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Estimation of zooplankton abundance from shipborne ADCP backscatter

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Abstract—The backscattered signal intensity from a shipborne RD Instruments 150 kHz Acoustic Doppler Current Profiler is compared with zooplankton abundance during surveys around the Indian Ocean island of Aldabra. Significant correlation is found between the range-corrected backscatter summed from the surface to a depth of 200 m and the biomass collected by a net haul over the same vertical range at the same station. Biomass is expressed as mg C m^{-3} and is obtained by using a modified displacement volume method. Unlike previous work by FLAGG and SMITH (1989, *Deep-Sea Research*, **36**, 455–474; 1989, Proceedings of OCEAN '89, Marine Technology Society and I.E.E.E.) the ADCP was unmodified. This indicates that, until such modifications and calibrations as they suggest are carried out, data from existing instruments are still worth investigating.

Problems involved in the determination of flow noise inherent in shipborne ADCP backscatter measurement are discussed. Care must be taken if backscatter is studied when the ship is steaming. Nevertheless the application of the ADCP to combined studies of flow fields and biological productivity offers promise of continuous along-track estimates of zooplankton biomass when supplemented by spot calibrations.

INTRODUCTION

THE Acoustic Doppler Current Profiler (ADCP) has become a standard tool for physical oceanographers, both as a self-contained moored unit producing a detailed time series of the current in a water column, and as a shipborne instrument to give real-time current surveys. A by-product of such acoustic measurements is the strength of the backscattered signal. Recently, FLAGG and SMITH (1989a) (henceforth denoted FS1) have succeeded in correlating this signal strength with the abundance of zooplankton. Their work promises to revolutionize the study of the dynamics of plankton distributions, by enabling currents and zooplankton abundance to be obtained simultaneously and routinely.

FS1 used a bottom mounted ADCP and compared the backscattered strength at various points in the water column above with zooplankton collected with a net towed nearby. The ADCP was a 307 kHz instrument manufactured by RD Instruments, modified to reduce the beam angle from 30° to 20° from the vertical (thereby increasing the maximum range) and also to record the signal strength from each of the four beams (standard ADCPs record the Automatic Gain Control, AGC, applied by the signal processing unit to increase the

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signal strength to a preset value). They showed that calibration of the transducer and electronics were important since the receiver gain of the transducers is affected by temperature of the unit. They caution that this may cause problems for shipboard ADCPs when traversing steep gradients. They do not resolve whether it is the temperature of the transducers (on the ship's hull) or of the electronics in the laboratory that is important. However, more recently, FLAGG and SMITH (1989b, henceforth denoted FS2), state that it is the temperature in the laboratory that is probably more important. They were still unable to distinguish between the temperature dependence of the transducer head (at room temperature) and that of the electronics in the unit.

We have studied the backscattered signal-strength of an unmodified, uncalibrated, standard shipborne 150 kHz RD Instruments ADCP installed on the R.R.S. *Charles Darwin*. We report here the results of a comparison between zooplankton samples from a net drawn from 200 m depth to the surface and a summation of the ADCP backscatter strength in the same water column. We do not have temperature calibrations for the transducer or electronics; neither do we have separate backscattered intensities for each of the four beams. Despite the lack of calibrations for the ADCP, and the low zooplankton counts (ranging from 93 to 569 zooplankton per cubic metre depending on position around the island), we found an encouraging correlation between range-corrected backscatter and zooplankton abundance. Without knowing the transmitter power output by the ADCP, we cannot determine an absolute calibration applicable to other instruments. However we show that even a standard shipborne ADCP can yield useful data to determine the spatial variation of zooplankton abundance.

METHOD

We describe here data collected during April, June and July 1987 during cruises 22 and 24 of the R.R.S. *Charles Darwin*. The cruises surveyed mainly the region around the Indian Ocean atoll of Aldabra (46°30′E, 9°30′S) with the aim of investigating the effects of such an isolated obstacle in the path of the South Equatorial Current (discussed in HEYWOOD *et al.*, 1990). Each survey consisted of two concentric rings of stations measuring conductivity, temperature and depth (CTD) around the island. The inner circle was located 5 km offshore (water depth 2000 m) and the outer one 15 km offshore (water depth 4000 m). Additional stations were included further from the island depending upon the incident flow direction. During cruise 24, two CTD surveys around the island were combined with zooplankton collections at the same stations. The shipborne ADCP recorded data throughout the cruises. The RDI DAS software in use was version 2.24, the firmware of the electronics was version 16.19 and the transducer was version 15.68. We compare the zooplankton abundance at the CTD stations around Aldabra with the strength of the backscattered sound signal recorded by the ADCP.

Zooplankton collection

Zooplankton samples were collected at each station by vertical hauls through the top 200 m of the water column with modified 0.5 m diameter WP2 fine mesh conical plankton nets (142 μm aperture). The volume of water filtered through the nets was monitored by TSK (Tsurumi-Seiki-Kosakusho Co., Japan) mechanical flow meters suspended across the mouth openings. Nets were hosed down thoroughly following each haul and the collected samples immediately preserved in 5% neutral formalin seawater solution. These were subsequently analysed back in the laboratory where zooplankton density was determined by volumetric sub-sampling with replacement and all groups identified to species and stage level from samples of at least 100 individuals (WINSOR and WALFORD, 1936).

Table 1 gives an indication of the dominant zooplankton taxa encountered around Aldabra along with their relative abundances and contribution to the total zooplankton. It can be seen that the copepods were the most important group, making up 72% of the total, with the copepodite stages being the most numerous at that time in the survey area. More detailed analysis of the zooplankton around Aldabra can be found in SCROPE-HOWE (in preparation).

