Availability to food drives phenological changes in pygmy blue whales in the middle of the Indian Ocean

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Abstract

Introduction

* Large scale marine system changes (marine environment)
  + Global warming, acidification (phytoplankton bloom), baseline shifting & food web changes
  + Central Indian Ocean, complex ecosystem, warmest ocean basin, poorly understood, diverse species, many pygmy blue whale populations
* Blue whale as a case study
  + Almost extinct, largest mammal, energetically cost,
  + Feeding behaviour – krill on patches
  + By studying the relationship between blue whales’ migration routes and some environmental conditions (e.g., SST, Chlorophyte-a), helping us understand larger scale ecology

Commercial whaling in the twentieth century has brought the blue whale (*Balaenoptera musculus*) almost to extinction (Clapham et al., 1999). Branch et al. (2004) demonstrated that globally, only 0.15% of the population survived whaling. The International Whaling Commission introduced a moratorium on commercial whaling in the 1960s (Aron et al., 2000), however, the recovery of the largest known animal on earth, has been slow (Thomas et al., 2016). Blue whales remain identified as ‘endangered’ on the International Union for Conservation of Nature’s Red List (IUCN, 2020).

Material and Methods

2.1 Study Area

Diagram

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Figure Map of the study area.

2.2 Whale presence data

The acoustic data was obtained from the international data system of the Comprehensive Nuclear Test-Ban Treaty Organisation (CTBTO). There are two hydroacoustic sites near the DG island. The two sites are around 220km apart. One is located on the northwest (DGN, referring as NW, hydrophone number: H08N1, 6.34°S, 71.01°E), and the other is located on the southeast (DGS, referring as SE, hydrophone number: H08S1, 7.65°S, 72.47 °E). At each site, a set of three hydrophones are moored in the sound fixing and ranging channel, where the sound achieves the maximum speed (Hanson, 2001). The depth of the station is around 1000 metres. The detection range of the pygmy blue whales has been reported to up to 300km (Samaran et al., 2010). Since the existence of the Seychelle-Chagos Thermocline Ridge, separating the two sites, making the sounds produce on the NW and SE unlikely to be heard on the other site (Pulli & Upton, 2001). Thus, we use the NW site representing the soundscape northwest of Diego Garcia, SE representing the soundscape southeast of Diego Garcia. Here, we used the acoustic recordings for the NW site from January of 2002 till February of 2014. We used the acoustic recordings for the SE site from January of 2002 till August of 2018.

(------ data extraction part -----)

Following the representation of Charif et al. (2020), we generated the whale presence data.

The presence data was aggregated into eight days (192 hours) in order to keep consistency with the environmental data. For each of the site, we recorded the absence/presence status for each hour. Whale presence is defined as the percentage of hours with whale calls detected. Insufficient data such as the recorded hours less than 90% of the time period was removed.

To define the peak seasons, we followed the following algorithms: 1. We found the outstanding whale presence which is greater than 90% throughout the entire study period. If there was more than one time period satisfied the criteria, we chose the largest whale presence block as the peak time (multiple peak times if the whale presence is 100%). 2. We calculated the growth rate of the whale presence for each eight-period. The maximum rate (defined as the start date of the peak) and minimum rate (defined as the end date of the peak) are the ones with the most rapid change at the local. 3. We define time period between the start date and the end date containing the outstanding whale presence as the peak season.

2.3 Environmental data

The environmental data including Sea surface temperature (SST) and chlorophyte-a (chlorophyll-a) data were downloaded from NOAA ocean watch website (<https://oceanwatch.pifsc.noaa.gov/doc.html#currents>).

SST was generated via the CoralTemp dataset. We used the analysed data which is continuous for each day through the entire study period. We computed the mean SST for the four data spots (2 units at each side, spatial resolution is approximately 5km) approximate 100 km2 area encompassing the hydrophone stations. Then we calculated the mean SST for the corresponding eight-day period. Mean SST and minimum SST were calculated for each year and for the two seasons. The seasons in DG were divided into two segmentations: hot season (December to May) and warm season (June to November) (ref).

