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Final Report on *Zooplankton Aggregation Near Sills*

Mark V. Trevorrow

Prepared for:
U.S. Office of Naval Research, ONR Code 322BC, Dr. James Eckman
ONR grant number N00014-01-0273

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External Client Report
DRDC Atlantic ECR 2004-086
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Abstract

This report outlines acoustic methods and results from a 3-year collaborative study of zooplankton aggregations in a coastal fjord. Mid-water aggregations of zooplankton were surveyed using a calibrated, three-frequency (38, 120, and 200 kHz) vessel-based echo-sounder system, a multi-net towed zooplankton net (BIONESS), and a high-resolution *in situ* camera system (ZOOVIS). Dense daytime layers of crustacean zooplankton near 70 to 90 m depth were found in the lower reaches of the inlet, especially concentrated by tidal flows around a sill which rises above the layer. Quantitative Euphausiid and Amphipod backscatter measurements, combined with *in situ* species, size, and abundance estimates, were found to agree closely with size- and orientation-averaged fluid-cylinder scattering models. Similar *in situ* scattering measurements of Siphonophores were found to have a much stronger low-frequency (38 kHz) scattering strength, in agreement with a simple bubble scattering model. Distinctive near-surface *flow lines* near the sill were found to coincide with strongly sheared pycnoclines and high levels of turbulent dissipation. The combination of a lack of zooplankton present in these layers and a reasonable agreement with turbulence scattering models suggests these acoustically-visible layers are due to micro-structure scattering. A new high-resolution multi-beam sonar was used to map the ecologically important sill at Hoeya Head with 3 m resolution, and to sample in two-dimensions mid-water aggregations of fish, zooplankton, and turbulence.

Résumé

Le présent rapport décrit les méthodes acoustiques et les résultats d’une étude en collaboration de trois ans portant sur les agrégations de zooplancton dans un fjord. Des agrégations pélagiques de zooplancton ont été étudiées au moyen d’un échosondeur étalonné à trois fréquences (38, 120 et 200 kHz) installé à bord d’un navire, d’un système de filets à zooplancton (BIONESS) et d’un système de caméra à haute résolution (ZOOVIS) *in situ*. On a trouvé des couches diurnes denses de zooplancton crustacé à une profondeur d’environ 70 à 90 m, près de l’embouchure du fjord, concentrées surtout par les courants de marée autour d’un seuil qui s’élève au-dessus des couches. On a constaté que les mesures quantitatives de la rétrodiffusion produite par les euphausiacés et les amphipodes, combinées aux estimations *in situ* de la taille et de l’abondance des espèces, concordaient de près avec les modèles de diffusion moyenne en taille et en orientation dans la colonne d’eau. Par contre, des mesures *in situ* semblables de la diffusion par les siphonophores ont indiqué un indice de diffusion à basse fréquence (38 kHz) beaucoup plus élevé, comparable à un simple modèle de diffusion des bulles. Des *lignes de flux* distinctes près de la surface, près du seuil, coïncidaient avec des pycnoclines fortement cisaillées et des niveaux élevés de dissipation turbulente. La combinaison d’un manque de zooplancton dans ces couches et d’une concordance raisonnable avec les modèles de diffusion turbulente suggère que ces couches acoustiques sont causées par la diffusion par la microstructure. On a utilisé un nouveau sonar multifaisceau à haute résolution pour cartographier le seuil écologiquement important de Hoeya Head avec une résolution de 3 m et échantillonner en deux dimensions les agrégations pélagiques de poissons et de zooplancton ainsi que la turbulence.

Executive summary

Introduction

This report summarizes the acoustic results arising from a collaborative 3-year study of zooplankton aggregations at a coastal sill, supported by the U.S. Office of Naval Research. In Knight Inlet, a coastal fjord in British Columbia, the interaction of strong near-surface stratification with tidally-driven flows over a relatively shallow sill creates dramatic internal hydraulic flows. It was hypothesized that zooplankton communities would be strongly influenced by these flows, for example by concentration within zones of flow convergence, and would exhibit significant behavioural responses, such as sinking in the presence of turbulence.

Principal Results

An observational approach combining a three-frequency vessel-based echo-sounder, a multi-net zooplankton trawl (BIONESS), and an in situ high-resolution camera system (ZOOVIS) was used to probe zooplankton distributions in two separate sea-trials in Nov. 2001 and Nov. 2002. Dense daytime layers of crustacean zooplankton near 70 to 90 m depth were found in the lower reaches of the inlet, especially concentrated by tidal flows around a sill which rises above the layer. Quantitative backscatter measurements, combined with *in situ* species, size, and abundance estimates, were found to agree closely with size- and orientation-averaged fluid-cylinder scattering models. Acoustic measurements of Siphonophore scattering were found to agree with simple bubble models. New multi-beam sonar technology was able to produce high-resolution bathymetry and useful two-dimensional maps of mid-water fish, zooplankton, and turbulence.

Significance of the Results

The combined acoustic and *in situ* measurements of various zooplankton types allowed a strong verification of both averaged fluid-cylinder and bubble scattering models. This verification then allows the wider-area acoustic observations to be used for zooplankton behavioural studies. This study also demonstrated (possibly for the first time ever) the utility of new multi-beam sonar technology applied to mid-water zooplankton and turbulence studies.

Future Plans

The near-term thrust is to write several scientific papers describing these acoustic results, specifically on the acoustic scattering model verification and wide-area zooplankton distribution in Knight Inlet. Further assessment and improvement of the multi-beam volumetric sampling capability should be pursued.

Trevorrow, M., 2004. Final Report on Zooplankton Aggregation Near Sills. ECR 2004-086 DRDC Atlantic.

Sommaire

Introduction

Le présent rapport résume les résultats d'une étude acoustique en collaboration de 3 ans portant sur les agrégations de zooplancton à un seuil côtier et appuyée par l'Office of Naval Research des États-Unis. Dans le fjord Knight, en Colombie-Britannique, l'interaction entre une forte stratification près de la surface et des courants de marée par-dessus un seuil relativement peu profond engendre d'importants écoulements hydrauliques internes. On pose l'hypothèse selon laquelle ces courants influent fortement sur les communautés de zooplancton (par exemple, les organismes seraient concentrés dans les zones de convergence des courants) et que le zooplancton présente d'importantes réactions comportementales, comme se laisser descendre dans la colonne d'eau lorsqu'il y a turbulence.

Résultats principaux

On a utilisé une méthode d'observation combinant un échosondeur à trois fréquences installé à bord d'un navire, un système de filets à zooplancton (BIONESS) et un système de caméra à haute résolution (ZOOVIS) in situ pour sonder les distributions de zooplancton dans deux essais en mer distincts en novembre 2001 et en novembre 2002. On a trouvé des couches diurnes denses de zooplancton crustacé à une profondeur d'environ 70 à 90 m, près de l'embouchure du fjord, concentrées surtout par les courants de marée autour d'un seuil qui s'élève au-dessus des couches. On a constaté que les mesures quantitatives de la rétrodiffusion, combinées aux estimations de la taille et de l'abondance des espèces *in situ*, concordaient de près avec les modèles de diffusion moyenne en taille et en orientation dans la colonne d'eau. Des mesures de la diffusion de siphonophores concordaient avec de simples modèles de diffusion des bulles. Une nouvelle technologie de sonar multifaisceau était capable de produire des mesures bathymétriques à haute résolution et des cartes bidimensionnelles utiles de poissons et de zooplancton pélagiques ainsi que de la turbulence.

Portée

La combinaison des mesures acoustiques et *in situ* des divers types de zooplancton a permis une confirmation probante du modèle de diffusion moyenne dans la colonne d'eau et du modèle de diffusion des bulles. Cette confirmation permet ensuite d'utiliser les observations acoustiques dans une zone étendue aux fins de l'étude du comportement du zooplancton. Cette étude a également démontré (peut-être pour la toute première fois) l'utilité de la nouvelle technologie du sonar multifaisceau appliquée à l'étude du zooplancton pélagique et de la turbulence.

Recherches futures

L'objectif à court terme consiste à rédiger plusieurs documents scientifiques décrivant les résultats de cette étude acoustique et portant notamment sur la confirmation du modèle de diffusion acoustique et sur la distribution du zooplancton dans une zone étendue du fjord Knight. Il faudrait procéder à une évaluation et à une amélioration plus poussées de la capacité d'échantillonnage volumétrique du sonar multifaisceau.

Trevorrow, M., 2004. Rapport définitif sur l'agrégation de zooplancton près des seuils. ECR 2004-086 RDDC Atlantique.

Acknowledgements

This work was supported by a grant from the U.S. Office of Naval Research, Biological and Chemical Oceanography program (Dr. James Eckman ONR Code 322BC). The author is grateful for the support and the opportunity to collaborate with Dr. David Mackas of the Canadian Institute of Ocean Sciences and Dr. Mark Benfield of Louisiana State University. The field trials in Nov. 2001 and Nov. 2002, and particularly operations with the BIONESS trawl system, were ably supported by Doug Yelland and Darren Tuele of the Institute of Ocean Sciences. The author is also indebted to Moira Galbreath (also of IOS) for her analysis and explanation of the zooplankton samples. Significant assistance in bathymetric post-processing of the RESON 8125 data was provided by Dr. Anna Crawford of DRDC Atlantic. CTD and echo-sounder data from the 1995 cruise on *CSS Vector* was provided courtesy of Dr. David Farmer, then at the Institute of Ocean Sciences. The assistance of Grace Kamitakahara at IOS in retrieving the echo-sounder and CTD data is greatly appreciated. Tide gauge, echo-sounder, and Advanced Microstructure Profiler data from the *RV Miller* were provided courtesy of Drs. Mike Gregg and Jody Klymak of the Univ. of Washington and Oregon State Univ., respectively. In particular, the author is grateful for the assistance of Jody Klymak in transferring and explaining the 1995 data.

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1. Introduction

Overall, this collaborative project sought to understand the biological and physical mechanisms for producing and maintaining dense aggregations of meso-zooplankton in regions where ocean currents interact with steeply-sloping coastal sills. This project brought together observational expertise in multi-frequency echo-sounders, *in situ* zooplankton trawls, and *in situ* optical measurements, providing an opportunity to assess the strengths and weaknesses of each approach. This particular grant was coupled with sub-projects headed by David Mackas from the Institute of Ocean Sciences (IOS) in Sidney, B.C. and Mark Benfield from Louisiana State University. Mackas and group were responsible for coordination of ship-time on the *CCGS Vector*, operation of the BONESS, bongo, and Otter trawls, and subsequent processing of the zooplankton samples. M. Benfield was responsible for the development and testing of an in situ optical zooplankton imaging system (ZOOVIS). This report will focus on the acoustics aspects of this investigation, leaving the other investigators to summarize their specific results.

