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Observations of marine life in the Indian Ocean by hydroacoustic water column imaging

A peer-reviewed paper by WILHELM WEINREBE

Present day multibeam echo sounder systems have the capability to record, display, and log backscattered signals from the water column (WCI = water column imaging) in addition to the echoes from the seafloor. This extra information can deliver interesting insights into marine life in the upper water layers but it produces a huge amount of data which requires tremendous time and effort for processing and interpretation. To tackle this, a semi-automated approach has been developed which is based on the conversion of the data into images and applying available image processing techniques. That way the WCI data acquired during eight expeditions in the Indian Ocean had been processed and the relative biomass abundance along an extended North-South profile had been determined. In addition, the WCI data displayed interesting observations of the diurnal migration of zooplankton and revealed an amazing correlation to nocturnal illumination.

Indian Ocean | INDEX project | multibeam echo sounder | single beam echo sounder | WCI | biomass abundance | zooplankton migration
Indischer Ozean | INDEX-Projekt | Fächerecholot | Single-Beam-Echolot | WCI | Biomasseverteilung | Zooplankton-Wanderung

Moderne Fächerecholotsysteme sind in der Lage, neben der Kartierung des Meeresbodens auch Reflexionen aus der Wassersäule (WCI: water column imaging = »Wassersäulen-Abbildung«) aufzunehmen, anzuzeigen und zu speichern. Diese zusätzlichen Informationen können interessante Erkenntnisse über das Verhalten mariner Organismen liefern; allerdings erzeugen sie eine riesige Datenmenge, die nur mit großem Zeitaufwand bearbeitet und interpretiert werden kann. Dazu wurde ein halbautomatischer Prozess angewendet. Die Echolot-Dateien der Wassersäule wurden in Bilder konvertiert, die dann mit verfügbaren Bildverarbeitungsprogrammen bearbeitet und analysiert werden konnten. Wassersäulendaten, die auf acht Expeditionen im Indischen Ozean aufgezeichnet worden waren, wurden auf diese Weise erfolgreich ausgewertet und die relative Verteilung der Biomasse entlang eines ausgedehnten Nord-Süd-Profils durch den Indischen Ozean bestimmt. Darüber hinaus konnten aus den Daten die täglichen Wanderungen des Zooplanktons sichtbar gemacht sowie Variationen dieser Bewegungen mit nächtlicher Beleuchtungsstärke korreliert werden.

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1 Introduction

As a country with a highly developed economy Germany is heavily dependent on the unhampered availability of raw materials. Though currently not at all feasible, mining mineral resources from the seafloor might be possible in the future. Consequently, in order to secure access to mineral resources and to avoid future short supplies, Germany applied for an exploration license on polymetallic sulfides at the International Seabed Authority (ISA) in 2014. The license area covers a region of 10,000 km^2 in the Indian Ocean southeast of Mauritius close to the Rodriguez Triple Junction and includes parts of the Central as well as the Southeast Indian Ridge. This area had already been studied by German scientists in the 1980s on several cruises with RV *Sonne* and RV *Meteor* and a couple of hydrothermal fields had been found. Again in 2011 to 2014, in preparation for the license application at ISA, this region was target of four expeditions of the German Federal Institute for Geosciences and Natural Resources (BGR), the government agency in charge of the license application. The license, granted in 2015, implied the obligations to carry out a comprehensive 15 years programme including one research cruise per year into the area. This detailed exclusive resource-oriented exploration programme has to be complemented by extensive and detailed base line studies for the sustainable protection of the marine environment including investigations of biodiversity and habitats.

Including the preparatory expeditions, ten large research cruises had been carried out since 2011 in the framework of the INDEX (»INDian Ocean

EXploration«) project yielding a huge amount of data. On all cruises multibeam echo sounders had been used to map the seafloor. Present day multibeam systems are able to image the water column in addition to the bathymetry (WCI = water column imaging). This information can eventually be used for biomass assessment, mapping of water layers, internal waves, or for the detection of gas bubbles ascending from the seafloor (Hughes Clarke 2006; Colbo et al. 2014; Schneider von Deimling and Weinrebe 2014). Consequently, WCI data were acquired during those cruises continuously to supplement sampling work and to gain additional information of the upper 2,000 m of the ocean. Interesting insights into marine life in the Indian Ocean had been revealed from the detailed analysis of the WCI data and are presented here.

