	26	0.006
Short-finned pilot whale	5.6	5.6	38.9	0.0	**44.4**	0.0	0.0	5.6	18	0.06
Rough-toothed dolphin	14.3	7.1	0.0	0.0	7.1	**64.3***	7.1	0.0	14	0.02
Striped dolphin	26.3	26.3	0.0	23.7	0.0	0.0	**15.8**	7.9	38	0.76
Spinner dolphin	21.1	15.8	0.0	5.3	0.0	10.5	21.1	**26.3**	19	0.96

Table 6.10. Correct classification scores for individual whistles classified to species by DFA and CART and for schools classified based on running tallies of DFA and CART results. *P*-values are given for comparisons of correct classification scores for individual whistles vs. schools (DFA and CART individually) and for individual whistles vs. schools (DFA and CART results combined).

	Whistles		**Schools**						
Species	**DFA % correct**	**CART % correct**	**DFA % correct**	***p* Whistles vs. schools (DFA)**	**CART % correct**	***p* Whistles vs. schools (CART)**	**DFA and CART % correct**	***p* Whistles (DFA) vs. schools (DFA and CART)**	***p* Whistles (CART) vs. schools (DFA and CART)**
Bottlenose dolphin	60.8	35.9	86.7	0.06	40.0	0.8	73.3	0.4	0.005*
Spotted dolphin	29.6	33.8	38.5	0.4	34.6	1.0	34.6	0.7	1.0
Striped dolphin	14.7	26.2	13.2	1.0	34.2	0.3	34.2	0.005*	0.3
Spinner dolphin	24.7	18.5	26.3	1.0	21.1	0.8	31.6	0.6	0.2
Rough-toothed dolphin	46.9	34.4	64.3	0.3	57.1	0.2	71.4	0.1	0.008*
Common dolphin	28.3	21.7	41.7	0.1	22.2	1.0	27.8	1.0	0.4
False killer whale	22.6	57.1	0.0	0.1	80.0	0.2	70.0	0.002*	0.5
Short-finned pilot whale	63.8	50.7	72.2	0.6	44.4	0.6	61.1	0.8	0.5
Overall	33.5	33.6	39.8	0.1	36.4	0.5	43.8	0.007*	0.007*

Table 6.11. Correct classification scores for individual whistles classified to species by hierarchical DFA and CART and for schools classified based on running tallies of hierarchical DFA and CART results. *P*-values are given for comparisons of correct classification scores for individual whistles vs. schools (DFA and CART individually) and for individual whistles vs. schools (DFA and CART results combined).

	Whistles		**Schools**						
Species	**DFA % correct**	**CART % correct**	**DFA % correct**	***p* Whistles vs. schools (DFA)**	**CART % correct**	***p* Whistles vs. schools (CART)**	**DFA and CART % correct**	***p* Whistles (DFA) vs. schools (DFA and CART)**	***p* Whistles (CART) vs. schools (DFA and CART)**
Bottlenose dolphin	60.8	37.9	86.7	0.06	53.3	0.3	80.0	0.2	0.002*
Spotted dolphin	29.6	25.4	34.6	0.7	50.0	0.4	50.0	0.04*	0.4
Striped dolphin	20.2	14.7	10.5	0.2	15.8	0.8	15.8	0.7	0.8
Spinner dolphin	24.3	19.7	15.8	0.6	21.1	0.8	26.3	0.8	0.6
Rough-toothed dolphin	42.7	41.7	57.1	0.4	57.1	0.3	64.3	0.2	0.2
Common dolphin	28.5	25.4	52.8	0.004*	47.2	0.006*	55.6	0.001*	< 0.001*
False killer whale	35.9	60.6	40.0	0.8	90.0	0.1	80.0	0.007*	0.3
Short-finned pilot whale	56.1	50.2	55.6	1.0	44.4	0.8	44.4	0.5	0.8
Overall	35.1	35.0	39.8	0.2	40.8	0.09	46.0	0.004*	0.004*

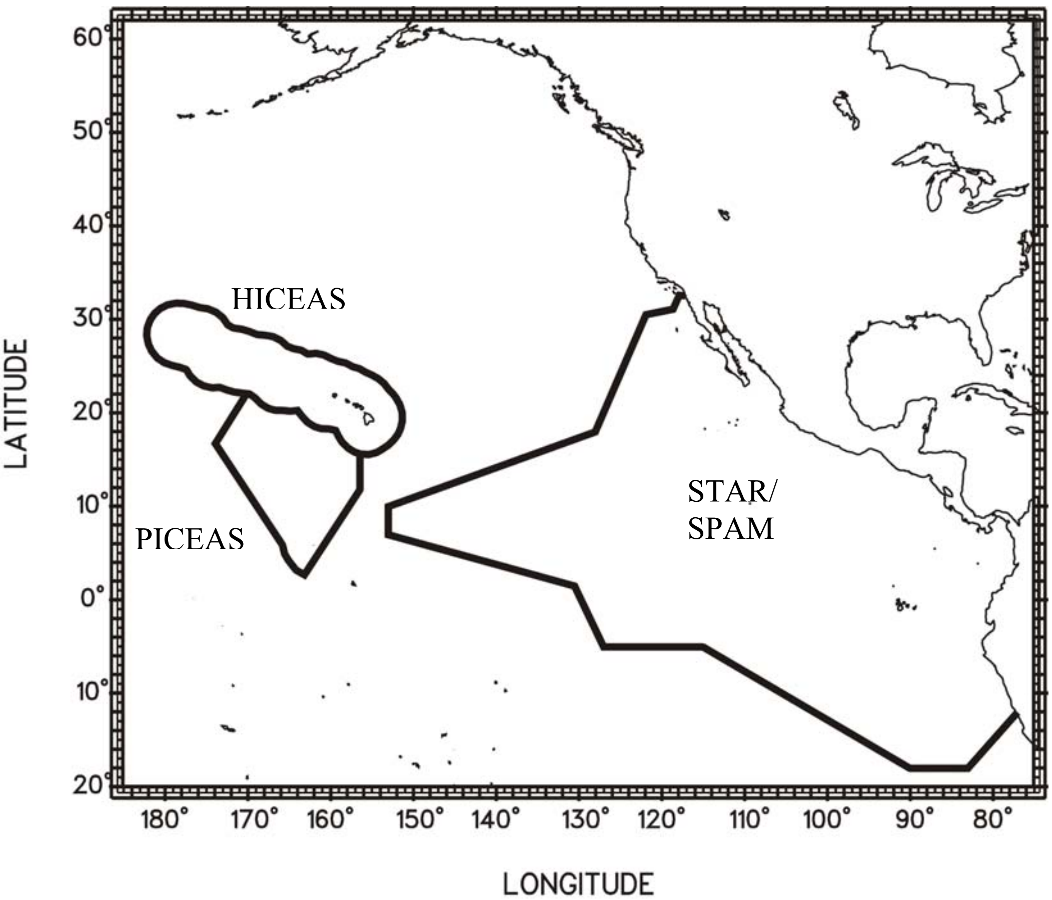

Figure 6.1. Study area boundaries for the HICEAS 2002, PICEAS 2005, SPAM 1998, and STAR 1999, 2000, and 2003 Southwest Fisheries Science Center (NOAA, NMFS) marine mammal abundance surveys.

