ANALYSIS OF FIN WHALE LUNGE-FEEDING IN SOUTHERN

CALIFORNIA USING MULTISENSORY BIOTAGS

An Undergraduate Research Scholars Thesis

by

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RESEARCH COMPLIANCE CERTIFICATION

Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

I, Leah K. Bogan, certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with my Research Faculty Advisor prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Analysis of Fin Whale Lunge-Feeding in Southern California Using Multisensory Biotags

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Balaenopterids are among the largest animals to have lived on earth, yet they are often the most elusive to research. Despite their size, we are still discovering new populations. As technology and the sciences converge, advancements in instrumentation are meeting the challenges where whale study and ocean research intersect. Multisensory bio-logging tags are at the forefront of research innovation able to customize a suite of sensors for remote observation of animals in extreme environments. Biotag data translate to behaviors that enable quantification of vital statistics and inform on individual and population health. Balaenopterids have a distinct feeding behavior termed lunge-feeding which exhibits a unique energetic signature. Quantifying these lunges provides information on dive efficiency, metabolic rates, feeding ecology etc. For this study, fin whale (*Balaenoptera physalus*) lunging depth was analyzed from 24 biotags deployed from 2010-2018 in southern California for 247 hrs. of recorded data. A generalized additive modeling framework was used to test whether lunge depth (deep, greater than 135m or shallow, less than 135m) was dependent on the time of day (day or night by way of hour), season (spring, summer, or fall) and region (Inshore North, Inshore Central, Offshore). There were

distinctions found in depth of lunges over the course of 24hrs with deep lunges occurring primarily during the day and shallow dives at night, likely following a diurnal prey migration pattern. Seasonal distinction in frequency and depth of lunges was also observed, with feeding-lunge depth and frequency increasing from spring, through summer, peaking in the fall. Standardization of rapid analysis using machine learning could lead to improved predictions of whale aggregations based on these feeding behaviors. Correlation of feeding whale density with krill aggregation has the potential of producing real-time density probability predictions of whales, based on the more easily monitored real-time krill densities through low-cost, low maintenance, autonomous systems.

DEDICATION

I would like to dedicate this body of work to my beloved aunt, the late Brenda Jo Franklin who received her Master's degree later in life and went on to serve as a planetary geologist at JPL for over 30 years. Through her time there she served primarily as the Hazcam and Navcam Payload Uplink Lead for the MER (Mars Exploration Rover) ops team. Brenda retired in June 2017 and passed away only six weeks after NASA officially announced an end to Opportunity's mission on March 29th 2019, which she had overseen since its inception. Brenda has always encouraged me to pursue my lifelong passion for marine science and was thrilled when I finally took her advice. She will be deeply missed by her family and many friends.

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Thanks as well to my friends, colleagues, faculty, and staff in the Marine Biology department for making my time at Texas A&M University at Galveston such a formative experience.

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The data used for Analysis of Fin Whale Lunge-Feeding in Southern California Using Multisensory Biotags was provided by Dr. Ana Širović. The analyses depicted in Analysis of Fin Whale Lunge-Feeding in Southern California Using Multisensory Biotags was conducted by myself, independently through the academic year '20-'21.

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1.   INTRODUCTION

1.1   Challenges of Ocean Research

The ocean is a complex network of systems converging into a mostly unknown, unexplored and inhospitable frontier. The adage still holds, we know more about the surface of the moon, maybe our entire solar system, than we do the ocean floor (van Haren, 2018; Young, 2014). The impenetrable nature of the ocean has meant things like mapping only have approximate precision of a 5km radius (van Haren 2018). Factors that inhibit something as simple as mapping, which has been attempted for millennia, extend also to ocean research. Challenges rang from the corrosiveness of sea water, extreme pressure increasing 1atm every 10m, and limited to no visibility. Depending on the project, further hurdles include things like prohibitively expensive or insufficient power supplies, logistics, and the level of expertise needed for the exploration and research itself. Considering what has been achieved through technology in other extreme environments, the idea of ocean research seems plausible yet considerable regions remain unknown, unregulated and unexplored.