Estimates of total zooplankton biomass were obtained for each station by measuring the displacement volumes (AHLSTROM and THRAILKILL, 1963) of whole samples and converting these to mg C m^{-3} using the equivalent tables recommended by WEIBE *et al.* (1975), with corrections for overestimates as indicated by FS2. Although the thaliacea (Table 1) were fairly common, occurring in 55% of the samples, they only accounted for around 1.3% of the total zooplankton. Due to this relatively low ranking of importance during the survey

Table 1. Mean abundance (No. m^{-3}), percentage of total, frequency of occurrence (in samples) and dominance of the 18 most abundant zooplankton taxa around Aldabra during June–July 1987

Rank	Taxonomic groups	Mean abundance (No. m^{-3})	%Total	Frequency (%)	Dominance
1	Calanoida copepodites	83	25.8	100	71
2	*Oithona plumifera*	45	13.7	100	50
3	Appendicularia	42	13.2	100	34
4	*Corycaeus speciosus*	31	9.7	100	22
5	Calanoida nauplii	31	9.2	96	15
6	Pteropoda	16	5.3	98	3
7	*Paracalanus aculeatus*	15	5.0	91	1
8	Chaetognatha	8	2.6	76	0
9	*Eucalanus elongatus*	8	2.5	87	0
10	*Acartia negligens*	7	2.1	84	0
11	Ostracoda	6	1.8	73	0
12	Polychaeta larvae	5	1.5	67	0
13	Euphausiacea larvae	4	1.4	58	0
14	Onacea species	4	1.4	27	0
15	Thaliacea	4	1.3	55	0
16	Echinoderma larvae	4	1.1	43	0
17	*Temora discaudata*	3	1.1	42	0
18	*Centropages furcatus*	2	0.7	25	0
Total copepods		229	72.0		
Total "others"		89	28.0		
Grand total		318			

Taxonomic groups are the sum of all species encountered. Taxa are listed in order of average abundance to indicate their relative importance in the survey area. Dominance: proportion of samples (n = 71) in which the taxon was amongst those making up 50% of the individuals; summation in each sample commenced with the most abundant species (FAGAR and MCGOWAN, 1963).

and their (at present) unresolved acoustic properties, we have followed FS1 in assuming that they make an insignificant contribution to the acoustic signal.

ADCP backscatter

Together with current profiles, the ADCP recorded routinely the values of the mean AGC per bin, a parameter indicating the gain necessary to increase the scattered signal strength to a constant value, as explained by FS1. Since the instrument was unmodified, parameters such as the received signal strength used by FS1 were unavailable, as were AGC values for the four individual beams. The ADCP was normally set up with 75 bins each of 8 m depth, 2 m blank after transmit, and a 10-min averaging interval. The bin nearest to the instrument was not included in the summation, since it is likely to be contaminated by flow noise and bubbles. The ADCP is at a depth of about 5 m on R.R.S. *Charles Darwin*; therefore the first bin is from 7 to 15 m below the surface. However the AGC value is biased towards the end of the bin and range values are calculated using the procedures described by RDI.

To calculate the sum of the backscattered signal strength of the water column from the second bin to 200 m for comparison with the zooplankton abundance, the following procedure was followed:

(1) An estimate of the noise level was found by examining the AGC at a depth of about 500 m, where the "Per cent good" parameter had fallen to zero and the AGC had flattened off to a constant value (GAST and GORDON, 1988). This was usually about 20 counts (but see Discussion later).

(2) The noise counts (N_c) were subtracted from all other signal counts (S_c) in the water column for each station.

(3) The corrected AGC was converted to backscattered power (dB) using the conversion factor of 0.46 dB/count at 22°C quoted as typical by RDI. This conversion is dependent on the temperature of the electronics of the laboratory unit (rather than the unit mounted in the hull). We shall use 0.46 since our unit was in an air-conditioned room maintained at approximately 22°C. The conversion factor varies by only 0.34% per °C, so errors introduced by temperature changes of a few degrees are negligible compared to other uncertainties such as patchiness in zooplankton, or the range correction.

(4) A small correction L_c, was applied for non-linearities in the log conversion circuitry at high amplitude, as found by C. FLAGG (reported by GAST and GORDON, 1988). This correction is simply an addition of L_c, where

$$L_c = (1.15 \times 10^{-16}) S_c^7,$$

where S_c is the number of signal counts.

(5) The range correction, R_c, was applied as described by FS1. The coefficient for sound absorption, α, was calculated to be 0.06 dB m^{-1}, using the formula given by URICK (1983), assuming water of temperature 25°C, salinity 35 ppt and a sound signal of frequency 153.6 Hz. The effect of temperature on α (for example, at 10°C the value of α would be 0.056) was found not to influence significantly the resulting correlation.

(6) The resulting backscatter is of course dependent on the signal output by the ADCP. This is not known for RDI ADCPs at present. In order to obtain scattering values of a reasonable size, a constant of 110 dB was subtracted from all values. This is an arbitrary constant and means that the calibration is a relative one rather than absolute.

(7) A total scatter for the column to 200 m was calculated by taking anti-logs, summing the scatter in each bin for the column, and taking a log of the result. This is necessary since the backscattered signal is a log value.