Appendix 6.A. Matlab code for Real-time Odontocete Call Classification Algorithm (ROCCA). ‘Ish2matlab.m’ saves sound samples as binary soundfiles. ‘ROCCA.m’ extracts whistle contour, measures variables, and runs classification algorithms. ‘ContourJ1id.m’ is a function that is called by ‘ROCCA.m’ to measure whistle variables.

Ish2matlab.m

```
% This script takes sound samples sent from Ishmael to Matlab (the variable
% (ishSelectionSamples) and saves them to a binary sound file.
%
% To use this script, run Ishmael. Do 'Compute->Configure Matlab command...'
% from the menu, then enter the name of this script (ish2matlab) in the command-to-
% execute edit box and this directory (C:\whistle_analysis) in the directory edit box.
% Then when you're viewing sounds in Ishmael, select an animal call, and do
% "Compute->Execute Matlab command" (ctrl-M).
%
% adapted from script written by
% Dave Mellinger
% mellinger@pmel.noaa.gov
% 7/28/01
% minor changes on 10/16/01
% adapted by Julie N. Oswald
% June 2005

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%               Step 1: Save samples from Ishmael            %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Fs = 60000;              % sampling rate
chan = 1;                % which channel of Ishmael data to use
soundfile = 'data.16';   % file name used by 'Run.bat'

% First a bit of error checking.
if (abs(ishSRate - Fs) > Fs*.02)        % must be within 2% of correct srate
  figure(1); clf; text(0, 0.5, 'Processing error: Sampling rate does not match Ishmaels
  sampling rate'); set(gca, 'Visible', 'off')
  return
end
if (size(ishSelectionSamples, 2) == 0)
  figure(1); clf; text(0, 0.5, 'You must make a selection in Ishmael for processing to
  work.'); set(gca, 'Visible', 'off')
  return
end
wavwrite_rocca(ishSelectionSamples(:,chan),Fs,16,'c:\ROCCA\toclass.wav');
```

ROCCA.m

```
% Rocca.m uses tria.m to extract whistle contours and whistle variables
% Tria.m is a comprehensive dolphin signal analysis program.  It takes binary files
% containing pulsed or tonal signals and stores the quantified parameter as a text files.
% Developed by Marc O. Lammers (9/24/03).
% Rocca.m measures additional whistle variables and uses DFA and CART to
% determine predicted species identification
% Julie N. Oswald
% July, 2005
% Do not distribute without permission.

colordef white
back0=1;
while back0==1

close all
clear

numspecies = 9;
path='C:\ROCCA\';
tally_file=[path 'rocca_tally.csv'];
sp_array=['Tursiops truncatus             ';
          'Delphinus species              ';
          'Pseudorca crassidens           ';
          'Stenella attenuata             ';
          'Globicephala macrorhynchus     ';
          'Steno bredanensis              ';
          'Stenella coeruleoalba          ';
          'Stenella longirostris          '];


%Check for file containing running tally of predicted species
fid=fopen(tally_file,'r');

%if file does not exist, reset variables
if fid==-1
   tally_sp_dfa = zeros(numspecies,1);
   tally_sp_cart = zeros(numspecies,1);
   snum=input('Enter acoustic sighting number: ');
   whistnum = 1;

%if file does exist, ask user if they want to continue
else
   fclose(fid);
```

```
   new_sighting=input('New sighting [y = 1, n = 2]? ');
   if new_sighting==2
      %read data into array
      tally_dummy = csvread(tally_file);
      snum = tally_dummy(1);
      whistnum = tally_dummy(2)+1;
      tally_sp_dfa = tally_dummy(3:numspecies+2);
      tally_sp_cart = tally_dummy(numspecies+3:2*numspecies+2);
   elseif new_sighting==1
      %clear array and delete file
      tally_sp_dfa = zeros(numspecies,1);
      tally_sp_cart = zeros(numspecies,1);
      snum=input('Enter acoustic sighting number: ');
      whistnum=1;

   end
end

%%%%%%%%%%%%%
%        TRIA          %
%%%%%%%%%%%%%

%Specifications to be changed as needed
FILENAME = 'toclass.wav';
Fs=48000;
bit=16;                 % sampling precision
window_size=1024;
XX=10;                  % number of samples on each side of max amp of click.
