

# Acoustic observations of micronekton fish on the scale of an ocean basin: potential and challenges

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Kloser, R. J., Ryan, T. E., Young, J. W., and Lewis, M. E. 2009. Acoustic observations of micronekton fish on the scale of an ocean basin: potential and challenges. – *ICES Journal of Marine Science*, 66: 998–1006.

Acoustic methods of characterizing micronekton communities ( $\sim 2$  to 20 cm length) on the scale of an ocean basin could provide valuable inputs to ecosystem-based fishery management, marine planning, and monitoring the effects of climate change. The micronekton fish are important forage for top predators (e.g. tunas), and information on their diversity, distribution, size-structure, and abundance is needed to increase accuracy of top-predator distribution and abundance predictions. At the scale of an ocean basin, four years of Tasman Sea transects using a fishing vessel provide fine-scale maps of acoustic backscatter at 38 kHz that reveal detailed spatial patterns and structure to depths of 1200 m. Research-vessel data provide detailed biodiversity, density, size structure, and acoustic-scattering information from depth-stratified net sampling and a lowered acoustic probe. Wet-weight biomass estimates of the micronekton fish in the region vary considerably by a factor of 5–58 between acoustics ( $16\text{--}29\text{ g m}^{-2}$ ), nets ( $1.6\text{ g m}^{-2}$ ), and large spatial-scale, ecological models ( $0.5\text{--}3\text{ g m}^{-2}$ ). We demonstrate the potential and challenges of an acoustic basin-scale, fishing-vessel monitoring programme, including optical and net sensing, which could assist in characterizing the biodiversity, distribution, and biomass of the micronekton fish.

**Keywords:** acoustics, ecosystem models, micronekton, ocean basin.

Received 8 August 2008; accepted 12 November 2008; advance access publication 8 April 2009.

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## Introduction

The large number of overfished fish stocks with affected habitats, as well as overcapacity in the world's fishing fleets, has been well reported (e.g. FAO, 2002; Hilborn *et al.*, 2003). This situation of overfishing and overcapacity led to the adoption of an ecosystem-based fishery management (EBFM) approach, to maintain or improve ecosystem health and productivity, and so to maintain or increase fishery production for both present and future generations (NOAA, 1999; FAO, 2003). The implementation of EBFM will require better governance and put greater demands on knowledge of the marine ecosystem beyond that of the targeted species (Browman and Stergiou, 2004). As a minimum, better knowledge of multispecies assemblages, their trophic interaction and biomasses will be required to monitor the performance of EBFM (Bertrand *et al.*, 2003).

Shelf- and basin-scale methods of characterizing and quantifying the biomass of micronekton,  $\sim 2\text{--}20$  cm length, communities should be a valuable tool for the EBFM approach and to monitor the effects of climate change (Beamish *et al.*, 1999). Micronekton communities form a link between primary production and top predators. Recent coupled ocean-biogeochemical-population models have identified a gap in knowledge of this area (Lehodey, 2004; Fulton *et al.*, 2005). Ecosystem models need observations on the distribution and abundance of these micronekton, mid-trophic functional groups at shelf and basin scale to validate predictions, but there have been very few observations in southern hemisphere waters (May and Blaber, 1989; Koslow *et al.*, 1997;

Young *et al.*, 2001; McClatchie and Dunford, 2003). These sparse observations derive from a variety of sampling devices of limited spatial and temporal extent, which makes it difficult to compare biomass estimates (McClatchie and Dunford, 2003).

In practice, observational sampling for EBFM will be decided by the overall management arrangements for the fishery, but a guide to the most useful indicators, e.g. abundance and length, can be obtained by modelling (Fulton *et al.*, 2005). Current fishery-dependent indicators, e.g. catch per unit effort, are inadequate to provide all the required trophic information for EBFM. Acoustic data can potentially provide both quantitative and qualitative metrics over the range of trophic, organism size and large spatial and temporal scales required for EBFM; this potential is slowly being realized as new methodologies and technologies are introduced (e.g. Korneliussen and Ona, 2003; Makris *et al.*, 2006). It is not always possible to achieve sampling at these scales with dedicated research vessels, but increased temporal and spatial coverage can often be obtained cost-effectively using acoustics from fishing vessels (Karp, 2007).

Integrated studies based on acoustics can also provide new insights into ecosystem function (e.g. Croll *et al.*, 1998, 2005; Bertrand *et al.*, 2003). Such studies provide large datasets that can be interpreted in terms of their qualitative and quantitative information (Kaufman *et al.*, 2004). Simple visual, qualitative descriptions of the way organisms are distributed can provide valuable information about ecosystem function that can be parameterized in ecosystem models (Lehodey, 2004). These acoustic

data also allow estimates of biomass for the dominant acoustic-scattering groups. At present, models are being parameterized with biomass data based on traditional technologies such as trawlnets that may have large selectivity or catchability biases, depending on the target species (Koslow *et al.*, 1997; Lehodey, 2004).