To summarize, our signal strength is calculated as

$$S = \log_{10} \Sigma \, 10^{0.46(S_c - N_c) + R_c + L_c}. \tag{1}$$

For comparison with the zooplankton data, a mean scatter was calculated for each station, consisting of profiles obtained during the net cast (usually one or two 10-min averaged profiles).

RESULTS

1. *Zooplankton—scatter relationships*

Figure 1a shows three examples of the backscattered signal recorded at one station during the survey, after conversion from counts to decibels (step 3 in the procedure above). The noise level has not been subtracted, nor has the range correction been applied. The backscattered signal is strongest at the surface (about 100 dB) and falls to a noise value of about 10 dB at about 400 m. This large dynamic range is due to the absorption of sound by the water and to spherical spreading of the sound pulse after leaving the transducer. When the noise counts are subtracted and the range correction is applied (Fig. 1b) the signal range is reduced to about 20 dB.

In Fig. 2 the total corrected ADCP backscatter at each station is plotted against the zooplankton biomass for the water column, for all 62 stations of cruise 24 at which both data exist. Fitting an exponential curve (as discussed by FS1) yields:

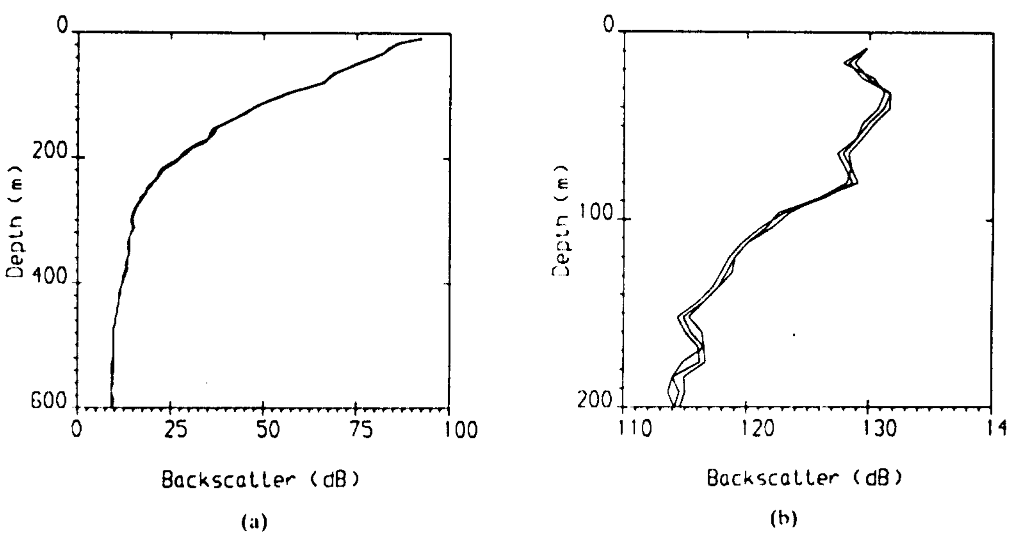


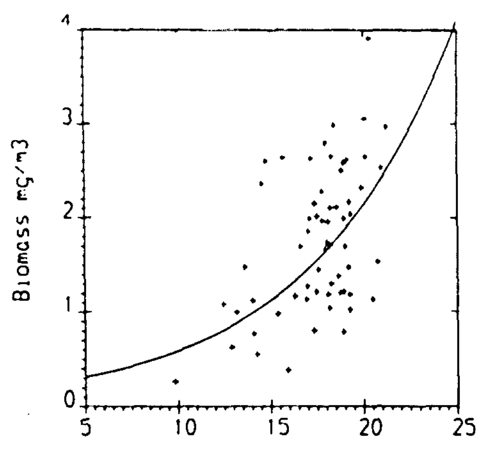
Fig. 1. (a) Backscattered ADCP signal before range-correction and subtraction of the noise level have been applied. Conversion from counts to decibels has been performed. (b) Range-corrected backscatter after noise level has been subtracted. Note that the maximum on the vertical scale is now only 200 m since below this depth noise is dominant. The dynamic range is now only 20 dB, showing that the large range in (a) was due mainly to the rapid absorption, spreading and scattering of the sound with depth.

$$\text{Zooplankton biomass} = a \exp(b \times \text{backscatter}). \quad (2)$$

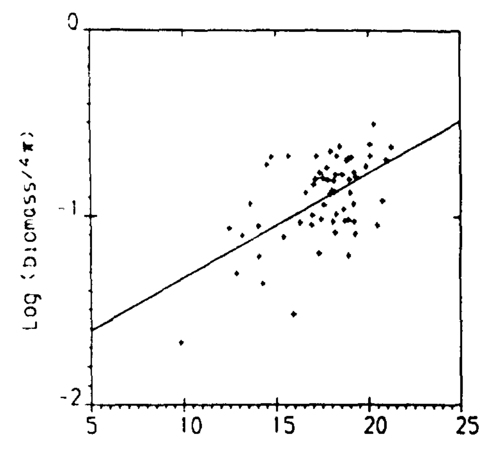
Although there is a large degree of variability in both estimates, the correlation coefficient is 0.57 which is significant at the 99.95% level for 62 points. The values of a and b are 0.16 and 0.13, respectively. This curve has been used as a calibration to predict the zooplankton during subsequent surveys.