                        % Beyond these click is zero-padded to elimiate ripples in
                        % spectrum.
overlap=0.25;           % percent overlap of windows (value of either: 0, 0.25, 0.5,
0.75)

% LOAD SOUND FILE -- MODIFY ACCORDING TO FILE FORMAT (E.G.
% BINARY, .WAV)
cd C:\ROCCA;            % the matlab directory containing data files
back0=0;
fid=fopen(FILENAME);
[file1,COUNT] = fread (fid,inf,'int16');
fclose(fid);

% Display a spectrogram of the signal so the user can select a frequency threshold.
figure(1);
[B,F,T]=specgram(file1,512,Fs);
```

```
imagesc(T,F,20*log10(abs(B)))
axis xy
v_upper = 110;
v_lower = 0;
v=[v_lower v_upper];
caxis(v);
colorbar;
uimenufcn(gcf,'WindowCommandWindow')   % returns focus to the command
                                        % window

% change intensity scale displayed?
change=input('Change intensity scale [y = 1, n = 2]? ');
while change==1;
   update = input('Darker (1) or lighter (2)? ');
      if update == 1;
         v_upper = v_upper - 5;
      elseif update == 2;
         v_upper = v_upper + 5;
      end
      v=[v_lower v_upper];
      close(1)
      figure(1)
      [B,F,T]=specgram(file1,512,Fs);
      imagesc(T,F,20*log10(abs(B)))
      axis xy;
      caxis(v);
      colorbar;
      uimenufcn(gcf,'WindowCommandWindow');   % returns focus to the command
                                               % window
      change=input('Change intensity scale [y = 1, n = 2]? ');
end

window_size=1024;                    % size of step size and FFT window to use.
sensL=0.89;                          % sensitivity to noise of contour algorithm
sensH=1.11;
X=(1:length(file1))./(Fs/1000);      % scaling for the x-axis of time plots.

% option to ignore frequencies if there is tonal noise in the recording
ig=0;ignoreY=[];
ignore=input('Ignore tonal noise [y = 1, n = 2]? ');
while ignore==1;
   title(['Point to the frequency of the tonal noise']);
   [igX,igY]=ginput(1);
   ignoreY=[ignoreY igY];
```

```
    ig=1;
    title(['Ignore ',num2str(ignoreY),' Hz']);
    uimenufcn(gcf,'WindowCommandWindow');       % returns focus to the command
                                                % window
    ignore=input('Another frequency to ignore [y = 1, n = 2]? ');
end

loop_again=1;
while loop_again==1
    figure(2);
    specgram(file1,512,Fs);
    caxis(v);

% Identify the begining of the whistle along the frequency axis
fprintf('Point to the beginning frequency of the whistle');fprintf('\r');
title(['Point to the beginning frequency of the whistle']);
hold off
[I,J]=ginput(1);
pk_hz_prev=round(J);
title(['Start at ',num2str(round(pk_hz_prev)),' Hz']);
uimenufcn(gcf,'WindowCommandWindow');   % returns focus to the command
window
start=input('Select another start [y = 1, n = 2]? ');

while start==1
   [I,J]=ginput(1);
   pk_hz_prev=round(J);
   title(['Start at ',num2str(round(pk_hz_prev)),' Hz']);
   uimenufcn(gcf,'WindowCommandWindow');   %returns focus to the command
window
   start=input('Select another start [y = 1, n = 2]? ');
end

  %------------ Spectral Calculations

  h=1;
  j=length(file1)/(window_size*(1-overlap));           % determine number of steps to
                                                        % take through signal
  window=1:(window_size*(1-overlap));                  % define the first window
     file_window=file1(window);                        % calculate rms for first window
        rel_win_sqrd=file_window.^2;
        rel_win_sum=sum(rel_win_sqrd);
        rel_win_mean=rel_win_sum/(window_size*(1-overlap));
        rel_win_rms=sqrt(rel_win_mean);
```

```
  harmonic_all=[];                                    % Declare some variables
  energyf=[];perc_f_all=[];
  energy1_all=[]; harm1_hz_all=[]; perc_h1_all=[];
  energy2_all=[]; harm2_hz_all=[]; perc_h2_all=[];
  energy3_all=[]; harm3_hz_all=[]; perc_h3_all=[];
  energy4_all=[]; harm4_hz_all=[]; perc_h4_all=[];

  time_index_all=[];
  dc_all=[];
  pk_hz_all=[];
  win_rms_all=[];

% define next window
  next_window=(window_size*(1-overlap)+1):(2*(window_size*(1-overlap)));
  next_file_window=file1(next_window);

  for i=1:fix(j)                   % Loop through entire signal taking 'j' number of
                                   % steps

    file_window=file1(window);
    max_value=max(abs(file_window));

    dc=(mean(abs(file_window)/max_value))/.636;         % calculate duty cycle
    [pxx,F]=FFTrans(file_window,window_size,Fs);        % calculate spectrum of
                                                        % window using fft

     % to ignore tonal noise in the recording
     if ig~=0
        for i=1:size(ignoreY)
           d=find((F<=ignoreY(i)+200)&(F>=ignoreY(i)-200));
           pxx(d)=0;
        end
     end

      if pk_hz_prev*sensH<max(F)
        f=find((F>=(pk_hz_prev*sensL))&(F<=(pk_hz_prev*sensH))); % set
                                              % minimum and maximum frequencies
                                              % considered
      else
        f=find((F>=(pk_hz_prev*sensL))&(max(F)));
      end
      max_amp=find(pxx==max(pxx(f)));                  % find peak frequency
      pk_hz=F(max_amp);
      fund_lower=min(find(F>=(pk_hz-250)));        % isolate fft values in 500 Hz bin
```

```
                                                                  % around peak frequency
    fund_upper=max(find(F<=(pk_hz+250)));
    fund_freq_bin=pxx(fund_lower:fund_upper);
    energy_fund=sum((fund_freq_bin).^2);            % calculate energy in this bin
    energyf=[energyf energy_fund];

% This routine ensures that random transient peaks in spectrum are not mistaken for
the % fundamental peak frequency.
