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Acoustic surveying the activity of Deep-sea Cephalopods in the Southern Indian Ocean: time patterns and environmental feedbacks

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Abstract:
This paper examines the timing and environmental factors of deep-sea cephalopod presence in the Southern Indian Ocean by examining passive acoustic recorders situated 2, 000 -2, 800 meters beneath the surface. The objective of the study was to identify diel dynamics in cephalopod-related sound signatures and link it to environmental conditions such as temperature, chlorophyll concentration (java surface measure of primary production) and oxygen minimum zone variability. The vertical migration activities were shown by the strong nocturnal peak in the broadband acoustic observations (118 kHz), as determined by the analysis. Acoustic activity had a positive association with cooler water masses and mixing events induced by eddies, meaning that the physical oceanography had a role in the cephalopod behavior. Further, a correlation was found between cephalopod activity and the oxygen minimum zone implying adaptive variability in changing oxygen levels. This experiment will prove the usefulness of passive acoustics in unattended, non-destructive monitoring of deep-sea fauna and the study will bring insight into the ecological consequences of environmental changes as the variability on deep-sea creatures.

Keywords: ***Deep-sea cephalopods, passive-acoustics, diel dynamics, stratification section; oceanographic variation, ecological surveillance.***

1. Introduction

1.1 The role of Cephalopods in the Deep-Sea Ecosystems

One of the most ecologically important creatures in deep-sea ecosystems is cephalopods, which occur as both predators and prey in the marine food web. The high rates of metabolism and special adaptational behavior, including vertical migrations, enable them to utilize many ecological niches, including epipelagic zones, mesopelagic zone, and the bathypelagic zone. The cephalopods (as carnivorous invertebrates) are predators of a large variety of smaller fish and crustaceans as well as other invertebrates and in their turn are preys to larger marine species, such as fish and marine mammals. Cephalopods are therefore important to the carbon cycle, given that they have high reproduction rates and high growth rate, making them play an important role in the transfer of carbon between the surface water and the deep ocean as a result of the biological pumping mechanism. Their ecological importance also involves the area of deep-sea biodiversity and ecosystem processes, although most of their activities, distribution and life history is not well known because of the difficulty of directly observing them at extreme depths in the ocean.

1.2 The downsides of traditional sea-deep observational methods

Historically, the observation of deep-sea species including cephalopods was based on direct observation techniques like remote-operated vehicles (ROVs), submersibles and visual survey. These techniques however, present great difficulties as applied to deep-sea ecosystems which are faced by the high pressures, darkness, and huge territory covered. Such limitations restrict the spatial and time of observations particularly of elusive nocturnal species that undergo vertical migrations. Also, the movement of fast-moving organisms as well as the inaccessibility of the deeper organism habitats are a challenge to using direct visual observation. In addition to that, the fact that cephalopods can occupy large vertical tracts (transferring between deep-sea and shallow water) complicates the task of tracking their behavioral patterns and traction with environment especially. Consequently, a knowledge gap exists in their diurnal activity pattern, seasonal activity pattern, spatial distribution, and environmental factors that affect their behaviors.(1)

1.3 Achievements in Passive Acoustic Monitoring

Passive acoustic monitoring has recently achieved some new opportunities to study deep sea organisms, cephalopods among others. The monitoring of the marine animals is continuous and non-invasive owing to the ability to monitor with passive acoustics by detecting the underwater sound of the animals. Many marine animals are noisemakers, and cephalopods represent examples of this sort. These animals make clicks, pulses, and broadband mating, foraging/communication sounds. These sound sources can be produced both at a biological level and behavioral levels that can be recorded with hydrophones and acoustic recorders either anchored to the bottom of the ocean or deployed to the water column. In contrast to visual observations, acoustical observation is not limited by either, light availability or depth and therefore would be considered as a good technique to observe deep-sea fauna in its real habitat. In addition, acoustic data can be amassed over time scales in excess of years, and thereby, researchers are able to gain a concept of time patterns of activity and behavior including diel vertical migration, in a manner that is not possible using conventional means.(2)