Typical vessel-based echo-sounders, operating at frequencies in excess of 30 kHz, offer high spatial-temporal resolution and useful sensitivity to depths up to 200 m. Operating at typical speeds of 6 to 8 knots, vessel-based systems are thus capable of wide-area surveys of zooplankton scattering layers, and are particularly useful for assessing small-scale patchiness and vertical layering. The drawbacks of purely acoustic surveys are an uncertain knowledge of the scatterer type (i.e. species and size), combined with an uncertainty regarding appropriate acoustic scattering models, making it nearly impossible to estimate the absolute abundance. However, when combined with net trawls and/or new *in situ* optical tools, direct comparisons allows verification of the acoustic scattering models necessary to link acoustic and biological parameters. Of course *in situ* sampling is more difficult, the post-analysis of net samples is time-consuming, and both nets and optical techniques lack the volumetric coverage *rate* of the echo-sounders. Thus, the thrust of this work is to demonstrate a combined acoustic vs. *in situ* approach, including a validation of generic scattering models for several zooplankton types. This validation then allows assessment of broader-scale zooplankton abundances in the Inlet, insight into predator-prey interactions, and comparison data for behavioral modeling studies.

Knight Inlet, British Columbia is a remarkable natural laboratory for investigating the physics of stratified tidal flows and internal solitary waves. Additionally, it was expected that zooplankton populations in this area would exhibit significant behavioral responses to these complicated stratified flows. This site provided (at least by oceanic standards) a very well-defined observational environment: i.e. a strong cross-isobath flow that was predictably time-varying at semidiurnal, diurnal and fortnightly time scales, a weak along isobath flow, and clearly identifiable upstream and downstream locations and populations. It was also possible to identify areas where the acoustic scattering was dominated by single zooplankton types, allowing straight-forward comparisons of acoustic and *in situ* samples. There was also a wealth of previously collected acoustic and physical oceanographic information from previous research programs (e.g. Farmer and Armi 1999a,b; Klymak & Gregg 2001,2003).

Knight Inlet is a fjord located on the south-central coast of British Columbia, fed by a glacier at its head some 90 km inland, and open to the coastal Pacific through Queen Charlotte Sound at its mouth (see Figure 1). Knight Inlet is relatively calm, with comparatively light winds and largely sheltered from oceanic wave action, making it ideal for survey operations. The lower part of Knight Inlet trends approximately WSW-ESE and has a roughly uniform width (see Figure 1), whereas the upper half of the Inlet trends more north-south. The inlet is quite steep-sided, with side-wall slopes near 45° and mountain peaks on each side reaching over 1000 m above sea-level. In the middle of the lower section there is an underwater sill running approximately North-South, roughly perpendicular to the East-West tidal flow, with typical crest depth near 65 m. This sill region has been the focus of extensive internal hydraulics investigations (e.g. Farmer & Armi 1999a,b; Klymak & Gregg 2001, 2003). To the west of the sill the seabed falls away to a flat bottom roughly 150 m deep, while on the eastern side and in the upper inlet there is a deeper basin with depths more than 500 m.

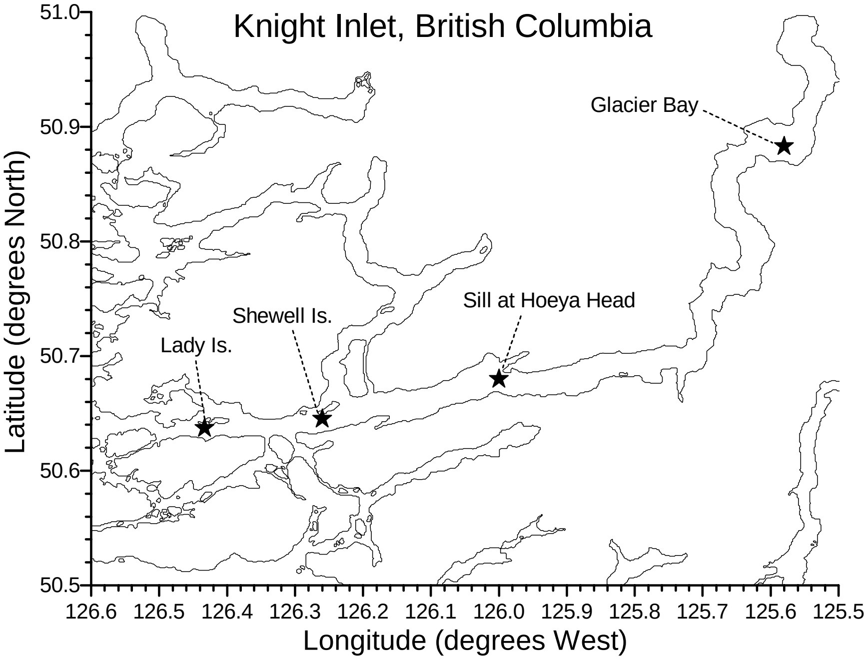

Figure 1 Map of Knight Inlet showing locations of data collection sites.

The area has dominantly semi-diurnal tides, with a strong fortnightly modulation and tidal heights ranging from 1.0 to 4.5 m. The flood tide runs eastward and northward. Typical peak tidal currents over the sill are near 1.5 $m \cdot s^{-1}$. During the late-autumn, Knight Inlet features a strong near-surface stratification, with a colder, fresher (7.5°C, 26 psu) surface layer from 6 to 10 m deep with relatively well-mixed conditions (8.0 °C, 32 psu) in the deeper waters. Vertical gradients of temperature, salinity, and density across the interface were typically strong (maxima approximately 2.0 $°C \cdot m^{-1}$, 8.5 $psu \cdot m^{-1}$, and 7.0 $kg \cdot m^{-4}$). The deep waters in the eastern basin and upper inlet tend to be slightly fresher than on the west side of the sill.

Ecologically, Knight Inlet is similar to other B.C. coastal inlets. In these inlets zooplankton scattering layers are commonly observed at 60 to 90 m depth in the daytime, exhibiting clear nocturnal migration to the near surface. These layers were found to be composed of larger crustacean zooplankton such as euphausiids (dominated by *E. pacifica*), amphipods (both hyperiid and gammarid), copepods, and various large Pandalid shrimp (Mackie & Mills 1983), with example pictures shown in Figure 2. Other species of pteropods, chaetognaths, ctenophores, and cnidaria are sometimes present, and known to migrate diurnally from the surface through depths of 250 m. Acoustically these other species can be largely ignored due to their low abundance and small target strength (these are soft-bodied animals). The exception to this is the hard-shelled planktonic pteropod *Limacina helicina*, which for typical animal size near 2 mm have a target strength at 200 kHz near -76 dB (Stanton et al. 1998), more similar to that of adult euphausiids. A few pteropods were collected in the BIONESS trawls, however all examples discussed in this work had negligible abundances of *L. helicina*. Similarly, scattering from copepod species is ignored in this work due to the combination of the small size of the adult copepods relative to the euphausiids and amphipods, and their relatively low abundances in the scattering layers. The most abundant large copepod species (e.g. *Neocalanus plumchrus*) would be absent from the surface waters in November due to deep seasonal migration.

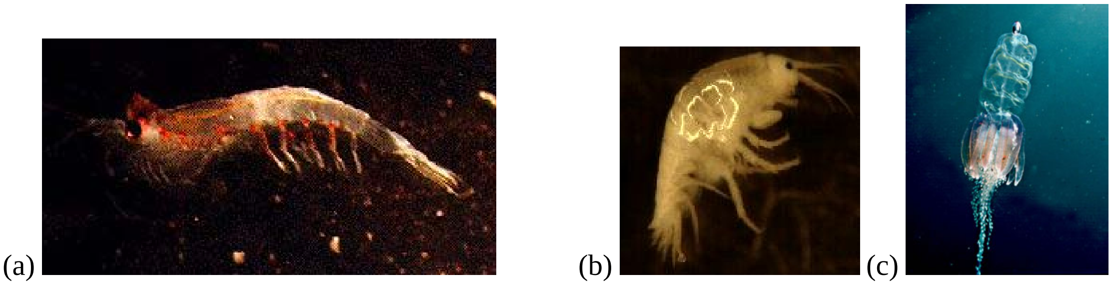

Figure 2 examples of typical zooplankters in Knight Inlet, (a) Euphausiid (*Euphausia pacifica*) 10-20 mm long, (b) Amphipod (*Cyphocaris challengeri*) 3-10 mm long, (c) Siphonophore (*Nanomia cara*) 1 mm diameter bubble, with colony up to 1 m long.

In contrast to the crustacean scattering dominant in the lower Inlet, acoustic scattering signatures in the upper Inlet appeared to be dominated by the physonect siphonophores. This type of siphonophore is a relatively strong acoustic scatterer due to the presence of a small gas-filled bubble (the pneumatophore) at the top of the colony. Unfortunately, trawl nets usually destroy these delicate siphonophore colonies, such that abundances can only be inferred from counting remaining component parts (e.g. bracts). Using visual observations from a submersible, Mackie (1983) observed significant abundances adult and larval *Nanomia cara* in Knight Inlet and other B.C. coastal inlets.

2. Retrospective Look at the 1995 Field Trials

In August and September 1995 a multi-disciplinary team converged on Knight Inlet to study the internal hydraulics of the tidal flows in this coastal fjord. The IOS ship *CSS Vector* along with two smaller launches (the *RV Miller* and *RV Bazan Bay*) were used. A wide variety of oceanographic instrumentation was employed, including echo-sounders, acoustic Doppler current profilers, CTDs, and turbulent microstructure profilers. Although the primary focus of the 1995 experiments was the physical oceanography of stratified flows (see Farmer & Armi 1999a,b; Klymak & Gregg 2001, 2003), as a by-product an impressive qualitative data set on the distributions of zooplankton and fish was collected. In the first phase of this present work, a retrospective study was conducted to assess zooplankton occurrence and behaviour observed in 1995, resulting in a 2001 technical report by the author. This section will summarize the lessons learned.