FS2 display the data from FS1 in a different way. Since dry weight is approximately proportional to cross-sectional area (which should be proportional to acoustic cross-section and thus our backscattered signal), it is logical to plot the logarithm of dry weight divided by 4π against the backscattered intensity. For comparison with their data, we have plotted our data set in a similar way (Fig. 2b). Using logarithms to base 10, and assuming simple scattering theory, FS2 expect a linear dependence with a proportionality constant near 0.1. They obtain a slope of 0.07 for a 300 kHz system and 0.12 for a 150 kHz system. Our 150 kHz system gives a slope of 0.056, with a standard deviation of 0.010. The intercept, which is expected to be instrument- and experiment-specific, is -1.89 here. Errors in the relative backscatter are estimated to be at most ± 2dB, indicating the variability of consecutive ensembles on the same station.

The reader may be interested to know whether the slope of the line depends critically on the coefficient for sound absorption, α, the value of which is debated. If a value of 0.04 dB m^{-1} is used, the slope is 0.052 and the correlation decreases to 0.54. Therefore, poor knowledge of α introduces a negligible error compared to other errors such as patchiness in zooplankton or errors in the displacement method (say 0.5 mg m^{-3}).



(a)



(b)

Fig. 2. (a) Correlation between zooplankton biomass (mg C m^{-3}) and total backscattered ADCP signal for the water column from the surface to 200 m. Each point represents one CTD station. An exponential curve has been fitted of the form: Zooplankton biomass = $a \exp(b \times \text{backscatter})$. The correlation coefficient is 0.57 which is significant at the 99.95% level for 62 points. The values of a and b are 0.16 and 0.13 respectively. Errors in the relative backscatter are estimated to be at most ± 2 dB, indicating the variability of consecutive ensembles on the same station. We estimate errors in the zooplankton to be at most 0.5 mg m^{-3}. (b) The data from Fig. 2a are here shown on a log-linear plot of log (biomass/4π) against backscattered intensity. The slope of the line is 0.056 with a standard deviation of 0.010.

It should be borne in mind that our net sampled plankton right to the water surface, whereas the ADCP data do not apply to the upper 15 m of the water column. Ideally a net which can be closed at a specific depth should be used for these studies. It is possible that our backscattered intensities are too low at night because the plankton population near surface may not be negligible. However we have divided the data shown in Fig. 2 into local day-time and night-time populations, and there is no difference in the resulting straight line.

2. *Zooplankton distributions*

The zooplankton distribution from nets during the first CTD survey of cruise 24 (36 stations around Aldabra) is shown in Fig. 3a. In Fig. 3b the predicted zooplankton population is plotted using equation (2) and the observed ADCP backscatter. These data are a subset of those in Fig. 2. Although there is bound to be a large degree of difference at certain stations, the patterns of high and low abundances are similar. In particular, the region of low productivity on the southeast flank of the island (upstream) is obvious in both. For comparison, we have included a map of the integrated chlorophyll content of the upper 200 m (Fig. 3c) (Heywood *et al.*, 1990). Again, the least productive (low phytoplankton) region is the southeast flank. However, the western area does not have similar chlorophyll and zooplankton distributions.

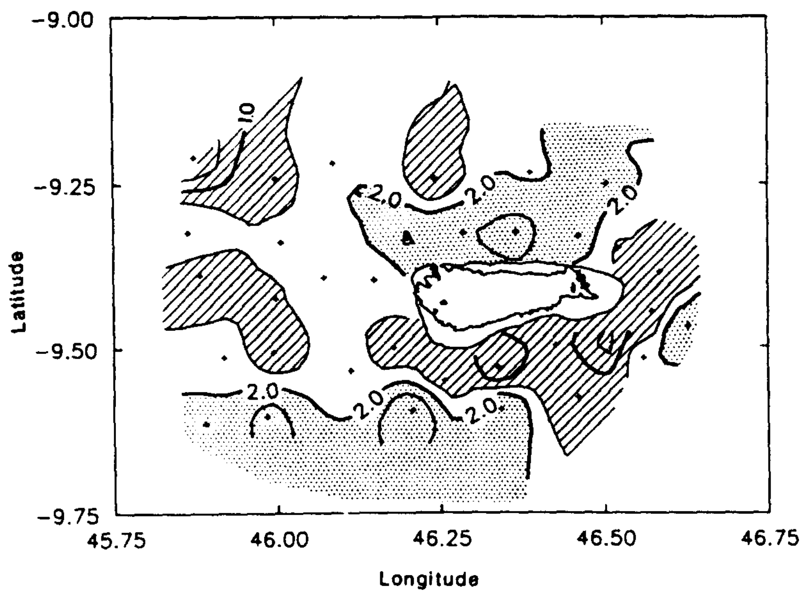
In general, the ADCP backscatter predicts a much smoother and less variable distribution, whereas the nets gave a wide range of abundances. This difference may be because the nets are a near-instantaneous sample at any one level, whereas the ADCP data are averages for 10 min. If the zooplankton were patchy, the ADCP might not record the extremes but the net samples might.

ADCP backscatter data obtained during a cruise on the same ship two months earlier (R.R.S. *Charles Darwin* cruise 22) also have been investigated. ADCP data were not recorded below 400 m, so this has been taken as the noise depth. As shown in Fig. 1a, the signal strength at 400 m may be up to about 5 dB higher than the noise value, so this approximation will reduce the resulting zooplankton estimate slightly.

No zooplankton samples were taken on this cruise, but a distinctive variation in the phytoplankton distribution (Fig. 4a) was observed around the island (Heywood *et al.*, 1990). We have applied the calibration equation (2) to investigate whether there is a zooplankton maximum corresponding to the region of high chlorophyll (Fig. 4b). There is indeed a region of much higher zooplankton abundance at the same group of stations where the primary productivity was large. From this it may be deduced that the region of high chlorophyll (associated with an eddy trapped downstream of Aldabra during periods of high incident current, Heywood *et al.*, 1990) must be persistent enough to allow growth of a zooplankton community.

