Some observations of biophysical interaction in the ocean using high frequency acoustics

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Abstract

High frequency echo sounders can provide quantitative measurements on the spatial variations of zooplankton and micronekton communities. In this paper two examples from contrasting oceanic regimes are discussed. The first is the interaction of zooplankton with their physical environment in the polar waters of the Bellingshausen Sea. The second example shows how information on the abundance of myctophid fish can be obtained using multifrequency measurements and a simple model of backscatter from their swim bladders.

1. Introduction

Biological distributions in the sea are patchy on a variety of time and space scales. Biological communities are composed of a mix of different animals with different shapes, sizes, characteristics and compositions. To understand the way this complex ecosystem works, we must be able to identify the different animals at the appropriate scales of variability. This can be done using sampling systems collecting multidisciplinary data concurrently and at the same time and space scales [1]. High frequency acoustics offers a way of obtaining a variety of quantitative and qualitative biological data remotely and non-intrusively. These data can be collected concurrently with other environmental parameters such as temperature, salinity, density, and dissolved oxygen and chlorophyll concentration. The data can be displayed in real time and therefore used to target sampling using towed nets. Finally the data can be collected at a range of time and space scales from seconds and metres to weeks and megametres.

There is an increasing number of papers describing the use of acoustics coupled with environmental data to study biological distributions and behaviour in relation to their physical environment. Examples include the biophysical environment at oceanic fronts and eddies [1-6]; upwelling [5]; oxygen [7]; light levels [8]; thermoclines, haloclines and pycnoclines [8]; turbulence and internal waves [9]; seamounts and topography [5, 10, 11]; island wakes [12] and predator-prey relationships [13]. This paper begins with a brief description of the acoustic instruments used in the observations. This is followed by two contrasting applications. The first describes how a single frequency echo sounder was used to observe the vertical and horizontal structure of animal distributions in the Bellingshausen Sea in the South East Pacific Ocean. The relationship of this structure to variations in the dissolved oxygen concentration and the temperature structure are discussed. The second example shows how an avoidance reaction by myctophids in the Gulf of Oman gave information on swim bladder size, target strength and numerical abundance.

2. Instrumentation

A number of recent papers have reviewed the instrumentation used for studies of marine life and biophysical interactions [2, 14, 15]. Investigators have used purpose-built sonars ranging from simple single frequency devices to complex multifrequency units, as well as using commercially available systems developed for other purposes (e.g. fisheries, current measurement). Digital recording and adequate calibration are two features of modern echo sounders that are central to the analysis and proper interpretation of the biophysical interactions discussed in this paper.

In the first example, digital recording was essential so that the data could be contoured and spectral analysis could be performed to obtain quantitative estimates of the spatial scales of variability. The absolute accuracy of calibration was a lesser issue. For this application the shipboard acoustic Doppler current profiler (ADCP) operating at the single frequency of 153 kHz was an acceptable tool.

The second example, which compares the difference in backscatter at two frequencies, requires good absolute calibration accuracy. For this application, an ADCP proves inadequate; not only is it a single frequency sonar, but it lacks the vertical resolution, the calibration accuracy and stability needed for the measurements. Instead, an EK500 scientific echo sounder operating at 38, 120 and 200 kHz was used, although only the 38 and 120 kHz measurements are shown. To ensure accuracy, backscatter at these two frequencies was calibrated at sea, in the working area, using copper spheres of known target strength. The calibration error was estimated to be less than 0.5 dB.

This paper does not discuss the analysis of net hauls from either area in detail. However, contemporaneous net hauls were made and remain essential to set the acoustic record into a biological context. However such 'ground truthing' comes with its own difficulties, as illustrated in the second example. The acoustic and net sampling methods each have their own domain; achieving overlapping domains, where sensible comparisons can be made, remains a challenging issue.

