THE USE OF REMOTE SENSING IN MONITORING BLUE WHALE HABITAT – A LITERATURE REVIEW

by

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ABSTRACT

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Key Words: blue whale, acoustic remote sensing, satellite remote sensing, sea surface temperature, chlorophyll-a, krill, blue whale habitat

Quickly changing environmental factors due to climate change are expected to have devastating consequences on blue whale populations. The use of acoustic and satellite remote sensing permits the monitoring of environmental factors essential to blue whale habitat. Determining areas with established levels of prey abundance, chlorophyll-a concentration, sea surface temperature, and bathymetric features has the potential to identify biological hotspots for blue whales. This thesis is a literature review of the use of acoustic and satellite remote sensing when monitoring blue whale habitat features. With climate change increasingly altering know blue whale habitats, conservation efforts must be made to maintain blue whale population levels.

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ACKNOWLEDGEMENTS

I would like to acknowledge and thank my thesis supervisor, Dr. Seth Moore, for advising me throughout my thesis. I would like to acknowledge Mr. Ryan Wilkie as the second reader for this thesis. I would also like to thank everyone who I have consulted with for helping give me insight and assistance with this thesis in any way.

1.0 INTRODUCTION

The IUCN Red List of Threatened Species announced the Blue whale (*Balaenoptera musculus*) as an endangered species in 2018 (Cooke 2018). Blue whales are the largest animal on earth. They are a migratory species found in each ocean, except the arctic. They migrate seasonally in pairs or small groups. Blue whales occupy vast areas of the ocean, migrating 18,000 kilometers annually. Blue whales' seasonal movements follow a north-to-south pattern, spending the summers feeding in polar waters and migrating towards the equator in the winter (Fisheries and Oceans Canada 2018). They spend 4 to 6 months feeding in productive waters to increase body fat and store reserves for the wintering months. Breeding and calving take place in winter. They aggregate in warmer, less productive waters to breed and gestate for 10 to 12 months. Females tend to reproduce every 2 to 3 years from the ages of 5 to 15 years old. Blue whales are filter feeders, their diet consisting primarily of euphausiids, *Euphausia pacifica,* and *Thysanoessa spinifera*, commonly known as krill (Fielder et al. 1998). An individual whale can eat up to 6 tons of krill daily. Hence, they require habitats with high euphausiid biomass density. Krill inhabit waters on the edge of the continental shelf, at topographic breaks, and channel and canyon heads. Blue whales predominantly seek krill aggregations within 80 and 100 meters from the surface. Krill primarily feed on phytoplankton (Lavery 2014). Phytoplankton are microscopic organisms that cover the ocean’s surface. They are a primary producer that use pigments, such as chlorophyll-a to photosynthesize. Determining levels of cholorphyll-a on the surface of the water indicates how much primary production occurs on the surface of the ocean. High levels of cholorphyll-a are a requirement in blue whale habitats.

Acoustic and satellite remote sensing is used to monitor the acoustic activity and habitat of blue whales. Remote sensing using acoustics characterizes the seasonal movements and abundance of blue whales (Burtenshaw et al. 2004). Beamforming and filtering are common methods of studying blue whale acoustics. Beamforming uses an array of hydrophones to pick up acoustic signals (McIntyre et al. 2015). Filter processing characterizes sounds by the amount of energy at specific frequencies. Meanwhile, remote sensing using satellites is useful in monitoring blue whale habitats. With the use of remote sensing, the seasonal movements and habitats of blue whale populations can be predicted based on the level of euphausiid populations, chlorophyll-a concentration, sea surface temperature, and bathymetry.

1.1 OBJECTIVE

The purpose of this thesis is to review the use of remote sensing in studying blue whale habitat. Acoustic and satellite remote sensing are tools used to monitor oceanic conditions. Remotely sensed environmental parameters have the potential to identify biological hotspots for blue whales. Blue whales are sensitive to changes in the environment. Climate change has altered the species range by influencing the distribution of prey, chlorophyll-a concentration, and sea surface temperature. This thesis will include a review of relevant literature.