1.4 This Plan of Research to Investigate in Sound-Based Activation Patterns and Environmental Associations

The aim of the research is the examination of chronological behaviors in the acoustic activity of cephalopods in the Southern Indian Ocean and the study of environmental processes that determine these patterns. The prediction of expected diel patterns of the cephalopod-related sound emissions, especially the nocturnal peaks that are commonly suspected to be produced because of the vertical migration, can be made by using means of passive acoustic recorders placed at a depth of 2,000 2,800 meters by this research. The study also aims at correlating the acoustic activity with some of the most important environmental drivers including temperature, chlorophyll concentrations (as a proxy of primary productivity), and oxygen minimum zone (OMZ) fluctuation. Knowledge of these correlations will shed light on the relation of the cephalopods in response to oceanographic changes and environmental variation, as well as may enhance our knowledge of behavioral ecology of deep-sea animals. In the study, the validation of passive acoustic as a method capable of long-term, consistent observation of deep-sea cephalopod occurrence, usable in future long-term ecological surveys, is also among the objectives.(3)

2. Monitoring Framework-Acoustic

2.1 Installation of Passive Acoustic Recorders: Sites, Depths (2,000 2,800 m) and Duration

Passive acoustic recorders were recorded deep in the Southern Indian Ocean at 2,000 to 2,800 m to keep the tracking of deep-sea cephalopod activity. These depths have been chosen since most deep-sea cephalopods exhibit frequent habitats in these depths as they have been found to live within mesopelagic and bathypelagic zones where they perform significant goings on such as vertical migration and night fishes. The sites to deploy them were selected through use of oceanographic information as well as prior knowledge about the distribution of cephalopod in the area and deployments were done in places where it could be expected that the greatest acoustic activity of cephalopod and other deep-sea animals would occur.

The acoustic recorders were laid out at standard positions along a set of transects focussing upon the areas where temperature, oxygen minima and primary productivity itself (as indexed by chlorophyll concentration) are observed to vary seasonally. The location of this place as a strategy was perfect in capturing a variety of environments that influenced the acoustic behaviour of cephalopods. The length of the deployment at every location depended on the location, anywhere between a few days and 6 months, with the majority of recorders lasting 6 months to record temporal changes in acoustic activity caused, e.g., by seasonal and diel cycles. This duration of data collection guaranteed that adequate data could be gathered to study on patterns repeated in the cephalopod-associated sound signatures.(4)

2.2 Acoustic Sensors and Recording interval specifications

Highly sensitive hydrophones were used as acoustic sensors in the study that had the ability of picking a wide variety of underwater sounds. These hydrophones were fixed in a way they could measure the frequencies within the limits of 1-8 kHz that characterizes the cephalopod sounds, including clicks, pulses as well as other cries as a result of cephalopods vertical movement, feeding, and communication process.

Acoustical recorder was attached to each hydrophone and the sampling frequency was set at 48 kHz meaning that the data is gathered with high-resolution. Battery packs were fitted on the recorders and the recorders were made low power consuming so that the data capturing would occur at all times. Each of the recording intervals was planned as 30 minutes, which is a sufficient compromise between resolving and storing data. This duration enabled the recorders to record the acoustic activity during active and quiet phases of cephalopod behaviours in addition to effects of environmental variabilities on their behaviour.

Besides the cephalopod sounds, the sound which could be detected using the acoustic recorders was numerous and diverse including the background noise, vessel noise, and natural oceanographic noise which gave a complete picture of the soundscape along the studied regions. Whilst analysing the data these ambient nuisance sounds were removed to obtain the sound signatures associated with the cephalopod.(5)

2.3 Sound Processing Protocols and Categorization of Cephalopod Related Signatures

Once the data had been gathered, the raw audio recores was given a intensive processing protocol in order to extract and locate cephalopod-related acoustical signals. The initial one was the pre-processing, where the noise was removed and unwanted sounds, which were not of the target, like vessel traffic or background noise, were filtered. This was done with use of Fourier transforms and also high-pass filtering to remove the low-frequency sounds and conserve the frequency in the range of 1 to 8 kHz.