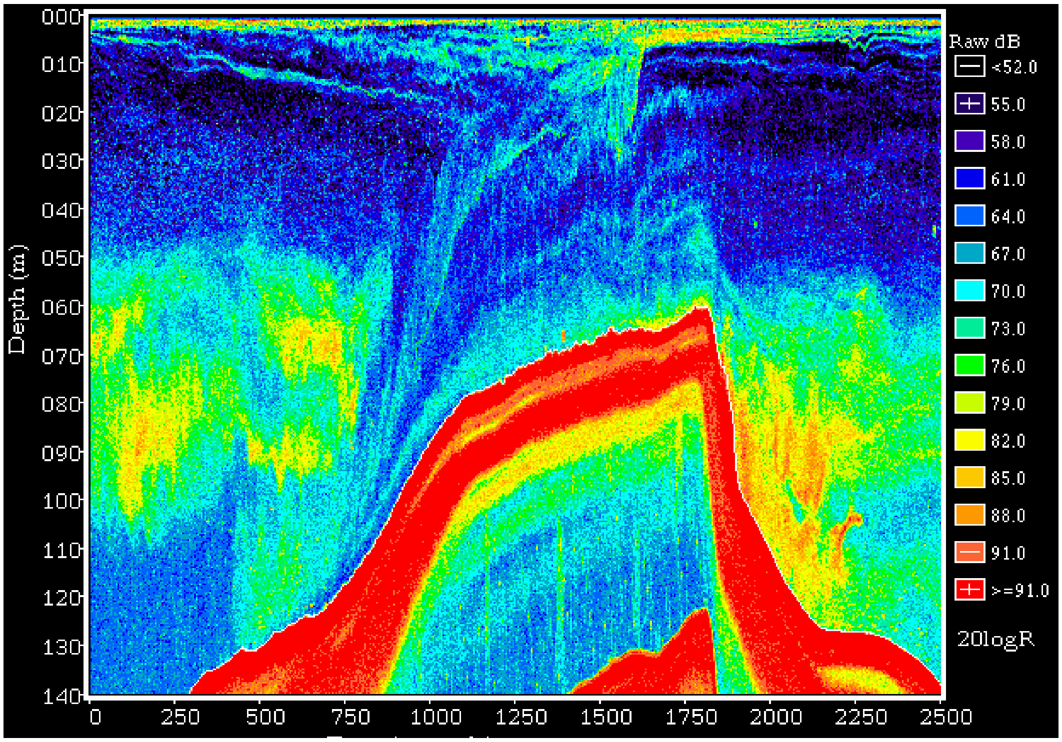

Figure 3 Uncalibrated 200 kHz echo-sounder intensity vs. depth and time (seconds) starting 1715UT Aug. 23rd, 1995 from *RV Miller* heading from east to west across sill during daytime flood tide. Tidal flow is from right to left. White line indicates the detected seabed. Data courtesy J. Klymak.

The high-frequency echo-sounders used during the 1995 field surveys provided high spatial and temporal resolution imaging of the tidal flows and zooplankton distributions. Two BioSonics model 101 echo-sounders were used: a 200 kHz system mounted on the *RV Miller*, and a 120 kHz system deployed on a strut from the starboard side of the *CSS Vector*. Unfortunately, neither system was acoustically calibrated, nor were any zooplankton net samples collected.. A great deal more could have been done with the acoustic data if either of the two echo-sounders had been acoustically calibrated. Such calibrations would have allowed quantitative assessment of zooplankton abundances and some verification of the microstructure scattering models.

Figure 3 shows a typical example of the echo-sounder data. During both flood and ebb tide there were strongly sheared internal hydraulic flows over the sill. A consistent feature of all acoustic echograms were distinct *flow lines* within the upper 15 to 20 that correspond closely to strong vertical gradients of temperature and salinity. During flood tide (as in Fig. 3) a flow bifurcation commonly appeared over the sill, with a strong downward jet of water extending from about 15 m depth down the eastern slope to approximately 130 m depth. Downstream of the bifurcation there was a near-surface region of flow stagnation with active mixing along the boundaries. Along the interface of this downward flow, shear instabilities, undulations, and overturns were often observed (described by Farmer and Armi 1999a,b).

The zooplankton exhibited their classic diurnal migration habits, forming into relatively dense layers at 70 to 120 m depth during the day and dispersing throughout the entire water column at night. This behaviour suggested that these zooplankton were dominantly Euphausiids, which was verified by later BIONESS trawls in 2001 and 2002. On both ebb and flood tides, there was evidence that the zooplankton layers were trapped and concentrated by the flow against the upstream side of the sill (which projects above this daytime scattering layer), and clearly demonstrated in Fig. 3. Upstream of the sill there was some evidence for zooplankters diving to the seabed to avoid being caught in the intensely turbulent flows, ending up as bottom-hugging layers along the upstream slope.

A comparison of acoustic scattering with the *in situ* temperature, salinity, and turbulence profiles suggested that microstructure scattering was responsible for the *flow lines* appearing in the strongly stratified near-surface region (upper 20 m). Over the crest of the sill the flow often separated into distinct layers with strong pycnoclines and current shear at the layer boundaries. Through the use of microstructure scattering models, volumetric backscatter levels were predicted along these boundaries which were roughly consistent with the acoustic measurements. In 1995 direct microstructure measurements were made using the Advanced Microstructure Profiler (AMP) deployed from the *RV Miller* while simultaneously conducting echo-sounder surveys. AMP measured high-resolution temperature, salinity, and velocity shear as a function of depth, from which estimates of ε, N, and gradients of Temperature and Salinity were extracted within 0.5 m depth bins.

Figures 4 and 5 show the echo-sounder and AMP profile data for a cast taken near the sill crest during ebb tide on Aug. 30th. The echo-sounder image shows the usual internal flow bifurcation above the sill crest, with a strong down-welling jet on the western side of the sill. The AMP profile crossed several distinct linear features within the upper 20 m before plunging through more diffuse scattering regions likely composed of zooplankton. Through comparison with the AMP data (Fig. 5), it can be seen that these distinct *flow lines* observed with the echo-sounder correspond to strong temperature and salinity gradients and to maximal values of dissipation rates and buoyancy frequency. Within the two strongest layers near 4 and 10 m depth there is good agreement between the acoustic data (converted using an approximate acoustic conversion factor) and the predicted microstructure scattering intensity. However, this cannot be construed as a verification of the scattering model, but rather a suggestion of the most likely source of the scattering. Below 20 m depth the scattering is not attributable to microstructure, leaving only zooplankton as the most likely source.

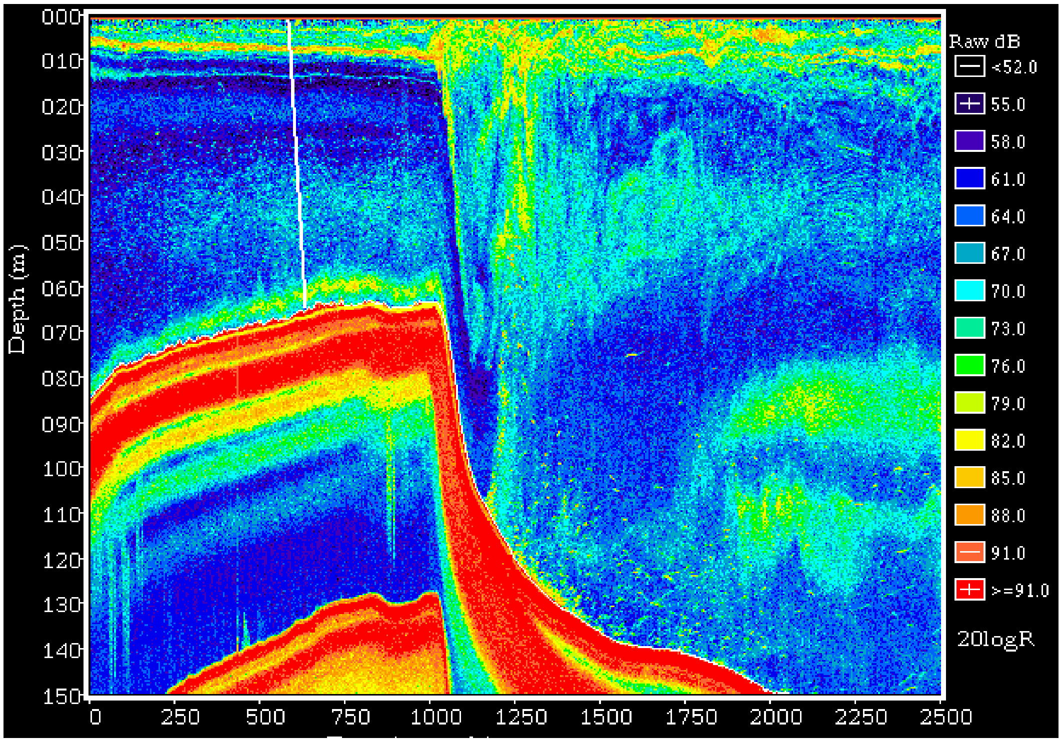

Figure 4 Raw 200 kHz echo-Sounder intensity vs. depth and time (seconds) starting 1514Z Aug. 30th, 1995 from RV Miller heading from east to west across sill during ebb tide. Tidal flow is from left to right. AMP profile indicated by white line near 600 s. Data courtesy J. Klymak.

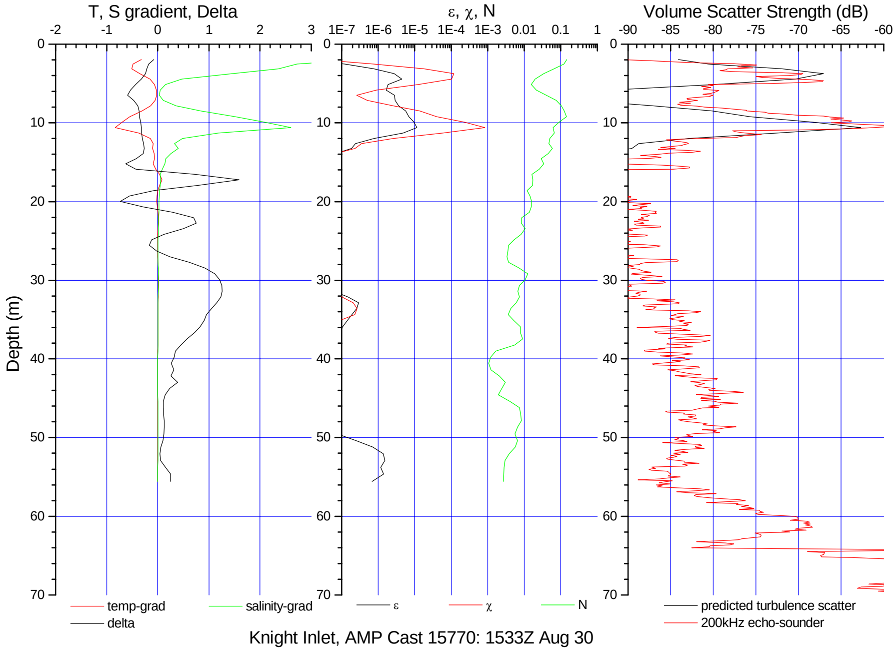

Figure 5 Advanced Microstructure Profiler data and comparison with 200 kHz echo-sounder at 1533Z Aug 30th, near eastern edge of sill during ebb tide. Seabed at 64 m. Data courtesy J. Klymak.