2.0 LITERATURE REVIEW

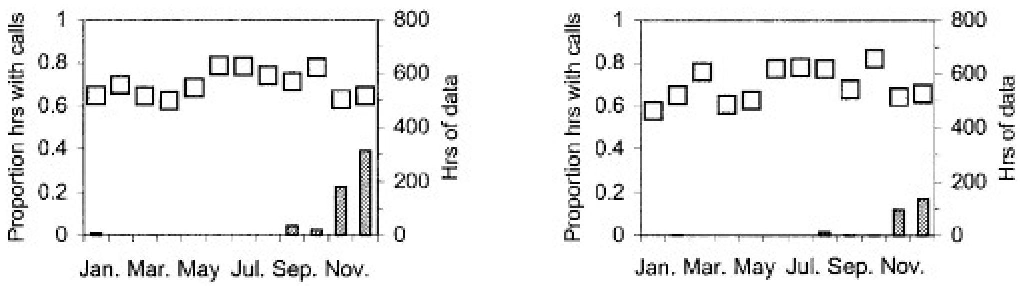
2.1. ACOUSTIC REMOTE SENSING

Beamforming and filtering, as well as, sonobuoy recordings are common methods of analyzing underwater acoustics. They are used to detect, localize, and classify sounds. (Bouffaut et al. 2017). Filter processing categorizes sounds based on the amount of energy produced at specific frequencies. This allows acousticians to distinguish marine mammals. Blue whale vocalizations range between 10 to 100 hertz (Hz) with a source-level of 189 underwater decibels (dB). Blue whales produce several call types (Sirovic and Hildebrand 2010). The tonal call is an 18-second call consisting of a tone followed by down swept segments. Tonal calls are often repeated at regular intervals and range around 28Hz. Frequency modulated calls, known as Downswept “D" calls, are short 4-second calls that sweep downward from 100 to 40Hz. Filters are implemented to isolate spectrums. Beamforming is a signal processing technique that increases the signal-to-noise ratio (McIntyre et al. 2015). Arrays of hydrophones are placed to triangulate the signal’s source. Hydrophones record blue whale vocalizations over a 500km distance. Beamforming amplifies the signal, blue whale call, and reduces the noise. Sonobuoys are radio-linked sonar systems that conduct underwater acoustic studies (Sirovic and Hildebrand 2010). Sonobuoys are deployed throughout a given area following the visual detection of blue whales, to provide coverage of the entire surveyed area. Omnidirectional and directional sonobuoys are used. Omnidirectional sonobuoys have a broader frequency response, 10-20,000 Hz, comparatively to directional sonobuoys, 10-2,400Hz. The use of directional sonobuoys is advantageous in determining data on the sound source direction.

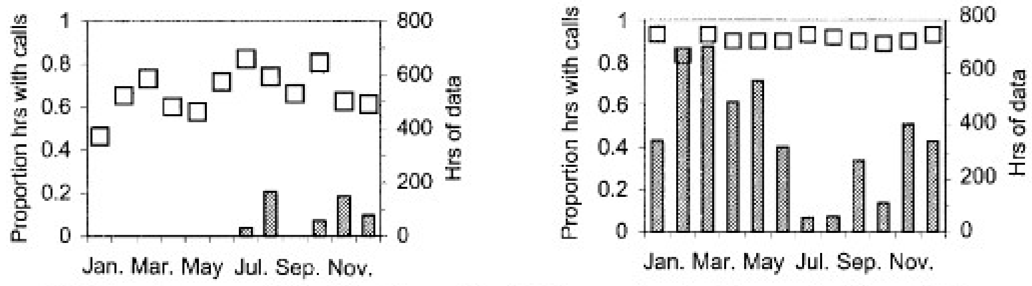
2.1.1. Blue Whale Call Detection

A trait common to baleen whales is the production of songs. Blue whales produce high intensity, low frequency, long-duration acoustic calls (Cummings and Thompson 1971; McDonald et al 2006). Whales are the third major source of ocean ambient sound following ships and wind (Curtis et al. 1999). Blue whale calls are long patterned sequences made up of pulsive and tonal units. The pulsive units are amplitude modulated series and tonal units are down sweeps with strong harmonics. The combination of sequences extends the reach of the call to be detected at a 600km range.