1.2   Dynamics of Multisensory Biotags

Marine animal research has undergone significant technological advancements over the decades. Multisensory biotags are at the forefront of these advancements and have changed the game of marine animal research (Goldbogen et al., 2013). Biotags can contain a host of customizable sensors encased in durable, buoyant housings that can be affixed to the dorsal side of a whale either via suction or shallow, subdermal darts (Goldbogen et al., 2014; Knowlton, 2017; Szesciorka et al., 2016; Ydesen et al., 2014). Biotags are a way to non-invasively observe the physiological and biomechanical processes of the animals they are attached to (Allen et al.,

2016; Calambokidis et al., 2007; Elc et al., 2010; Ja et al., 2006; Potvin et al., 2012; Williams et al., 2017; Ydesen et al., 2014). Acoustics, acoustical telemetry and multisensory bioacoustics capitalize on the physical properties of water as a way to see the whale in their environment where visual observation ends. Marine animals as well, have adaptations to the properties of sound in water through behavior and morphology (Brodie, 2011; Cranford & Krysl, 2015; Payne & Webb, 1971). Using acoustics in concert with other sensors has proved to be an effective approach to elucidating animal movements through the depth and darkness (Allen et al., 2016; Calambokidis et al., 2007; Goldbogen et al., 2006; Goldbogen et al., 2013; Knowlton, 2017; Williams et al., 2017; Ydesen et al., 2014). Biotags can record audio, accelerometer position (triaxle positioning), compass coordinates (GPS), temperature and pressure that serves as a proxy for depth in meters. In the scope of marine research, sensory tags are a relatively recent contribution to marine data capture (Allen et al., 2016; Goldbogen et al., 2013; Williams et al., 2017). The novel use of these tags in research means there is currently no standardized method of analysis, nor is there a database for comparative refinement. The media from these data captures are often difficult to store, measure and share between researchers and institutions. Consequently, there is a growing need for timely, unified and affordable methods of analysis (Allen et al., 2016; Goldbogen et al., 2014; Leos-Barajas et al., 2017).

1.3   Balaenopterids are Unique Among Baleen Whales

Mysticetes are a suborder of the recent conglomeration, Order Cetartiodactyla and are distinct from the Odontocetes or toothed whales by their baleen. Baleen consists of plates of keratin in place of teeth and are used to filter food from the water. All baleen whales are suspension filter-feeders and prey predominantly on small crustaceans and schooling fish. Though the prey is relatively small, this method of filtering plankton, fish, and crustaceans from

the water is primarily why mysticetes achieve such enormous size (Brodie, 2011; Cade &

Benoit-Bird, 2015; Doniol-Valcroze et al., 2011; El Adli & Deméré, 2015; Friedlaender et al.,

2020; Potvin et al., 2012; Pyenson et al., 2012; Williams et al., 2017). The largest animals that

have ever lived in fact are members of a family within this suborder called Balaenopteridae. This

family of mysticetes also known as rorquals, a name derived from Norwegian whalers, have

morphological adaptations that maximize this filtration process into one of the "greatest

biomechanical actions in the animal kingdom" (Brodie, 2011; Pyenson et al., 2012).

This biomechanical action is a form of filter-feeding singular to balaenopterids referred to

as lunge-feeding. The execution of a lunge produces an extreme physical transformation in the

whale, facilitated by an almost reptilian-shaped head and a distinct set of jaw joints that allow for

a 90 degree gape (Calambokidis et al., 2007; Friedlaender et al., 2020; Goldbogen et al., 2013).

Rorquals also have a distinct third joint on the distal lower jaw allowing for bilateral separation

of the lower mandible. This separation provides additional moderate articulation and may also

support organs for mechanoreception that could aid in detecting the presence and size of krill

swarm (Brodie, 2011; Pyenson et al., 2012). Additionally there is evidence to support this distal

jaw-bone separation can produce a synovial joint-crack upon realignment of the mandible tips to

startle prey further into the buccal cavity (Brodie, 2011). An additional rorqual adaptation, are

the vertical pleats along the whale's ventral side from rostrum to navel. These pleats are lined

with muscles that expand and contract for active inflation during a lunge (Doniol-Valcroze et al.,

2011; Goldbogen et al., 2013). Also singular to balaenopterids is their relatively flaccid and

loosely-muscled tongue that can invtert into the cavum ventrale allowing for even further

expansion of the buccal cavity during a lunge (Friedlaender et al., 2020; Goldbogen et al., 2013;

Pyenson et al., 2012).

These morphologies found only in balaenopterids provide the whales with the ability to take on as much as 70,000 liters of water, more than their total weight, in a matter of a few seconds. The drag generated from this action forces water into the buccal cavity, inverting the tongue and expanding the pleats to as much as four times the resting size. In this way, the rorquals can forage up to a ton of krill a day (Brodie, 2011; Calambokidis et al., 2007; Goldbogen et al., 2013; Potvin et al., 2012; Pyenson et al., 2012).