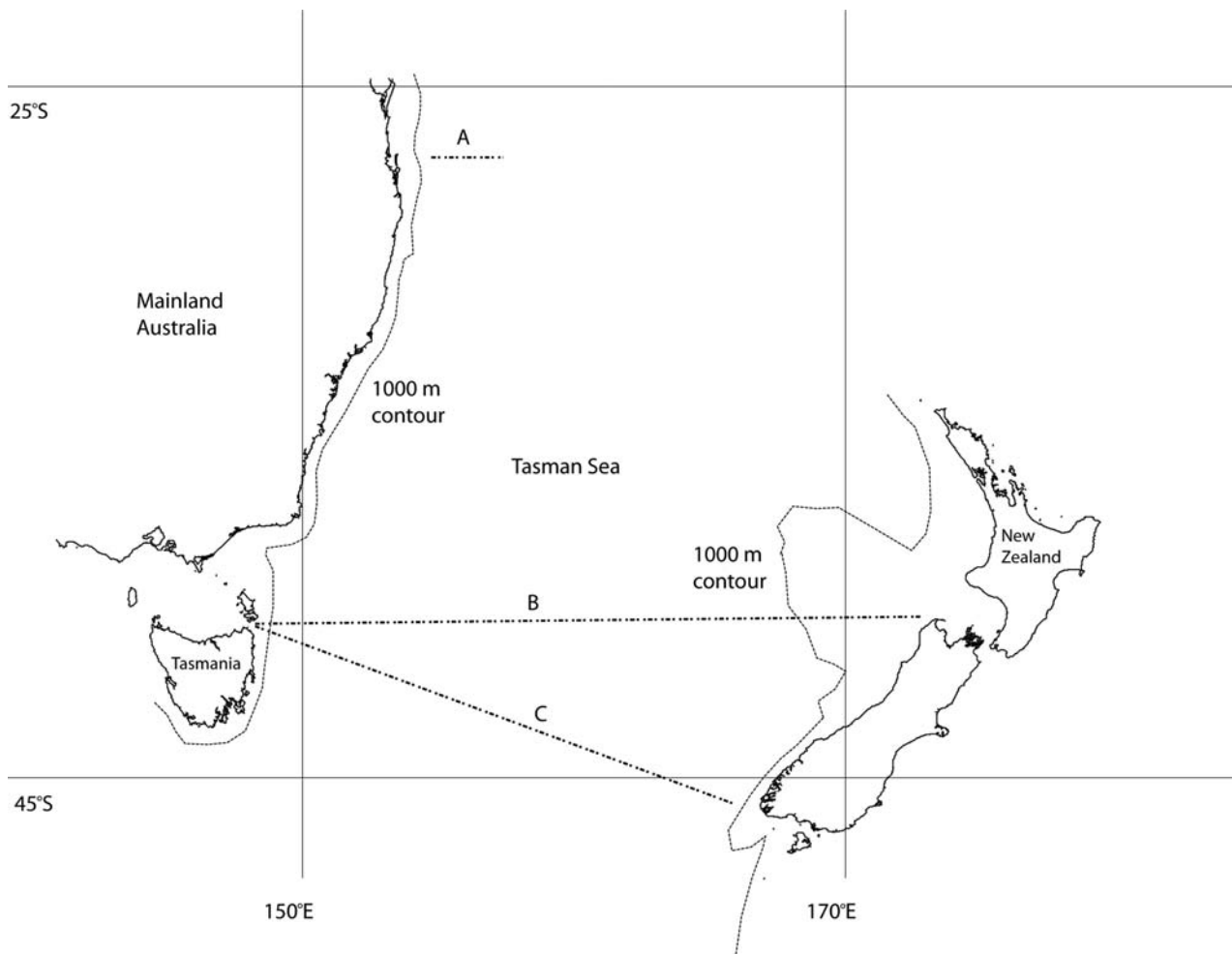
Current biomass estimates of micronekton from nets may underestimate the true population size by factors of between 7 and 21 when compared with estimates based on acoustics (Koslow *et al.*, 1997). Both net and acoustic sampling cause selectivity and catchability biases. For nets, the mesh sizes and effective sampling volume are key factors, along with species behaviour and size. For that reason, comparing species' biomass, size classes, and diversities obtained using different nets is problematic. Acoustic sampling by echo integration or echo counting can generate both selectivity and catchability biases, depending on the operating frequency and the species targeted. For micronekton in acoustic functional groups such as small (<10 cm) fish, gelatinous organisms, crustaceans, squid, and large (>10 cm) fish, the dominant scatterers are small fish with gas-filled swimbladders. The reflectance of an individual bladdered fish, target strength or *TS*, dB re 1 m<sup>2</sup>, will change with depth and frequency as a consequence of resonant scattering (Kloser *et al.*, 2002). For that reason,

detailed information about gas-filled, swimbladder target strength is required for echo-integration methods. In contrast, echo counting of individual fish reduces the sensitivity of abundance estimates to target strength, but requires low densities of organisms in the volume sampled. These low densities can be achieved if the acoustic system is lowered or towed at depth (Kloser, 1996; Kloser *et al.*, 2007b).

In this paper, we explore the differences in biomass estimates between net and acoustic sampling and ecological models from a well-sampled region in the Tasman Sea. We apply our acoustic estimates to basin-scale, acoustic data collected from fishing vessels while monitoring the distribution and abundance of micronekton fish over a 4-year period.

## Methods

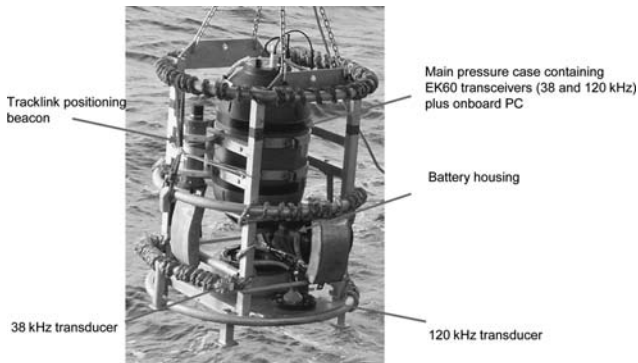
Tasman Sea basin-scale measurements of 38 kHz backscatter were obtained from echosounders on fishing vessels during the austral winter from 2004 to 2007, between longitudes 149 and 170°E, with three transects along 41°S (951 nautical miles) and three between 41 and 46°S (914 nautical miles; Figure 1). These transects can potentially provide biomass estimates of the micronekton community. To convert these large-scale backscatter data to biomass, we investigated a conversion factor between biomass



**Figure 1.** Designated Tasman Sea area 4.1 million km<sup>2</sup> bounded by 25–45°S 147–170°E and depths greater than 1000 m, with research-vessel net sampling (A) and fishing-vessel transects along 41°S, for 2005, 2006, and 2007 (B) and transects from 41 to 46°S for 2004, 2006, and 2007 (C).

estimates from nets and acoustics based on previously reported sampling at 44°S and new measurements at 28°S (Koslow *et al.*, 1997; Young and Hobday, 2004). In all, 13 sets of fine-scale data from acoustics and net sampling were collected during the 2004 research voyage in the Tasman Sea at 28°S, of which one complete indicative dataset is described here.