Acoustic monitoring of blue whale calls provides the seasonality and movements of calling individuals. A blue whale monitoring study used acoustic recordings from the U.S. Navy Sound Surveillance System (SOSUS) arrays (Stafford et al. 2001). Sixteen hydrophones were placed in the North Pacific Ocean and monitored the distribution of blue whale calls from 1994 to 2000. Arrays are mounted on the continental slope to receive sound from the deep sound channel (Burtenshaw et al. 2004). The acoustic arrays are capable of detecting calls over a 500km distance using numerous hydrophones. A monthly call average was determined by evaluating the number of vocalizations recorded (Stafford et al. 2001). The seasonality was established by grouping the monthly proportions. Blue whale populations were recorded on the eastern pacific coast, near the Gulf of Alaska, from July to November (Figure 1). Blue whale vocalizations are most frequently recorded in the summer and fall and least often in the winter and spring. This suggests a migration from higher to lower latitudes throughout late fall. The seasonal pattern and location of calls indicate annual migration (Moore et al. 2002).


a) Hydrophone No. 1

b) Hydrophone No. 2


c) Hydrophone No. 3

d) 8n 95w

Figure 1. Hours of blue whale calls recorded on hydrophones by month in the eastern Pacific Ocean. The open squares represent the number of hours of data examined by month (Stafford et al 2001).

A study by Sirovic and Hildebrand (2010) compared the abundance of blue whale call detections and various blue whale habitat features. Chlorophyll-a concentration, mean krill biomass, and sea surface temperature were recorded from April to June of 2001 and 2002. Blue whale calls were analyzed from sonobuoy recordings. In 2001, 59 sonobuoys were deployed, 57 of which were directional and 2 being omnidirectional. While in the 2002 study, 47 sonobuoys were distributed, 44 being omnidirectional and 3 being directional. The sonobuoys provided coverage of the entire surveyed area. The radio-linked listening devices have a radio transmission range, weather dependent, of 10 to 16 nautical miles. The scanner radio receiver, onboard ships, recorded calls to digital audiotapes. Data was filtered to sort the calls of interest and later analyzed to identify blue whale tonal calls. D calls are difficult to detect due to their variability and are determined by visually scanning data. In 2001, blue whale calls were detected on three sonobuoys (Figure 2). Tonal calls were detected on one sonobuoy and D calls on the other two sonobuoys. Comparatively, in 2002, 21 sonobuoys detected tonal calls, four of which also detected D calls.

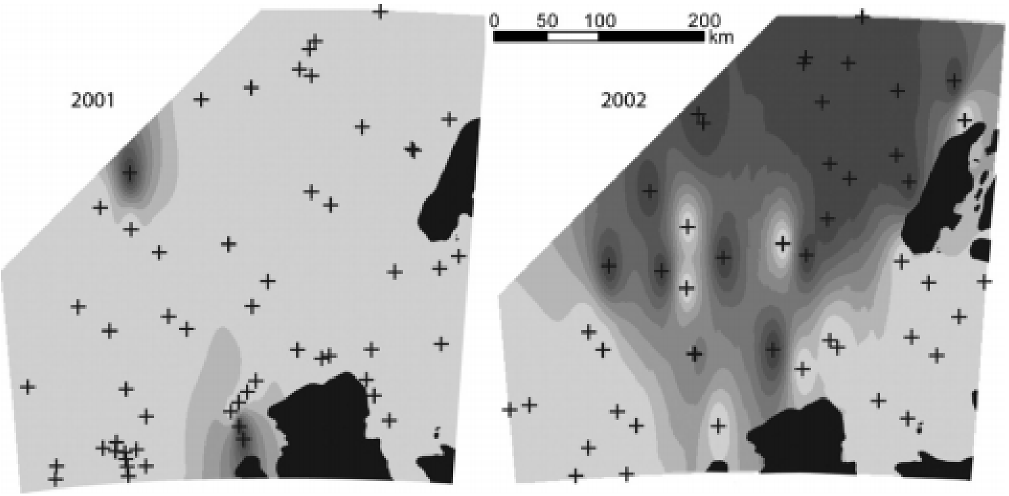


Figure 2. Areas with a high abundance of blue whale calls during the 2001 and 2002 survey periods are shown with darker shading. Sonobuoys locations are represented by pluses (+). Black area representing land (Sirovic and Hildebrand 2010).

2.1.2 Blue Whale Prey

The distribution of blue whale populations is associated with phytoplankton aggregation (Burtenshaw et al. 2004). Euphausiid species, *Euphausia pacifica* and *Thysanoessa spinifera*, are the primary diet of blue whales (Brinton 1981). Euphausiids are abundant at shelf edge areas and offshore deep-water sites (Burtenshaw et al. 2004). Shelf regions have higher rates of primary production and feature high krill biomass

(Sirovic and Hildebrand 2010). Both species distributions follow the offshore, near-shore ranges from the Gulf of Alaska to southern California (Burtenshaw et al. 2004). They are cold-water species and are thus restricted by the sea surface temperature. Euphausiids experience their maximum population biomass during the summer and early fall. Euphausiid biomass increasing along the eastern pacific coast directly influences the distribution of blue whale populations.