Summarizing the acoustic scattering observed in 1995, it was found that the predicted microstructure scattering at 200kHz had a similar level to that predicted for zooplankton (i.e. euphausiid and copepod). This made it difficult to distinguish between the two types solely on the basis of scattering strength. Fortunately, the suspected microstructure scattering was confined to narrow, easily identifiable *flow lines* near 10 to 20 m depth. Acquiring high-resolution temperature, salinity, and/or microstructure measurements co-located with the acoustic sounding would be sufficient to identify regions where turbulence is present. On the acoustic side, a multi-frequency approach would seem to be the obvious solution. At a minimum two echo-sounder frequencies should be used, one operating in the 10 - 50 kHz range and the other at 100 - 200 kHz. At or below 50 kHz the zooplankton scattering should be greatly reduced relative to the microstructure scattering level.

In addition to the above mentioned requirements for acoustic calibration, direct turbulence measurements, and *in situ* zooplankton sampling, this study suggests a number of hypotheses which should be investigated in future field surveys, namely:

1. It was asserted that the zooplankton clouds observed during daylight at 70 to 120 m depth were dominated by Euphausiids (largely *E. pacifica*), with other species making negligible contributions to the acoustic scattering. It was further assumed that zooplankton abundances were low or negligible within the strongly stratified upper layers during the day. Net trawls and other *in situ* sampling are clearly necessary, with particular attention paid to the potential presence of species that are strong scatterers, such as hard-shelled Pteropods and Siphonophores.
2. Simple fluid cylinder models for the zooplankton scattering were proposed, based on previous modeling and measurement work. It was asserted that these low-resolution models were appropriate for measuring average scattering levels over populations with some variation in size and orientation. Clearly, it is necessary to investigate the validity of these models, through both net trawls to establish abundances and animal sizes, and through some form of *in situ* monitoring of animal orientation.
3. During daylight, it was speculated that some zooplankton from the pool trapped against the upstream slope were caught by the currents and carried up and over the sill, creating the observed near-bottom layer flowing over the sill crest. Simultaneous net and acoustic surveys overtop of the sill would shed light on this.
4. It was tentatively concluded that the distinct flow lines observed with the echo-sounder were due to turbulent microstructure scattering, with negligible contributions from zooplankton within these regions. Conversely, predicted microstructure scattering levels were negligible outside of these highly stratified zones, leading to the conclusion that zooplankton scattering dominated over the bulk of the water column. However, these conclusions are based on microstructure scattering models that have never been adequately field tested. Future efforts should be placed in establishing some confidence in these turbulent scattering models, particularly measuring the frequency dependence.
5. Very high levels of acoustic scattering were observed within the near-surface region (depths <10m), above the main pycnocline and away from zones of high turbulence. This scattering is possibly of biological origin, but the exact source is unknown. Near-surface zooplankton samples are necessary.

3. Observational Approach

Two separate 2-week-long sea-trials were conducted on the *CCGS Vector* in Nov. 2001 and Nov. 2002 (specifically Nov. 12-25, 2001 and Nov. 11-24, 2002). The main acoustics tool used during both trials was a vessel-based, three-frequency echo-sounder system. The echo-sounder transceiver and data acquisition computer systems were custom-made at IOS in mid-2001, and specifically tuned for the hull-mounted transducers on the *CCGS Vector*. For the 2001 sea-trials operating frequencies of 40, 100, and 200kHz were used. In 2002 the three hull-mounted transducers were replaced, with new operating frequencies of 38, 120, and 200 kHz and more closely matched beam widths (7° to 9°). Overall, this echo-sounder system was operated for three primary objectives, specifically:

1. To measure detailed zooplankton vertical and horizontal distributions for comparison with the BIONESS towed plankton nets, the ZOOVIS in situ camera, and bongo net hauls.
2. To assess spatial distributions of zooplankton, fish, and turbulent microstructure over and around the sill at Hoeya Head during *daylight* hours at various phases of the tide.
3. To assess broad-area zooplankton distributions in the upper/eastern and western areas of Knight Inlet.

Thus, this three-frequency sounder was operated during most of the *CCGS Vector* operations, generally either while (a) performing profiles across the sill or along the inlet, or (b) supporting the BIONESS or ZOOVIS deployments. The echo-sounder operating parameters were largely the same during the two field trials. During most survey runs the echo-sounder was operated at a 1.0 Hz ping-rate, with all channels transmitting a 0.5 ms (37 cm) pulse. Each channel was sampled at 12,500 samples per second (6 cm) with 16-bit (93 dB) resolution. The normal maximum recording range was 200 m. DGPS position data was recorded in the sounder data files.

The acoustic analyses required that the raw echo-sounder data be converted to calibrated volume backscatter strength. Towards this end, acoustic calibration data was collected during both the early parts of sea-trials. These calibrations used as reference the backscatter from precisely machined tungsten-carbide spheres (38, 40, and 42.9 mm diameter). Then, using standard echo-sounder equations, the raw digital data was converted to volumetric scattering strength profiles. The echo-sounder insonified volumes varied with transducer beam-width and strongly increasing with range, typically spanning 1 to 50 m^3.

In the Nov. 2002 sea-trial a new RESON 8125 multi-beam swath-bathymetric sonar was evaluated. This sonar operated at 455 kHz, collecting echoes within a fan of 240 x 0.5° beams to 120 m range with range resolution near 3 cm. The along-track beam-width was 1.0°. In it's normal bathymetric mode, simultaneous range-to-seabed and sidescan sonar imagery were produced. This sonar also included real-time corrections for ship's heading (gyro-compass), attitude (pitch-roll-heave sensor), and position (DGPS). The sonar head was mounted on a port-side strut with the 120° fan of beams athwartships from a depth of 3.35 m (see Figure 6). A detailed bathymetric survey of the sill at Hoeya Head was performed on Nov. 21st. Additionally, the RESON multibeam sonar had a volumetric sampling mode which enabled imaging the across-track extent of fish schools, zooplankton layers, and turbulent billows.

Figure 6 Reson 8125 multibeam sonar mounted on the bottom of a strut mounted on the port side of the *CCGS Vector*, Nov. 2002. For deployment the strut swings downward to a vertical position with the sonar head at 3.35 m depth.

Sea-truth samples of zooplankton abundance, size, and species composition were obtained by towing a BIONESS instrumented multiple net sampler (Sameoto et al. 1980) at selected locations. The BIONESS carries 9 nets that are opened in sequence (see Figure 7). Depth and cumulative volume filtered are continuously monitored with a pressure sensor and flow-meter. The BIONESS is typically towed horizontally or obliquely at a forward speed of about 1.5 m·s^{-1}. The nets are opened and closed in sequence, either to divide the water column into a stacked series of depth strata, or to obtain a horizontal sequence of samples from one depth stratum (e.g. tracking an euphausiid scattering layer), or some combination of these two strategies. The echo-sounders were used during the BIONESS tows to guide the nets to particular zooplankton scattering layers, and to prevent running into the seabed. The entire sample from each BIONESS tow stratum was preserved in formalin and for later laboratory for identification and enumeration.

Figure 7 BIONESS multi-net zooplankton trawl ready for deployment. System has 9 remote-controlled nets with 0.25 m^2 mouth opening and 0.23 mm mesh size.

The ZOOVIS system was a high-resolution digital camera capable of resolving individual zooplankters (see Figure 8). A detailed description of this system can be found in Benfield et al. (2002). For the Knight Inlet 2002 surveys, ZOOVIS had a sampling volume of 10.95 x 10.95 x 3.69 cm (overall sampling volume of 0.442 liters), and was capable of resolving animals greater than 2 mm in size at a distance of approximately 40 cm. Images were acquired at 4-s intervals while the instrument was profiled up and down at 50 $cm \cdot s^{-1}$ through a given zooplankton layer. Images were analyzed using a combination of visual inspection and automated image processing. Average euphausiid size and abundance estimates were calculated for comparison with the acoustic and BIONESS estimates. A unique benefit of the ZOOVIS system was the ability to determine *in situ* animal orientation.

Figure 8 ZOOVIS profiling digital camera system.

4. Summary of New Acoustic Results

4.1 Acoustic Scattering Models

To proceed from acoustic back-scatter strength to *in situ* abundance estimates, the local species and size distributions need to be determined, followed by use of this information in an appropriate scattering model. In this study the ground truth was provided by mainly by the BIONESS trawls, supplemented by Bongos, Otter trawls, and ZOOVIS. For the purposes of verifying scattering models it is preferable that the acoustic scattering be dominated by a particular species or scatterer type. In the case of Knight Inlet, the BIONESS trawls showed that the acoustic scattering in the lower inlet were generally dominated by euphausiids with length near 16 mm, as they are larger and generally in greater abundance than other species. Other zooplankters, such as amphipods, adult copepods, pteropods, and siphonophores were sometimes found in moderate quantities, and at low euphausiid abundances they sometimes gave significant contributions to the acoustic backscatter. In the upper Inlet (Glacier Bay), the back-scattering was dominated by physonect siphonophores, and the net trawls found negligible quantities of euphausiids and amphipods in this area. Acoustic vs. BIONESS and ZOOVIS comparisons are the summary of a new manuscript to be submitted to the Journal of the Acoustical Society of America, and will be only be summarized here.