1.4   Rorquals Predominantly Feed on Krill

Krill are the primary source of food for many rorquals and are found in areas with strong upwelling such as the waters off the southern California coast (Calambokidis et al., 2007; Rockwood et al., 2020; Santora et al., 2012). Upwelling seeds the upper trophic levels with surface-deprived nutrients and combines with sunlight to create ideal conditions for phytoplankton blooms. Krill will graze on phytoplankton blooms in swarms that stretch for miles along the shelf-edge of the coast following the upwelling in the California Current System (CCS) (Amakasu et al., 2011; Bianchi & Mislan, 2016; Cade & Benoit-Bird, 2015; Fiechter et al., 2020). Many species feed on these krill swarms in every area of upwelling making the organisms foundational to the marine food web (Fiechter et al., 2020; Gómez-Gutiérrez & Robinson, 2005; Dorman et al., 2015; Rockwood et al., 2020; Santora et al., 2012). Consequently, krill have developed a method of defense known as diurnal vertical migration (DVM). This vertical movement occurs over hundreds of meters into the deep waters during daylight hours, where light is diminished. This provides both cover from predators and colder temperatures to slow metabolism for energy conservation (Fiechter et al., 2020; Santora et al., 2011; Santora et al., 2012). At night, the krill return to the surface to graze freely on the phytoplankton under cover of darkness. Though individually they are small (~6 cm), aggregations of krill swarm can reach

densities of 30,000-100,000 individuals per $1m^2$ and span several miles across and hundreds of

meters in depth (Amakasu et al., 2011; Rockwood et al., 2020; Santora et al., 2012). In these

instances, rorquals can take up as much as 10kg of krill per 70,000 liters or per single, full-gaped

lunge (Friedlaender et al., 2020; Goldbogen et al., 2006).

1.5   Objective of Research

Between the challenges of oceanic research and their scarcity in numbers from over a

century of whaling, balaenopterid behavior and population has been difficult to delineate.

Whaling culled fin whales from 725,000 in the Southern Hemisphere to just over 80,000 in the

1970s when the moratorium went into effect (Cooke, 2018; Fisheries, 2021; Širović et al., 2015).

Although many populations are in recovery, southern California's fin whale population is only

around 3200 at best estimate (Bedriñana-Romano et al. 2021; Calambokidis et al. 2019; Fisheries

2021; Moore 2019; Širović et al. 2015; Širović et al. 2017). Despite their size, new populations

of rorquals are still being discovered underscoring the difficulty in population estimates for fin

whales (Cerchio et al. 2020). Major short-term threats to the whales in southern California are

mainly ship strikes, entanglement and anthropogenic noise (Bedriñana-Romano et al. 2021;

Calambokidis, et al. 2019; Cooke 2018; Doniol-Valcroze et al. 2011; Fisheries 2021; García-

Reyes et al. 2015; Hazen et al. 2017; Irvine et al. 2014; Moore 2019). Determining best-practices

for conservation is difficult without the ability to gauge and trend current population numbers.

Predicting what areas fin whales are frequenting, their location in the water column and their

density probability, could lead to better protection policies. The primary objective of this

research was to generalize and classify rorqual-specific feeding behaviors with the ultimate

purpose of an automated method of data analysis and eventual estimation of feeding-presence

probability. Classification was centered on specific regions, season, and hour of day for feeding-

lunge depths. Using a dataset of over 247hrs, day and night lunging depths were classified within a Generalized Additive Modeling (GAM) framework into a class of either shallow or deep (shallow lunges being less than 135m and deep lunges, greater than 135m) across peak feeding seasons (spring, summer, fall) in regions off of southern California (Inshore North, Inshore Central, Offshore). Spatial and temporal fluctuations in lunge-depths were examined for diurnal patterns and seasonal or regional variance.

2.   METHODS

2.1   Data Collection

Two types of multisensory biotags were used in this research:

DTAG (digital acoustic recording tag): These tags were originally designed for passive acoustic audio surveillance but have evolved to include compact digital sensors housed in a buoyant and water-resistant capsule affixed with suction cups (16cm). The housings contain a lithium rechargeable battery, digital signal processor, depth (pressure sensor), compass, temperature sensor, audio board, preamp, hydrophones, analogue-to-digital converter, a suite of movement sensors including accelerometers, magnetometers and a flash memory. This project incorporated the DTAG-2 and DTAG-3 models; DTAG-2 were used from 2002-2012 and DTAG-3 have been used since 2012.