2 Data acquisition

Various research vessels had been used for the ten cruises since 2011: the Dutch RV *Pelagia* (2014, 2015, 2018), the former German RV *Sonne* (2011, 2013), the new German TFS *Sonne* (2017, 2019), the German RV *Maria S. Merian* (2016), the French N/O *Pourquois Pas?* (2016) as well as the commercial MV *Fugro Gauss* (2012). With the exception of the old RV *Sonne* all vessels are equipped with multibeam echo sounder systems capable of recording WCI data, hence on eight of the ten cruises water column data had been acquired. The systems were in operation continuously with only a few short interruptions. In total an amount of 1.3 TB of WCI data had been recorded covering a track length of nearly 40,000 kilometres and spanning a period of 5,500 hours. A track plot of the cruises during which WCI data had been acquired is shown in Fig. 1.

This giant data set yields a wealth of information about marine life in the Indian Ocean, however, there are some serious drawbacks which inhibit a systematic and quantified analysis of the data. Most important, the echo sounder systems differ from vessel to vessel: whereas TFS *Sonne*, RV *Maria S. Merian* and MV *Fugro Gauss* feature a 12-kHz Kongsberg EM122 (yet in varying configurations) and RV *Pelagia* a 30-kHz Kongsberg EM302, the N/O *Pourquois Pas?* operates a Reson 7150 dual frequency system using 12 kHz or 24 kHz. In addition to the multibeam EM122, the TFS *Sonne* provides a split-beam »fishery« echo sounder Simrad EK60 which was also used for the collection of WCI data. As the weak reflections of biomass or particles in the water column are strongly dependent on frequency, the water column data of the systems differ considerably, thus WCI data from different cruises lack comparability.

Beyond that, WCI data had not been recorded on dedicated surveys but just along the way while other investigations were carried out which predominantly determined speed and course of the vessel. As a result WCI data were not collected in a systematic pattern. Furthermore, other acoustic devices such as USBL navigation systems or ADCP instruments occasionally interfered with the echo sounder signals and deteriorated the echograms. Above all, deployment, operation or recovery of instruments often required a precise dynamic positioning of the vessel, consequently bow thruster and pump-jet were used excessively. Those operations generated significant noise and aeration by bubble wash down which seriously disrupted the acoustic signals of the echo sounder.

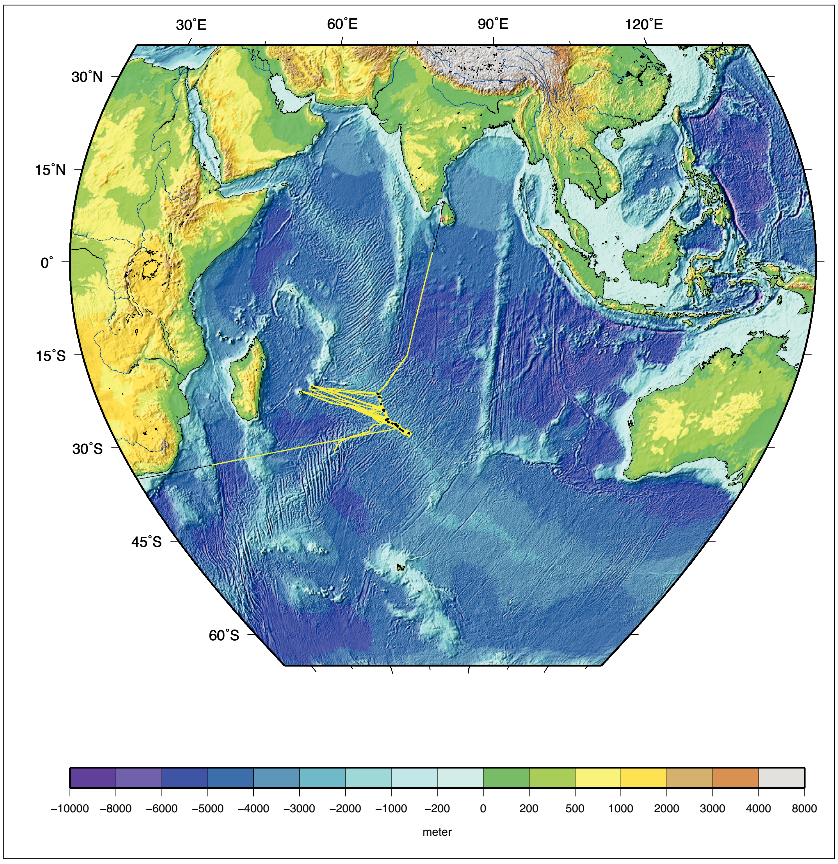

Fig. 1: Map of the Indian Ocean with ship tracks of INDEX cruises during which hydroacoustic water column data had been acquired, processed and analysed. Small black squares mark the area of the German exploration license. Topographic heights and water depths after GEBCO (2008)

Nevertheless, in spite of those drawbacks, the tremendous amount of WCI data revealed many indications of marine life in the Indian Ocean. Though the data was not suitable for a certified quantitative study of the biomass, it gave important insights into the distribution of biomass and documented an intriguing behaviour of the zooplankton in the survey area.