Chlorophyll-a was used as a proxy of phytoplankton biomass. Chlorophyll-a was acquired from the MODIS-Aqua 8-daily dataset. Similar to SST, we computed the mean chlorophyll-a for six data spots (2 units at one side, 3 units at the other side, spatial resolution is 4km per unit approximately) containing the hydrophone stations of 96 km2. Mean chlorophyll-a was calculated for each year and each season of the year. One potential caveat is that the measurement of the chlorophyll-a is from the water surface, hence they may not reflect the krill density in the deep water (Branch et al., 2007).

2.4 Statistical analysis

We used maximum likelihood method (ref) to find the coefficients for the trend of whale calls, SST and chlorophyll-a for each year during the study period.

To interpret the relationship between the whale presence and environmental factors, we used generalized linear models. Whale presence is paired with SST and chlorophyll-a at each site with a binomial family (weight= number of recording hours in the corresponding eight-day period). The effect of year is considered by using ‘glm.er’ function (ref) in Rstudio.

Results

We have assessed the chagos whales calls for a total of 92180.8 hours on the NW site and 13228.4 hours on the SE site, over 598 and 783 eight-day periods, spanning across 13 and 17 years respectively. 83.2% (480 eight-day periods) of the NW recordings and 86.8% (680 eight-day periods) of the SE recordings are sufficient data (i.e., consist 70% of the maximum hours).