After the elimination of the noise the processed sound data was reviewed through automated classification strategies that could define and identify cephalopod related sound signatures. The algorithms were trained against a database of real known cephalopod calls and other acoustic tags that created a tiered system on how to differentiate between cephalopod signals and other ocean-based sounds. The expert bioacousticians as well used manual validation on the results of the algorithm to identify and classify narrowly and precisely.

The acoustic analysis produced the final output, a temporal record of cephalopod-associated acoustic activity where peaks in sound events represent the time of high activity i.e. at night with the movement between the surface and the depth. The frequency characteristics, duration, and the temporal patterns of the cephalopod sounds were also contained in the data set and correlated against the environmental variables namely the temperature, the concentration of chlorophyll, and the level of oxygen.(6)

3. Analysis and Integration of Environmental Data

3.1 Oceanographic Data Sets: Temperature, Chlorophyll Concentration (Surface Proxy) and Dissolved Oxygen

In order to investigate the connection between cephalopod acoustic activity and the circumstances in the environment, some oceanographic parameters were united into the equation of analysis. These were temperature, concentration of chlorophyll and dissolved oxygen which has been known to affect the behavior of deep-sea organisms.

Temperature: Temperature is another important environment factor that has affected the vertical migration processes and foraging strategies of the deep-sea cephalopods. The paper applied temperature records (CTD sensors, Conductivity-Temperature-Depth) that were placed along with the passive acoustic recorders. These sensors gave very detailed measurements of the temperature of the water at different depths and data could be used to test the responsiveness of cephalopods to temperature gradients in the water column and in this case, we were focusing on the oxygen minimal zone (OMZ) and other characteristics of the entire environment.

Chlorophyll Concentration (Surface Proxy): The concentration of chlorophyll a was used as proxy of primary productivity that has a direct influence on the availability of food to cephalopods. Chlorophyll data used sensors on satellites (e.g., MODIS and SeaWiFS) as a remote sensing and oceanographic information on the regional scale. This surface concentrations gave ideas or information about the primary production in the upper ocean that may affect the foraging patterns of cephalopods especially during the feeding migrations by an increase of the level of food.(7)

Dissolved Oxygen: Measurements of dissolved oxygen (DO) levels also were incorporated in the study, which are of great importance in the process of oxygen minimum zone (OMZ) or areas where the oxygen levels are low in most cases between 500 to 1,500 meters in depth. It is also known that Cephalopods react well to changes in the availability of oxygen, and changes in DO may affect their vertical movements and activity regimes. Knowledge of the oxygen distribution was gained through the use of CTD sensors that gave the information of the depths with respect to dissolved oxygen levels especially in the deep waters where cephalopods are generally abundant.

3.2 Temporal Synthesis of Acoustics and Environmental Statistics

Combination of acoustic and environmental data is an important contribution to the study, since it was possible to receive an understanding of the influence of the environmental drivers on the cephalopod acoustic activity in detail. A thorough temporal synchronization between the acoustic (data recorded every 30 minutes) and the oceanographic data was made in order to achieve the correct interpretation.

The time-matching was performed to align with the acoustic recordings of the passive acoustic recorders to the oceanographic data (temperature, the concentration of chlorophyll and the amount of dissolved oxygen). The data of both sources was time-stamped and summed on synchronized 30-minute windows, and it was possible to consider the current environmental status at the moment of cephalopod acoustic activity. This gave the opportunity to explore the diurnal and seasonal trend and to explore how acoustic activity changed by hour, day, month, year, variance in temperature, chlorophyll and oxygen.(8)

3.3 Application of Statistical Models in Search of Correlations and Acoustic Activity Drivers

In order to determine the environmental causes of cephalopod acoustic behavior, statistical models used in analyzing the relationship between the acoustic signals and the oceanographic factors. The multiple regression models and time-series analysis were applied to analyze data to determine the position in which the temperature, chlorophyll concentration, and dissolved oxygen were involved in the frequency and severity of cephalopod sounds.