3 Data processing

WCI data acquisition had been accomplished through the controlling software of the echo sounder. Raw data had been stored in vendor-specific format in files generally holding records of 30 to 60 minutes each, bathymetry and ancillary values such as navigation and motion had been directed into accompanying files. The first processing steps include the merging of the raw sonar data with navigation and motion information and conversion into a generic water column imaging format. For this purpose the FM-Midwater tool of the QPS-Fledermaus software suite had been used. Subsequent processing steps in FM-Midwater are generally performed in an interactive mode. As this is not really feasible for a collection of more than 10,000 files, a semi-automated approach of analysing the WCI data had been chosen. As basic prerequisite all files must have been recorded with constant gain and acquisition parameter. At first, all sonar files had been loaded into FM-Midwater and displayed with absolutely identical gain, view, colour, and histogram settings. Thereafter the displays had been converted into images in TIFF-format and saved. Such a conversion of the WCI data into an image implies a very effective data reduction procedure. Moreover, as image processing algorithms are readily available, it enables an automated analysis of an entire collection of images. In this study we used the software ImageJ (Schneider et al. 2012), a standard scientific image analysis software widely used in bioinformatics to analyse microscope images.

WCI multibeam data can be displayed in FM-Midwater in different views. For our biomass studies predominantly the »beam« or the »stacked« view had been used, which both resemble the typical echogram display of a single-beam echo sounder. The »beam« view presents the data of one particular beam of the entire file as vertical curtain, here predominantly the »central beam« had been used. In the »stack« view all beam »curtains« of a file are stacked into a single image which provides a quick overview about the overall contents of the file.

4 Estimation of relative biomass abundance

Living organisms in the water, particularly if they have an air-filled swim bladder, mirror the acoustic waves of an echo sounder and generate reflections and scattering in the echograms. It is assumed that this is a linear relationship: more biomass will lead to more echoes and scattering and thus to darker water column images. Consequently, the »darkness« or optical density of an echogram can be used to estimate the biomass abundance, at least on a relative scale for a set of water column data.

Using the software ImageJ (Schneider et al. 2012), the WCI files in TIFF-format had been converted linearly from colour (R-G-B) into greyscale presentation and the mean optical density of each file had been calculated. Evidently, that file respectively echogram showing the highest density represents the maximum number of reflections. So this value was defined as 100 % relative biomass (Fig. 2, left). Correspondingly, the lowest density represents the least number of reflections and hence was classified as 0 % (Fig. 2, right). Subsequently all echograms had been rated according to this scale resulting in a time series of relative biomass abundance. This data set can be correlated e.g. to ship's position, speed, water temperature or other parameters.

This approach assumes that there are no non-biological processes contributing to the density of the echogram. Yet, particularly noise and aeration in the water significantly account for the scattering of acoustic energy resulting in corrupted echograms which could severely distort the results. In order to avoid erroneous estimations all images dominated by noise had been excluded from further analysis. Generally, this was accomplished by visual inspection. Only on TFS *Sonne* where time-stamped engine parameter were available from a database, echograms were filtered out automatically when they had been recorded while propeller revolution values exceeded a threshold.

In addition to the multibeam EM122, TFS *Sonne* features a split-beam EK60 operating at four different frequencies providing the opportunity to compare systems and data sets. Higher frequency signals yield more detail at the expense of a reduced range, which is okay for biomass studies. So for the cruises with TFS *Sonne* predominantly the EK60 data had been used. Beyond that, additional information could be achieved from data recorded with different frequencies simultaneously. In fishery research, techniques have been developed to identify species of schooling fish by their multi-frequency signature (Korneliussen et al. 2009; 2016). Yet these methods require calibrated echo sounder and dedicated surveys, however, we will try to adapt this in the future.