3.1 Overall trend of the Chagos whale calls

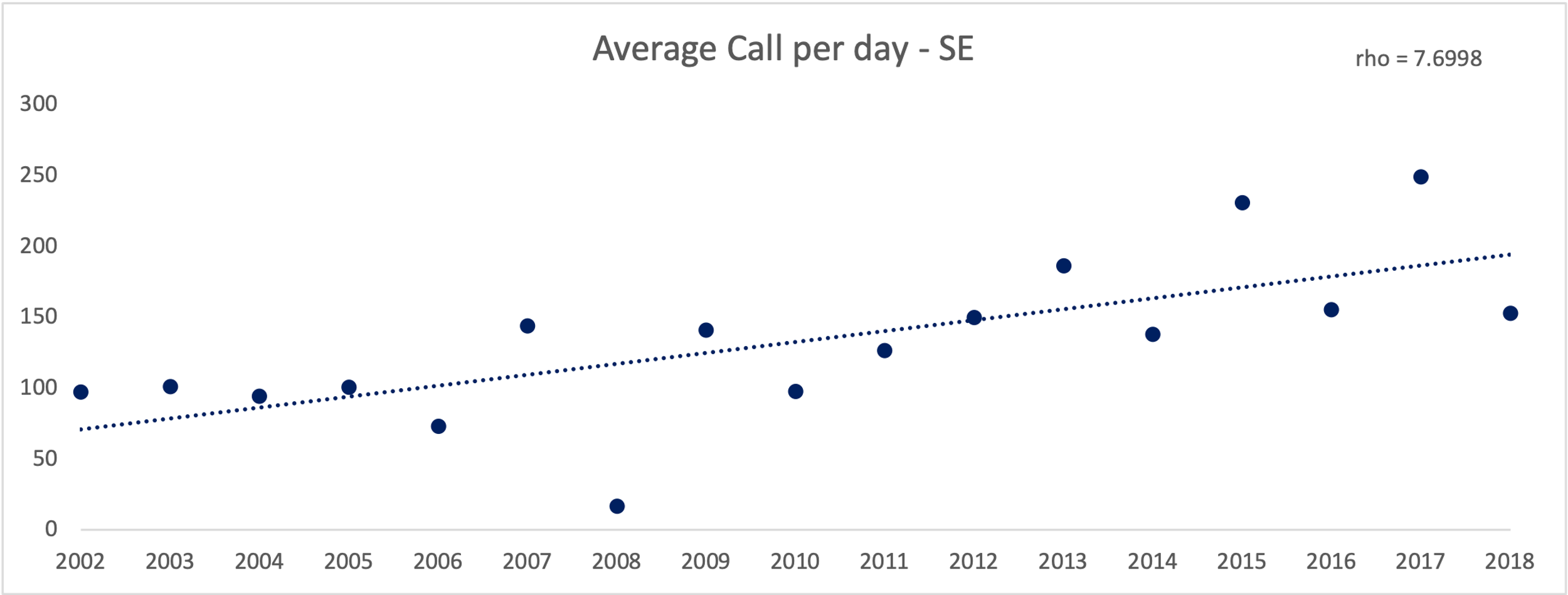
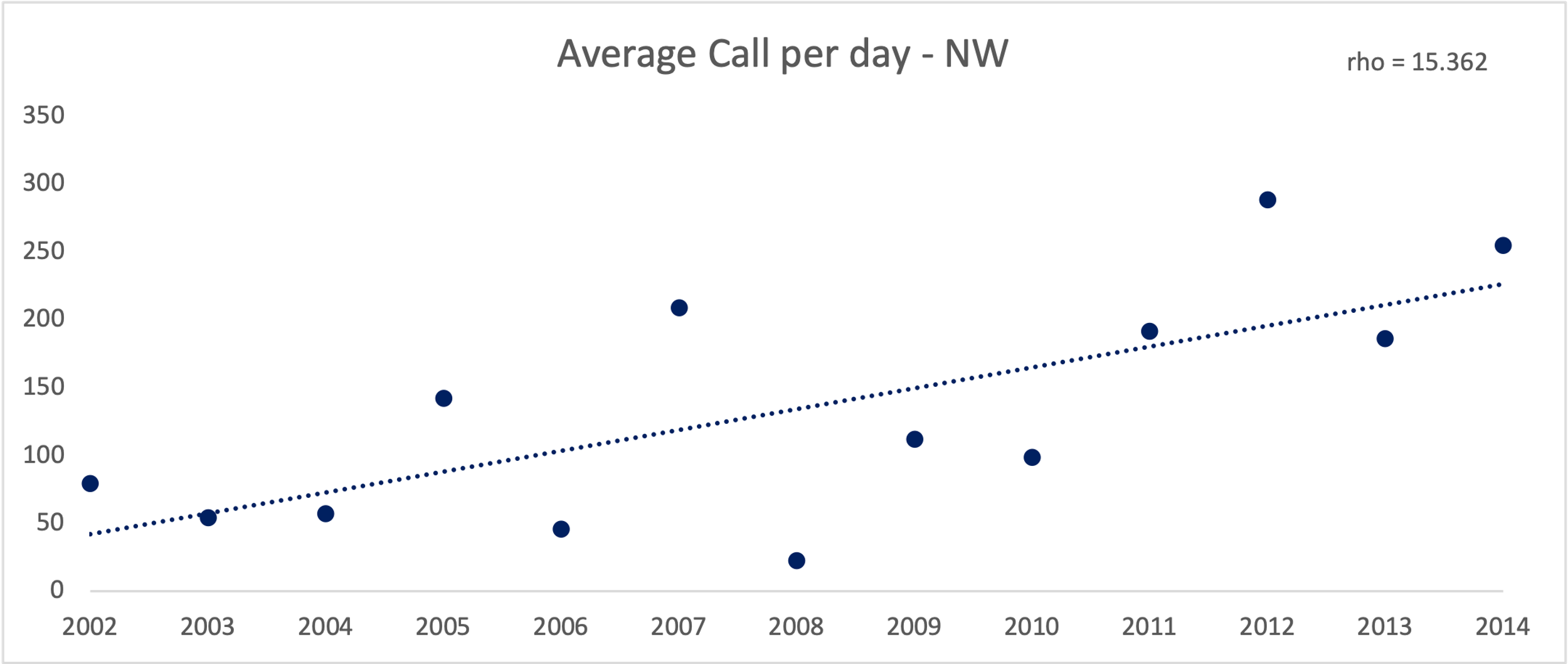


Figure Average Chagos whale call per day on the NW and SE site in Diego Garcia over the study period.