3. Biophysical interaction visualised using acoustics

3.1 Spatial patterns in relation to dissolved oxygen concentration in the Bellingshausen Sea

In temperate waters the acoustic backscatter record is dominated most often by diel migration. This signal can mask biophysical relationships. Summer in the polar regions is a time of constant daylight and there are areas where the diel migration is suppressed. This simplifies, to some extent, studies of biophysical interaction near the retreating ice edge, a region of significant phytoplankton growth and carbon dioxide draw-down, hence an important part of the global carbon cycle. The *Sterna* cruise on *RRS Discovery* to the Bellingshausen Sea in November-December 1992 was designed to examine biogeochemical fluxes in the seasonal ice zone. As part of this study, acoustic observations of zooplankton and micronekton were made using the shipboard ADCP. The distribution of backscatter in relation to the physical structure of the South Polar Front and to the radiance has already been described [8]. In this paper the spatial scales of variations in backscatter within three depth bands are shown to correspond with spatial variations in temperature, oxygen and chlorophyll.

The four panels on the left of Figure 1 show (a) calibrated mean volume backscatter strength (S_v), (b) potential temperature, (c) dissolved oxygen and (d) chlorophyll concentration, a measure of the phytoplankton biomass. The edge of the pack ice was at about 69° S, to the south (right) of this section. The intense chlorophyll bloom in the upper 70 m extended some 100 km from north to south, with sharp shoulders down to 1 mg m^{-3}. Photosynthesis within this patch of phytoplankton resulted in higher oxygen concentration than was found to the north or to the south of the patch. The acoustic backscatter also showed higher levels within the chlorophyll patch. However there was no indication of a corresponding region of different temperature (or density – not shown) constraining its north-south extent.

These relationships in the upper 70 m can also be seen in the spatial spectra in Figure 1 of (e) backscatter, (f) potential temperature and (g) oxygen. That is, the spectral peak in the surface to 70 m depth range in backscatter occurs at a frequency of about 0.01 cycles per km (cpk), a wavelength of 100 km, consistent with the north-south extent of the chlorophyll patch. The same frequency peak is seen in the oxygen spectra, but not in the potential temperature.

Moving to the next layer, between the seasonal halocline at 70 m and the pycnocline at ~175 m, the spectra of backscatter show little variation near 0.01 cpk. Rather, two broad peaks emerge, near 0.025 cpk (40 km) and 0.05 cpk (20 km) extending from ~ 75 m down to ~125 m. Curiously, the potential temperature also shows significant variations at these two frequencies, but between depths of ~ 120 to ~ 175 m, some 45-50 m deeper than the backscatter variations. The oxygen concentration variations occur at the same depths as those of temperature, not those of the backscatter.

The lowest layer observed extended from the pycnocline at ~ 175 m to at least 300 m. Within this layer, the backscatter was characterised by its uniformity as much as by its level. At the northern and southern extremes of the section *Sv* was lower, with the spectra showing that the upper part of this layer, at least, had a similar spatial extent to the near-surface backscatter, hence the near-surface chlorophyll bloom. It is tempting to relate the spatial extent of the deep layer to a source of food from the surface – descending detritus, faecal pellets and dead phytoplankton. Interestingly, between 200 and 225 m depth, there was evidence of some variability on the 20 and 40 km scales in backscatter and some weak variability in temperature. Variations in oxygen concentration were mostly at the longest spatial scale, probably reflecting respiration by the animals locally consuming oxygen, a weak signature in the oxygen at 40 km was also present.