Acousonde: Uses similar multisensory tag technology to DTAGs but has broader bandwidth availability and the option to customize and develop additional add-ons. These tags can house up to 120 gigabytes of storage along with a 3D compass, 3D tiltmeter, temperature sensor, high-frequency low-power hydrophone, depth (pressure sensor), and an A-cell lithium battery (allowing for the broader, more dynamic data capture). Acousonde has been in use since 2006.

This project incorporated data from 24 multisensory biotags that recorded over 3,000 lunging events across an eight year time-frame for 247 recorded hours in southern California. The effort for these tag deployments focused on three regional sites: Inshore North, Inshore Central and Offshore (Fig. 2.1). The data was read, tabulated and prepared by myself and others in the bioacoustics lab for analysis.
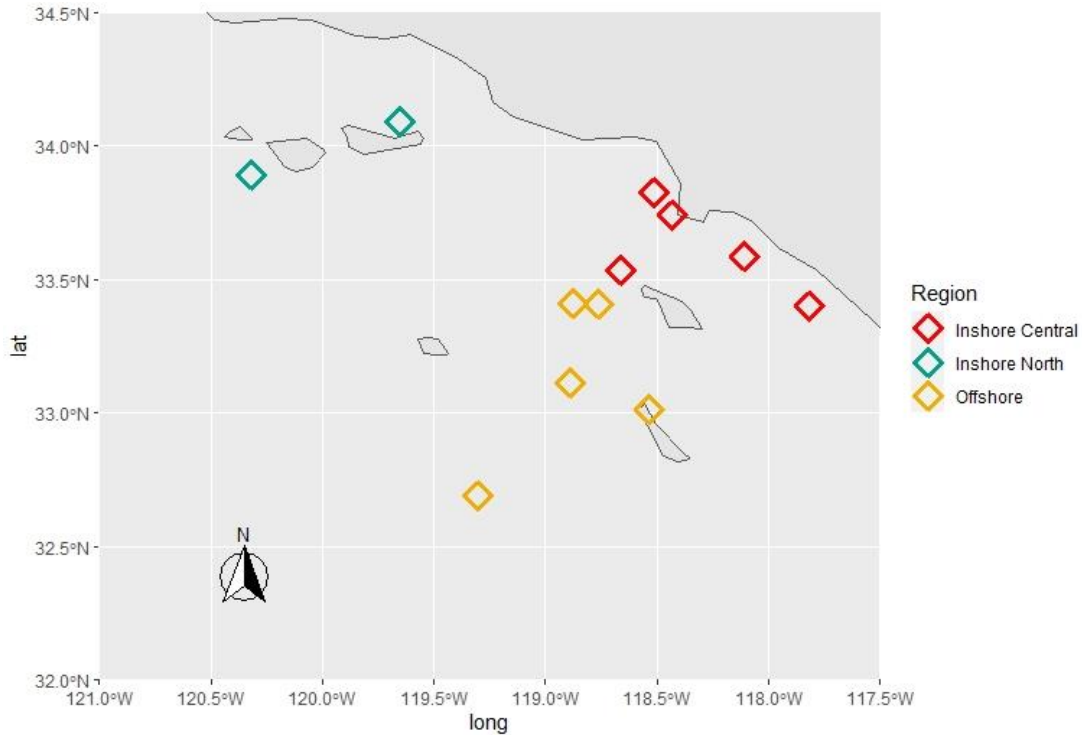
Figure 2.1: Map of Research Area where 24 tags were deployed over a block of eight years with a focus on regions: Inshore North, Inshore Central, and Offshore. Months of focus were spring summer and fall.

2.2   Tag Tabulation

Raw data from the biotags was tabulated in MatLab through Triton and its MTViewer remora, a program developed specifically for reading Acousonde tags (DTAG data was tabulated in a separate program prior to this project). Triton allows visualization of raw data for the different sensors: depth (pressure sensor), temperature, compass coordinates, and accelerometer, concurrently with a displayed spectrogram of the acoustic recording. This visualization can be used to identify specific behavioral events. When a known signature for an inhalation or a tail fluke or feeding-lunge is identified, the occurrence and date can be logged through Triton along with depth, coordinates, orientation and temperature.