In total, around 500,000 DGW calls are recorded in the NW site over twelve years and more than 700,000 DGW calls are detected in the SE site during the 16-year period. The average call per hour is higher in the SE site (5.57 per hour) than the NW site (5.27 per hour). Increasing trends of the DGW calls are observed at both the northwest site and the southeast site through the entire study period. The increasing rate is higher at the northwest site (increasing 15.4 calls per day per year on average) comparing to the southeast site (7.7 calls per day per year on average). It is noticeable that in the year of 2008, on both sites the least average DGW calls were recorded as well as total number of calls among the entire study period.

|  |  |  |
| --- | --- | --- |
|  | NW | SE |
| Mean SST | 0.0154 | 0.0187 |
| Min SST | 0.0183 | 0.0388 |
| Mean chlorophyll-a | -0.0025 | -0.0007 |

At the same time, average SST and minimum SST have overall increasing trends on both sides of Diego Garcia. The mean concentration of chlorophyll-a has been more stable with a slight decreasing trending at either site.

Chart, bar chart

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Figure Mean Chagos whale presence on the SE and NW site for each eight-day period (46 bins) during the study period (2002- 2014 on the NW site, 2002- 2018 on the SE site). Vertical bars (blue bars for SE site, red bars for NW site) represent the average whale presence.

Whale presence percentage varies significantly on both sites (Wilcoxon rank sum test p= 0.03).

The mean peak whale presence is higher on the SE site than on the NW site. There are more whales at the NW site in the warmer season (May to October). In the cooler time of November to April, there are more whale presence on the SE site.