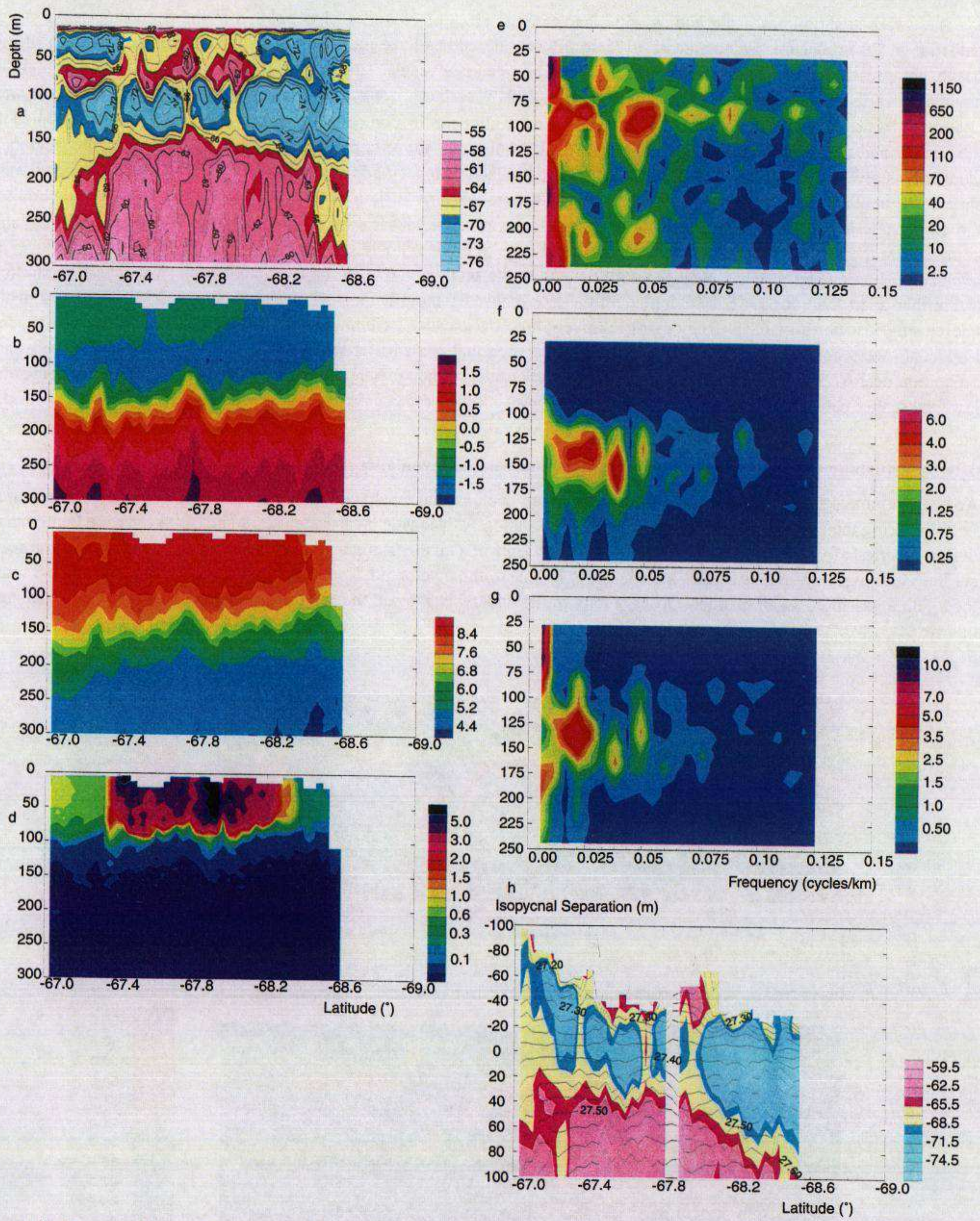

Figure 1. Contoured sections of measured variables (left) and spectra (right) obtained on a North-South section in the Bellingshausen Sea in December 1992 immediately north of the ice edge and straddling the South Polar Front. The panels are: (a) calibrated S_v from a 153 kHz ADCP in dB m^{-1}; (b) potential temperature in •C; (c) oxygen concentration in ml l^{-1}; (d) chlorophyll concentration in mg m^{-3}; spatial spectra of (e) acoustic backscatter; (f) potential temperature and (g) oxygen; (h) colour contoured backscatter (as in a) regridded in the vertical as depth from the σ=27.39 kg m^{-3} isopycnal, with the isopycnals superimposed.

These results show mesoscale eddies with characteristic sizes of 20 and 40 km trapped in the pycnostat between the halocline at 70 m and the pycnocline at ~175 m. Mesoscale eddies have the effect of distorting the stratification of the ocean, compressing and expanding the depth intervals between isopycnals. This can be used to visualise the eddies and the associated variations in acoustic backscatter. First, a density surface (isopycnal) within the centre of the pycnostat was chosen, in this case $\sigma = 27.39$ kg m^{-3} (where σ is the density after subtraction of 1000 kg m^{-3}). Then a re-grid was applied to the density and the acoustic backscatter in the vertical, as distance above and below this isopycnal. That is, the reference isopycnal is always at zero depth, with the depth axis for each time step adjusted to keep it at zero, the same depth axis shift being applied to each backscatter time interval. If there were no variations in stratification due to mesoscale eddies, the isopycnals above and below our reference would be parallel to each other and to our reference. Stretching and compressing the vertical separation between isopycnals due to eddies should be more visible in this frame of reference, as is indeed the case (Figure 1(h)). Near the northern end of the section, at 67.0°S the isopycnals each side of zero separation are further apart than at 67.4°S. Moving south the isopycnals separate, before compressing near 67.7°S, separating again and closing just north of 68°S. Regions of relatively high backscatter ('chimneys'), shown in yellow, occurred when the isopycnals were compressed. There is even some evidence that the smaller-scale horizontal variations in the isopycnal separation near 67.5°S were reflected in a change in backscatter: although here the 'chimney' did not form, nevertheless the low backscatter patch was pinched from above and below.