Net sampling of night-time scattering layers was done with a multiple opening-and-closing codend system attached to a modified international young-gadoid pelagic trawl. The trawlnet had an opening between wingtips of typically 21 × 9 m (189 m<sup>2</sup>) and a length of 35 m, with the 200-mm stretched mesh in the front panels decreasing to 10 mm in front of the codend. The six-codend nets of 1 m<sup>2</sup> opening had a 10-mm mesh with 1 mm detachable ends. The oblique night-time tows fished the first codend down to 600 m, the second for 20 min from 600 to 400 m, and the third and subsequent nets for 20 min each from 400 to 300 m, 300 to 200 m, 200 to 100 m, and 100 m to the surface. Catches from individual nets were sorted into species, weighed, and photographed for length estimates. Species were separated into functional groups of (i) small fish (<10 cm; dominated by gas-bladdered myctophids), (ii) large fish (>10 cm, many with gas bladders), (iii) gelatinous organisms, (iv) squid, and (v) crustaceans. The density of each functional group at each depth was estimated from the retained catch weight and the



**Figure 2.** Battery-operated, two-frequency *TS* probe operating at 38 and 120 kHz down to 600 m, used for *TS* measurements and echo counting.

volume of water filtered, calculated from the net opening, tow speed, and duration.

At the net-sampling location, *in situ TS* measurements at 38 kHz, 4 Hz ping rate, and 0.5 ms pulse duration were collected with a two-frequency, battery-operated *TS* probe with a 38.1 mm tungsten-carbide calibration sphere suspended 25 m below, lowered vertically to 600 m (Kloser *et al.*, 2007b). At each 50-m interval of the descent and ascent, the probe was held stationary for 5 min. The *TS* probe houses 38 and 120 kHz split-beam transducers. It has Simrad EK 60 transceivers and a Microstrain 3DM-GX1 for motion measurement (Figure 2). The acoustic, temperature, depth, and motion data were logged to a PC with battery power sufficient for 3–5 h duration. The specifications of the split-beam transducers (38 and 120 kHz) and relevant calibration constants are outlined in Table 1. Ryan *et al.* (2009) detail the variation in the on-axis calibration of these transducers with depth. Only data from the 38-kHz transducer are reported here. The directivity compensation of the split-beam transducer was optimized for a flat response over along- and athwart-target angles up to 3° by adjusting the half-power beam width and along- and athwart-offset angles as a function of depth.

Within EchoView (SonarData; <http://www.echoview.com/>), the raw *TS* data were determined using target-selection criteria adjusted to optimize the maximum amount of targets while rejecting the returns from high-density regions (Table 1). Single targets were tracked to explore uncertainties in the single-target detection process, the compensation for off-axis detection angles and noise, as described by Kloser and Horne (2003).

Estimates of small, gas-bladdered fish density were based on two methods. First, the wet-weight biomass,  $B_{ij}$  (g m<sup>-2</sup>), of species group  $i$  in a depth layer  $j$  of height  $R_j$  (m) and mean volume-backscattering strength (MVBS)  $\overline{S_{v_j}}$  (dB re 1 m<sup>-1</sup>) was calculated for each depth range matched to the net sampling, using

$$B_{ij} = \frac{R_j F_{ij} W_{ij} 10^{\overline{S_{v_j}}/10}}{\sum_i F_{ij} 10^{\overline{TS_{ij}}/10}} \text{ (g m}^2\text{)}, \quad (1)$$

where  $\overline{TS_{ij}}$  (dB re 1 m<sup>2</sup>) is the mean *TS* of the species group with mean wet weight  $W_{ij}$  (g) and relative proportion by numbers in the net catch  $F_{ij}$ . *TS* estimates of the dominant small, gas-bladdered fish were determined from *in situ* measurements. The associated

**Table 1.** *TS*-probe specifications and calibration details for the 38 and 120 kHz transducers and single-target selection criteria.

Parameter	Channel 1	Channel 2	Units
Frequency	38	120	kHz
Simrad transducer type	ES38DD	ES120-7DD	Split beam
Power	2 000	500	W
Beam width –3 dB power (along/athwart)	6.9/7.1	6.7/6.5	degrees
Equivalent beam width	–20.70	–21.30	dB re 1 steradian
Nominal absorption	0.01	0.034	dB m <sup>-1</sup>
Transducer gain	23.9	23.6	dB
Angle sensitivity	21.9	23	
Calibration-sphere <i>TS</i>	–42.4	–39.5	dB re 1 m <sup>2</sup>
<i>TS</i> threshold	–80	–80	dB
Pulse-length determination level	12	12	dB
Minimum normalized pulse length	0.3	0.3	
Maximum normalized pulse length	1.8	1.3	
Maximum beam compensation	12	12	dB
Maximum phase deviation	1	1	degrees