3.2 Correlation with SST and chlorophyll-a concentration

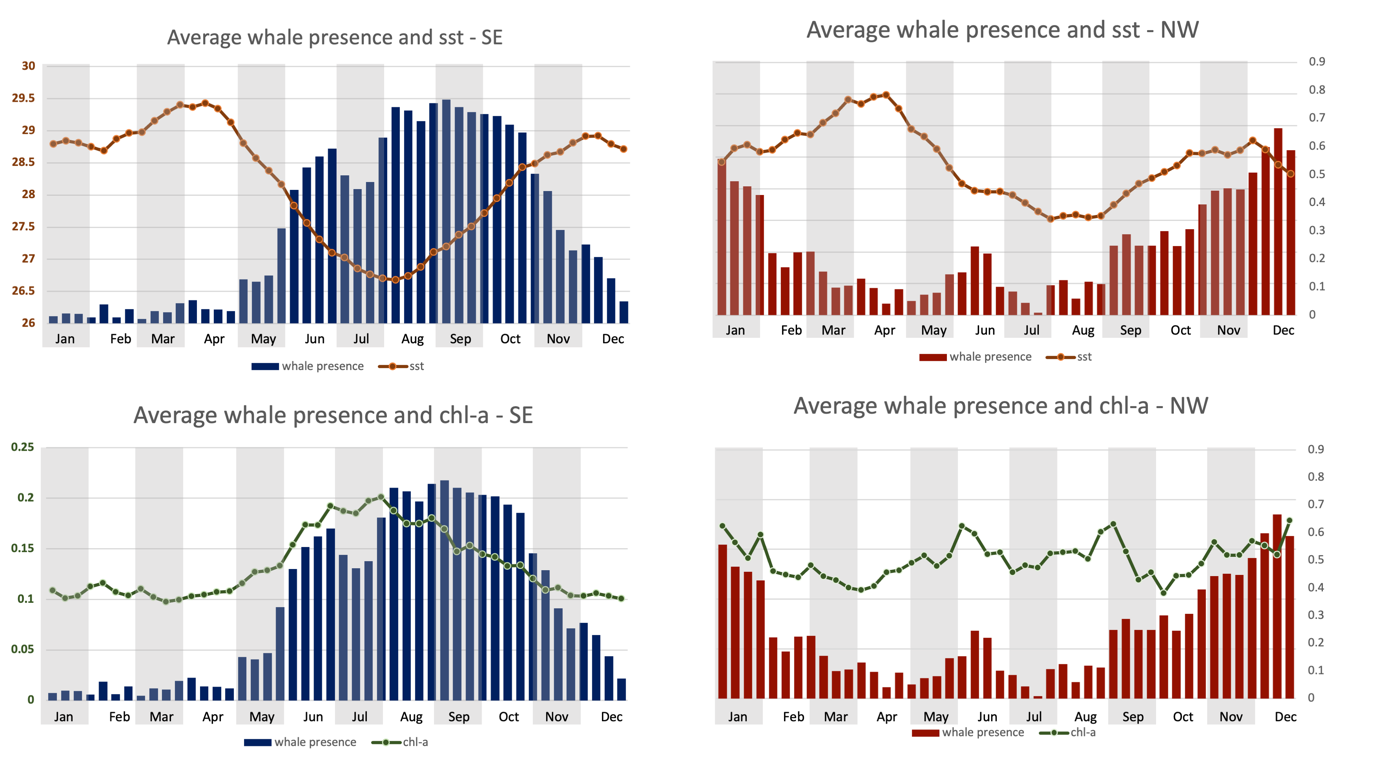


Figure Average whale presence during each eight-day periods and their corresponding SST and chlorophyte concentration.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | SE | | NW | |
| Variable | coefficient | p-value | coefficient | p-value |
| SST | -1.138422 | <2e-16 \*\*\* | 0.27922 | <2e-16 \*\*\* |
| chlorophyll-a | 16.4514 | <2e-16 \*\*\* | -1.7808 | <2e-16 \*\*\* |

There is strong seasonality effect observed in the two sites. On the SE site, SST negatively correlates with the whale presence. While on the NW site, they have a positive relationship.

As for the food availability, the coefficients are significantly greater than the SST. At the NW site, there is a negative relationship between chlorophyll-a and whale presence. At the SE site, chlorophyll-a and whale presence have a positive correlation. In the NW, chlorophyll-a slightly makes the odds of experiencing a call less. In the SE, chlorophyll-a strongly makes the odds of experiencing a call less.

3.3 Peak seasons of the DG whale calls

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Figure Long term whale presence on the NW site. Blue bars indicate whale presence. Stars indicate the peak period. Blue bars

On the NW site, we detected 15 peak seasons over 13 years and the average time period is 74 days. The end date of the last peak cannot be determined due to missing data. Most peaks started between October to December and finished in January or February. However, two extra peaks were found in 2005 and 2010 respectively and one extra peak was detected in 2006,2010 and 2014. Peak seasons are in similar patterns during 2002 to 2004. There are more and longer peak seasons in 2005. However, information is limited in 2006 and 2007 due to missing data. There is no peak found in 2008. In 2009 and 2010, peaks were similar to the previous pattern. Longer and stronger peak seasons were observed from 2011 and 2013. The peak season analysis is not complete in 2014 due to missing data.