3. *Noise*

All ADCP data plotted so far have been extracted while the ship was on station. We have found that the ACDP backscatter profile has different characteristics when the ship is moving. Consider a portion of the survey (Fig. 5) consisting of a station, a transit section, and another station, approximately one hour of each. The mean backscatter at each depth (before range-correction or noise elimination) for the 3 h period has been calculated, and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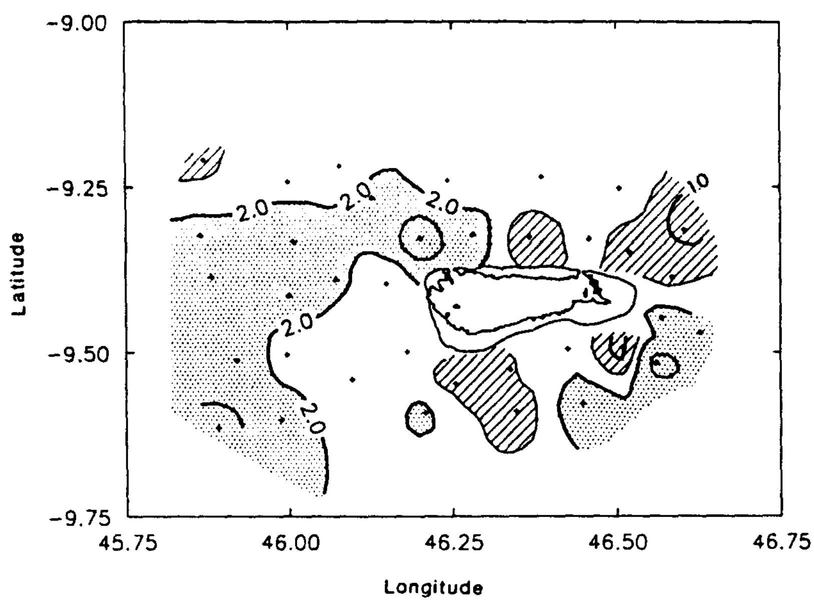
(a)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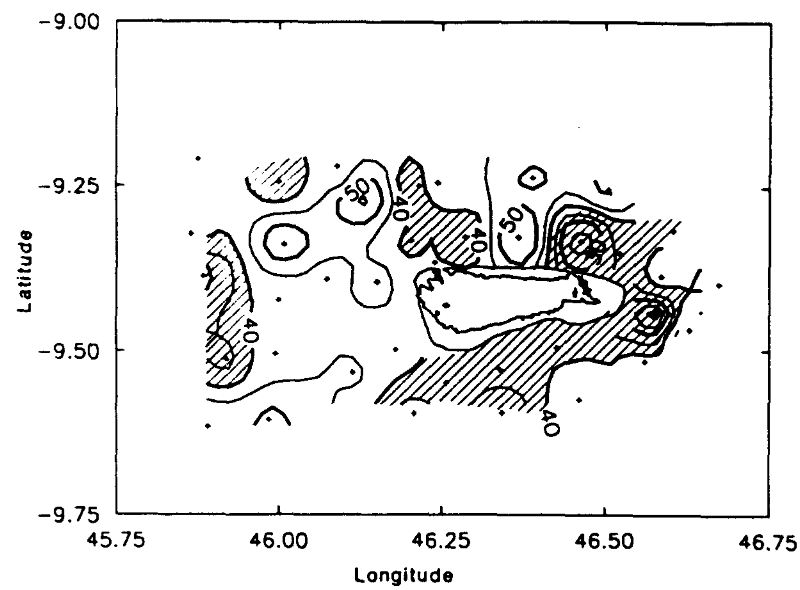


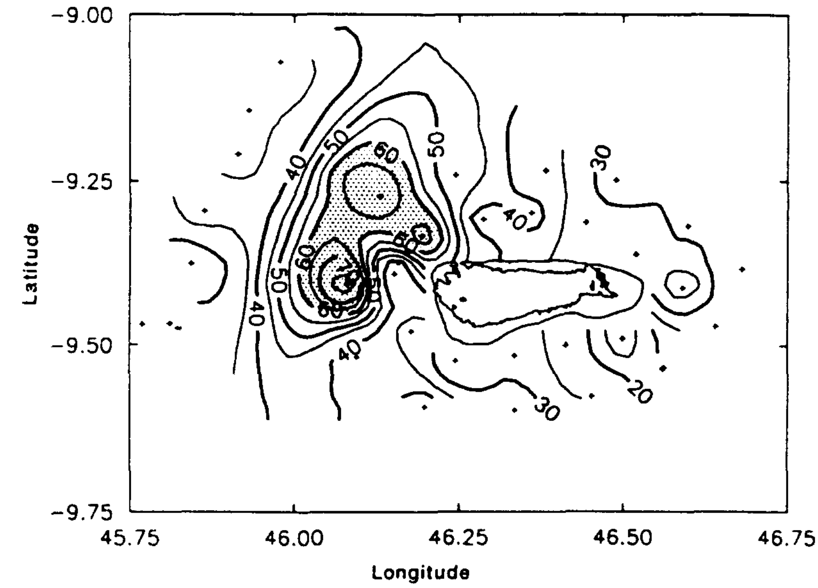
(c)

Fig. 3. Oceanographic parameters measured during CTD survey 1 of cruise 24, 23 June 1430–27 June 0930. Station positions are marked (+). (a) Zooplankton biomass in the upper 200 m (mg C m^{-3}). (b) Zooplankton abundance deduced from ADCP backscatter at stations. (c) Integrated chlorophyll content (mg m^{-2}) of the water column from the surface to 200 m.