species groups of gelatinous organisms, squid, other fish, and crustacean species were only a small (<20%) contribution to the acoustic backscatter, and their  $TS$  was estimated from their length  $L$  (cm) using the formula  $TS = 20 \log L + B$ , with  $B$  as  $-85$ ,  $-80$ ,  $-70$ , and  $-90$  dB for the groups, respectively, see Simmonds and MacLennan (2005). Second, the wet-weight biomass of small gas-bladdered fish ( $B_j$ , dominated by myctophids) for each net-sampled depth layer  $R_j$  was calculated from the average number of single targets  $\bar{s}_j$  detected within a volume  $V$  ( $\text{m}^3$ ), defined as that within  $3^\circ$  of the transducer axis and a range of 5–15 m from the transducer to minimize beam compensation and signal threshold bias:

$$B_j = \frac{R_j \bar{s}_j W_j}{V} (\text{g m}^{-2}). \quad (2)$$

For basin-scale sampling, the fishing vessels with Simrad 38-kHz ES60 echosounders and ES38B transducers were calibrated each year with a standard sphere before surveys of blue grenadier were done (Kloser *et al.*, 2007a). Acoustic data were recorded to hard disk at full sample resolution. Calibration data files were corrected for echo-amplitude, triangle-wave variability before analysis (Ryan and Kloser, 2004). This correction was not made for transit data, because the error as a result of triangle-wave variability averages to zero for large datasets. In summary, pulse lengths of 1 and 2 ms were used with results at 2 ms preferred because of lower noise. The transmission power was 2 kW. The calibration-default offsets varied 1 dB between the three vessels and by 0.3 dB for the same vessel between years.

The fishing-vessel data were processed in EchoView (version 4.40) where calibration offsets were applied and absorption  $9.75 \text{ dB km}^{-1}$  and sound speed  $1500 \text{ m s}^{-1}$  were used. Background noise was removed on a per-ping basis by subtracting the average MVBS between 1300 and 1490 m, with time-varied-gain removed from each ping (Kloser, 1996). The calibrated 38-kHz volume-backscattering strengths ( $S_v$ ,  $\text{dB re } 1 \text{ m}^{-1}$ ) were resampled by averaging horizontally over 1-km intervals and vertically from 0 to 1500 m in 1-m depth bins. To estimate basin-scale biomass metrics, the water column was segmented into 100-m depth layers down to 800 m and three time zones of day, night, and twilight. Twilight was defined as 1.5 h either side of sunrise and sunset. Echo integrals of the acoustic data were linearly averaged vertically by longitude and summarized per transect. Temperature and salinity profiles along the transect were derived by inference based on satellite altimetry, SST, and all available subsurface information was interpolated within a  $0.1^\circ$  grid scale (Ridgway *et al.*, 2008).

## Results

### Fine-scale net and acoustic observations

The night-time net and *in situ*  $TS$  data were obtained in an open ocean region,  $28^\circ\text{S } 159^\circ\text{E}$ , which comprises continuous horizontal scattering layers with distinct vertical stratification of higher intensity ( $S_v$ ,  $-70$  to  $-65$  dB re  $1 \text{ m}^{-1}$ ) at depths of 0–200 m and 400–600 m. The five net samples of 100 min total duration from 600 to 0 m retained 5.4 kg of wet-weight biomass, comprising 2.7 kg of small fish with gas-filled bladders, 1.0 kg of squids, 0.8 kg of large fish with gas-filled bladders, 0.5 kg of gelatinous organisms, and 0.4 kg of crustaceans. The micronekton fish represented 32 taxa, dominated by four families (Myctophidae, Sternoptychidae, Gonostomatidae, and Photichthyidae) exceeding 1% by numbers. Myctophids, represented by five taxa, were the most dominant (84%). *Ceratoscopelus warmingii* was the dominant species with a gas-filled bladder (75%). Myctophids represented 51% of the total catch by weight, representing 80% of the acoustic signal with a wet-weight catch rate of  $1.6 \text{ g m}^{-2}$  from 0 to 600 m. The highest catch rates ( $0.42$ – $0.60 \text{ g m}^{-2}$ ) were obtained with nets fishing the surface layer, 0–100 m, and the deepest layer, 400–600 m (Table 2). The mean standard length and weight of myctophids increased with depth, being 50 mm and 3.5 g near the surface and 70 mm and 6 g at 400–600 m depths, respectively (Table 3).

Myctophid biomass was estimated from the MVBS of the layer fished by the net, combined with the net-species composition and *in situ*  $TS$ . The  $TS$  of the dominant myctophid (*C. warmingii*) obtained from the  $TS$  probe ranged from  $-40$  to  $-65$  dB at 38 kHz and from  $-45$  to  $-75$  dB at 120 kHz. Based on the 38 kHz data, the mean  $TS$  of assumed myctophids was  $-56.6$  dB (range  $-65$  to  $-45$  dB) near the surface to  $-49$  dB (range  $-55$  to  $-40$  dB) at 500–600 m (Figure 3; Table 3). Using these  $TS$  values, the acoustic biomass ranged from 1.2 to  $10.3 \text{ g m}^{-2}$ , being highest in the 0–200-m and 400–600-m depth intervals, with a total biomass at 0–600 m depth of  $29.1 \text{ g m}^{-2}$  (Table 3). The acoustic-biomass estimate of micronekton gas-bladdered fish (dominated by myctophids) was 17.9 times higher than the net biomass of  $1.6 \text{ g m}^{-2}$ .