The Southern Ocean Global Ocean Ecosystem Dynamics (SO GLOBEC) program was established to identify the relationship between Antarctic krill and their environment and predators (Hofmann et al 2002). Hydroacoustic surveys determined the abundance and distribution of Antarctic krill in Marguerite Bay region. They detected a greater abundance of krill surrounding the West Antarctic Peninsula (WAP) and offshore sites. Sirovic and Hildebrand (2010) further analyzed the mean volume of krill biomass from April to June of 2001 and 2002, conducted by SO GLOBEC. They compared the concentration of krill and zooplankton to blue whale call occurrence. Krill had higher biomass and zooplankton had higher abundance in 2001 than 2002. Both the mean krill biomass and the mean zooplankton abundance were higher in the 100 to 300 m depth range than in the top 100 m. In 2001, blue whale D calls were detected twice in the area with the highest krill biomass and zooplankton abundances, but the next year, 21 tonal calls were detected in the areas of high krill biomass and zooplankton abundances.

In 2014, 2016, and 2017, an analysis of prey availability and blue whale distribution was conducted in the South Taranaki Bight region (Barlow et al 2020). Hydroacoustic backscatter data were collected with a frequency of 120 Hz. Raw acoustic data were processed and developed indicating date, time, geographic location, and volume backscattering strength (S_v). Aggregations were mapped by period using a 4km grid

(Figure 3). In 2014 and 2017, whale sightings coincide with the greatest number of large and small krill aggregations and high aggregation density, primarily inshore. Whereas, in 2016, blue whale sightings were detected offshore, where there were few large aggregations of krill and low mean density.

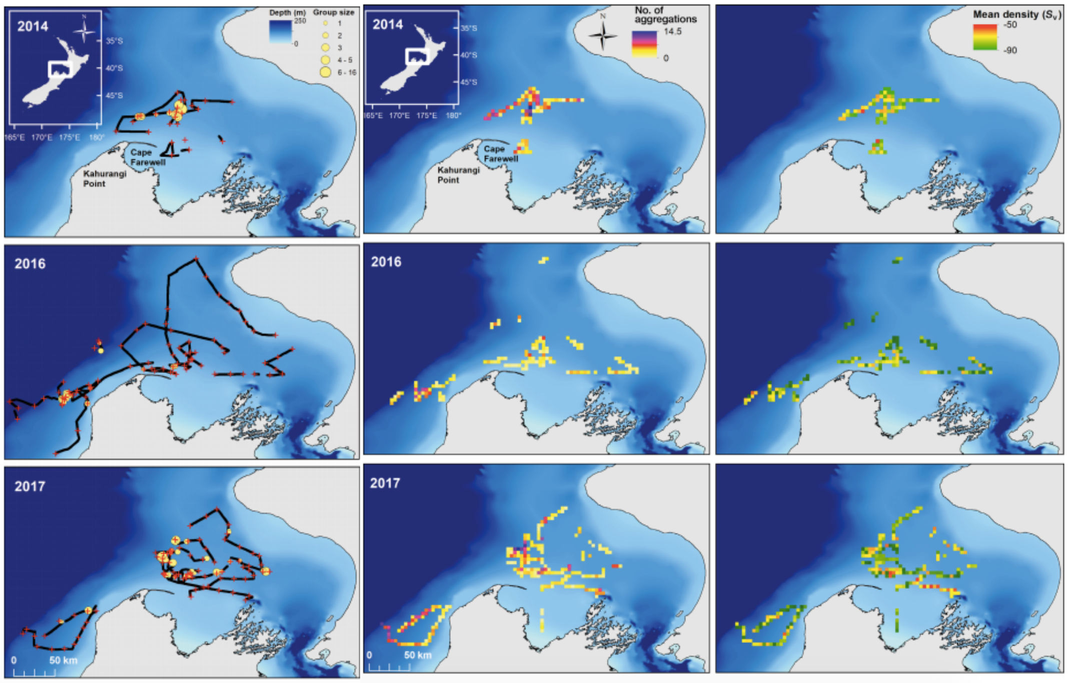


Figure 3. Blue whale sightings locations (left), represented by yellow circles, number of krill aggregations (middle), and krill aggregation density (right) for each of the three surveys in the South Taranaki Bight region (Barlow et al 2020)

2.2 SATELITE REMOTE SENSING

Satellite imagery is used to determine the relationship between marine mammals and their habitats. Ocean color remote sensing measures radiance from the Earth's surface (Nagajara 2020). The amount of radiance correlates to the concentration of phytoplankton and chlorophyll-a. Euphausiid aggregations can be tracked by following areas of corresponding chlorophyll-a concentrations. Spectroradiometer remote sensing uses two satellites to record the changing sea surface temperature. The satellites measure the temperature of the top millimeters of the ocean’s surface.