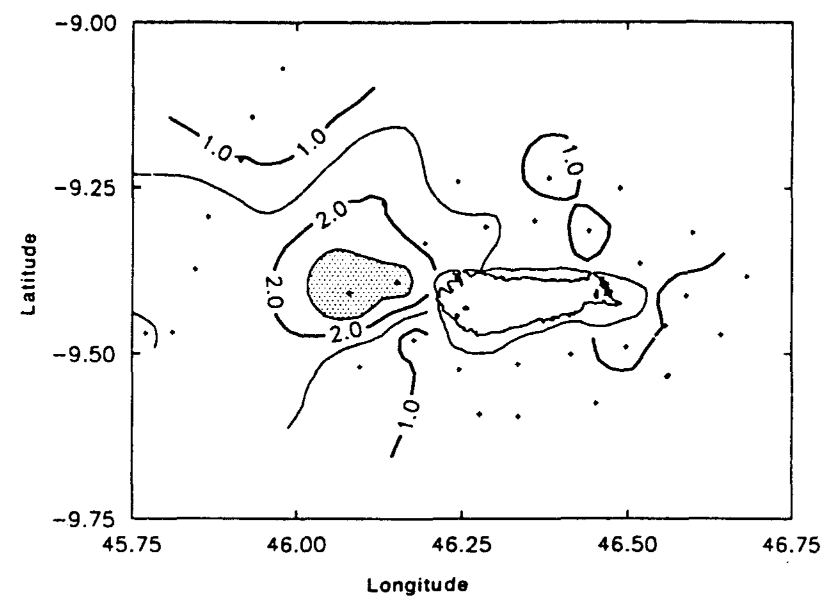
subtracted from each individual profile. The mean is, of course, biased towards the station data since two of the three hours are on station. Figure 5 shows these signal anomalies (differences from the mean) for one typical profile on station (continuous line) and one when the ship is travelling at ≈10 kn (dashed line). At the surface, the backscattered signal is about 8 dB smaller when the ship is moving than when it is on station. At depths where the signal is simply noise (400–600 m), the backscatter is about 8 dB larger when the ship is moving than when it is on station. Therefore, when one applies the correction for noise (subtraction of counts at 500 m), the estimate for backscatter during transit legs is considerably reduced by both effects.

There are therefore two problems: (1) Why does the backscattered intensity increase at depth while steaming? (2) Why does the backscattered intensity decrease near the surface while steaming?

The increased backscatter at the lower depths (where the signal is purely noise) is probably due to flow noise caused by the ship. In Fig. 6a we plot the noise value (counts at 500 m) against ship's speed for two periods of 24 h at the start and end of the CTD surveys. The ship's speed is the average for the 10 min ensemble, and therefore rapid manoeuvres may not necessarily be well-represented. There are few points between 1 and 5 m s^{-1} because the ship is usually either on station or steaming at full speed. However, it is apparent that the backscattered intensity at 500 m is highly correlated with ship's speed (correlation coefficient 0.895 for 283 points). The slope of the line is 4.56, with a standard deviation in the slope of 0.14. It can be seen that using the backscattered intensity at 500 m as an estimation of ADCP noise while steaming may introduce an error of 10–15 dB into the relative backscattered intensity measurement.



(a)



(b)

Fig. 4. Observations during the CTD survey on cruise 22, 18 April 0000–21 April 1200. CTD stations are marked (+). (a) Integrated chlorophyll content (mg m^{-2}) of the water column from the surface to 200 m. (b) Predicted zooplankton abundance deduced from the ADCP signal backscatter at stations.

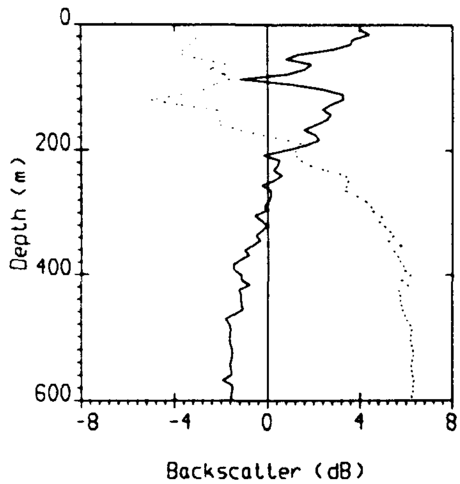


Fig. 5. Signal anomalies (from the mean at each depth over a 3 h period) for a profile in transit (dashed line) and on station (continuous line). The 3 h period included an hour on station, an hour in transit and another hour on station. These profiles are calculated before range correction is applied or noise level subtracted.

This finding is perhaps not particularly surprising; indeed RDI do state that the ship should be stationary during calculation of the noise level. However, it is difficult to obtain a ship completely stationary with respect to the water beneath it, so care should be taken when determining noise.

A more surprising result is that the backscattered intensity nearer to the surface also may vary with ship's speed. At a depth of about 30 m (the third bin below the instrument), the backscattered intensity is negatively correlated with ship's speed (Fig. 6b). The slope of the line is −2.26, with a standard deviation of 0.17; the correlation is 0.62. The near-surface bin (bin 1—not shown) gave a similar slope. It is therefore obvious that even if the noise value from a stationary ship were always used, different backscattered intensity values will be obtained throughout the water column when the ship is moving. One could not, therefore, combine together zooplankton estimates from stations with those in transit, since the transit values will be biased low.