2.3   Data Analysis

To investigate the relationship between the response variable lunge-feeding depths (continuous) as a function of xyz, and the predictor variables hour (numerical) throughout peak feeding seasons (spring, summer and fall, fixed categorical) and across three known feeding areas (Inshore North, Inshore Central, and Offshore, fixed categorical). I used a generalized additive modeling (GAM) framework with a Gaussian distribution for the two and three-way interaction terms (Zuur & Ieno, 2016). However upon data exploration it was found the data points for spring only covered 6 hours and 74 data points. Additionally, there are 322 lunging events for the Offshore location which is several times fewer events than occurred at the other two locations. A low k-value spline fit, shaped the model to basic parameters of shallow and deep lunging throughout the course of the day and for which location and season. This was done with the intent to continue with comparative analysis for this dataset, as well as adding additional raw tag data recorded from this area in other months. This data set can then train a prediction probability algorithm for a machine-learning lunge-feeding detector.

Several tags read negative values for depth when the whale was feeding at surface, these events were treated as zeros. The R package (R Core Team 2020) mgcv (Wood, 2017) was used to model the data to fit a GAM using the following equation:

$$lunge\_depth \sim 1 + s(hour, bs = \text{"ts"}, k = 3) + season + tag\_location \quad (2.1)$$

The independent variables used in the model were hour, a numerical variable, and season and location (tag_location) which were treated as categorical variables with three levels each (Fig. 3.1; Table 3.1).

3.   RESULTS

Lunge-depths between 21:00am PST and 4:00am PST, were significantly different

(<135m) than the lunges between the hours of 5:00am and 20:00pm (>135m) (Table 3.1; Fig 3.1;
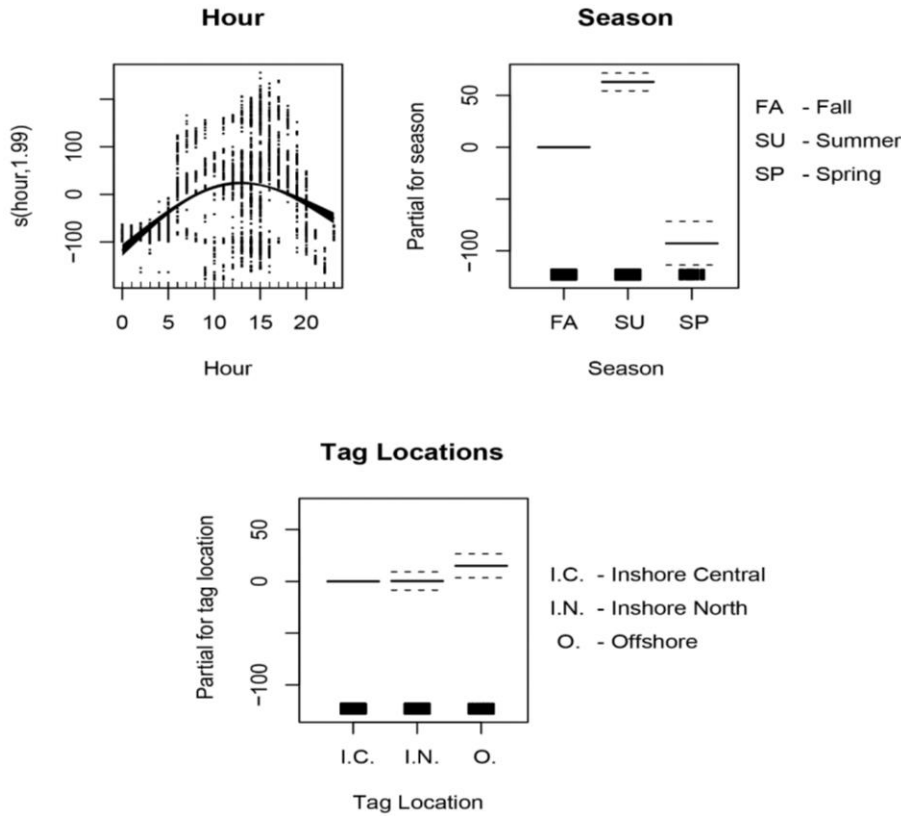
Fig 3.2; Fig 3.3).

Figure 3.1 Mean-adjusted partial fits of lunge-feeding for the predictor variables: hour (top left), season (top right) and location (bottom). Deeper lunges are indicated by positive partial and shallower lunges are indicated by a negative partial.

There was a significant effect of the southern California deployment location on the

depth of the lunge (Table 3.1; Fig 3.2). This location effect was driven by significant differences

between lunge-depths from Inshore North and Inshore Central and Inshore Central and Offshore.