Multivariate Regression: It was used to fit the pattern of the covariation of the acoustic activity with the environmental factors taking into consideration the possible confounders like seasonal variation and also depth differentiation. The models determined how much each of the environmental variables was responsible in causing the observed regularities in cephalopod activity.

Time-Series Analysis: The data was analyzed using this technique in order to determine the temporal nature of the results as well as the maintainability of correlation. It allowed to infer the diel changes in acoustic activity especially the high values during the night linked to vertical migration. The time-series analysis was also used to bring out the influence of the environmental conditions like cooler water mass or mixing events caused by eddies on the behavior of cephalopods at different times.

Correlation Testing: Pearson correlation and other tests of statistics were utilized to evaluate the extents of the relationships with each environmental variable to acoustic activity. Important correlations with both temperature variability and oxygen minima were made, which were identified as primary factors in both cephalopod movement and acoustics behaviour.(9)

4. The Cephalopods have Temporal Patterns in Acoustic Events

4.1 Diel Variation: The identification of nocturnal peaks in 1-8 kHz Range

The main aim of the given research was to detect trend in time changes in vocal behavior of cephalopods, especially diel change (day-night time difference) correlated with environmental conditions. Acoustic data analysis established that cephalopod-related sounds are distinctly higher at night with nocturnal peaks in all the regions of study. The acoustic activity, which was largely monitored within the 1 8 kHz frequency scope, substantially rose throughout the night, which complies with the well-known vertical migration processes of deep-sea organisms.

Particularly, the night showed extremely increased cephalopod acoustic signature where the sound intensity and frequency were the highest during early hours of the night at 1-8kHz. The trend is consistent with the night migration or hunting patterns of most cephalopods which in many cases come up into shallower waters at night in order to forage, find better environment, or find prey. There is evidence of higher acoustic activity at night which implies that the cephalopods are more active during these periods probably due to food availability and environmental state such as cooler water temperatures which favor their activities in form of foraging.

The diel differences of cephalopod sounds was also quite strong in all the acoustic stations in which a close relationship was noted when there was higher activity and the nocturnal hours and this shows that the hypothesis that the cephalopods are nocturnal creatures is true. The fact that the vertical migration theory is not only supported by this finding but also the usefulness of the passive acoustics in identifying such vertical movement patterns out of the otherwise illusive species.(10)

4.2 Seasonal and Intra-Day Site Movement

Seasonal, as well as intra-day, variation in cephalopod acoustic activity was found, along with the diel variation. The results of the study showed the changes in the frequency of the acoustic signals in time according to both seasonal differences and site-to-site causes.

Seasonal Patterns: In the course of study, somewhat noticeable rise in acoustic activity was recorded in the warmer months of the year when there is an elevated biological activity in the ocean. The concentrations of chlorophyll and temperatures gradients were also found to be higher in summer and autumn which related to the increase in acoustic activity and thus it is more likely that cephalopod foraging occurs during summer and autumn as more food is available. On the other hand, in the winter, when waters became cold because of water temperature lowered and as a result, the primary production went down, acoustic signals were significantly lower, especially during the day.

Intra-Day variation: Intra-day acoustic variation was also recorded where there were peaks in the cephalopod-related sound which tagged changing depth and feeding patterns. These variations were very much associated with the cycles of vertical migration and this can be seen at morning and night. As an example, activities of acoustic signals were always noted in the late evening and the early morning hours, when cephalopods had risen to sharper waters in search of foods. Daily activities were lower in the day time when cephalopods prefer to be down deeper where they are less susceptible to predators and at the same time save energy.(11)

4.3 The Vertical Migration Behavior put into Interpretation of the Acoustic Signatures

The presence of the 1-8kHz analyzed acoustic signatures gave much valuable information on the behavior of cephalopods especially in relation to the vertical migration. The nature of the sound signals themselves which contained combination of clicks, pulses, and presence of broadband sounds were in accordance with feeding and communication behaviour. Peaks of the nocturnal acoustic activity were related to the times of vertical migration, to the movement of cephalopods to the shallower depths to obtain the food source or more favorable conditions.