Using data from the  $TS$  probe, the micronekton density was estimated from the average number of targets within the volume defined by the range interval 5–15 m and target angles within  $3^\circ$  of the beam axis. Target detections were at a maximum within this range and reduced by a factor of two when the depth range increased to 25 m in high-density regions. The  $TS$  range assumed for myctophids was  $-45$  to  $-65$  dB for depths of 0–300 m and  $-40$  to  $-60$  dB for depths of 300–600 m. The number of targets within the insonified volume varied from 0.01 to 0.22 fish, being highest within the 0–200-m and 500–600-m

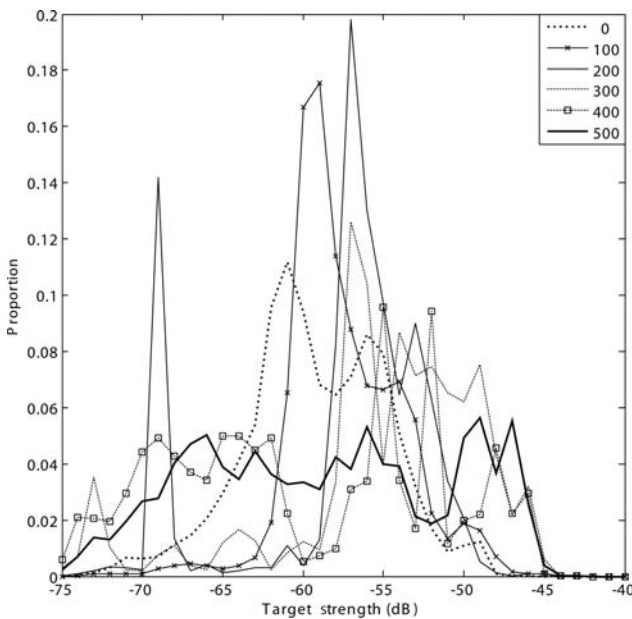
**Table 2.** Wet-weight biomass ( $\text{g m}^{-2}$ ) of mid-trophic level organisms retained in the depth-stratified tow from 600 m to the surface with 20 min fishing time per depth range.

Depth (m)	Myctophids ( $\text{g m}^{-2}$ )	Gelatinous organisms ( $\text{g m}^{-2}$ )	Squid ( $\text{g m}^{-2}$ )	Other fish ( $\text{g m}^{-2}$ )	Crustaceans ( $\text{g m}^{-2}$ )
0–100	0.43	0.20	0.02	0.14	0.03
100–200	0.42	0.04	0.18	0.05	0.03
200–300	0.06	0.04	0.24	0.09	0.05
300–400	0.11	0.02	0.00	0.04	0.04
400–600	0.60	0.07	0.01	0.15	0.06
Total	1.62	0.37	0.44	0.47	0.22
Proportion of total	0.52	0.12	0.14	0.15	0.07



**Table 3.** Wet-weight biomass comparisons of small gas-bladdered fish (predominantly myctophids) for a depth-stratified net tow in five depth zones using filtered water volume and results from echo integration and echo counting.

Depth (m)	MVBS (dB re $1 \text{ m}^{-1}$ )	Myctophids				Biomass		
		TS (dB re $\text{m}^2$ )	Number	Length (mm)	Wet-weight biomass (g)	Net ( $\text{g m}^{-2}$ )	Integration ( $\text{g m}^{-2}$ )	Counting ( $\text{g m}^{-2}$ )
0–100	–70.0	–56.6	466	50	2.1	0.43	7.64	4.26
100–200	–70.0	–56.0	458	50	2.1	0.42	7.66	3.32
200–300	–74.0	–54.4	42	60	3	0.06	1.20	1.59
300–400	–73.8	–52.0	50	70	5	0.11	2.33	1.15
400–600	–68.1	–49.0	137	70	5	0.60	10.26	5.35
Total						1.62	29.08	15.67
Factor difference						1.0	17.9	9.6



**Figure 3.** Proportion of target strengths (dB re  $1 \text{ m}^2$ ) for each 100-m depth range for targets within 30 m range and  $3^\circ$  off-axis, depth ranges starting at 0 m (dashed) and at 500 m (solid) are in bold lines. Small gas-bladdered fish are assumed to have a TS between  $-45$  and  $-65$  dB for ranges starting at 0 m and  $-40$  to  $-55$  dB for ranges starting at 500 m.

depth intervals. Based on the volume insonified ( $10.8 \text{ m}^3$ ), the density of micronekton fish within 100 m bins ranged from  $1.15$  to  $5.35 \text{ g m}^{-2}$  with a total biomass (0–600-m depth) of  $15.7 \text{ g m}^{-2}$ , which is 9.6 times higher than that from net sampling,  $1.6 \text{ g m}^{-2}$  (Table 3).

### Basin-scale observations

At constant latitude,  $41^\circ\text{S}$ , across the Tasman Sea (from  $149$  to  $170^\circ\text{E}$ ), the 38 kHz echosounders on the fishing vessels recorded the vertical migration of oceanic micronekton over 3-d periods in 2005, 2006, and 2007 (Figure 4). Notable features included noise interference from 800 to 1200 m in 2006, and in 2005 the backscatter (inferred biota) appeared to be much reduced by a large warm-water eddy centred at  $151^\circ\text{E}$  (Figure 4a). Over the basin, the MVBS between 10 and 800 m varied by 25% among 2005, 2006, and 2007 [ $-71.2$  dB (s.d. 1.5),  $-70.2$  dB (s.d. 1.1), and  $-70.4$  dB (s.d. 1.2), respectively]. In contrast to the stability