3.2 Perturbing the environment: Observations following an avoidance reaction

Acoustic remote sensing of zooplankton and nekton can demonstrate a behavioural response to the presence of a research vessel. During the night of 18-19 February 1997, observations of acoustic backscatter at 38 and 120 kHz were being made during a series of closely spaced CTD stations in the Gulf of Oman. At night the backscatter was dominated by a near-surface layer, which previous studies had shown to be due to the myctophid *Benthosema pterotum* [16], a fish some 32 mm long with a gas-filled swim bladder. Observations whilst underway showed the layer to be centred at 42 m with a thickness of 7 m.

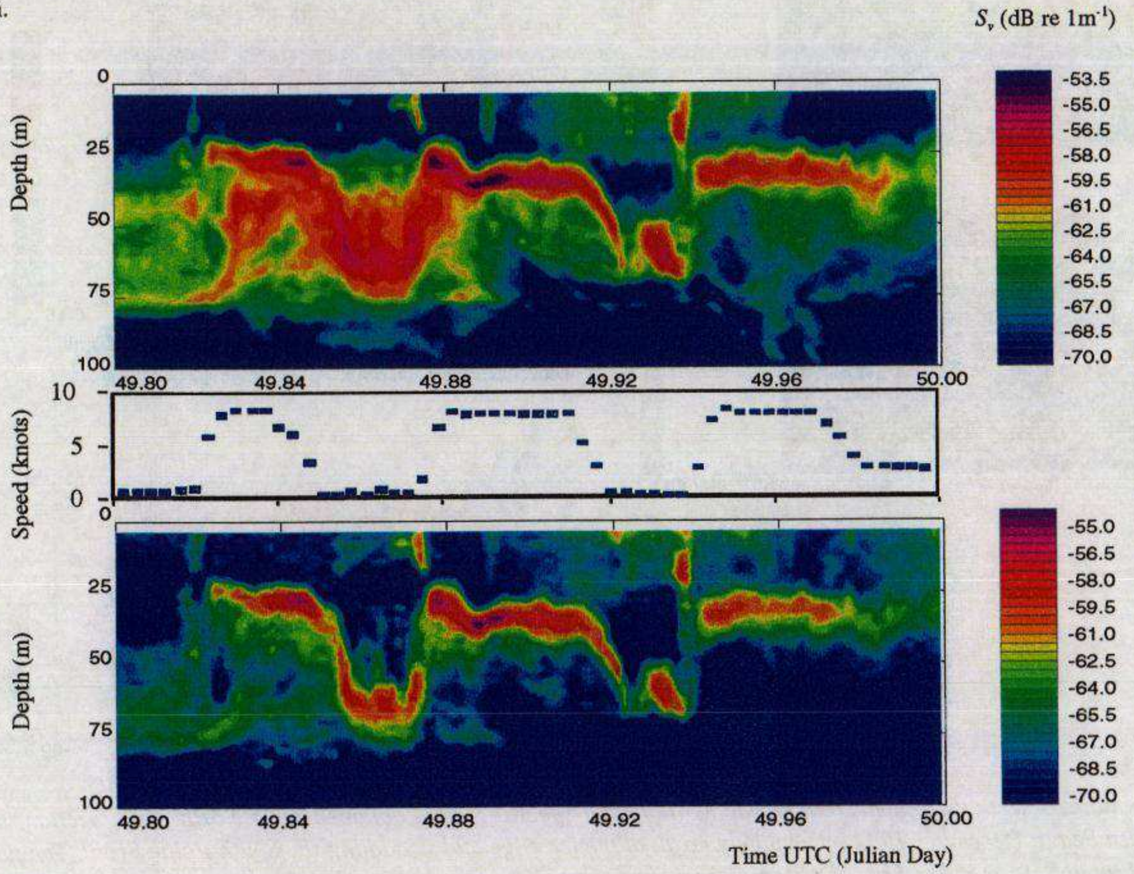

Figure 2. An avoidance reaction to ships lights observed during the night of 18-19 February 1997 in the Gulf of Oman using a well-calibrated EK500 echo sounder. The upper panel is the 38 kHz echogram, the lower panel the 120 kHz echogram, with time as UTC Julian Day (local solar time being UTC+3 hours) and depth in metres on the y axes with the ship's speed in knots in the centre panel.

However, as the ship slowed down to come on to station the layer descended (Figure 2). On station, the layer centre depth was about 79 m. On leaving the CTD station the layer appeared abruptly at the shallower depth; the layer was not rising, rather the ship had begun to move over undisturbed fish. This suggests that the pattern of behaviour was caused by the lights of the ship inducing an avoidance reaction in the fish. However, this reaction did allow a number of observations and estimates to be made with greater certainty than from observations of the population at a single depth.

First, the descent rate could be estimated. From Figure 2 it can be seen that the fish did not begin to descend until the ship speed was close to zero. Therefore, the time taken for the fish to descend, 13 minutes to descend 37 m or 4.7 cms^{-1}, was independent of the time taken for the ship to slow down.

Second, the difference in backscatter amplitude at 38 and 120 kHz at the two depths can be used to estimate the swim bladder size. Andreeva [17] derived expressions for the resonant frequency f_o and the Target Strength (TS) for fish with swim bladders:

$$f_0 = \{(3\gamma P + 4\mu)/\rho\}^{1/2}/2\pi a \tag{1}$$

$$TS = 10Log\{a^2/(((f_0/f)^2 - 1)^2 + (1/Q^2))\} \tag{2}$$