For a given scatterer type, an accurate model for the acoustic scattering strength as a function of acoustic frequency and zooplankter size must be found. While a number of models have been proposed in the literature, the most relevant in this situation is a size- and orientation-averaged model recommended by Stanton and Chu [2000], based on earlier models by Stanton et al. [1993]. This model is appropriate due to the moderately large insonified volumes of these echo-sounders (typically near 30 to 50 m^3 at the euphausiid layer depth of 60 - 80 m), such that each echo sample has contributions from potentially hundreds of animals. The specific model used here assumes the euphausiids or amphipods to be bent fluid cylinders with radius of curvature 3 x body length, a specific length to radius ratio, a Gaussian-distributed length (i.e. characterized by a mean and standard deviation), and a Gaussian-distributed orientation angle, again quantified by a mean and standard deviation. The data on euphausiid and amphipod length and aspect ratio come from BIONESS trawl data collected near the sill and at several sites in the western inlet.

The back-scatter from siphonophores is dramatically different from the crustacean model discussed above. The presence of the gas-filled pneumatophore yields a much higher scattering strength than equivalent fluid models, and the radial oscillations of the approximately spherical bubble give rise to a resonant peak. One feature of siphonophores is their apparent ability to maintain a constant pneumatophore size over a large range of depths, thereby maintaining a constant buoyancy (Benfield et al. 2003). As a first approximation, the back-scatter from the pneumatophore can be modeled as a bubble (Stanton et al. 1998; Warren et al. 2001; Benfield et al. 2003), for which there are well-established models (e.g. Medwin & Clay, 1998). The back-scatter from other fluid-like tissue in the siphonophore colony is significantly weaker than the bubble scatter and can be ignored.

4.2 Euphausiid Aggregations in the Lower Inlet:

Scattering layers dominated by euphausiids were commonly observed in the lower inlet and near the sill at Hoeya Head. A specific deep-water comparison between the echo-sounder and BIONESS results taken at 0830h Nov. 23 near Shewell Island will be examined here in detail. This example was chosen because it was located well away from the complicated, turbulent flows in the sill region and because the net trawls indicated moderate euphausiid abundance with only minor amounts of other species.

Figure 9 shows a volumetric scattering strength (S_v) vs. depth and time echogram, overlain with the trajectory of the BIONESS sampler. The BIONESS acquired three nets in the lower sub-layer at 85 – 105 m depth and three more nets within the upper sub-layer at 72 – 90 m. Each net sampled between 50 and 80 m^3 of the zooplankton layer. Euphausiid abundances vs. size (1 mm size classes) were averaged over each set of three, with resulting size distributions Gaussian-distributed with a mean length of 15.9 mm and 1.4 mm standard deviation. Also estimated from this data were averaged total abundances of 5.6 and 3.2 euphausiids per m^3 for the lower and upper sub-layers, respectively. This averaged abundance is considered low to moderate, as abundances in excess of 200 per m^3 were observed in other parts of the inlet. Finally, an examination of euphausiid captured at several sites in the lower inlet determined that the mean aspect ratio (length to width) was 7.6 ± 0.7.

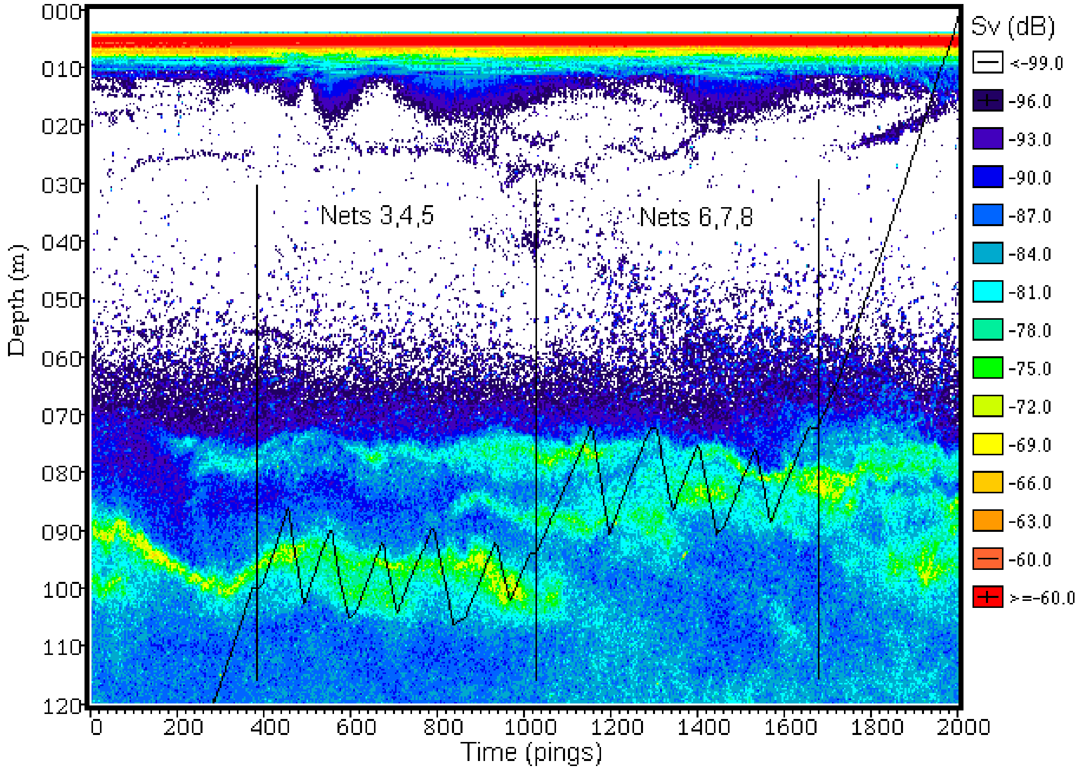

Figure 9 Volumetric scatter strength vs. depth and time at 120 kHz for 33.3 minutes starting 0833h, 23 Nov. 2002 near Shewell Island in Knight Inlet. Black line shows the trajectory of the BIONESS multi-net sampler, with labels indicating zones of net opening.

Summary profiles of volume scatter strength at the three frequencies for the two zooplankton sub-layers are shown in Figure 10. These S_v profiles were averaged in time over the same interval as the BIONESS net samples shown in Fig. 9. These profiles show the distinctive increasing scattering strength with frequency signature of euphausiid scattering layers. Specifically, the ratio between the scattering strength at 120 kHz to that at 38 kHz was approximately 14 dB, and between 200 kHz and 120 kHz the ratio was 4.5 dB. Within the lower sub-layer (88 - 102 m in Fig. 10a), the depth-averaged volume scattering strengths were -89.8, -75.7, and -70.45 dB (re 1 m^{-1}) at 38, 120, and 200 kHz respectively. The equivalent depth-averaged S_v in the upper sub-layer (70 - 88 m in Fig. 10b) were -90.1, -77.1, and -72.4 dB. Within the euphausiid scattering layers the signal-to-noise ratios were generally good, however the 200 kHz channel was largely noise dominated at regions above and below the euphausiid layer.

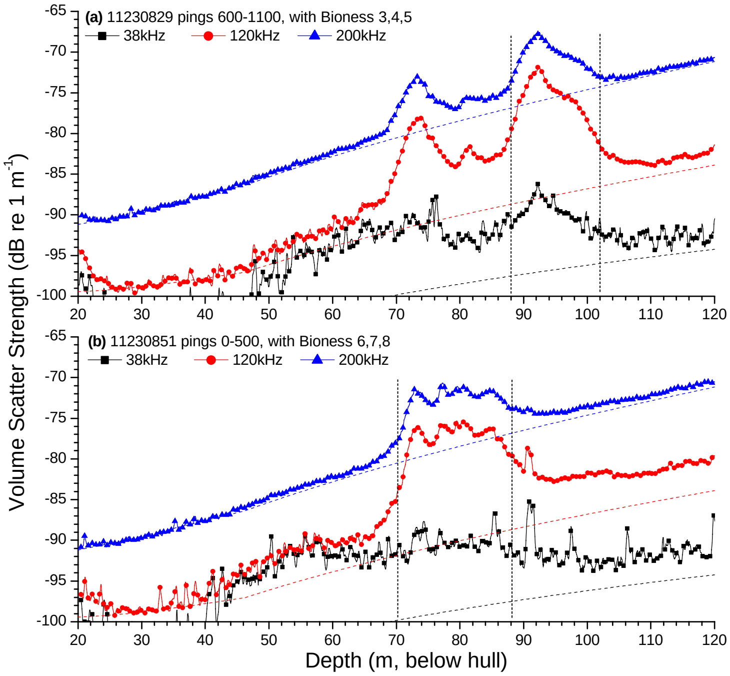

Figure 10 Observed Volume Scatter Strength vs. depth profiles at 38, 120, and 200 kHz, averaged over 500 pings (8.3 minutes) starting at (a) 0839h and (b) 0851h on Nov. 23, 2002 near Shewell Island. Dashed lines are corresponding systemic noise levels. Vertical dashed lines show depth-intervals corresponding to BIONESS net trawls dominated by *E. pacifica*.

By dividing the averaged volumetric scattering cross-section by the measured abundance estimates from the BIONESS within each sub-layer, estimates of the averaged Target Strength (*TS*, in dB re 1 m^2) per animal at each frequency can be made (Figure 11). Overall, there is good agreement in the estimated *TS* between the two sub-layers, with the exception of a 2.0 dB mismatch at 38 kHz, likely due to contamination from *other scatterer* (e.g. off-axis isolated small fish echoes). Also, there is excellent agreement between the *TS* estimates and averaged bent fluid cylinder model prediction using a swimming distribution with zero mean angle (horizontal) with 30° standard deviation. There is no agreement with the uniform angle distribution prediction, which is typically 5 dB lower.

A similar net trawl vs. acoustic analysis was conducted on Amphipods, with similar agreement between the estimated and modeled *TS*. This provides additional confidence in this averaged fluid cylinder model for crustacean zooplankton.