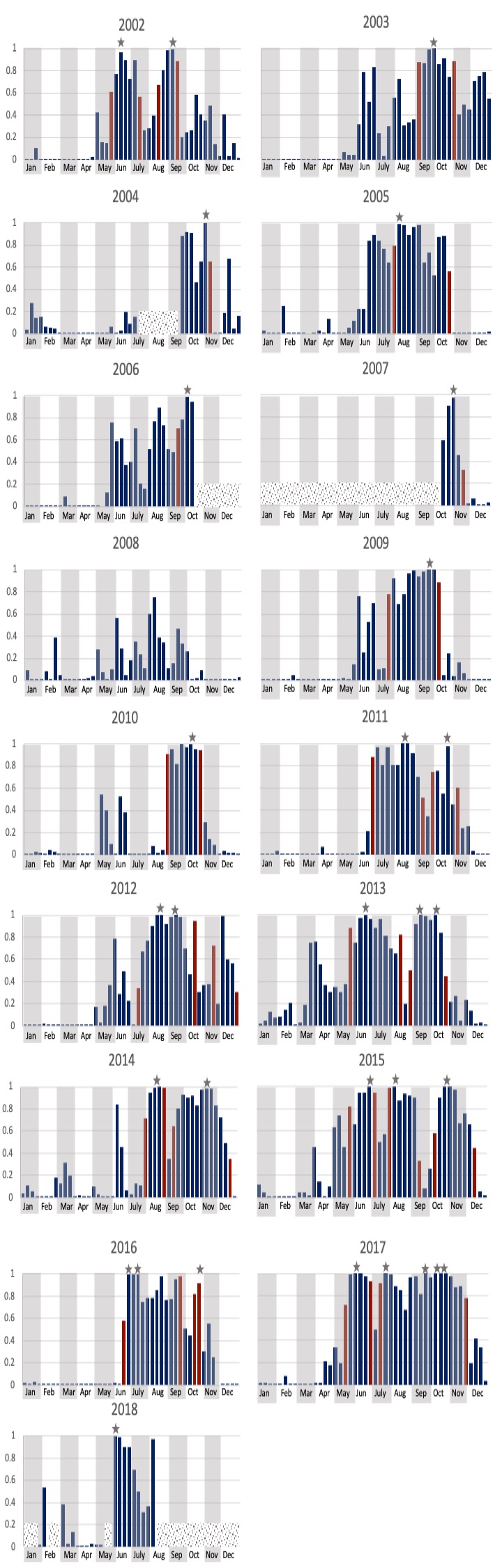


Figure Mean whale presence on the SE site

On the SE site, 24 peak seasons were identified with the study period of 17 years. Mean duration of peak seasons was 62 days. Unlike the NW site, most peak seasons were between May to December which is the cooler time of Diego Garcia. In 2002, we detected two consecutive peaks from May to September. There was one peak respectively in 2003 and 2004.

There was a trend that there were more throughout the entire period since there were always more than two peaks from 2011 (except for 2018 since the dataset was incomplete). Nevertheless, stronger peaks (more than 90% of whale presence) were more frequent in the later years. No peak seasons were detected in 2008.

Discussion

*Structure*

* Summary
* Why our research is significant and meaningful
  + Long-term monitoring
  + By discussing how the changing environmental condition is affecting this large marine mammal migration pattern, as a case study to understand the large-scale marine eco system shifting
* Whale calls across all years
  + They are the residents of the CIO, comparing with other acoustic studies using CTBTO data
  + Increasing trend of whale calls (fig2), Consist with the Antarctic blue whale increasing trend (may add one more figure?)
* Seasonal variance of the Chagos whale
  + Why we use the two sites as acoustic independent site (fig 1)
  + Significant difference (add wilcoxon rank-sum test)
  + Where they are in the different seasons (consist with previous studies)
  + SST shifting vs chagos whale peak seasons (fig 5,8)
* Chagos whale vs chlorophyte-a concentration
  + Migration pattern (clockwise) (fig 8)
  + Chlorophyte-a variance across seasons on both sites (fig 7)
  + Correlation between the whale presence and chlorophyte-a, comparing with the SST (fig 4)
  + Possible feeding at the vicinity of se, but still low chlorophyte-a concentration + feeding on patches, why are they here all time?
  + Are they feeding here, or are they fasting? Blue whales feeding everywhere rather than patches? (paper)
  + Where they may be during March – May be going to Kimberley/Sri Lanka
  + Do they fast when they are singing?
  + Note that the chlorophyte-a is not measured at the same layer of blue whales, but they may be influencing the whales (paper)
  + Other indirect oceanographic features
* Potential impact
  + Wildlife conservation
  + Understand how marine environmental changes are influencing this vulnerable energetically costly large mammal

Our study provides an examination of the Chagos blue whale distribution in association with environmental factors and their possible migration pattern in the study area. We investigate the continuous hydroacoustic recordings of this novel pygmy blue whale subspecies, Chagos blue whale (Leroy et al., in press), at two distinct sites during the entire study period (17 years for the south-eastern site and 12 years for the north-western site). The CTBTO hydroacoustic stations continuously monitors underwater sound waves (by measuring changes in water pressure) and thus records whale calls in the remote mid Indian ocean, which would not be possible by any other means (ref). This allows us to explore long-term variation in timing and magnitude of the peak season in association with changes in environmental conditions.