where Q is taken as 5; γ, the ratio of specific heats at 1.4; μ, the real part of the shear modulus of fish flesh, taken as 10^5 Pa; and ρ, the density of seawater, taken as 1025 kgm^{-3}; P is the pressure in Pa. An estimate of the swim bladder radius a can be made from difference in TS at the two frequencies. At the shallower depth the difference was 1.25 dB being the average difference $(\langle Sv_{38}\rangle - \langle Sv_{120}\rangle)_{42m}$ before and after the first station. A second estimate can be made at the deeper level, where $(\langle Sv_{38}\rangle - \langle Sv_{120}\rangle)_{79m}$ was 2.53 dB. At 42 m a=0.48 mm and a=0.49 mm at 79 m, the two estimates being consistent and not unreasonable for a 32 mm fish.

Third, TS was calculated using the value for a using (1), giving TS=-63.8 dB at 38 kHz based on the gas bladder alone. This compares to a TS of –68 dB from a model of scattering from a fish of the same length without a gas bladder [18]. Combining the estimated TS due to the fish flesh and the gas bladder results in a TS of –62.4 dB.

Fourth, the volumetric density of the myctophids within the scattering layer was estimated. At 38 kHz the mean volume backscatter strength (S_v) was -56.45 ±0.46 dB. This, with the TS of a single fish at –62.4 dB, suggests a density of some 3.9 fish per cubic metre. This contrasts strongly with the population density of myctophids obtained from net hauls using an RMT 1+8 Rectangular Midwater Trawl (RMT) with an 8 m^2 opening towed at 1-2 kt that caught typically 1 myctophid per 1000 m^3 at night.

Two hypotheses have been proposed for this very large difference in population estimates between the acoustics and the net:

- Acoustic backscatter from very fragile gelatinous animals with gas inclusions (e.g. siphonophores) may have dominated the record, and not backscatter from myctophids as previously assumed. RMT nets destroy these fragile animals and counting incomplete or damaged pneumatophores was fraught with difficulty. Consequently, there was a poor estimate of the number of gas-bearing siphonophores in the area.
- The myctophids actively avoid the net, reducing the catch efficiency to below 0.1%. The RMT net is known to be inefficient to some degree at catching actively swimming animals because of its small capture area and its relatively slow tow speed of 1-2 kt. Bioluminescence was very marked in the area and could have contributed to net avoidance.