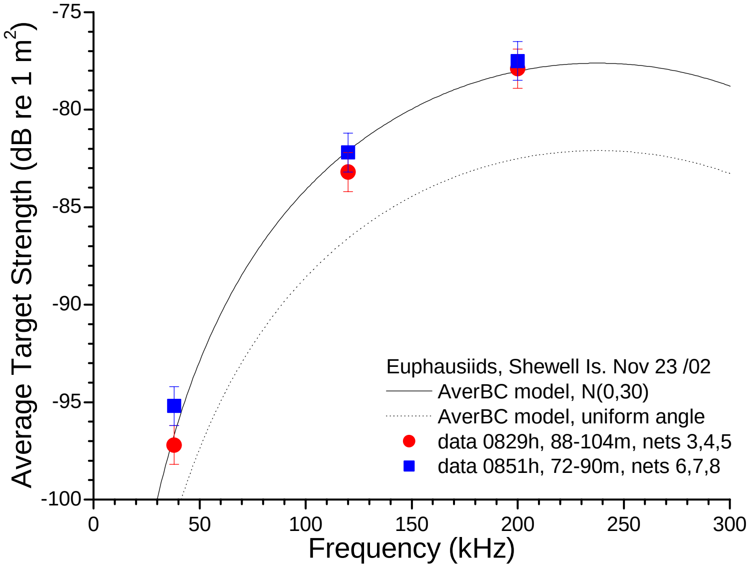

Figure 11 Comparison between measured and predicted averaged Target Strength (*TS*) vs. frequency for *E. pacifica* near Shewell Island, 0830h Nov. 23, 2002. Predicted *TS* uses euphausiid length and standard deviation of 15.9 mm and 1.4 mm, with two different distributions of orientation angle.

4.3 Siphonophores in Glacier Bay

Acoustic scattering signatures in the upper Inlet were found to be drastically different from those found in the lower Inlet. In this case the S_v vs. frequency profiles were reversed, with the 38-kHz being the strongest and the 200-kHz the weakest, as shown in Figure 12 with an example from Glacier Bay in 2002. The simultaneous BIONESS trawl from 30 - 65 m depth showed the presence of siphonophore bracts and siphonulae, and a distinct absence of euphausiids and amphipods (averaged euphausiid and amphipod abundances were < 0.15 and 0.5 per m^3, respectively). Clearly, all three echo-sounders were able to resolve the scattering layer with excellent signal-to-noise properties. For this layer, the depth- and ping-averaged S_v were -76.6, -80.3, and -81.7 dB (re 1 m^{-1}) at 38, 120, and 200 kHz respectively. Using the euphausiid and amphipod target strengths outlined above, these measured abundances of euphausiids and amphipods predict much smaller scattering strengths, particularly for the 38-kHz channel.

Because of the relative fragility of the siphonophores, it is very difficult to quantify abundances with standard net trawls. However, a reasonable estimate of the average target strength can be derived from an examination of the scattering layer statistics, using a technique outlined in Stanton (1985) and more recently used by Trevorrow and Tanaka (1997) to estimate in situ amphipod *TS*. The basis of this technique, dubbed *critical density analysis*, is that scattering strength probability density functions show drastically different shapes between the two extremes of overlapping and non-overlapping scatterer echoes. The transition between these two extremes, which is generally rather sharply defined in depth and easy to identify from PDF shape, identifies a point where *on average* there is one scatterer per insonified volume (i.e. a *critical* density). With knowledge of the calibrated S_v and insonified volume at this depth of critical density, the average backscatter cross-section can be extracted. In the specific example examined here, critical density points for the 38 and 120 kHz channels were found at 29.4 m depth, with corresponding critical densities of 0.162 m^{-3} for both, and ping-averaged S_v of -76.1 and –80.3 dB (re 1 m^{-1}), respectively. Combining the estimated abundance and scattering strength produces averaged *TS* estimates of -68.2 and -72.4 dB (re 1 m^2) at 38 and 120 kHz respectively. A *TS* estimate at 200 kHz of -73.8 dB can be derived from subtracting the difference in layer-averaged S_v (1.4 dB) between the 120 and 200kHz channels. Using these *TS* values, layer-averaged siphonophore abundance was near 0.15 per m^3. A similar critical density analysis on a separate data set taken at 1020h on Nov. 22, 2002 in Glacier Bay produced similar results.

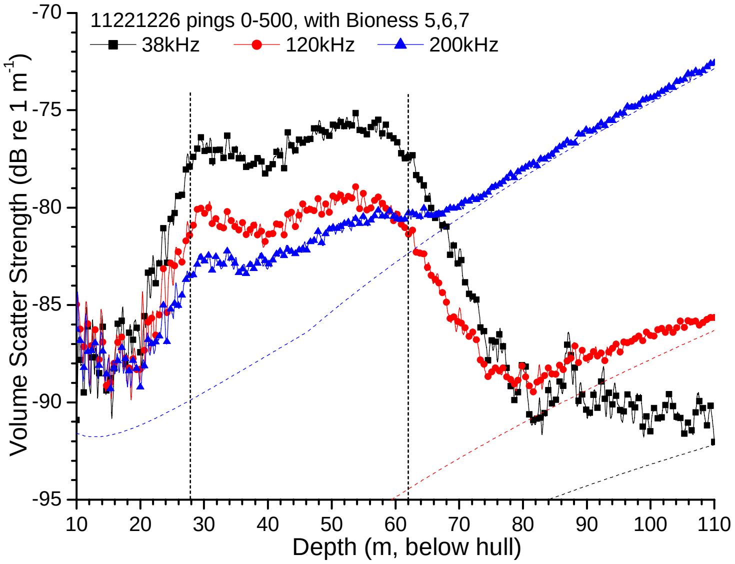

Figure 12 Observed Volume Scatter Strength vs. depth profiles at 38, 120, and 200 kHz, averaged over 500 pings (8.3 minutes) starting 1226h, Nov. 22, 2002 in Glacier Bay, Knight Inlet. Dashed lines are corresponding systemic noise levels. Vertical dashed lines show depth interval corresponding to BIONESS net trawl showing presence of siphonophores and lack of euphausiids or amphipods.

A comparison between these *TS* estimates and siphonophore scattering models is shown in Figure 13. Scattering models for three different bubble (pneumatophore) diameters are included, clearly showing the resonant peak in the 10 to 30 kHz region and its variation with bubble size. The best overall fit at frequencies well above the resonance (i.e. 120 and 200 kHz) comes from 0.4 mm diameter bubble, however for this size the simple bubble model over-predicts the measured *TS* at 38 kHz. A reasonable fit at 38 kHz can be found by arbitrarily increasing the viscous damping component by a factor of 1000, suggesting a hypothesis that the membrane surrounding the gas bubble in the pneumatophore adds damping. Also shown in the figure are *in situ* siphonophore scattering data at 24 and 120 kHz from Warren et al. (2001) on a similar species, which can be reasonably fit with a bubble diameter of 0.7 mm. This 0.4 mm pneumatophore diameter lies in-between adult pneumatophore sizes of 0.7 to 1.0 mm examined by Warren et al. and siphonulae pneumatophore diameters of 0.1 to 0.4 mm found by Benfield et al. (2003).

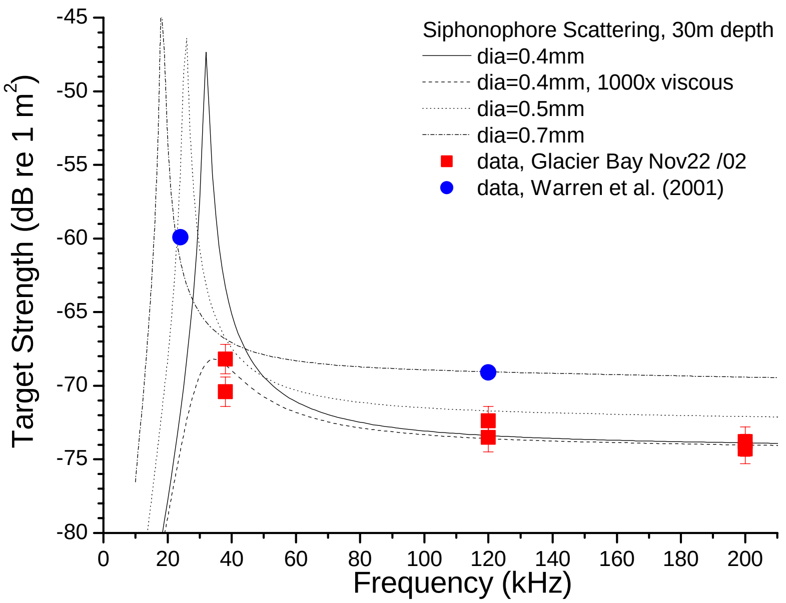

Figure 13 Comparison between measured and predicted averaged Target Strength vs. frequency for siphonophores in Glacier Bay, Knight Inlet. Measured *TS* taken from critical scatterer density analysis from data at 1017h and 1226h, Nov. 22, 2002. Predicted *TS* derived from bubble model at 30 m depth using several different pneumatophore diameters. Also included are *in situ* siphonophore *TS* measurements from Warren et al. (2001).

4.4 Effects of vessel lights on near-surface euphausiids

A dramatic example of the effects of animal orientation were found during a night-time survey on near-surface euphausiids near the Hoeya Head sill on Nov. 21, 2002. At this time the vessel was moving slowly during a deployment of ZOOVIS. When the aft-deck flood lights were turned on, the euphausiid scattering layer near 20 m depth suddenly dropped in intensity by roughly 5 to 15 dB depending on frequency. This change in the scattering layer was found to be repeatable by alternating 2-minute periods with the lights on and off. Figure 14 compares scattering strength profiles averaged over 1 minute intervals immediately before and after the lights were turned on. The figure clearly shows two scattering layers, one at 6 - 9 m and the other at 17 – 26 m depth. The averaged scattering strength within layer 2 is consistent with euphausiids (as described above) with average density of 6.6 per m^3. When the lights were turned on there was a clear decrease of up to 15 dB in layer 2. In the shallower portion of layer 2 (at 17 – 21 m depth) the depth- and ping-averaged scattering strength decreased by 9.8 and 10.8 dB at 120 and 200 kHz, respectively. Since this decrease was sudden (occurring within a few seconds), the euphausiids could not have had time to swim down, but rather must have simply changed their orientation. Since this magnitude is much larger than can be accounted for by going from a near-horizontal to a uniform swimming angle (which is about 5 dB, see Fig. 11), it can be concluded that the euphausiids have turned to near vertical incidence (either head or tail up). Since there is a suggestion in the *Lights On* profile that the scattering layer 2 has migrated downward to almost 35 m, the most likely explanation is that these euphausiids have turned to swim downwards. Interestingly, the zooplankton scattering strength in layer 1, much nearer the ship and the surface, actually increased by approximately 1.5 dB during the same period.