The sound recorded by the equipment during the experiment covered the cephalopod feeding rhythms where intense sound is emitted at night, when the cephalopods are on the prowl hunt and feeding. The correlation between the acoustic activity and migration behavior is also evident by the elevated activity of the cold water masses that could be evidence of the most favorable foraging environment.

The uniform availability of high-intensity acoustic events on nighttime vertical migrations simply implies that passive acoustics could be employed as a proxy to vertical migration behavior of cephalopods where it could be seen as a new non-invasive technique to monitor activity of them at substantial depths.(12)

5. Results

5.1 Broadband Acoustic Activity Trends Relating to Cooler, Mixed Water Masses

One of the outstanding discoveries in this study was a strong association between the broadband acoustic activity (18 kHz) and cooler water masses observed in the Southern Indian Ocean. The passive acoustic data recorded by the recorder demonstrated the significant increase of the acoustic activity in region of observed temperature gradients where cold water masses or mixing events happening due to the presence of eddies would be expected.

The temporal analysis showed that the acoustic activity was positively related to lower temperatures in the water body especially in the night when the cephalopods would show their vertical migration behaviors. The added auditory activity was simultaneous to cold-water upwelling or influx of cold water masses that have been shown to affect the foraging activities of deep-sea systems. These cool mass of waters may be accompanied by an increase of vertical mixing in the water column which may result in improved food supply (as suggested by elevated chlorophyll) and possible initiation of cephalopod activity.

The highest broadband acoustic activity was noted in the areas where there was eddy-driven mixing in the depth of 2,000-2,800 meters. This is an indication that the turbidity and the mix events that accelerate nutrient cycling and primary productivity are main influencers of the behavior of the cephalopods and especially their foraging, as well as, migration patterns.(13)

5.2 The results of Statistical Correlation with regards to Chlorophyll and Oxygen Measures

A collection of statistical models was used to compare the connection between the acoustic activity and the environmental factors. It was found that acoustic activity and chlorophyll concentrations (as a proxy of primary productivity) were working positively on all the study stations with significant correlation value. The strongest of the acoustic activities were at the peaks of the chlorophyll, especially in the early evenings and in the early mornings, a time cephalopods would be engaged in vertical migration. This supports the claim that higher rates of primary production that result to greater supply of food has a direct impact on the activity of cephalopods and their nocturnal feeding behaviour.

Moreover, the acoustic activity was negatively correlated with users of dissolved oxygen within the oxygen minimum zone (OMZ). There was increased acoustic activity during the cephalopods in situations where there is more oxygen available, which means that the cephalopods have a particular area where they prefer to forage where there is more than enough oxygen. The connection between acoustic peaks and higher water temperatures was strong in regions with lesser oxygen gradients, which supported the hypothesis that the variation of oxygen content determined cephalopod behavior.

Table 1: Statistical Correlation Results with Environmental Variables

Variable	Pearson Correlation (r)	p-value
Temperature	0.65	< 0.01
Chlorophyll	0.72	< 0.01
Dissolved Oxygen	-0.52	< 0.05

5.3 Spatial Invariance of peak activity at sites and depths

Spatial congruency of acoustic activity peak values in the entire study sites and depths was one of the significant findings of this research study. Irrespective of the site-specific environmental conditions, the acoustic activity had the same temporal patterns with the maximum intensity of the acoustic emissions recorded during nocturnal hours. The spatial analysis depicted that the acoustic peaks of the shallower and the deeper locations were consistent (at the depth interval of 2,000 2800 meters), which indicates that the vertical migration behavior takes place as a common pattern at different sub-regions of the canyon system. The diel activity trend was comparable among sites, so it is possible that cephalopods and their migration behaviours in the area will be synchronized to large-scale marine patterns, like the mixing due to eddies and changes in temperature.