2.2.1 Chlorophyll-A

Chlorophyll-a has been used as an environmental indicator since the Coastal Zone Color Scanner launched in 1978 (Dierssen 2010). Satellite measurements of ocean color provide the level of phytoplankton biomass and primary production (Cullen 1982). Satellite measurements of ocean color are the principal remote-sensing tool for measuring the ocean’s impact on the climate cycle. Radiance satellites are programmed to depict chlorophyll-a concentration (Nagaraja 2020) Satellites will use an algorithm calculating chlorophyll-a concentration based on the amount of radiance over large-scale areas. The global chlorophyll-a concentration estimates are produced and archived by the National Aeronautics and Space Administration (NASA) using the Sea-viewing Wide Field-of-view Spectroradiometer (SeaWiFS) ocean color sensor (Burtenshaw et al. 2004). The SeaWiFS instrument is mounted on the OrbView-2 satellite and has collected global data from the date of its launch in September 1997 to December 2010 (Patt et al 2003). The spectroradiometer uses eight spectral bands, ranging from visible to infrared light, to measure the radiance by the earth’s surface (Cannizzaro and Carder 2006). Chlorophyll-a reflects green light into space.

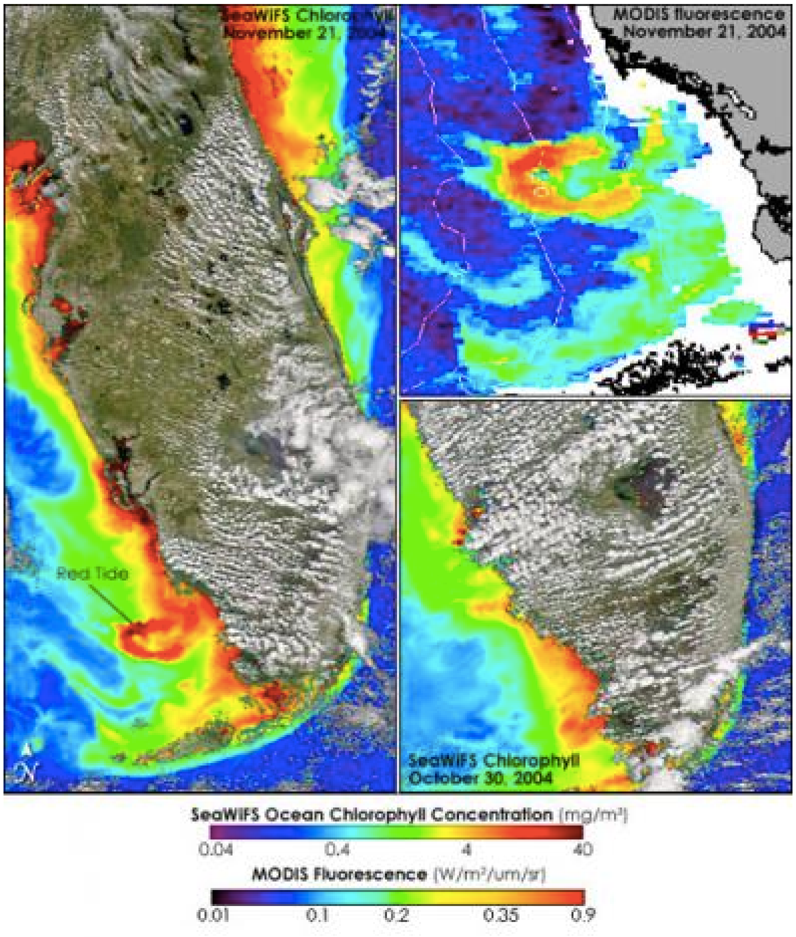


Figure 4. SeaWiFs chlorophyll concentration in the Gulf of Mexico, 2004 (Nagaraja 2020).

The chlorophyll maps (Figure 5 and 6) depicts the monthly proportion of chlorophyll (mg) per cubic meter of seawater of May 2003 and 2020. Phytoplankton shifts the reflected color spectrum from blue to green (NASA 2020). High concentrations of chlorophyll, areas of dark green, indicate increased phytoplankton growth. Whereas low chlorophyll concentration, blue areas, represent low phytoplankton activity. Blue whales reside predominantly in areas with a chlorophyll-a concentration between 0.5 mg/m^3 and 4 mg/m^3 (Nagaraja 2020).