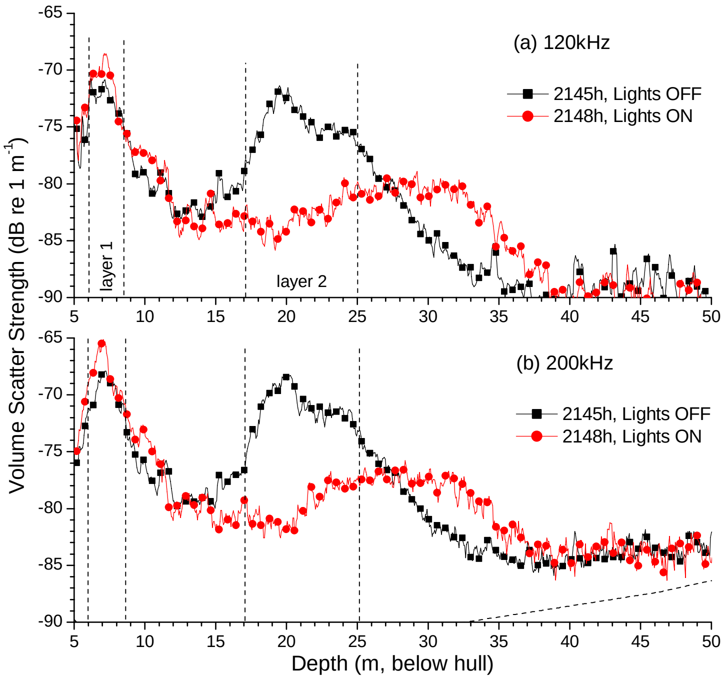

Figure 14 Comparison of Sv vs. depth profiles at (a) 120 and (b) 200 kHz, showing effects of light on euphausiids at night. Each profile averaged over 60 pings (1 minute) starting at 2145h and 2148h on Nov. 21, 2002 near the sill at Hoeya Head. Dashed lines are corresponding systemic noise levels. Vertical dashed lines show two distinct scattering layers.

4.5 Near-Sill Zooplankton Aggregations

Using the previous verification of the acoustic scattering model for Euphausiids, some wider-area acoustic survey data can now be converted to zooplankton abundances. For example, aggregations of zooplankton on the upstream side of the sill can be quantified, as shown in Figure 15. The estimated abundances were calculated by first computing a high-resolution average of the volumetric scatter strength, i.e. by 4 samples in range (24 cm) and over 2 successive pings (2 s). The 120 kHz channel is used as this provides the best signal-to-noise measurement of Euphausiids to depth up to 200 m. This scheme provides some overlap in range (the pulse length was 37 cm) and along-track dimension, but avoids smearing the small, high-density aggregations observed in the raw data. Then this averaged volume scatter cross-section was divided by the mean Euphausiid target cross-section (4.90 x 10^{-9} m^2 at 120 kHz), producing abundance estimates in depth and time. The figure shows Euphausiids confined to their usual daytime layer between roughly 80 and 110 m depth. Prior to reaching the sill (i.e. before JD 327.474) the denser portion of the layer is roughly 10 m thick with typical abundances of 100 per m^3 and some isolated patches up to 200 per m^3. As the zooplankton approach the sill the scattering layer drops and expands in depth-extent towards the bottom, with several small aggregations in excess of 400 per m^3. In this turbulent environment it must be remembered that the Euphausiid average TS was based on an assumed near-horizontal orientation distribution. If the Euphausiids were uniformly distributed, or perhaps swimming downwards, then their average TS would be smaller and thus the estimated abundances much higher. A seabed hugging layer, within 2 to 4 m of the seabed, shows very high Euphausiid abundances, possibly in excess of 1000 per m^3. However, in addition to Euphausiids this benthic layer had significant quantities of prawns (Pandalus spp.) with mean length of 113 mm (see Figure 16), determined from a seabed Otter trawl conducted roughly one hour later. It was hypothesized that the prawns were feeding on the dense aggregations of Euphausiids concentrated by the tidal flow interaction with the sill. A coupled fluid-dynamics and zooplankton behaviour modeling effort (conference presentations Allen et al. 2003, 2004) is ongoing to explain this aggregation phenomenon, hopefully culminating in a journal publication submitted in mid-2004.

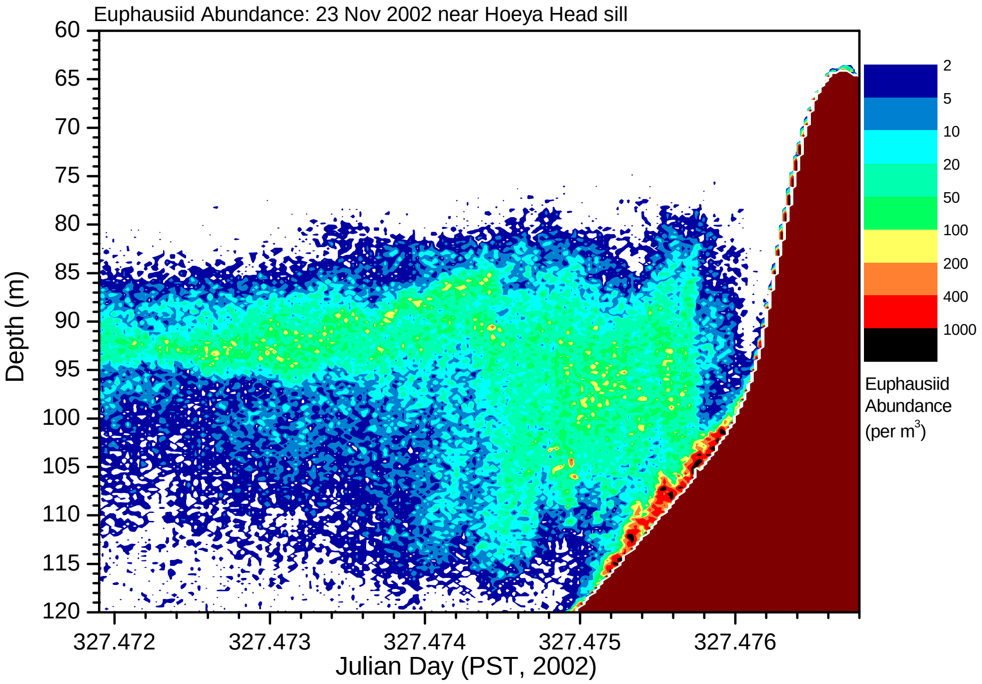

Figure 15 Estimated Euphausiid abundance near the Hoeya Head sill based on conversion of 120kHz echo-sounder volume scatter strength. Data collected 1119-1127 PST, Nov. 23, 2002. Flood tide flow from left to right.

Figure 16 Sample of prawns caught by seabed Otter trawl on the western slope of the Hoeya Head sill, 1220 PST, Nov. 23, 2002.

4.6 RESON 8125 Multi-Beam Sonar Results

Owing to its importance to the overall flow and resultant zooplankton aggregations, a detailed bathymetric survey of the sill at Hoeya Head was performed on Nov. 21st, 2002 using the RESON 8125 sonar, with result shown in Figure 17. The survey was composed of 21 parallel lines approximately 1.0 nautical miles in length, oriented 110°-290° True, with line spacing of 100 m. The survey spanned water depths from 115 m on the east and west sides of the sill to 20 m in the shallows on the north and south sides of the inlet. After some post-processing to correct for such things as ship pitch-roll, tidal heights, and sound velocity profiles, the survey depths were averaged into a 3 x 3 m bathymetric grid. This bathymetric data file has been distributed to all interested investigators.

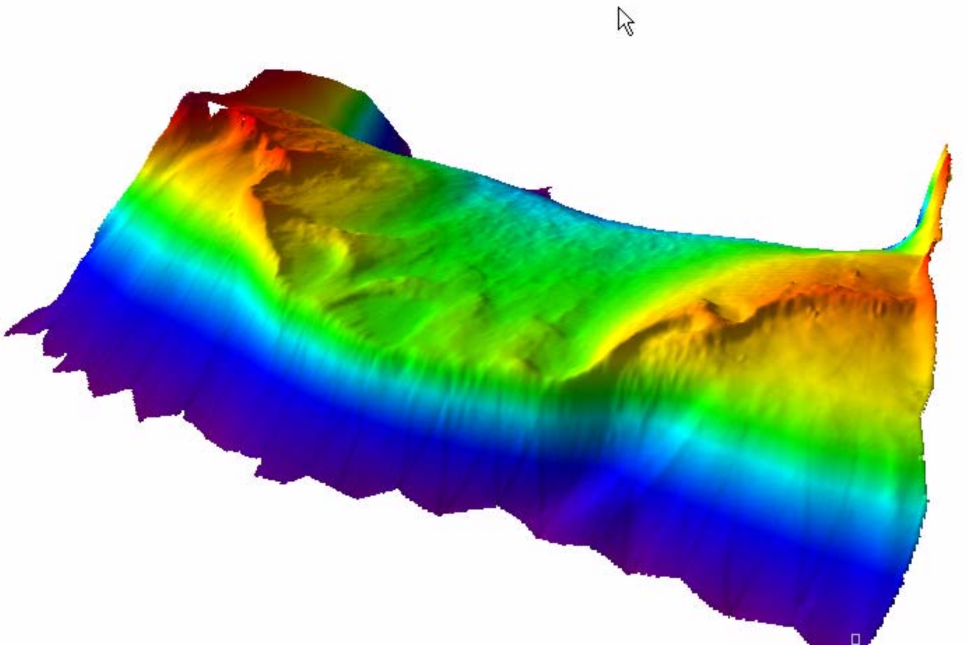

Figure 17 Three-dimensional view looking NE of bathymetric survey data from sill at Hoeya Head, Knight Inlet. Color-coded depths vary from 115 m (violet) to 20 m (red). Central sill crest (in green) is at 62 to 65 m depth. North-south distance is approximately 1.8 km.

Additionally, the RESON multi-beam sonar was able to image the across-track volumetric extent of fish schools and zooplankton layers. In this mode the sonar was set to maximum gain, transmit power, pulse length (290 μs), and range (120 m). Example images of fish schools, euphausiid swarms, and microstructure scattering around turbulent billows are shown in Figure 18. Unfortunately, the prototype data acquisition program was only able to acquire roughly 1 image every 10 s, spatially aliasing some of the shorter scale variations. In spite of this limitation, it is believed that these RESON images can be used to a create quasi-3-d picture when combined with the along-track data collected with hull-mounted single-beam sounders. The simultaneous calibrated echo-sounder data can also be used to generate an ad hoc calibration by comparing the echo-sounder with the nadir beam from the Reson sonar. Data on Euphausiid aggregations and turbulent billows was collected in across-sill transects on Nov. 17th and 23rd, and at the western sill on Nov. 19th (all 2002).