Certainly, the approach of calculating the relative biomass abundance is a rough estimation. Several factors which might influence the image density are not taken into account. Furthermore, the linearity of the relation between scattering and biomass abundance is not proven. Beyond

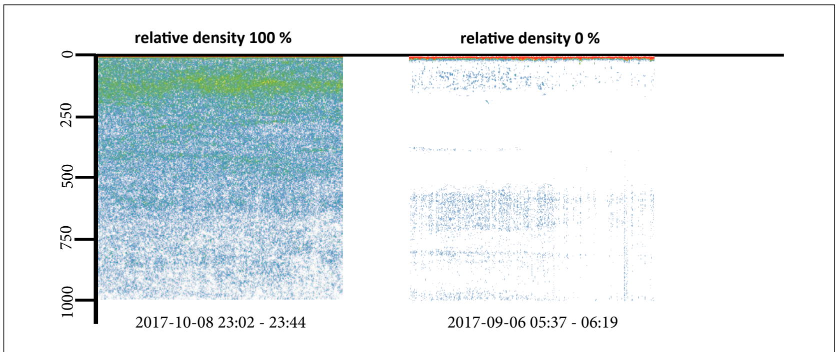

Fig. 2: Left: EK60 18-kHz echogram recorded on October 8, 2017, 23:02 – 23:44 UTC, showing the highest colour density of all recorded 18-kHz files of INDEX2017. This value is defined as 100 % relative biomass abundance for 18-kHz files of the INDEX2017 survey.
Right: EK60 18-kHz echogram recorded on September 6, 2017, 05:37 – 06:19 UTC, showing the lowest density of all recorded 18-kHz files. Accordingly, this value is defined as 0 % relative biomass abundance

that, biomass are living organisms which are not at all sessile but floating around. So interpretations of the data on a scale too fine will just represent momentary and random results. Admittedly, the approach might be a crude simplification, however, it is the most comprehensive estimation so far.

5 Biomass estimation along a North-South profile in the Indian Ocean

Whereas nearly all cruises of the INDEX project started or ended close to the survey area either in Port Louis, Mauritius, or Le Port, La Reunion, the INDEX2017 cruise started in Colombo, Sri Lanka, and ended in Cape Town, South Africa, thus providing water column data along an extended North-South profile through the entire Indian Ocean. The water column images of the EM122 multibeam echo sounder (12 kHz) as well as the echograms of the EK60 (18 kHz and 38 kHz) had been processed and the relative biomass abundance determined. All frequency sets exhibit an analogous trend. In Fig. 3, the results of the 38-kHz EK60 data are displayed along the timeline of the cruise. The values are represented by dots on a scale of 0 % to 100 %. As the data points show a significant scattering, the point cloud has been filtered by a boxcar filter with a length of six hours, the output is shown as red line in Fig. 3.

During the first days of recording quite high values of around 60 % were determined which indicate a pervasive number of reflections and hence a high amount of biomass in the water. From August 29 on, while approaching the license area, the values dropped remarkably to 20 % to 30 % which prevailed as long as the vessel stayed in the area. From October 1 on, during the transit to South Africa, the relative biomass abundance increased steadily to values of 60 % and more. This variation of marine life is also nicely visualised in the water column images itself. Fig. 4 (top) presents a selection of echograms (30 to 60 minutes each) recorded at daylight on consecutive days during the transit into the license area. A similar gallery of echograms recorded while leaving the license area until reaching the EEZ of South Africa is displayed in the bottom of Fig. 4. The variation of

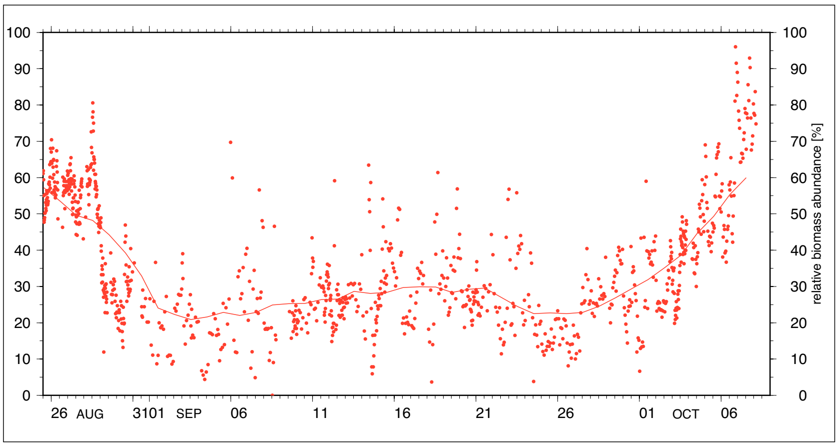

Fig. 3: Percentage of biomass in 38-kHz EK60-echograms for the time period August 25 to October 8, 2017 (INDEX2017). The red line displays the results of filtering the point cloud with a boxcar filter