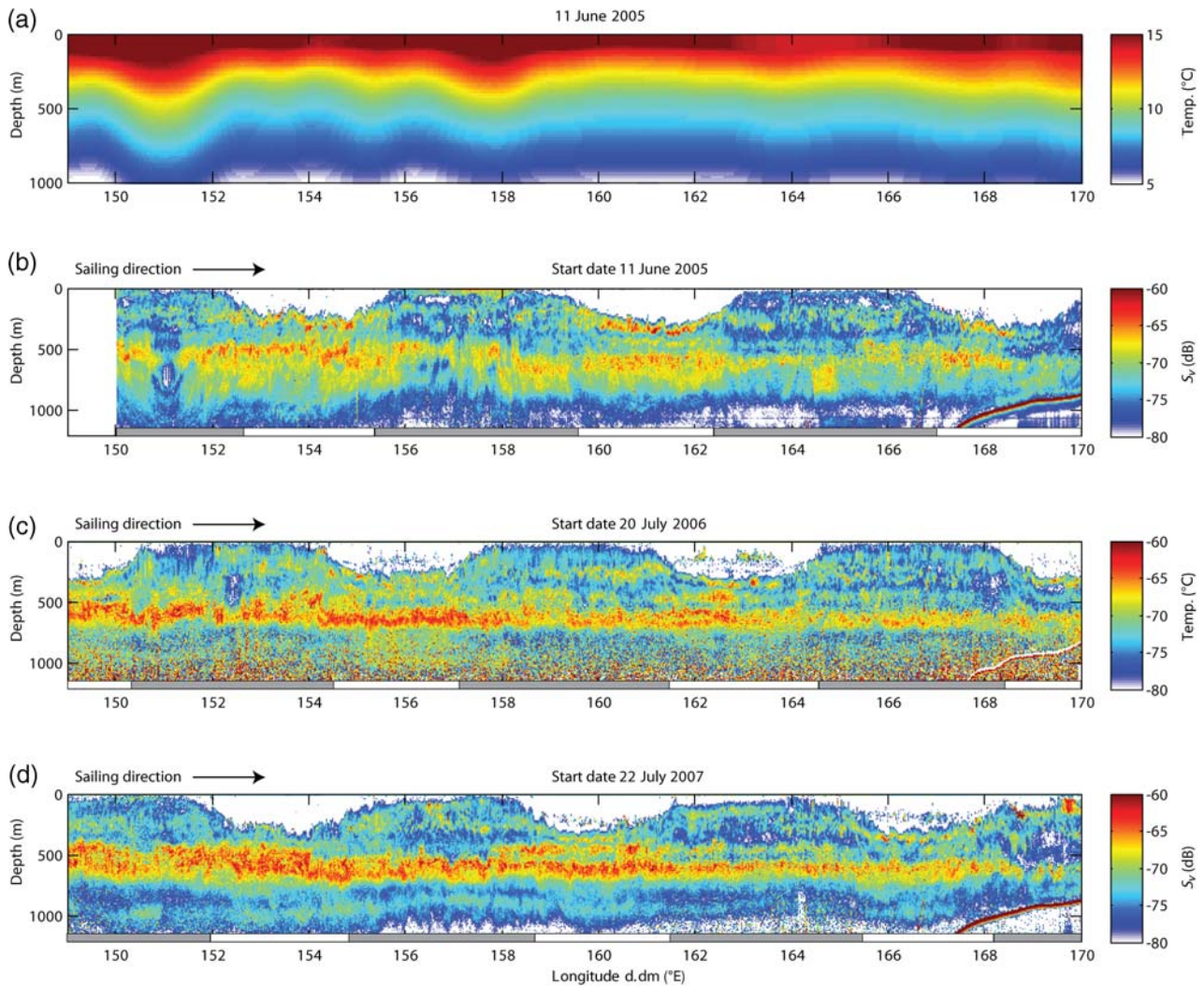
in backscatter observed from the constant-latitude transects, there was a 5.5 dB difference between the 2004 and 2007 transects from  $41$  to  $45^\circ\text{S}$  and  $149$  to  $165^\circ\text{E}$  (Figure 5). The 2004 acoustic data, collected in late August, emanated from cooler water, averaging  $9.6^\circ\text{C}$  (range  $7.8$ – $10.7^\circ\text{C}$ ), than the 2007 data collected in mid-June from water averaging  $10.3^\circ\text{C}$  (range  $9.0$ – $12.0^\circ\text{C}$ ; Figure 5). Of note is the deepening (2004 and 2007) and stronger intensity (2007) of the deep scattering layer with increasing latitude and longitude (Figure 5).

## Discussion

### Comparison of net-biomass estimates with acoustic estimates

The estimated biomass of small, gas-bladdered fish in the open ocean varied considerably between acoustic and net-sampling methods. We report here a factor of 9.6–17.9 difference between acoustics (echo counting and echo integration) and trawl biomass estimates of small gas-bladdered fish (dominated by myctophids). Both the trawl and acoustic estimates are prone to catchability and selectivity bias. Biomass estimates from trawling have well-known biases as a result of mesh selectivity and towing speed, whereas catchability is affected by avoidance and the effective volume sampled. In our study, we used a net-opening area of  $189 \text{ m}^2$ , which may be compared with previous studies of a similar but smaller net with a  $105\text{-m}^2$  mouth opening (Koslow *et al.*, 1997; Williams and Koslow, 1997). Our night-time, fish-biomass estimate of  $1.62 \text{ g m}^{-2}$  is similar to the  $2.2 \text{ g m}^{-2}$  reported for a southern sampling site at  $44^\circ\text{S}$  that was also dominated by gas-bladdered myctophids (Williams and Koslow, 1997). Comparison of acoustic and net-sampling estimates of biomass at this site revealed a 7–21 factor difference between acoustic and net-biomass estimates (Koslow *et al.*, 1997). Defining and comparing the effective fishing area or catchability coefficient of the nets is problematic on account of the different net dimensions and mesh sizes. In our case, the catchability difference between acoustic and net-sampling estimates of biomass can be explained by a reduction in the effective net-sampling area from  $189 \text{ m}^2$  to some  $10.6$ – $20 \text{ m}^2$ , where the mesh size of the net reduces from 200 mm at the mouth to  $\sim 40$  mm near the codend.