    if pk_hz*sensH<=max(F)
     if (pk_hz < (pk_hz_prev*sensL))|(pk_hz > (pk_hz_prev*sensH))
      pk_hz=pk_hz_prev;
     else
      pk_hz=pk_hz;
      pk_hz_prev=pk_hz;
     end
    elseif pk_hz*1.05>max(F)
     pk_hz=max(F);
     pk_hz_prev=pk_hz;
    end

    win_sqrd=file_window.^2;                  % find rms of window
    win_sum=sum(win_sqrd);
    win_mean=win_sum/(window_size*(1-overlap));
    win_rms=sqrt(win_mean);

    if h<=fix(j-1)       % Compare rms value with previous and subsequent windows.
      next_file_window=file1(next_window);
      next_win_sqrd=next_file_window.^2;
      next_win_sum=sum(next_win_sqrd);
      next_win_mean=next_win_sum/(window_size*(1-overlap));
      next_win_rms=sqrt(next_win_mean);
      % If >20% larger than either the previous or subsequent windows,
      % average between the two windows.
      if (win_rms > (rel_win_rms*1.2)) | (win_rms > (next_win_rms*1.2))
        win_rms = (rel_win_rms+next_win_rms)/2;
      else
        win_rms = win_rms;
      end
      rel_win_rms = win_rms;
    end
  % indexes the window in time
  time_index=(round(mean(window)))/Fs;
```

```
 % store values in vectors
    time_index_all=[time_index_all time_index];
    win_rms_all=[win_rms_all win_rms];
    dc_all=[dc_all dc];
    pk_hz_all=[pk_hz_all pk_hz];
    window=window+(window_size*(1-overlap));
    next_window=next_window+(window_size*(1-overlap));
    h=h+1;
  end

% make all amplitude estimations relative to the maximum
  max_rms_file=max(win_rms_all);
  rel_amp_all=win_rms_all/max_rms_file;

% Round to the appropriate significant figure
time_index_all=(round(time_index_all*1000))/1000;
rel_amp_all=(round(rel_amp_all*1000))/1000;
dc_all=(round(dc_all*1000))/1000;
pk_hz_all=round(pk_hz_all);

% Storage vectors
duration_f=max(time_index_all);max_hz_f=max(pk_hz_all);min_hz_f=min(pk_hz_all
);beg_hz_f=pk_hz_all(1);
end_hz_f=pk_hz_all(length(pk_hz_all));
dc_mean=mean(dc_all);dc_std=std(dc_all);mean_hz_f=mean(pk_hz_all);std_hz_f=std
(pk_hz_all);
range=max_hz_f - min_hz_f;

% matrix for storage of the whistle contour
SIGNAL= [dc_all;pk_hz_all;rel_amp_all;time_index_all];

%-------------Figure #4 Characterization Vectors
figure(4);
clf;
colordef(4,'white')
plot(SIGNAL(2,:),'b.:');
title(['Characterization vectors for ',FILENAME])
ylabel('Hertz')
hold off

uimenufcn(gcf,'WindowCommandWindow');   % returns focus to the command
                                         % window
loop_again=input('Extract contour again [y = 1, n = 2]? ');
if loop_again==1
```

```
   sensitivity=input('Decrease or increase noise sensitivity  [decrease = 1, increase =
                        2]?');
   if sensitivity==1
      sensH=sensH+0.02;sensL=sensL-0.02;
   else
      sensH=sensH-0.02;sensL=sensL+0.02;
   end
   close(4);
end
end

uimenufcn(gcf,'WindowCommandWindow');   % returns focus to the command
                                         % window
analyze_c=input('Analyze contour and harmonics [y = 1, n = 2]? ');
tot_step=0;
tot_inflect=0;
if analyze_c==1

harms=input('Are any harmonics present [y = 1, n = 2]? ');
if harms==1
   harms =1;
elseif harms ==2
   harms = 0;
end

median_hz_f=median(pk_hz_all);range_hz_f=max(pk_hz_all)-min(pk_hz_all);
center_hz_f=min(pk_hz_all)+((max(pk_hz_all)-min(pk_hz_all))/2);  % center freq
rel_bw=((max(pk_hz_all)-min(pk_hz_all))/center_hz_f);   % relative bandwidth
maxmin=max(pk_hz_all)/min(pk_hz_all) ;              % ratio of max freq to min freq
last=length(pk_hz_all);
begend=pk_hz_all(1)/pk_hz_all(last);                % ratio of beg freq to end freq

% to find freqs at 1/4, 1/2, and 3/4 points of whist:
L=length(pk_hz_all);quart_hz=pk_hz_all(round(L/4));half_hz=pk_hz_all(round(L/2));
threequ_hz=pk_hz_all(round(3*L/4));
spread=iqr(pk_hz_all);  % diff bw 75th and 25th percentiles of freq (interquartile
range)

% to find mean dc of each quarter of whistle
Ldc=length(dc_all);meandc_quart=mean(dc_all(1:fix(Ldc/4)));
meandc_2quart=mean(dc_all(fix(Ldc/4):fix(Ldc/2)));
meandc_3quart=mean(dc_all(fix(Ldc/2):fix(3*Ldc/4)));
meandc_4quart=mean(dc_all(fix(3*Ldc/4):fix(Ldc)));
```

```
% Coefficient of frequency modulation (COFM) (based on Morisaka et al 2003, based
% on McCowan and Reiss 1995)
% take 20 frequency measurements equally spaced along contour
cofm_20=pk_hz_all(4:3:L-3);  % Step through fundamental contour four points at a
                                          % time
cofm_calc=[];
jmp=1;
for jmp2=2:length(cofm_20)
   calc=abs(cofm_20(jmp2)-cofm_20(jmp));
   cofm_calc=[cofm_calc calc];
   jmp=jmp2;
end
cofm=sum(cofm_calc)/10000;

% storage vector for Julie's signal stats
ALLVARS=[dc_mean;meandc_quart;meandc_2quart;meandc_3quart;meandc_4quart;
…dc_std;mean_hz_f;median_hz_f;std_hz_f;spread;quart_hz;half_hz;threequ_hz;...