2.2.2 Sea Surface Temperature

Sea surface temperature is measured using multiple satellites (National Oceanic and Atmospheric Administration 2020). The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument aboard NASA's Terra and Aqua satellites. The satellites cover Earth's surface every one to two days. The satellite measures the temperature of the top millimeter of the ocean surface. Satellites enable measurement of sea surface temperature from approximately 10 μm below the surface (infrared bands) to 1mm (microwave bands) depths using radiometers. Sea surface temperature

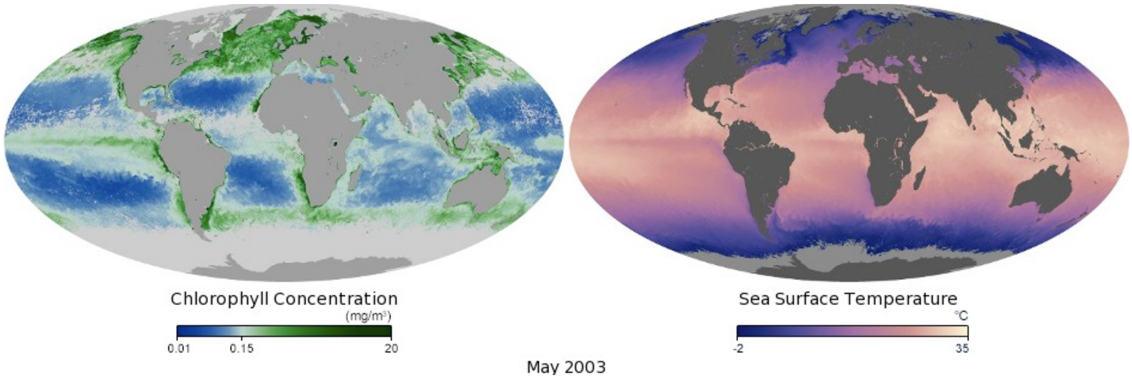


Figure 5. Chlorophyll concentration and sea surface temperature in May 2003 based on MODIS's Aqua satellite (NASA 2020).

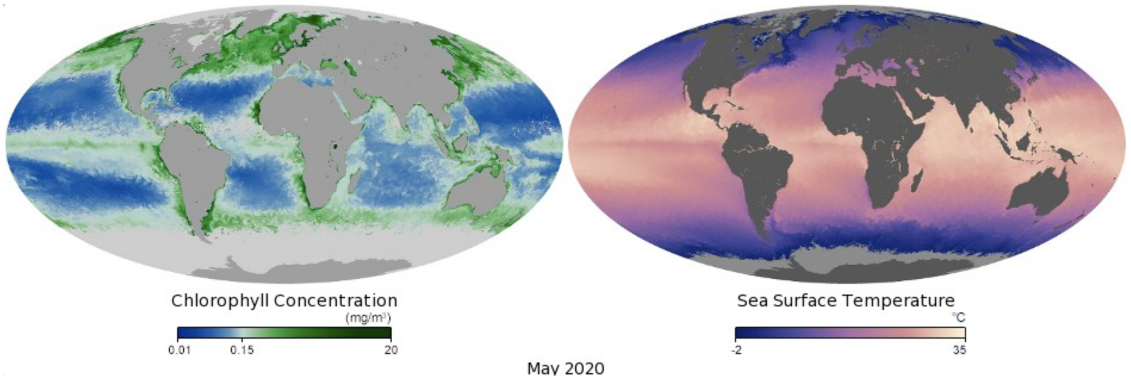


Figure 6. Chlorophyll concentration and sea surface temperature in May 2020 based on MODIS's Aqua satellite (NASA 2020).

Etnoyer et al (2006) conducted a study to define pelagic habitat hotspots for blue whales through sea surface temperature frontal features. Surface-mounted satellite tags were applied to six blue whales. Relevant sea surface temperature was identified by comparing NASA's MODIS Aqua satellite to blue whale trajectories. The blue whales remained around offshore Baja California for weeks and months. The shortest resident remaining in the vicinity for 13 days, while others for 91 days. Blue whales were commonly found in waters with sea surface temperatures between -1.4°C and 3.5°C. \

2.2.3 Bathymetry

Bathymetry is a key factor in blue whale habitats. Matched filtering is a technique that uses echosounders to measure water depth (Nagaraja 2020). Echosounders transmit a signal that reflects off the ocean floor before being recorded. The signals travel time to and from the bottom indicate the water depth. Blue whales reside primarily at a depth of 100 meters. Boundary currents, eddies and, bathymetric features, such as seamounts and slopes, are common habitats for blue whales (Moore et al. 2002; Burtenshaw et al.