Consider now the variation of noise values (counts at 500 m) when the ship is on station (in theory the ship is stationary although sometimes the bow thruster is used to maintain position while the CTD is lowered). When calibrating the backscattered intensity against zooplankton biomass, we used the actual noise value for each ensemble, since we had realised that these values varied during the cruise. Why should the noise values vary? There is no correlation between noise values at 500 m and wind speed (Fig. 6c), so the increased noise is not some effect of surface-generated bubbles, or of the ship pitching and rolling more. There appears, however, to be some correlation with time of day (Fig. 6d), although we cannot think of a convincing reason why the backscattered intensity should be decreased at 500 m during the day. Five hundred metres is well below the mixed layer, so no temperature change was seen at that depth. The ship is air-conditioned so the temperature at the ADCP should be constant; however, it is conceivable that the electronics did undergo some temperature variation. Other possible explanations are that

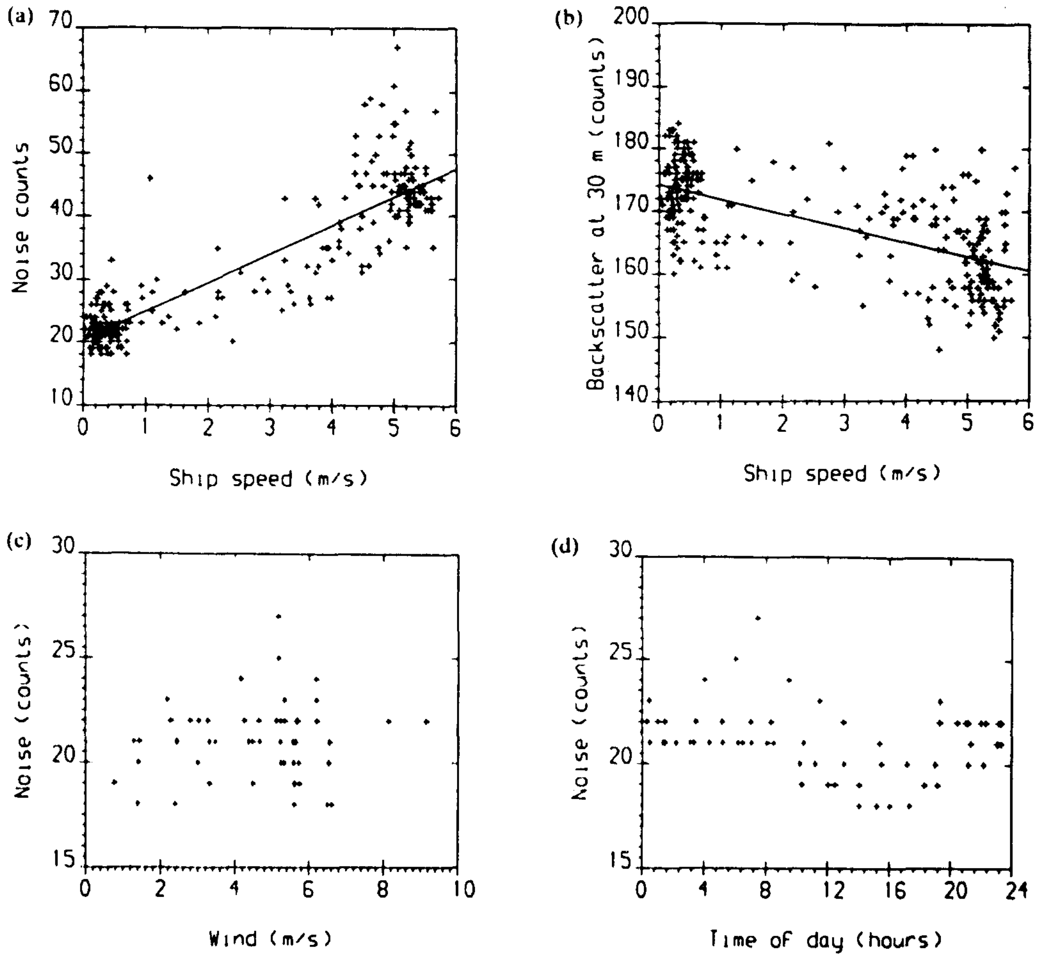


Fig. 6. (a) Noise counts (at 500 m) from the AGC against the ship's speed. (b) Counts in bin 3 (at about 30 m) against ship's speed. (c) Noise counts against the wind speed. (d) Noise counts against local time of day.

it is easier to keep a ship stationary during daylight, or that some of the ship's officers make more liberal use of the bow thruster during their watches than others.

4. *Diel migration*

It is known that zooplankton migrate between a deep scattering layer and the surface during a 24-h cycle. Bary (1967) documented their migration using a 12 kHz sounder. At dusk, the zooplankton ascended first slowly and then quickly. During the night, the animals slowly dispersed themselves throughout the surface layers. At dawn, the zooplankton descended to the deep scattering layer, presumably to reduce their chances of being seen and eaten.

G. Griffiths (personal communication) has observed diel migration using 150 kHz ADCP data in the North Atlantic on R.R.S. *Discovery*. Because of the noise problems described above, we cannot combine station data with transit data to form a time series for the CTD surveys. In addition, variation in zooplankton around the island due to upwelling, mixing and enhancement of productivity (Scrope-Howe, in preparation) means that diel variations are difficult to see in the station data previously described. However we undertook one 24-h station that provides data at one position (9°15′S, 46°21′E). Water will be advecting past this point with the mean current, so there may be inherent patchiness, but the island effects do not dominate here.