center_hz_f;rel_bw;maxmin;begend;cofm;beg_hz_f;end_hz_f;min_hz_f;max_hz_f;…
range_hz_f;duration_f;harms];

% call contourJ1id to measure the rest of the whistle variables
namefile='a';
contourJ1id(SIGNAL',ALLVARS',file1,Fs,namefile,snum,whistnum);

close(figure(5));

%%%%%%%%%%%%%%%%%%%%%%%
%     CLASSIFICATION STATISTICS   %
%%%%%%%%%%%%%%%%%%%%%%%

% format of DFA training datafile:
%    1 header row
%    first column: species name
%    second column: species code
%       1=Tursiops truncatus, 2=Delphinus species, 3=Pseudorca crassidens, 4=Stenella
%        attenuata, 5=Globicephala macrorhynchus, 6=Steno bredanensis, 7=Stenella
%        coeruleoalba, 8=Stenella longirostris
%    remaining columns: whistle variables
%
%   *** DATA MUST BE SORTED BY SPECIES NUMBER, AND THEN
%         SIGHTING NUMBER *****

% open the file containing the training data
file_input = 'c:\ROCCA\train2.csv';
```

```
[FID, MESSAGE]=fopen(file_input, 'r');      % opens file for reading

% read comma separated file.  Starts at second row and second column (because first
% row is header, and first 2 columns contain words)
% csv read is zero based so 1st row = row 0 and 1st column = column 0
all = csvread(file_input,1,1);

% count the number of rows and the number of columns in the matrix 'all'
[totrows, totcolumns]=size(all);
group=all(:,1);          % extract column to be the 'group' vector
train=all(:,2:end);      % extract 'train' matrix

% open file containing measured variables for whistle to be classified
toclass_input = 'c:\ROCCA\toclass.csv';
[FID, MESSAGE]=fopen(toclass_input, 'r'); %opens file for reading
toclass = csvread(toclass_input);

% transform variables for dfa
toclass_trans=[toclass(:,1) toclass(:,2) toclass(:,3) toclass(:,4) toclass(:,5)…
log10(toclass(:,6)) toclass(:,7)^0.5 toclass(:,8)^0.5 toclass(:,9)^0.5…
log10(toclass(:,10)+1) toclass(:,11)^0.5 toclass(:,12) toclass(:,13)];

%%%%%%%%%%%%%%%%%%%%%%%%%
%   DISCRIMINANT FUNCTION ANALYSIS   %
%%%%%%%%%%%%%%%%%%%%%%%%%

% compute mahalanobis distances
% create a different matrix for each species
[totrows, totcolumns]=size(all);
species_col=1;
row=1;
mahaldists=[];
mahalsp=[];
while row < totrows;
   species=all(row,species_col);
   last_row=row;
   % while loop to find last row of that species
   while species == all(last_row,species_col) & last_row<totrows;
      last_row=last_row+1;
   end
   last_row=last_row-1;
   formahal=all(row:last_row,2:end);
   spcode=all(row,species_col);
```

```
    mahaldist=mahal(toclass_trans, formahal);
    mahaldists=[mahaldists mahaldist];          % vector of mahalanobis distances
    mahalsp=[mahalsp spcode];                   % vector of species codes
    row=last_row+1;
end

% create a matrix that includes mahalanobis distances and species codes
mahalspecies= [mahalsp' mahaldists'];
% loop to put matrix in order from smallest to largest mahalanobis distances
j=8;
for j=8:-1:1;
    for i=1:j;
        if mahalspecies(i,2)>mahalspecies(i+1,2);
            dummy1=mahalspecies(i+1,1); %species
            dummy2=mahalspecies(i+1,2); %mahal
            mahalspecies(i+1,1)=mahalspecies(i,1);
            mahalspecies(i+1,2)=mahalspecies(i,2);
            mahalspecies(i,1)=dummy1;
            mahalspecies(i,2)=dummy2;
        end
    end
end

% print the predicted species information
   if mahalspecies(1,1)==1;
        spname='Tursiops truncatus';
    elseif mahalspecies(1,1)==2;
        spname='Delphinus species';
    elseif mahalspecies(1,1)==3;
        spname='Pseudorca crassidens';
    elseif mahalspecies(1,1)==4;
        spname='Stenella attenuata';
    elseif mahalspecies(1,1)==5;
        spname='Globicephala macrorhynchus';
    elseif mahalspecies(1,1)==6;
        spname='Steno bredanensis';
    elseif mahalspecies(1,1)==7;
        spname='Stenella coeruleoalba';
    elseif mahalspecies(1,1)==8;
        spname='Stenella longirostris';
    end
fprintf('\r'); fprintf('***************'); fprintf('\r');
fprintf('* DFA RESULTS *'); fprintf('\r');
fprintf('***************'); fprintf('\r');
```

```
fprintf('PREDICTED SPECIES: '), fprintf(spname), fprintf('\n');
fprintf('Mahalanobis distance = %1.2f \n', mahalspecies(1,2));