Lunge depths at locations Inshore Central and Offshore were not significantly different (Fig 3.1; Fig 3.3).
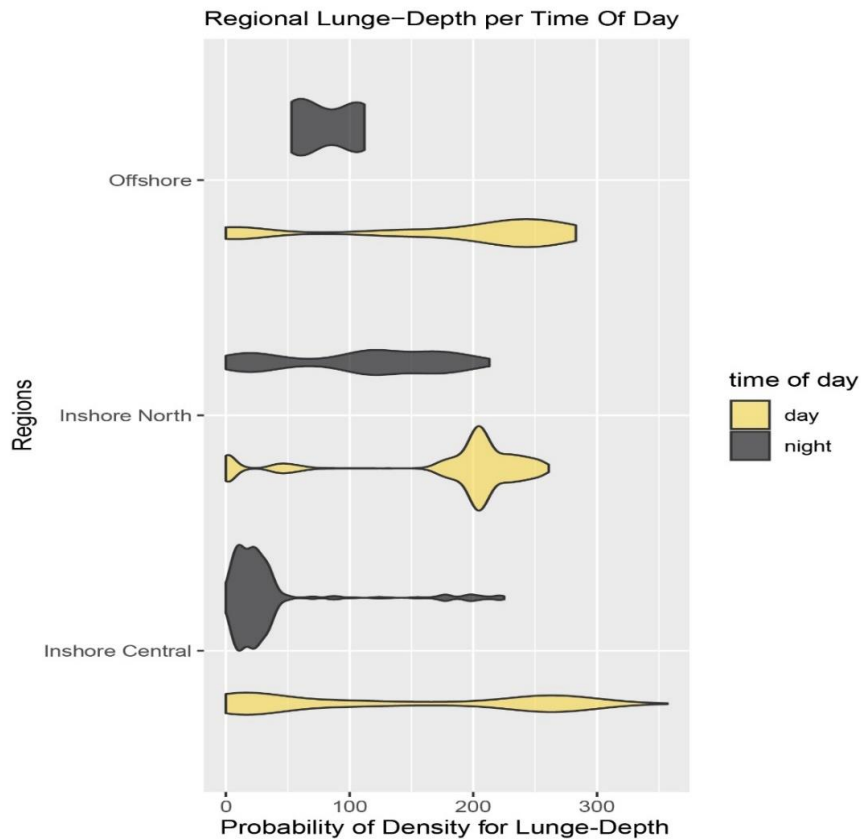

Figure 3.2: Probability of feeding lunge depths for day and night per region sampled; The more vertical distribution along the y-axis, the higher the probability of a lung at that depth for that time of day, depth of the lunge is along the x-axis. From Top: Offshore. Center: Inshore North. Bottom: Inshore Central

Season also had a significant effect on lunge-depth (Fig 3.1), driven by significant differences across all seasons (Table 3.1; Fig 3.1; Fig 3.2; Fig3.3).
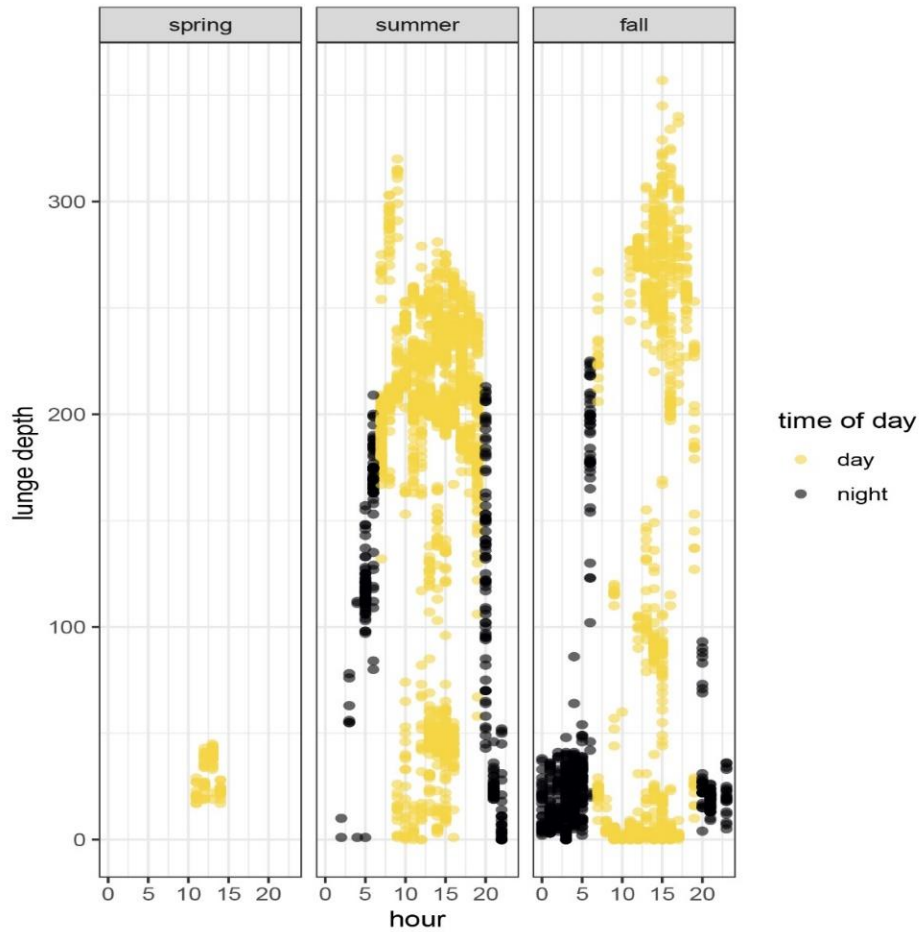
Figure 3.3 Lunge-depth density per hour for each season; from Left: spring. Center: summer. Right: fall