Experiments to test both of these hypotheses are planned to take place during a cruise to the Gulf of Oman in late 2001/2002.

4. Discussion

Biophysical interaction between animals and their physical environment in the ocean is such a multidimensional process that relating cause to effect in many situations remains very difficult. The problem can be somewhat simplified by choice of location for study, or it can be simplified by altering one aspect of the environment and examining the response. In this paper simple examples of each approach have been shown.

Constant daylight in the Bellingshausen Sea in summer suppressed diel migration enabling us to observe spatial changes without interference from the diel cycle. This enabled three clear layers to be identified in the backscatter. The upper layer was related unambiguously to a patch of high chlorophyll concentration extending 100 km from north to south. Contemporary, but not simultaneous, Rectangular Midwater Trawl hauls from the RRS *James Clark Ross* showed that the upper layer animal population was dominated by the euphausiid *Thysanoessa sp.* and by chaetognaths (A. Atkinson, personal communication). This was a biological-biological interaction: the animals observed through their backscatter were in the upper layer to feed, either directly on the phytoplankton or on the microzooplankton that were feeding on the phytoplankton [19]. Between 70 m and 175 m, the interaction was biological-physical: variations in the backscatter were related directly to the mesoscale physical structure. Below 175 m the mechanism determining the interaction was less clear, but it is likely that the north-south extent of the backscatter patch was related to fall-out from the near-surface phytoplankton patch, and hence was a biological-biological teleconnection.

The response of zooplankton and micronekton to light was a topic of much discussion in the early part of the 20th century, see for example [20, 21]. One hypothesis suggested that light levels were triggers for upward and downward migration [20], another that animals migrated vertically to remain, as far as possible, at an optimum isolume [21]. Surprisingly little has been published on any effects that perturbations to the solar cycle might have on vertical migration. A recent study [22] showed that the 'midnight sinking' of the euphausid *Meganyctiphanes norvegica* was delayed by a nighttime lunar eclipse. The implication was that 'midnight sinking' was a reaction to the lunar light, and that this response was suppressed during the eclipse. The first purposeful experiment to attempt to influence scattering layers with lowered lights and to observe the results with sonar was carried out in 1965 [23]. Working near the Canary Islands in 1400 m of water Blaxter and Currie's net hauls suggested that myctophids were the most likely source of the backscatter (*Diaphus* sp. and *Lampanyctus* sp.). Seventeen out of twenty of their observations showed the animals descending in response to the lights at rates of 1.4 to 7.5 m min^{-1}, with a median of 4 m min^{-1}. Our observation of a descent rate of 3 m min^{-1} for *Benthosema* in response to ship's lights is within this range.

Avoidance of scientific nets by zooplankton, micronekton and fish is an issue that has arisen in many recent studies (e.g. [11, 24, 25]). Attempts to reconcile net and acoustic estimates of biomass prove particularly difficult for some groups of animals. Previous studies have shown that when the acoustic backscatter was dominated by slow swimming scatterers, such as pteropods, good agreement has been obtained in population estimates between nets and acoustics [11, 15]. However, where the backscatter was dominated by more mobile euphausids, there was significant scatter and bias between the two techniques [11, 15, 25]. In general, net avoidance led to under-estimates of the euphausid population by nets compared to the acoustics. Conversely, in areas dominated by poorly scattering slow-moving gelatinous animals such as salps, biomass estimates from nets may well exceed those from acoustics. Based on the assumption that the backscatter in the Gulf of Oman was dominated by the fish *B. pterotum* [16] this paper suggests that the catch efficiency of the RMT 1+8 net was below 0.1%, for this species, at night, in near-surface waters. Nets must be considered as filters whose catch efficiency depends on species, region, depth and hour-of-day. Acoustic backscatter is also an imperfect sampling tool. It is dependent on species, size and frequency. Simple comparisons of net biomass against single frequency backscatter in multi-species environments almost invariably result in scatter plots with low correlation coefficients (see for example [12]). Further work needs to be done to characterise net and acoustic sampling systems before we can have a high degree of confidence that the results of either technique lead to an accurate assessment of animal populations in the marine environment.

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