fprintf('\r');
pred=mahalspecies(1,1);

% print 2 alternate identities with Mahalanobis distances
k=2;
for k=2:3;
  if mahalspecies(k,1)==1;
      spname='Tursiops truncatus';
   elseif mahalspecies(k,1)==2;
      spname='Delphinus species';
   elseif mahalspecies(k,1)==3;
      spname='Pseudorca crassidens';
   elseif mahalspecies(k,1)==4;
      spname='Stenella attenuata';
   elseif mahalspecies(k,1)==5;
      spname='Globicephala macrorhynchus';
   elseif mahalspecies(k,1)==6;
      spname='Steno bredanensis';
   elseif mahalspecies(k,1)==7;
      spname='Stenella coeruleoalba';
   elseif mahalspecies(k,1)==8;
      spname='Stenella longirostris';
   end
fprintf('Alternate Species: '), fprintf(spname), fprintf('\n');
fprintf('Mahalanobis distance = %1.2f \n', mahalspecies(k,2));
fprintf('\r');
end

%%%%%%%%
%   CART   %
%%%%%%%%

% open classification tree
  load ([pname CART_file]);

% count the number of rows and the number of columns in the matrix 'toclass'
% (untransformed variables because it's CART)
  [totrows, totcolumns]=size(toclass);

  for i = 1:totrows
   % pass the novel whistle down the tree
     [c,tnode,spname]=treeval(prunedtree,toclass);
```

```
    toclass(i,totcolumns+1) = c;
    toclass(i,totcolumns+2) = tnode;
  end

  % print predicted species to screen
  fprintf('\r'); fprintf('****************'); fprintf('\r');
  fprintf('* CART RESULTS *'); fprintf('\r');
  fprintf('****************'); fprintf('\r');
  fprintf('\r');
  fprintf('PREDICTED SPECIES: '), spname,
  fprintf('\n');

 % print terminal node information
  termnode_info=prunedtree.classprob(tnode,:);
  termnode_save=termnode_info;
  sp_array2=sp_array;

 % loop to put matrix in order from largest to smallest cart probabilities
  for j=numspecies-1:-1:1;
    for i=1:j;
      if termnode_info(i) < termnode_info(i+1);
        dummy1 = termnode_info(i+1);                 % cart probability
        dummy2 = sp_array2(i+1,:);                   % species name
        termnode_info(i+1)=termnode_info(i);
        sp_array2(i+1,:)=sp_array2(i,:);
        termnode_info(i)=dummy1;
        sp_array2(i,:)=dummy2;
      end
    end
  end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% create vector of classification results to save to a csv file
% file will be appended during the sighting
% new file for each sighting
% file contains: whistle number, cruise number, sighting number, correct species, dfa
% predicted species, 8 mahalanobis distances, cart predicted species, 8 cart
% probabilities

cs_current_sav(whistnum,:)=[whistnum cruise snum correct_spcode pred mahaldists c
termnode_save];
```

```
% generate file name based on sighting number and check if it exists
path2='C:\ROCCA\saved\';
csname=[path2 's' num2str(snum) '_class_results.csv'];
fid=fopen(csname,'r');

% if file does not exist, move the save data to the correct variable
if fid==-1
   cs_full_sav = cs_current_sav;

% if file does exist, load the existing data and add the current data to the end
else
   cs_dummy = csvread(csname);
   cs_full_sav = [cs_dummy; cs_current_sav];
   fclose(fid);
end

% write the CS output file
csvwrite(csname,cs_full_sav);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% display running tally of species prediction in a message box
% print out cart probabilities
[sp_array2 num2str(termnode_info)]

tally_sp_dfa(pred)=tally_sp_dfa(pred)+1;
tally_sp_cart(c)=tally_sp_cart(c)+1;
tally_dummy=zeros(numspecies+2,1);
tally_dummy(1,1)=snum;
tally_dummy(2,1)=whistnum;
tally_dummy(3:numspecies+2,1)=tally_sp_dfa;
tally_dummy(numspecies+3:2*numspecies+2,1)=tally_sp_cart;
space=['   ';'   ';'   ';'   ';'   ';'   ';'   ';'   ';'   '];
header=['D' '   ' 'C' '   ' 'Species                    '];
divider=['-' '---' '-' '---' '----------------------------'];
csvwrite(tally_file,tally_dummy);
msg = msgbox([header; divider; num2str(tally_sp_dfa) space num2str(tally_sp_cart)
space sp_array],'replace');

end
end
```

ContourJ1id.m

```
% Contour2.m is a function that works with Tria.m to quantify dolphin whistle
% contours and harmonics.
% Developed by Marc O. Lammers (9/24/03). Do not distribute without permission.