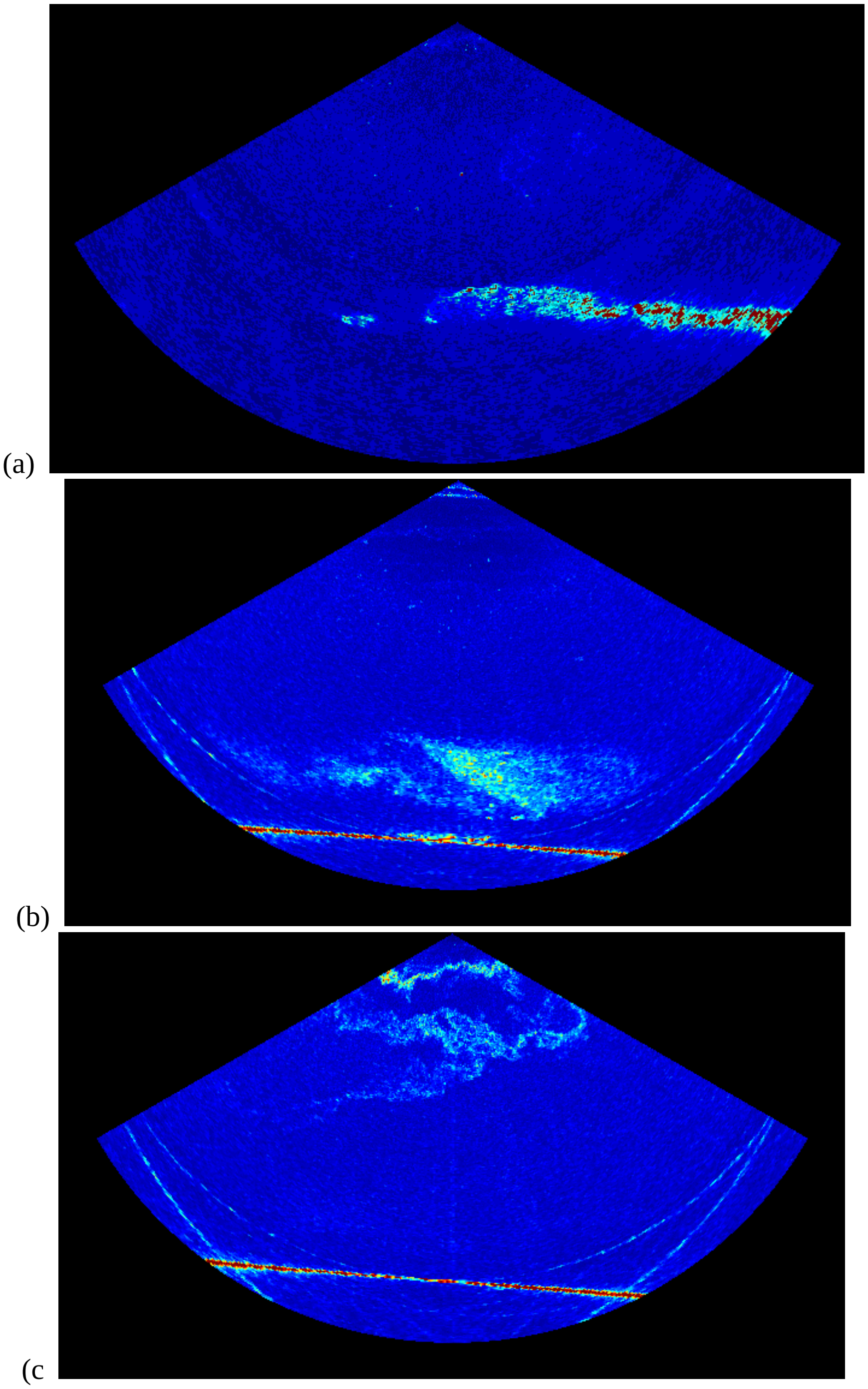

Figure 18 Example raw intensity images from the RESON 8125 in volume sampling mode: a) mid-water fish school (likely herring), b) krill layer near bottom, c) near-surface turbulent billows. All images show a 120° downward-looking sector to 120 m maximum range. Near-horizontal linear feature in (b) and (c) is seabed.

5. Summary and Recommendations

Overall, the combined observational approach yielded valuable insights into the zooplankton communities in Knight Inlet. The anticipated synergies between the investigators and their three different measurement approaches did arise, producing several significant results:

1. There was considerable value in combining multi-frequency acoustic with *in situ* plankton sampling techniques such as nets trawls and optical systems. The most obvious advantage was the ability of the net trawls and camera to quantify the dominant (generally largest) acoustic scatterers in terms of species, size, shape, abundance, and potentially swimming orientation. The echo-sounder with it's much greater *coverage rate* could then provide the spatial link between the samples. The ability of the echo-sounders to image the *flow lines* around the sill also provided an oceanographic context for the *in situ* zooplankton samples. Another operational synergy was the simultaneous operation of the echo-sounder to guide the trawl nets or cameras to specific zooplankton scattering layers. This resulted in more precise sampling of these thin and spatially varying zooplankton layers.
2. The validity of several classes of existing acoustic scattering models for crustacean meso-zooplankton and siphonophores was evaluated through closely-coupled comparisons with BIONESS and ZOOVIS data. Excellent agreement was found using an averaged fluid cylinder model for crustaceans (e.g. Euphausiids and Amphipods) and a simple bubble model for Siphonophores. Examples were found where orientation effects might be important, such as nocturnal sensitivity to light in the near-surface regions and a hypothesized diving response to turbulence near the sill.
3. Data illuminating the links between zooplankton spatial aggregations, predator species (such as planktivorous prawns and fish), and physical oceanographic phenomena were found. For example, a dense near-seabed scattering layer on the upstream side of the sill was observed coincident with flow-induced aggregations of Euphausiids. A seabed Otter trawl found this layer contained a combination of Euphausiids, prawns, and benthic fish. In the 2001 observations series of profiles followed a presumed fish school migrating back and forth across the sill crest in response to tidal flow changes. Furthermore, there is some evidence for an inlet-scale zooplankton abundance minimum in the vicinity of the sill, suggesting predation by planktivorous prawns and fish at the sill was enhanced by the flow aggregation phenomenon. Additionally, the presence of Siphonophores and corresponding lack of Euphausiids and Amphipods in the upper inlet (Glacier Bay) suggested significant predation of the crustaceans by the Siphonophores.
4. Combining understandings from the 1995 oceanographic cruise data with the calibrated acoustic results from 2001 and 2002 highlighted features of acoustic scattering induced by turbulent microstructure. The acoustic scattering was observed to be confined to narrow shear layers in the upper 20 m, coincident with sharp pycnoclines and high turbulent dissipation rates. BIONESS tows through these flow layers found no significant zooplankton abundance that could account for the observed scattering. Additionally, 2-dimensional multi-beam sonar images showed these lines occasionally spatially organized into *billows*, a characteristic of turbulence.

Ongoing work by the author and co-PI's will be focused on writing of scientific manuscripts along these themes. At present the detailed acoustic vs. in situ (BIONESS and ZOOVIS) comparisons, as described in sections 4.1 – 4.5, are written into a manuscript (nearing completion) for J. Acoustical Society of America. Additional near-term focus areas are:

1. The available data from 2001 and 2002 can be used to assess broad-area time- and geo-referenced zooplankton abundance estimates around the sill and along the larger expanses of the inlet. The echo-sounder provides the spatial link between the in situ samples, and builds upon the acoustic scattering model verifications outlined in this report.
2. A reconciliation amongst the various zooplankton sampling devices should lead to new insights into the strengths and weakness of these various measurement approaches. In particular, the large differences in the sampling and averaging volumes of the various measurement types complicates direct comparisons of abundances. For example, ZOOVIS has a sample volume of 0.44 litres, whereas the echo-sounder insonified volumes in the 70 - 100 m depth daytime scattering layer are roughly 50 m^3. Thus, for typical abundances a sequence of ZOOVIS images will contain only a few isolated hits, while the echo-sounder averages over contributions from potentially hundreds of animals. The implication for the differing sampling statistics should be explored.
3. A combined fluid-dynamic and zooplankton behaviour study is underway, attempting to model the observed zooplankton aggregations at the sill (e.g. Figure 15). Some reasonable agreement has been found assuming the Euphausiid respond to the enhanced seabed boundary layer turbulence by swimming downwards.
4. Comparisons between the RESON 8125 volumetric images and the simultaneous echo-sounder traces should be made, generating ad hoc calibrations for the RESON and demonstrating the concept of 3-dimensional imaging. In particular, the three-frequency echo-sounder provides some of the first ever quantitative measurements of micro-structure scattering, and the combination of the two acoustic devices provides insight into the spatial structures and physical oceanographic context.

6. Bibliography

6.1 Refereed Journal articles arising from this project

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Trevorrow, M., Mackas, D., and Benfield, M., 2004. Comparison of multi-frequency acoustic and in situ measurements of zooplankton abundances in Knight Inlet, B.C., in preparation for J. Acoust. Soc. Am.

6.2 Recent Conference Presentations and Reports

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(U) This report outlines acoustic methods and results from a 3-year collaborative study of zooplankton aggregations in a coastal fjord. Mid-water aggregations of zooplankton were surveyed using a calibrated, three-frequency (38, 120, and 200 kHz) vessel-based echo-sounder system, a multi-net towed zooplankton net (BIONESS), and a high-resolution *in situ* camera system (ZOOVIS). Dense daytime layers of crustacean zooplankton near 70 to 90 m depth were found in the lower reaches of the inlet, especially concentrated by tidal flows around a sill which rises above the layer. Quantitative Euphausiid and Amphipod backscatter measurements, combined with *in situ* species, size, and abundance estimates, were found to agree closely with size- and orientation-averaged fluid-cylinder scattering models. Similar *in situ* scattering measurements of Siphonophores were found to have a much stronger low-frequency (38 kHz) scattering strength, in agreement with a simple bubble scattering model. Distinctive near-surface *flow lines* near the sill were found to coincide with strongly sheared pycnoclines and high levels of turbulent dissipation. The combination of a lack of zooplankton present in these layers and a reasonable agreement with turbulence scattering models suggests these acoustically-visible layers are due to micro-structure scattering. A new high-resolution multi-beam sonar was used to map the ecologically important sill at Hoeya Head with 3 m resolution, and to sample in two-dimensions mid-water aggregations of fish, zooplankton, and turbulence.

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