Acoustic estimates of biomass were made using both echo integration and echo counting to minimize the effect of TS bias. For the echo-counting method, avoidance and increased sampling volume with range combine to decrease the density of the resolved targets and consequently the biomass estimate. A decrease in the biomass estimate can also happen at low densities when valid targets are not detected by the single-target selection algorithm. For these



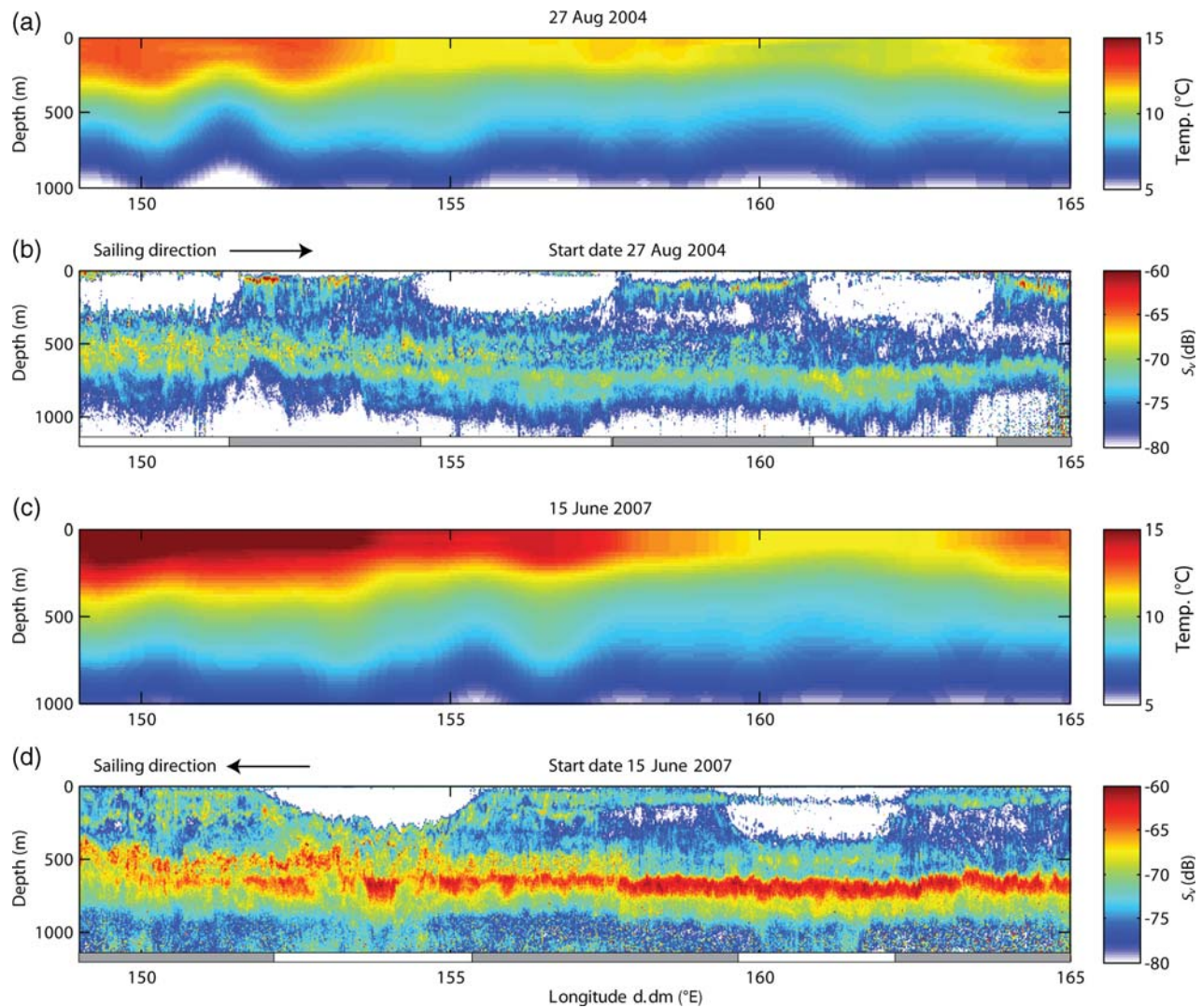
**Figure 4.** Cross section: (a) estimated temperature section for the transect in 2005, noting the large warm-water eddy centred at  $151^{\circ}\text{E}$  associated with low backscatter below and  $S_v$  ( $\text{dB re } 1 \text{ m}^{-1}$ ) from fishing-vessel acoustic data for years (b) 2005, (c) 2006, and (d) 2007. Data collected at 38 kHz along  $41^{\circ}\text{S}$  between  $149^{\circ}\text{E}$  and  $170^{\circ}\text{E}$ . Day/night sampling of the transects over three days are indicated by clear and dark bars, respectively.

reasons, echo counting tends to underestimate the true densities, which in this case is half of the echo-integration density. The echo-integration biomass estimate depends on the  $TS$  estimate. In this case, we estimated  $TS$  from *in situ* measures, but needed the  $TS$  distribution to obtain a linear average. The latter was determined by tracking single targets when the probe was drifting at designated depths and from experience with experiments and models for similar species (Kloser *et al.*, 2002). There is no direct visual verification that the  $TS$  values attributed to micronekton fish dominated by myctophids caught in the trawl reflect their true length and weight. The catch-length and -weight distributions may be biased on account of mesh selectivity and variable catchability. As a result of resonant scattering, the  $TS$  of myctophids at depth may be biased towards a particular species and length, depending on the bladder shape and volume (Kloser *et al.*, 2002). The increased length and weight of myctophids with depth observed in this study is consistent with net-sampling results reported elsewhere (Koslow *et al.*, 1997; Smith and Brown, 2002).