We converted the AGC counts to decibels, and then calculated the mean at each depth for the whole 24-h cycle. This mean was subtracted from the signal for each 10-min ensemble to give a signal anomaly (Fig. 7). The highlighted areas are those with a positive anomaly, identifying where the zooplankton density is greatest. During the day (0700–1900 local time), the zooplankton density is greatest at about 150 m, whereas at night, they are distributed in the surface layers between 100 m and the surface.

DISCUSSION

In agreement with the work of Flagg and Smith (1989a,b), we find that the Automatic Gain Control parameter recorded as a by-product in the signal conditioning prior to calculation of current by the Acoustic Doppler Current Profiler can give an estimate of the zooplankton abundance in the water. Unlike them, however, we have used an unmodified, shipborne instrument. Their work shows that temperature effects on the transducer can be important. We have had to assume that the temperature remains approximately constant during the period of each survey. This is probably justified since the ADCP was in an air-conditioned laboratory, but there is the possibility of some day to night variation. The surveys described took only a few days to complete and air

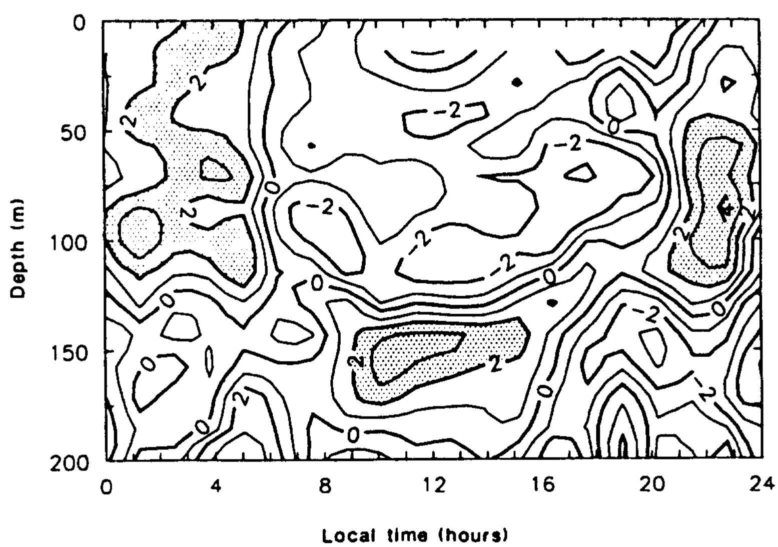


Fig. 7. Backscattered signal anomaly against local time of day over a 24-h station. The AGC has been converted to decibels, and then the mean over the whole 24 h subtracted at each depth. The highlighted region shows where the zooplankton density is highest, and this can be seen migrating to about 150 m during the day.

temperatures were fairly constant (within a few °C); it should be remembered that our results may not be applicable to cruises on the same ship in mid-latitudes.

Scatter plots of the zooplankton biomass against the backscattered signal show a significant correlation. By considering the total signal over 200 m for many stations, the number of data points available for the correlation is much larger than in FS1. An exponential curve has been fitted and used as the calibration to predict zooplankton abundance in other surveys. The acoustic backscatter distribution was similar to that of chlorophyll around the island of Aldabra.

It might be suggested that the coincidence of high backscattered ADCP signal and enhanced phytoplankton means that the acoustic signal is being scattered by the phytoplankton rather than the zooplankton. This is unlikely, since phytoplankton are too small. The wavelength of the acoustic signal is about 1 cm, zooplankton are usually regarded as having dimensions of between 200 μm and 20 mm, while phytoplankton are usually less than 200 μm.

Plotting the backscattered intensity against the logarithm of the zooplankton biomass yields a straight line of gradient 0.06, which suggests that our ADCP was about twice as sensitive as the 150 kHz system used by FS2. Indeed the gradient is similar to that found with their 300 kHz system. C. FLAGG (personal communication) has suggested that our increased sensitivity might be due to our zooplankton being larger. Table 1 shows that 25% of the zooplankton were calanoida copepodites, whose mean length is about 0.7 mm, oithona (14%) are about 0.8 mm and appendicularia (13%) about 0.9 mm. Thus, over 50% of the population are less than 1 mm in length, and are, in general, smaller rather than larger than the populations described in FS1. This is perplexing, and we recommend further work using different ADCPs under varying conditions with a range of zooplankton abundances and size distributions, to determine whether the slope of the calibration is indeed transferable from instrument to instrument (as we hope).

RD Instruments are presently completing modifications so that the transmitter power output will be known for each instrument. This should yield a calibration that would be transferable from one instrument to another, providing long-term temperature changes in the ship's environment are taken into account. We would endorse proposals that the modifications and calibrations described by FLAGG and SMITH (1989a,b) be applied to both existing and future ADCPs. However, we have shown that unmodified ADCP data are worth examination, assuming temperature variation is limited during the period of interest.

Care has been taken here to exclude from the averages at each station ADCP data when the ship was moving. We have seen that the scattered intensity recorded is different when the ship is in transit, both near surface and at the noise level. It is assumed that this is due to the signal processing built into the instrument. The result is to reduce considerably the estimate of zooplankton. This requires further research and is under investigation. If the effect may be easily corrected, there will be no difficulty in using all the ADCP data obtained during a survey to give a synoptic view of both physical and biological parameters.

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