Central Indian Ocean is a relatively complex ecosystem with rich cetacean fauna (Anderson et al., 2012). There are several distinct blue whale acoustic groups in the Indian Ocean, producing the most diverse array of call types to any other region (Balcazar et al., 2015; McDonald et al., 2006). At Diego Garcia, besides the best-described Antarctic blue whale (McDonald et al., 2006) , there are at least four other pygmy blue whale population (*B. m. indica or B. m. brevicauda*) species detected from the acoustic recordings including Sri Lankan(NIO), Madagascan(SWIO), Australian(SEIO) and Arabian Sea(NWIO) (Cerchio et al., 2020; Double et al., 2014; Leroy et al., 2018; Leroy et al., 2016; Samaran et al., 2013; Stafford et al., 2011; Stafford et al., 2004). Our study demonstrated that there is a significant existence of Chagos whales near Diego Garcia each year, making them not negligible in this tropical water. More than five calls per hour are identified on both sites during the entire study period. We also detected disperse peak seasons on both sites almost every year (except for 2008 when there were least Chagos calls at both acoustic stations). This suggests that the central of Indian Ocean is possibly a crucial habitat for this subpopulation of pygmy blue whales, in contrast of other populations. For example, Cerchio et al. (2020) recorded NWIO calls from 2010 – 2013 from the same acoustic dataset and the amount of calls and peak seasons are considerably less than Chagos calls on the same sites.

We cannot estimate the distance of the whale calls through the acoustic data, therefore it is hard to estimate their population, but we can infer the relative densities from the number of calls that were recorded (Branch et al., 2007). Our observations (Fig 2) manifest an increasing trend of calls on both sites through the study period.

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Figure 7 Peak seasons of the Chagos whale from 2002 to 2018. Red bars indicate peak seasons on the NW site. Blue bars indicate peak seasons on the SE site.

Our study also showed that the Chagos whales’ temporal occurrence presented high seasonality throughout the year. Clear seasonal patterns were detected across the entire study period. The reason why we are comparing the abundance of Chagos songs between the two sampling areas thar are relatively close (220km, see Fig 1) are as followings: 1. DGN and DNS are acoustically independent due to the existence of Chagos-Laccadive Ridge. The Chagos Bank which supporting its archipelago acts as a natural acoustic barrier (Cerchio et al., 2020; Leroy et al., in press). Sounds produce on either side of the Chagos Bank are unlikely to be detected on the other side (Pulli & Upton, 2001). Our results (Fig 3) also show a significant difference (Wilcoxon rank sum test p=0.03) between whale presence on both sites, which is consistent with the independence assumption. Thus, the north-western site represents the soundscape of the northwest of Diego Garcia, whereas the south-eastern site represents the southeast of Diego Garcia. 2. Acoustic data is not a reliable source to estimate the abundance of whale population, but we can infer the relative densities from the number of calls recorded (Branch et al., 2007). Changes of acoustic presence could to some extend reflect changes in numbers of whales in the given area (Charif et al., 2020). Therefore, we compare the hourly whale presence data on both sites of Diego Garcia to study their seasonal occurrence and migration pattern.

In consistence with Leroy et al. (in press) and Sousa and Harris (2015), we found that Chagos whales were more frequently in the NW site in the hot/summer season (average SST NW site:28.85°C; SE site:28.92°C) of December to May, whereas in the warm/winter season (average SST NW site:28.01°C; SE site:27.53°C) we detected most peak seasons of whale presence at the SE site (Fig 7). Temperature is generally higher (average SST is above 28°C) in the tropical regions, comparing to ocean basins elsewhere (ref).