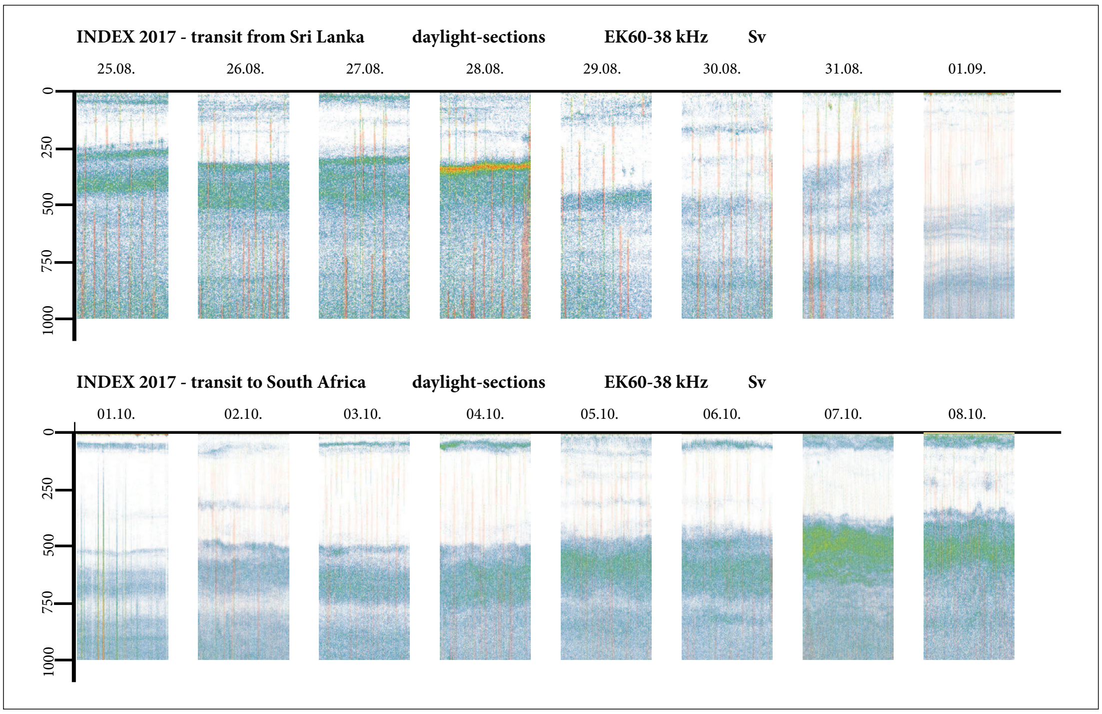

Fig. 4: Top: Gallery of EK60 38-kHz echograms recorded from August 25 to September 1, 2017 during the transit from Colombo into the license area. Each panel displays a section of about one hour recorded during daylight (2 to 4 hours after sunrise).
Bottom: Gallery of EK60 38-kHz echograms recorded from October 1 to October 8, 2017 during the transit from the license area to Cape Town. Each panel displays a section of about one hour recorded during daylight (2 to 4 hours after sunrise)