2004). The increased whale populations within these bathymetric features indicate elevated productivity enables feeding throughout the year. Fielder et al (1998) proposed that inland shelves or shelf edges are required for euphasiid aggregations to be exploited by blue whales. The concentration of prey around abrupt features is in part due to being retained in areas of strong upwelling (Nickels, Sala, and Ohman 2018).

Previously, Moore et al (2002) suggested the relation of whale distribution and the Emperor Seamounts. The Emperor Seamount is a continental slope off the Kamchatka Peninsula and the Aleutian Island chain in the Pacific Ocean, on the coast of Hawaii. Moore determined that throughout the winter, 50%, 75%, and 90% of call locations were centered over the seamount. While in the summer, call locations shifted. The call locations were found most frequently at depths of 4,000 meters comparatively to the surrounding waters with depths greater than 6,000 meters (Figure 7). Blue whales prefer shallower waters.

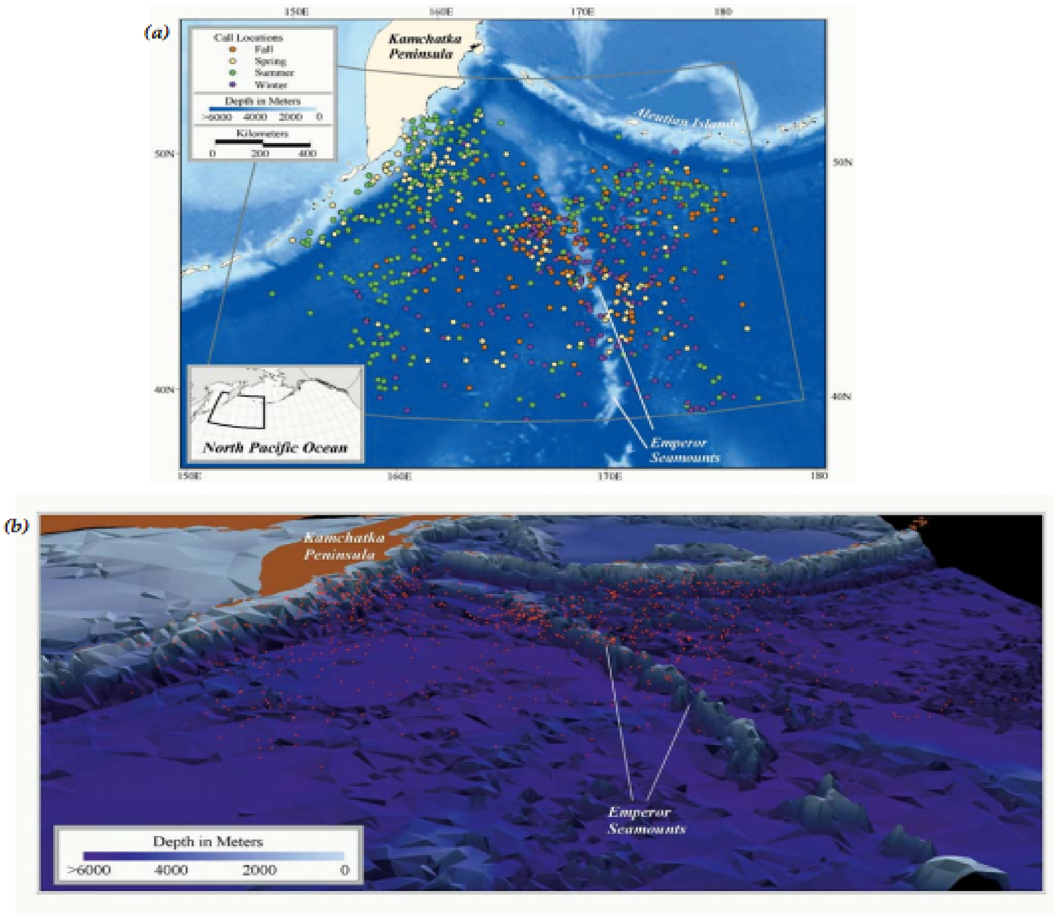


Figure 7. Seasonal blue whale calls over the Emperor Seamount (Moore et al. 2002).