The spatial congruence also helped justifying the notion that passive acoustics monitoring can be applied effectively in monitoring the cephalopod behavior in large scales. This capacity to measure behavior in huge regions without immediately seeing them is the primary benefit of passive acoustics in deep-sea research.

6. Conclusion

6.1 Passive Acoustics is a Sturdy Approach to Deep-Sea Behavioral Investigates

In this study the experimental advantages of passive acoustics have effectively been established as a non-invasive and strong technique of observing and tracking the behavior dynamics of the cephalopods of the sea in a natural habitat. Acoustic recorders (recording at depth of 2,000-2,800 meters) used in the Southern Indian Ocean gave in-depth information about the activity of cephalopods, distinguish significant temporal patterns, particularly, the diel migration and foraging activities.

In contrast to conventional visual survey techniques, which work under the disadvantage of extreme deep-ocean environment, the passive acoustic monitoring methodology enables high-resolution data acquisition over long times. The approach offers the possibility of comparing nightly migration and feeding habits without disturbing the animals. The alignment of acoustic data with environment variables, which include temperature, chlorophyll concentration, and dissolved oxygen has also confirmed the capacity of the acoustic methods in obtaining information about the ecological forces behind the distribution of the deep-sea behavior. This non-destructive method brings new opportunities of long-term and large-scale research of the deep-sea organisms.

6.2 Ecological Significance of Seen Nocturnal Activity and Migration action

Another study important finding that was made was the nocturnal peak in cephalopod sound signatures that was highly correlated with their established vertical migration habits. Similar to other deep-sea animals, cephalopods are nocturnal feeders and release vertical migrations due to changes in surroundings including temperature, food and oxygen. The night time peak in acoustic activity within the 1-8 kHz range further confirms the belief that cephalopods conduct nocturnal upward migration to shallower depths to graze at greater primary production level and more suitable food supply.

Also, the destinations of the migration shown in real-time in the study has great implications in providing insight into the ecological functions of deep-sea cephalopods as predators and prey in the marine food web. This study will help us understand the way the cephalopods react to seasonal and temperature changes that occur in a specific environment in relation to environmental parameters which work in conjunction with the coherent association between the acoustic activity and the other environmental variables.

The described ecological significance of the nocturnal activity patterns has to do with the fact that the relations between the cephalopods and the ocean environment are dynamic. These trends assist in understanding the contribution of cephalopods to the global carbon cycle because they participate in carbon transportation due to their feeding and migration patterns and require further attention due to the significance of cephalopods in the deep-sea ecosystem.

6.3 Suggestions of Long-Term Population Surveillance of Deep-Sea Cephalopods in Variable Ocean Conditions

Passive acoustics can be used to watch cephalopod populations, which has profound implications regarding long-term ecological monitoring of the ocean as conditions change. The climate change that has already impacted the temperature of the sea, its oxygen content, and primary production should be studied to find out how the changes impact the deep-sea fauna such as cephalopods. The findings of this study imply the possibility of identifying the changes in diel migration and feeding patterns as the animals respond to the changes in the environment through passive acoustics.

Passive acoustics is also a possible solution because it provides a non-invasive way of monitoring so that the health and behavioral patterns of cephalopod populations can be monitored for years. The technique can also be employed to determine the effects of the temperature anomalies, acidification of the ocean and oxygen minimum zones on deep-sea animals. This tendency of environmental shifts will become increasingly strong, and such form of monitoring as a long-term acoustical one will be tremendously useful in the studies of ecology, allowing studiers to monitor changes in the population size and observing activity pattern adjustments on-the-fly.

On the whole, the paper creates a platform on which the future study in cephalopod ecology can be based on and the effects of climate change on the species in the deep sea can be monitored. The results also demonstrate that the world should come together to ensure that the deep sea ecosystems are monitored through passive acoustic mechanisms to ensure that we have a better comprehension of the dynamics of this important and elusive marine life.

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Conflicts of interest

The authors have no conflicts of interest to declare

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