% ContourJ1id.m is Contour2.m with additional variables included
% this program steps through the fundamental two points at a time
% June 2005

function contourJ1id(SIGNAL, ALLVARS,file1,Fs,namefile,snum,whistnum)

SIGNAL=SIGNAL';                                        % Transpose data file
ALLVARS=ALLVARS';
fund=SIGNAL(2,:);amp=SIGNAL(3,:);time=SIGNAL(4,:); % Separate signal
                                                   % characterization vectors

stepH=1.11;   % Sensitivity to contour step size
stepL=0.86;
analyze_again=1;
while analyze_again==1
contour_all=[];step_all=[];slope_all=[];
i=2;cont=0;step=0;
for i=2:1:(length(fund)-1)  % Step through fundamental contour two points at a time
                            % and compare with previous and next points to establish
    current=fund(i);        % whether it is at an upsweep, downsweep or flat
    current_time=time(i);   % contour section.
    previous=fund(i-1);
    prev_time=time(i-1);
    next=fund(i+1);
    cur_pre=current-previous;
    cur_next=current-next;
    run=current_time-prev_time;
    slope=cur_pre/run;

    if cur_pre<=0 & cur_next>=0
      cont=-1;
   end
    if cur_pre>=0 & cur_next<=0
      cont=1;
   end
    if previous==current & next==current
      cont=0;
   end
```

```
    if next>=current*stepH     % Step through the fundamental contour two points at a
                               % time and compare with next point to establish
                               % whether a step is present
       step=1;
    elseif next<=current*stepL
       step=2;
    else
       step=0;
    end

    step_all=[step_all step];
    contour_all=[contour_all cont];
    slope_all=[slope_all slope];
end

% calculate last slope
i=length(fund);
cur_pre=fund(i)-fund(i-1);
run=time(i)-time(i-1);
slope=cur_pre/run;
slope_all=[slope_all slope];

% Establish how many jumps (steps) of each kind there are.
step_up=length(find(step_all==1));
step_down=length(find(step_all==2));
tot_step=length(find(step_all));

% slope calculations
p=find(slope_all>0);                % extract the positive slope values from
slope_all
pos_slope=slope_all(p);
n=find(slope_all<0);                % extract the negative slope values from
slope_all
neg_slope=slope_all(n);
mean_slope=mean(slope_all);         % overall mean slope
mean_pos=mean(pos_slope);           % calculate mean positive slope
mean_neg=mean(neg_slope);           % mean negative slope
mean_abs=mean(abs(slope_all));      % mean of absolute values of slope
ratio_posneg=mean_pos/mean_neg;     % ratio of mean pos slope to mean neg slope

% calculate the slope of the beginning sweep and slope of the end sweep
% beg and end sweep include 3 slopes (when sampling at 48kHz)
mean_beg=mean(slope_all(1:3));
```

```
if mean_beg > 0;
   beg_sweep = 1;
   begup = 1;
   begdwn = 0;
elseif mean_beg < 0;
   beg_sweep = -1;
   begup = 0;
   begdwn = 1;
elseif mean_beg == 0;
   beg_sweep = 0;
   begup = 0;
   begdwn = 0;
end

len=length(slope_all);
mean_end=mean(slope_all(len-2:len));
if mean_end > 0;
   end_sweep = 1;
   endup = 1;
   enddwn = 0;
elseif mean_end < 0;
   end_sweep = -1;
   endup = 0;
   enddwn = 1;
elseif mean_end == 0;
   end_sweep = 0;
   endup = 0;
   enddwn = 0;
end

close(figure(4));
figure(5)                   % Plot the frequency and contour vectors
clf
subplot (2,1,1),
plot(SIGNAL(2,:),'b.:');
hold on;
title(['Number of steps = ',num2str(tot_step)]);
ylabel('Hertz')
hold off

uimenufcn(gcf,'WindowCommandWindow');   % returns focus to the command
window
analyze_again=input('Change step size sensitivity [y = 1, n = 2]? ');
if analyze_again==1
```

```
   sensitivity=input('Look for larger or smaller steps [larger = 1, smaller = 2]? ');
   if sensitivity==1
      stepH=stepH+0.02;stepL=stepL-0.02;
   else
      stepH=stepH-0.02;stepL=stepL+0.02;
   end
   close(5);
end
end

% number of inflection points
inflect_again=1;
while inflect_again == 1
inflection_all=[];inflect_time=[];
j=1;
direction=contour_all(j);
tot_inflect = 0;
for j=1:length(contour_all)-1            % Step through contour vector and find full and
                                         % partial inflection points.  Classify accordingly.
  if contour_all(j)==1 & contour_all(j+1)==-1
    inflection=1;        % up-down
  elseif contour_all(j)==-1 & contour_all(j+1)==1
    inflection=2;        % down-up
  elseif contour_all(j)==1 & contour_all(j+1)==0
    inflection=3;        % up-flat
 elseif contour_all(j)==-1 & contour_all(j+1)==0
    inflection=4;        % down-flat
  elseif contour_all(j)==0 & contour_all(j+1)==-1
    inflection=5;        % flat-down
  elseif contour_all(j)==0 & contour_all(j+1)==1
    inflection=6;        % flat-up
  else
    inflection=0;
  end
  inflection_all=[inflection_all inflection];
  j=j+1;

% Establish percentage of time that the fundamental is an upsweep, downsweep or is
% flat.
   perc_up=((length(find(contour_all==1)))/length(contour_all))*100;
   perc_down=((length(find(contour_all==-1)))/length(contour_all))*100;
   perc_flat=((length(find(contour_all==0)))/length(contour_all))*100;

% count inflection points and ignore zero slopes
```

```
  if contour_all(j) == (-1)*direction & contour_all(j)~=0
     tot_inflect = tot_inflect + 1;
     direction = (-1)*direction;
     inflectiontime=time(j);
     inflect_time=[inflect_time inflectiontime];
  elseif direction == 0
     direction = contour_all(j);
  end
end

% Establish how many inflection points of each kind there are.