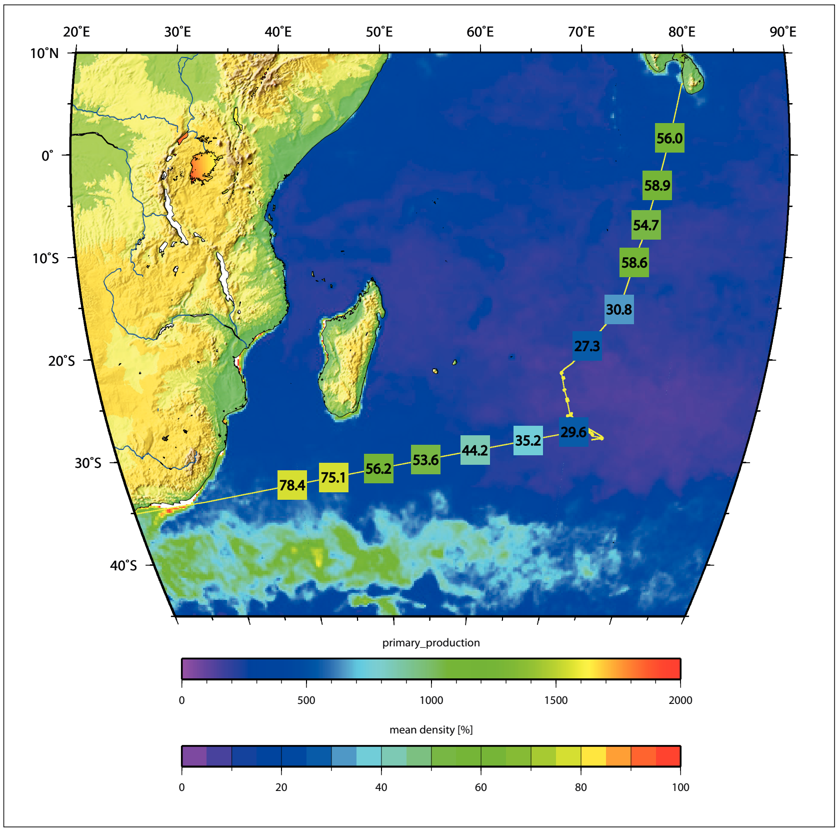

Fig. 5: Relative abundance of biomass (percent) determined from EK60 38-kHz echograms recorded during the transits from Colombo to the license area and from the license area to Cape Town. The values are averaged per day and plotted on top of the primary production for November, 2017 derived from satellite data (https://science.oregonstate.edu/ocean.productivity)

stratification and image densities is clearly visible. This is attributed solely to variation of the amount of biomass as changes of the physical parameter of the water column do not exhibit an impedance contrast large enough to generate reflections in the echogram.

Another aspect of the data is presented in Fig. 5. The relative biomass determined for both transits are averaged per day and plotted as overlay on the primary production for November, 2017 as derived from satellite data (https://science.oregonstate.edu/ocean.productivity). The results confirm the trend observed in Fig. 3 and Fig. 4: low relative biomass abundances in the middle of the ocean and significantly increasing marine life towards the continents. While the values on the way to South Africa are steadily increasing, the biomass abundance on the transit from Sri Lanka remain high until passing the latitude of about 15° south when it drops significantly. This correlates nicely with the primary production.

Interestingly, similar results had been reported from the Malaspina 2010 cruise (Irigoien et al. 2014) along an extended East-West profile from Australia to South Africa. Again here, low biomass abundance in the middle of the ocean was complemented by higher values towards the continents.

6 Diurnal migration of zooplankton

In addition to the ocean-wide biomass estimation, a closer look on the WCI data on a smaller scale might uncover interesting insights into marine life. In order to detect diurnal behavioural patterns all water column images had been compiled into echogram sections covering a time span of 13 hours each (day or night). An intriguing phenomenon is documented in Fig. 6 which displays a night section recorded on November 2, 2018. At about 18:00 local time (13:00 UTC) at sunset a synchronised upward movement of biomass was observed in the WCI data. The migration started at several hundred metres depth and continued up to the surface, building an about 150 m thick layer. The layer was very stable and had been observed the whole night until about 04:30 local time (23:30 UTC), the moment of sunrise in the survey area. Then a downward migration was observed and the layer diminished.

This widely observed phenomenon describes the synchronised migration of zooplankton and is known as diurnal or diel vertical migration (Record et al. 2006; Cisewski et al. 2010; Brierley 2014; Bianchi et al. 2015). It may be the largest natural daily movement of biomass on the planet (Brierley 2014). The zooplankton finds nutrition in the near-surface zone where photosynthesis happens. But just here their visually hunting predators lurk looking for prey. Thus, to avoid being eaten the zooplankton waits until darkness before ascending to