In general, the deepest lunges occurred most commonly along the shelf-edge off the coast of southern California for both Inshore North and the Offshore location in the late summer and early fall months with the deepest feeding depths between the late afternoon-early evening hours of the day and were shallower for the hours after dark.

Table 3.1 Degrees of freedom (df for hour is effective*), standard errors, t-values, and P-values for the predictor variables hour (20:00-5:00=night, 5:01-19:59=day), season (spring, summer, fall) and location (Inshore North, Inshore Central, and Offshore).

Predictor Variable	df	std. error	F	t-value	p-value
Intercept		2.42		41.79	2e-16
hour	1.993*		197.1	84.56	2e-16
season	2				
summer		4.27		14.75	2e-16
spring		10.51		-8.83	2e-16
tag_location	2				
Inshore North		4.38		0.074	0.941
Offshore		5.80		02.59	0.010

4. CONCLUSION

4.1 Interpreting Results

Fin whales like most rorquals, feed primarily on krill which are known to follow a diurnal vertical migration based on light levels throughout the day. The data analysis from this study underscores the evidence from prior studies and enforces this assessment (Goldbogen et al., 2015; Dorman et al., 2015; Santora et al., 2011). During the day, when krill are known to be at depth, the fin whales executed their deepest lunge-feeding dives (Fig. 3.1; Fig. 3.3) (Fiechter et al., 2020; Santora et al., 2011). Lunge-feeding also likely increased in depth and frequency based on the seasonal increase in krill availability following the seasonal increase in phytoplankton that the krill are known to graze on (Fig. 3.1; Fig. 3.3) (Calambokidis et al., 2007; Fiechter et al., 2020; Goldbogen et al., 2015; Rockwood et al., 2020; Szesciorka et al., 2020). This dataset also showed an increase in feeding-lunge depth depending on location, where locations with likely more upwelling (closer to the shelf) had deeper lunges where krill are known to aggregate (Table 3.1; Fig. 3.1; Fig. 3.2) (Fiechter et al., 2020; Santora et al., 2011; Santora et al., 2012). However, the presence of krill alone is not sufficient to signify whale presence as balaenopterids in general show different and complex strategies for prey capture based on species (Calambokidis et al., 2019; Potvin et al., 2012; Rockwood et al., 2020; Szesciorka et al., 2016). Baleen whales are central place foragers where the oxygen at the surface is their "central-place," but how depth and density of krill swarm determine each species approach is still unknown (Bedriñana-Romano et al., 2021; Cade & Benoit-Bird, 2015; Friedlaender et al., 2016; Friedlaender et al., 2020; Goldbogen et al., 2015) Rorquals show selective and complex prey-patch foraging methods and some species show a temporally plastic migratory response based on fluctuations in krill

availability per season (Goldbogen et al., 2015; Robertson & Bjorkstedt, 2020; Szesciorka et al., 2020). This migratory variability may increase with the increasing changes of climate that can influence both upwelling and phytoplankton blooms (Amakasu et al., 2011; Goldbogen et al., 2015; Robertson & Bjorkstedt, 2020; Rockwood et al., 2020; Szesciorka et al., 2020). There would be an intersection of factors to consider in delineating the complex strategies for when a whale selects a krill patch. This would require a more comprehensive method of data acquisition than is currently in practice for each species. Additional inter-seasonal tags that have been tabulated but not yet analyzed can be added for a broader sampling set, while continuing additional tagging efforts. Continuing to elaborate on the current data is necessary for the possibility of using krill-swarm as a proxy for whale feeding presence in the future (Bianchi & Mislan, 2016; Cade & Benoit-Bird, 2015; Chai et al., 2020; Doniol-Valcroze et al., 2011; García-Reyes et al., 2015; Goldbogen et al., 2015).