Nickels, Sala, and Ohman (2018) conducted a study to evaluate the relation of blue whale distribution and the steep bathymetric features of the Nine Mile Bank, California. Of the 26 blue whales encountered, 21 were surveyed on the bank, the remaining 5 were encountered inshore and zero offshore. Both the bank and inshore exhibited a greater abundance of blue whales, comparatively to offshore; suggesting the bank and regions surrounding it are preferred blue whale habitat.

3.0 MATERIALS AND METHODS

To evaluate the methods of remote sensing used to study blue whales, *Balaenoptera musculus,* literature spanning the last 50 years was compiled. The literature collected discusses the environmental factors used in monitoring blue whale habitats. The Lakehead University Library Database was the primary database in finding literature. Key terms such as acoustic remote sensing, blue whale call detection, satellite remote sensing, chlorophyll-a concentration, sea surface temperature, euphasiid aggregation, and bathymetry were searched. Publications focused on previous acoustic and satellite remote sensing studies, primarily in the Pacific Ocean.

4.0 DISCUSSION

Remotely sensed environmental parameters have the potential to identify biological hotspots for blue whales (Sirovic and Hildebrand 2010). Remote sensing has been used increasingly in monitoring oceanic conditions. Throughout this thesis, relevant literature was reviewed to determine what key environmental factors are present when blue whales are detected and how remote sensing is used within these surveys.

Several studies use acoustic remote sensing to determine blue whale migration patterns (Bouffaut et al. 2017; Burtenshaw et al. 2004; Cummings and Thompson 1971; Curtis et al. 1999; McDonald et al 2006; Moore, S.E. et al. 2002; Sirovic and Hildebrand 2010; Stafford et al. 2001). Hydrophones and sonobuoys are used to detect blue whale calls by recording underwater acoustics. Calls are filtered; isolating tonal and D calls from the oceans numerous ambient sounds. The distribution of calls recorded allows researchers to follow the movement of blue whales; determining areas of feeding and breeding.

The analysis of krill concentration uses both acoustic and satellite remote sensing. A study using hydroacoustic backscatter data (Barlow et al 2020) determined the relation between krill aggregation and phytoplankton abundance. Meanwhile, Sirovic and Hildebrand (2010) evaluated the abundance of krill in areas with blue whale presence. Satellite remote sensing studies (Brinton 1981; Burtenshaw et al. 2004) monitored krill biomass through the amount of primary production on shelf edge areas and offshore deep-water sites

Distribution patterns of blue whales have been linked to predictable highly and seasonally productive waters associated with high chlorophyll-a. Radiance satellites are programmed to depict chlorophyll-a concentration (Burtenshaw et al. 2004; Cannizzaro and Carder 2006; Dierssen 2010; Lavery 2014; Nagaraja 2020; Patt 2003). High concentrations of chlorophyll indicating increased phytoplankton growth are hotspots for blue whales. Blue whales reside predominantly in areas with a chlorophyll-a concentration between 0.5 mg/m^3 and 4 mg/m^3.

Sea surface temperature can be used to identify biological hotspots for blue whales. Satellite remote sensing studies (Becker et al 2010; Etnoyer et al 2006) identified areas with sea surface temperatures between -1.4°C and 3.5°C experience higher blue whale density.

Bathymetric remote sensing determines areas with suitable depths for blue whales. Fielder et al (1998) proposed that inland shelves or shelf edges are required for euphasiid aggregations to be exploited by blue whales. Numerous studies concluded that the presence of blue whales among shelf edges is due to the higher rates of primary production and high krill biomass within the top 100m depth range (Burtenshaw et al. 2004; Moore et al. 2002; Nagaraja 2020; Nickels, Sala, and Ohman 2018; Sirovic and Hildebrand 2010).

5.0 CONCLUSION

Blue whale populations inhabit regions with specific environmental characteristics. Numerous studies have been conducted to determine what makes a blue whale habitat. Key features are continuously monitored to establish oceanic conditions to conserve blue whale habitat. Remote sensing practices aid in the monitoring of environmental features, such as the level of euphausiid aggregation, chlorophyll-a concentration, sea surface temperature, and bathymetry. The use of remote sensing allows the seasonal movements and habitats of blue whale populations to be recorded and potential blue whale habitats can be predicted. With climate change increasingly altering known blue whale habitats, conservation efforts must be made to maintain blue whale population levels.

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