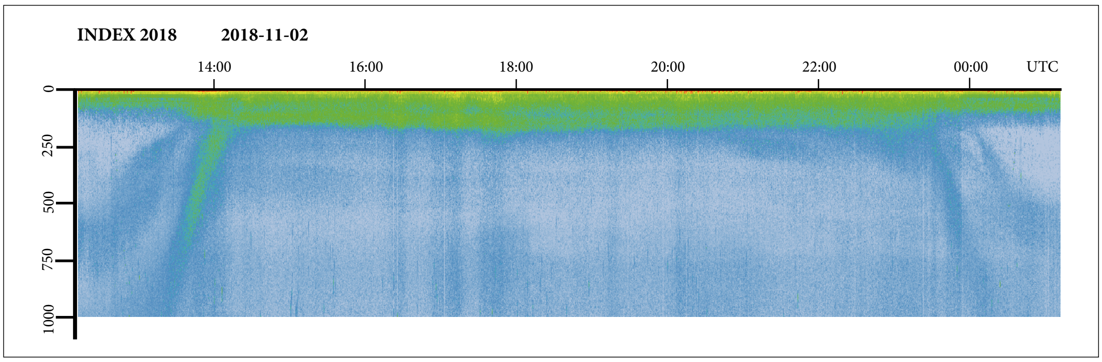

Fig. 6: EM302 stack echogram recorded on November 2, 2018, 12:00 to 00:42 UTC from dusk to dawn. With decreasing daylight zooplankton is migrating upwards agglomerating to a layer close to the surface. With sunrise at about 00:00 UTC the zooplankton is migrating back downwards

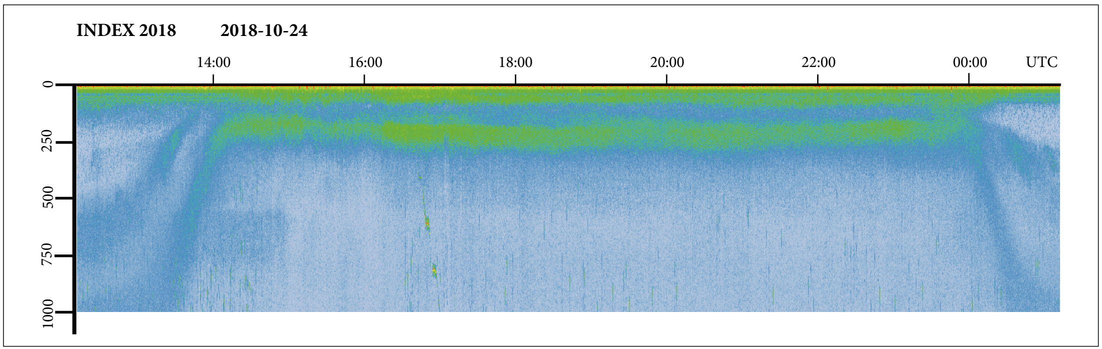

Fig. 7: EM302 stack echogram recorded on October 24, 2018, 12:00 to 00:42 UTC from dusk to dawn during a full-moon night. With decreasing daylight zooplankton is migrating upwards agglomerating to a thin layer close to the surface and a second layer at greater depths. With sunrise at about 00:30 UTC the zooplankton is migrating back downwards

the nutrient-rich surface layers to feed and again descends back to greater depths before dawn.

By checking all water column data it turned out that the nocturnal behaviour of zooplankton was not as uniform as expected. The general pattern of migration had been detected every night, however, strong variations of the near-surface accumulations had been observed. In Fig. 7 a night section of echograms recorded on October 24, 2018 is displayed. The vertical migration is obvious, however, a significant part of the biomass avoided the surface forming a detached second layer at about 200 m depth. In Fig. 8 water column images from the INDEX2018 cruise, always acquired at the same time around midnight local time, are compiled into a gallery. The variations are clearly visible: in certain nights the zooplankton accumulated right at the surface whereas in other nights two distinct layers were observed.

Interestingly, if the illumination by moonlight is taken into account, it turns out that October 24, 2018 was a full-moon day. The moon actually was visible around midnight (local time) from October 16 to 28 in the license area provided a cloudless sky. From October 29, 2018 until November 5, 2018 (end of the cruise) the moon did not illuminate the license area. Though the cloudiness of the sky is not taken into account, there is a strong indication of a correlation between moonlight and nocturnal zooplankton accumulations. Between October 16 and 28 the zooplankton was forming two layers whereas between October 29 and November 5 only one single layer was recorded. These observations document that the diel vertical migration is obviously controlled by illumination.