Figure 8 Mean chlorophyll-a concentration

Leroy et al. (in press) proposed a possible clockwise migration of the Chagos-whales. Our findings further support the migration pattern. Blue whale distribution is strongly linked to latitudes in the Indian Ocean (Branch et al. 2007). Antarctic blue whales are frequently found in the austral summer, south of 70º S where they feed, and in the winter, migrate to different northern locations to calve and mate (Branch et al. 2007, Samaran et al. 2010). Although not all whales migrate as Širović et al. (2004) detected Antarctic blue whales calls all year round in the Southern Ocean, in the Antarctic Peninsula. The proportion of the blue whale population that migrates remains unclear. Pygmy blue whales are the most common in the Indian Ocean, however their movement and migration pattern are poorly known (Samaran et al. 2013, Leroy et al. 2018, McDonald et al. 2006). Sri Lankan, Madagascan and Australian blue whale calls are recorded all through the Indian Ocean, which confirms the importance of the Indian Ocean for the pygmy blue whales. Sri Lankan blue whale calls are detected mostly in the northern Indian Ocean. Anderson et al. (2012a) suggest that the Sri Lankan whales feed in the Arabian Sea, off the coasts of Somalia and the Arabian Peninsula, from May to October during the intense upwelling due to the southwest monsoon. They then migrate to the east coast of Sri Lanka, off the western Maldives, to catch the other upwelling associated with the northeast monsoon during December to March. Samaran et al. (2013) recorded the Madagascan blue whale calls at Crozet Island (in the sub-Antarctic Indian Ocean) from January to June, and north of Diego Garcia in Autumn. This suggests a migration pattern from sub-tropical to sub-Antarctic during summer. Australian whales move between Australia and Indonesia, satellite-linked tracked individuals, initially tagged off the southeast coast of Australia in summer, migrated north to Indonesian waters during the austral winter (Double et al. 2014). However, preliminary reports of occurrence of DG whale calls suggests these whales may have a different migration pattern, rather than moving north-south, as the other blue whales do, that instead they migrate from east-to- west.

Our study also found that the yearly average of chlorophyll-a concentration is almost indifferent at both sites (NW site:0.14 mg/m3; SE site: 0.13 mg/m3). However, the average concentration on the SE site varies between warm and hot seasons while on the NW site, the difference is not as significant (fig 8). It is likely that the Chagos-whales are feeding at the vicinity of SE site because their occurrence positively correlated to the chlorophyte-a concentration, which represents the density of blue whale’s main preys. From our generalised linear model, chlorophyll-a also has a significant impact on the whale presence, however, the coefficient is negative also the absolute value is much smaller comparing to the NW site (table 2). The Chagos-whales may not be feeding at or near the northern site of Diego Garcia. The average detections of the Chagos-whales are both high at NW and SE sites. We detected on average more than 5 calls per hour at both sites with seasonal difference.

In brief, the hypothesis tested and developed here is that many Chagos whales are migrating clockwise in the equatorial Indian Ocean. They stay near the southeast of Diego Garcia, potentially to feed in vicinity of the highly productive zones, around June to November, during the cooler time. They swim to northwest in November/December, staying till February or March, then maybe dispersing as north as Laccadive Sea off Sri Lanka or as south as Kimberley (ref).

This study demonstrates continuous multiyear acoustic surveillance, revealing habitat use shifting during environmental change. The migration pattern of the pygmy blue whales is poorly known in the Indian Ocean (ref). Understanding the migration pattern will help model the distribution of these whales and assist the prediction of whale presences into the future. It can also benefit conservation managers to develop strategies for wildlife protection (i.e., establishment of marine protected area). Studying the movement of the DG whales’ movement will give an insight into this newly discovered population of blue whales (Leroy et al., 2021).

Acknowledgement

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