#### Comparison of acoustic estimates of biomass with estimates using ecological models

We estimated that the micronekton fish biomass off eastern Australia using acoustic-echo integration was  $29 \text{ g m}^{-2}$ , significantly higher than previous estimates from both net-sampling and modelled results for the same area (Lehodey, 2004). Fulton *et al.* (2005) estimated the migratory and non-migratory micronekton fish biomass for the oceanic Australian southern region EEZ to be  $0.5 \text{ g m}^{-2}$  on average. Lehodey (2004) estimated the total wet-weight forage biomass, in a similar region to our experiments, to be between  $2$  and  $6 \text{ g m}^{-2}$ . Based on our trawl composition, small fish comprise 50% of the wet-weight forage biomass, and our acoustic estimates of small-fish biomass are a factor of 5–58 higher than these model estimates. However, a recent Ecopath model of a northern part of the Tasman Sea estimated micronekton biomass (including myctophids but also fish from the families Sternoptychidae, Gonostomatidae, and Photichthyidae) at  $45 \text{ g m}^{-2}$ . This was supported by direct measures of primary





**Figure 5.** Estimated temperature profiles for (a) 2004 and (c) 2007 and associated  $S_v$  (dB re  $1 \text{ m}^{-1}$ ) from fishing-vessel acoustic data at 38 kHz in the region  $41\text{--}45^\circ\text{S}$   $149\text{--}165^\circ\text{E}$  for the same years (b) 2004 and (d) 2007. Day/night sampling of transects over three days are indicated by clear and dark bars, respectively.

productivity and other functional groups (Griffiths *et al.*, 2009). Clearly, our estimates are preliminary and require more sampling throughout the region, but they represent a good start to validating the biomass at these large scales.

#### Potential and challenge of basin-scale estimates of micronekton fish biomass

The present work demonstrates that the acoustic backscatter can be mapped at basin scales in three days using commercial fishing vessels. From these maps, the mean backscatter along  $41^\circ\text{S}$  has been stable within 25% over a three-year time-frame, and fine-scale day/night and longitudinal differences are evident. Regional models estimate the epi-, meso-, and bathypelagic fish biomass at  $0.5\text{--}3 \text{ g m}^{-2}$  (Lehodey, 2004; Fulton *et al.*, 2005). Results from net sampling within the north and south of the region are documented at  $1.6$  and  $2.6 \text{ g m}^{-2}$  and from acoustics  $16$  to  $29 \text{ g m}^{-2}$ , respectively. Our backscatter maps with MVBS of  $-70.5 \text{ dB re } 1 \text{ m}^{-1}$  at  $10\text{--}800 \text{ m}$  for the basin transects are similar to the data recorded for the northern and southern sites.

For that reason, preliminary estimates of wet-weight biomass for small fish in the entire Tasman Sea, which has an area of  $4.1$  million  $\text{km}^2$ , bounded by  $25\text{--}45^\circ\text{S}$   $147\text{--}170^\circ\text{E}$  and depths greater than  $1000 \text{ m}$ , are in the range  $2.1\text{--}8.2$  million tonnes for models,  $6.7\text{--}10.7$  million tonnes for nets, and  $64.3\text{--}119.2$  million tonnes for acoustics.

Acoustic methods are potentially useful for cost-effective sampling of micronekton fish at basin scales, but they require refinement. To determine the true density of biota with acoustics, the acoustic signal must be correctly allocated between the various dominant species. Multifrequency techniques have been used to separate species-functional groups and assist in interpreting the composition of net samples (Kloser *et al.*, 2002; Korneliussen and Ona, 2003). Targeted, depth-stratified trawling is also required to get biological data, such as species composition, lengths, and weights, as well as clarifying life-history characteristics to improve understanding of ecosystem function. A cost-effective way of obtaining both species and visually verified *TS* information is to deploy the sampling net with an attached acoustic-optical

system (Ryan *et al.*, 2009). Particular vessels could be selected for this sampling over a greater latitude range to improve description of the distribution and abundance of micronekton fish throughout the Tasman Sea.

The challenges facing basin-scale monitoring with acoustics are how to quantify the dominant functional groups and detect meaningful changes over time. The Tasman Sea is dominated by gas-bladdered myctophids that produce a substantial proportion of echoes at 38 kHz. Detecting shifts in the size and composition of species with and without swimbladders will be challenging because of resonant scattering and weak echoes. Using vessels of opportunity for sampling restricts the spatial and temporal coverage to locations where these vessels operate. Alternative sampling platforms, such as gliders or buoys, could give greater synoptic spatial and temporal coverage for acoustic estimates, but should still be complemented with physical and visual sampling. The spatial and temporal coverage of all sampling methods needs further investigation. The present work has demonstrated the fine-scale, acoustic, and net-sampling measurements that will be necessary for extrapolation to the larger basin-scale acoustic transects.

### Acknowledgements

We acknowledge several people who have assisted with this work. Graham Patchell (Sealord Group Ltd.) and Les Scott (Petuna Sealord Ltd.) are thanked for support in collecting the data from their vessels. We thank the National Facility Southern Surveyor for supporting the detailed net and acoustic-TS probe deployments. The CMAR instrument-design group of Matt Sherlock, Mathew Horsham, and Jeff Cordell deserve recognition for engineering the TS probe. C. Bulman and B. Fulton provided constructive comments on an earlier draft of the manuscript, as well as three external referees. D. MacLennan is thanked for improvements to the structure and flow of the text.

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doi:10.1093/icesjms/fsp077