up_down=length(find(inflection_all==1)); down_up=length(find(inflection_all==2));
up_flat=length(find(inflection_all==3)); down_flat=length(find(inflection_all==4));
flat_down=length(find(inflection_all==5)); flat_up=length(find(inflection_all==6));
subplot (2,1,2), plot(contour_all,'b.:');
title(['Number of inflection points = ',num2str(tot_inflect)]);
axis([0,length(contour_all),-1,1])
xlabel('Window number')
ylabel('Down     Flat      Up')
hold off

% Establish time between inflection points
if tot_inflect>1
   delta_time=[];
   for i=1:length(inflect_time)-1
      for k=i+1:length(inflect_time)
         dtime=inflect_time(k)-inflect_time(i);
      end
      delta_time=[delta_time dtime];
   end
   max_delta=max(delta_time);                % max time between inflection points
   min_delta=min(delta_time);                % min time between inflection points
   maxmin_delta=max_delta/min_delta;
   mean_delta=mean(delta_time);              % average time between inflection points
   std_delta=std(delta_time);                % stdev of time between inflection points
   median_delta=median(delta_time);
else
   max_delta=999;
   min_delta=999;
   maxmin_delta=999;
   mean_delta=999;
   std_delta=999;
   median_delta=999;
end
```

```
uimenufcn(gcf,'WindowCommandWindow');   % returns focus to the command
                                         % window
inflect_again=input('Change a contour value [yes = 1, no = 2]?'); % Manually change
                                        % contour values that don’t appear
                                        % correct
if inflect_again==1
[E,F]=ginput(1);                        % Use mouse to locate value to be changed
  E=round(E);
  sure=menu('Change value' ,num2str(E-1),num2str(E),num2str(E+1),'None');
  if sure<4
  changeto=menu('Change value to' ,'-1','0','1'); %Change to either -1, 0 or 1
  if sure==1
    contour_all(E-1)=changeto-2;
  elseif sure==2
    contour_all(E)=changeto-2;
  elseif sure==3
    contour_all(E+1)=changeto-2;
  end
  end
  subplot (2,1,2), plot(contour_all,'b.:');
  xlabel('Window number')
  axis([0,length(contour_all),-1,1])
  hold off
end
end

%-------------------------------Julie's variables
ALLVARS2=[tot_step;tot_inflect;up_down;down_up;up_flat;down_flat;flat_down;…
flat_up;step_up;step_down;max_delta;min_delta;maxmin_delta;mean_delta;std_delta;
…median_delta;mean_slope;mean_pos;mean_neg;mean_abs;ratio_posneg;perc_up;…
perc_down;perc_flat;beg_sweep;begup;begdwn;end_sweep;endup;enddwn];

ALLVARS=[ALLVARS' ALLVARS2'];
%----------------------------------------------

harms=ALLVARS(1,25);
beg_hz_f=ALLVARS(1,19);
end_hz_f=ALLVARS(1,20);
min_hz_f=ALLVARS(1,21);
duration_f=ALLVARS(1,24);
range_hz_f=ALLVARS(1,23);
max_hz_f=ALLVARS(1,22);
```

```
% Save vector for species id
TOCLASS=[begup;begdwn;endup;enddwn;harms;beg_hz_f;end_hz_f;min_hz_f;…
duration_f;tot_inflect;tot_step;range_hz_f;max_hz_f];
csvwrite('toclass.csv',TOCLASS');

uimenufcn(gcf,'WindowCommandWindow');   % returns focus to the command
window
% ...enter whistle quality
% ...1 = good whistle, extracted well, variables are accurate for future analysis
% ...2 = good whistle, didn't extract well, re-measure for future analysis...or overlaps
% with other whistles or clicks
% ...3 = bad whistle, don't use for future analyses
quality=input('Enter whistle quality [good = 1, redo = 2, bad = 3]: ');
if quality == 1;
   qualname = 'good';
elseif quality == 2;
   qualname = 'redo';
elseif quality == 3;
   qualname = 'bad';
end

% Save 4 files: csv file of whistle variables, csv file of whistle contour, csc file of vars
% used for DFA and CART and wav file of whistle
   path3='C:\ROCCA\saved\';
   namefile=['s' num2str(snum) ];
   namefile1=[path3 qualname '_' namefile '_' num2str(whistnum)];
   namefile2=[path3 qualname '_' namefile '_' num2str(whistnum) '_contour.csv'];
   namefile3=[path3 namefile '_variables.csv'];
   namefile4=[path3 namefile '_toclass.csv'];

% save wav file and contour
   csvwrite(namefile2,SIGNAL');
   wavwrite_rocca(file1,Fs,16,namefile1);

% check if ALLVARS file exists
fid=fopen(namefile3,'r');

% if file does not exist, move the save data to the correct variable
if fid==-1
   ALLVARS_sav = ALLVARS;

% if file does exist, load the existing data and add the current data to the end
else
   ALLVARS_dummy = csvread(namefile3);
```

```
   ALLVARS_sav = [ALLVARS_dummy; ALLVARS];
   fclose(fid);
end

% write the ALLVARS output file
csvwrite(namefile3,ALLVARS_sav);

% check if TOCLASS file exists
fid=fopen(namefile4,'r');

% if file does not exist, move the save data to the correct variable
if fid==-1
   TOCLASS_sav = TOCLASS';

% if file does exist, load the existing data and add the current data to the end
else
   TOCLASS_dummy = csvread(namefile4);
   TOCLASS_sav = [TOCLASS_dummy; TOCLASS'];
   fclose(fid);
end

% write the TOCLASS output file
csvwrite(namefile4,TOCLASS_sav);
```

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