4.2   For the Short-Term

Though multisensory bio-logging is an innovative approach to marine animal research, it requires an equally innovative approach to analysis. Presently, the rate limiting step of biotag technology is the manual analysis time required by skilled experts that know what to look for (Allen et al., 2016). This involves familiarity with the physics of the data capture and the species under study. With technology continually expanding the capability and accessibility of these recording devises, the backlog of data also grows (Allen et al., 2016). Standardized automation of certain physiological elements in the tag data is a reasonable trajectory to explore for the bank of hard drives accumulating. As industry standards of automation become available, so would the potential for standardized analysis, making analysis more broadly accessible. This would likewise diversify the platform of analyzers leading to faster innovation for conservation and

would additionally be a countermeasure to the growing data streams. Automation could also be applied to the tags themselves producing real-time ethograms from a basic GAM framework classifier. This would minimize the need for manual analysis of basic physiologies like breathing and feeding that can take months. Onboard, real-time analysis of biotag data could eventually inform broad strokes conservation efforts like the regulation of shipping routes, shipping schedules or coastal development (Bedriñana-Romano et al., 2021; Calambokidis, et al., 2019; Hazen et al., 2017; Irvine et al., 2014; Melcón et al., 2012).

4.3   Long-Term Possibilities

There is yet to be a singular and standardized method for efficient whale population estimates, making comprehensive marine mammal conservation an ongoing challenge (Cerchio et al., 2020; Hazen et al., 2017; Oleson et al., 2007; Širović et al., 2015; Širović et al., 2017). Taking a systematics approach to the population effort offers possible alternatives to estimating the whales themselves, and shifts the locus to more accessible proxies like krill aggregations (Amakasu et al., 2011; Bianchi & Mislan, 2016; Guihen et al., 2014; Dorman et al., 2015; Rockwood et al., 2020). Krill densities have been successfully approximated throughout the water column with active acoustical telemetry, echo sounders and satellite imaging (Guihen et al., 2014; Jaffe et al., 2017). Autonomous gliders equipped with a thresholded schools analysis technique (SHAPES) for identifying krill targets have used onboard stochastic distorted-wave Born approximation (SDWBA) to successfully establish krill density in the water column, on a level comparable to ship monitoring systems (Guihen et al., 2014). These gliders have a buoyancy propulsion drive which can provide months of performance on pre-programmed routes that can be altered in real-time through satellite communication or surface buoys (Chai et al., 2020; Mellinger et al., 2012). Autonomous gliders are inexpensive and require little by way of

power supply and can be customized with multiple sensors able to take up complex ecosystem assessments over the long-term as it travels within ocean currents (Mellinger et al., 2012).

In summary, for short-term goals of data analysis, a basic onboard automated classification algorithm based on a GAM framework could provide real-time ethograms on tagged whales. This would significantly lower manual analysis time and streamline correlation analysis of whale-feeding densities and krill-aggregation densities.

Once krill density components are properly quantified and successfully correlated as a proxy for feeding whales, autonomous gliders could be incorporated into a long-term continuous monitoring system. This would provide real-time updates of krill densities and system fluctuations that affect their aggregations like temperature and biochemistry. Systems like these are already being proposed for long-term biogeochemical analysis through the International Biogeochemical-Argo (BGC-Argo). Equipment for monitoring prey patch formation could easily be added to these gliders much of which would correlate with the equipment used to monitor biogeochemical processes (Chai et al., 2020; Guihen et al., 2014; Jaffe et al., 2017). The development of a real-time whale density alert system would be a malleable and feasible infrastructure for addressing the fluctuations of the many factors that coincide to elicit feeding whale aggregations.

This work was limited in scope due to overall restricted access to resources in a general sense. My greatest limitation was for time. This year in Texas we weathered a pandemic lockdown, and several natural disasters resulting in evacuations and power outages. For future work, I plan to continue with the development of an automated, onboard classifier for the biotags used in this project. I look forward to the contributions multisensory biotags and autonomous

ocean vehicles can offer marine scientists as we continue to explore the unknown frontiers of our

oceans.

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