7 Summary and conclusions

During the INDEX cruises large volumes of the water of the license area as well as along the transits had been sounded by echo sounder and a huge

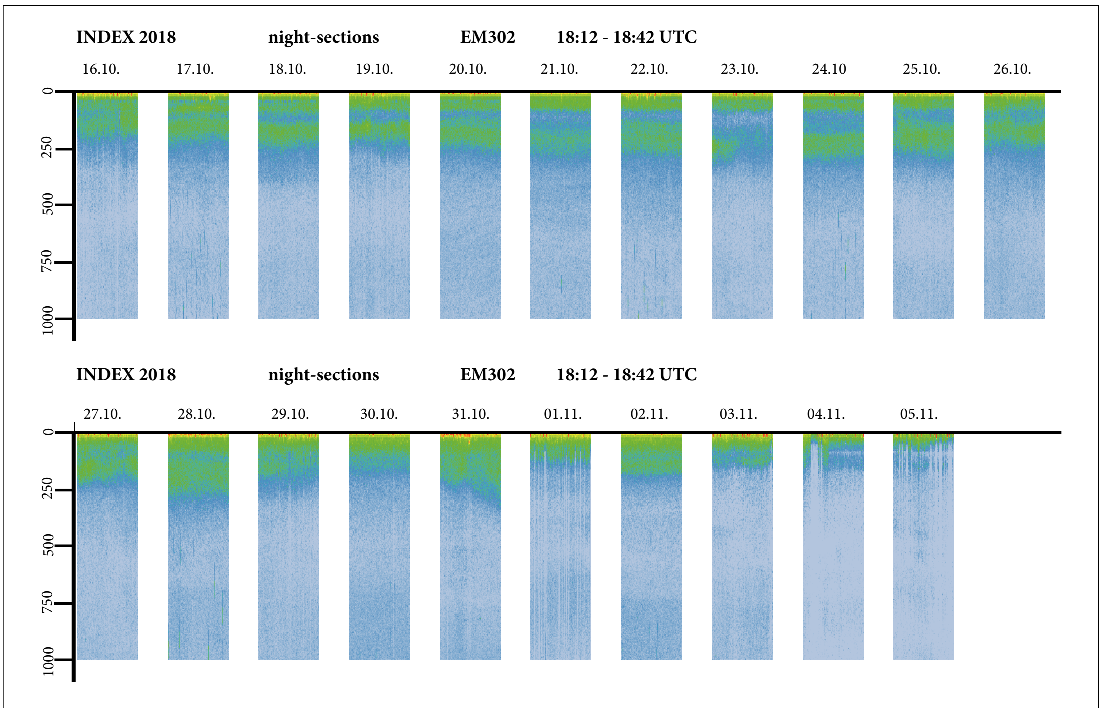

Fig. 8: Compilation of EM302 stack echograms, each recorded always from 18:12 to 18:42 UTC (about local midnight) on consecutive nights from October 16 to November 5, 2018 during the INDEX2018 cruise

amount of hydroacoustic water column data had been recorded. In total, in 5,500 hours more than 10,000 files of water column data covering nearly 40,000 km profile had been acquired.

Water column data can successfully be used for an assessment of biomass. Actually, fishery research and the sustainable management of the seas depend to great extent on hydroacoustic data. Yet, those operations require calibrated echo sounders and dedicated surveys. The INDEX water column surveys did not meet these requirements at all. On INDEX cruises, water column data was recorded along the way by the available, non-calibrated echo sounders. Speed, course and track of the vessel were determined by the station work. Yet, it had been shown successfully that reasonable estimations of relative biomass abundance can be achieved from the hydro-acoustic data.

A semi-automated approach for processing and analysing the WCI data had been developed. Following a pre-processing, WCI files were converted into images. This step implies a very effective data reduction. In addition, it opens up possibilities to apply a multitude of image processing software which are readily available. So based on the evaluation of image densities a determination of relative biomass abundances had been achieved. It provides reasonable values, however, it has to be noted that it's an estimation. Several effects which certainly influence the image density are not taken into account. Yet, the results present the most comprehensive estimation achieved so far. So the analysis of the INDEX2017 transits along an ocean-wide profile revealed significant higher biomass abundance closer to continents than in the licence area in the middle of the Indian Ocean.

In addition to the biomass estimations, water column data enable interesting insights into marine life. The intriguing diurnal migration of zooplankton had been documented nicely in the echograms. Moreover, the data indicate that the diurnal behaviour seems to be more variable than expected. There are indications that moonlight illumination exert an influence on the nocturnal movements and aggregations of zooplankton.

To conclude, in spite of the limitations inherent to water column imaging investigations, a couple of valuable results have been obtained which justify the effort spent to acquire, process and analyse the data. Furthermore, future research cruises are encouraged to record WCI data routinely as many interesting insights into marine life can be gained from the data along the way without much additional effort. //

Acknowledgements

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