

Designing an Ocean Mid-trophic Automatic Acoustic Sampler (MAAS) - thoughts on how to include echo sounder observatories in ecosystem models

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Abstract

Echo sounders are a widely used tool for observing marine ecosystems. Traditionally, carefully designed surveys are used to integrate biomass to a global estimate, which is coupled to traditional stock assessment models. More recently, the focus has shifted from single species assessment to an ecosystem approach, taking into account ecosystem function and dynamics. As a response, several coupled ecosystem models have been developed. The data requirements for these models are different than for the traditional models, and new sensors and platforms have been developed as a response to this need. However, examples on how to integrate these observations with these new models are scarce. We present an overview of ongoing work trying to use acoustic data from autonomous platforms. The work is a pre-requisite for designing an ocean mid-trophic automatic acoustic sampler.

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1 Introduction

With the introduction of the Ecosystem Approach to fisheries Management (fao, 2003), the focus has shifted from traditional single species management to an overall evaluation of the ecosystem, including the effects of climate change. As a response, modelling approaches that couple traditional population-, biogeochemical-, and ocean-circulation models are emerging (e.g. Maury et al. (2007); Lehodey et al. (2008)). In parallel, novel observational systems are emerging (Godø et al., 2005; Doksæter et al., 2009; Trevorrow, 2005). Since a large part of exploited marine resources concerns species at a high trophic level, this new generation of population dynamics and ecosystem models need to include a representation of the prey at the Mid-Trophic Level (MTL), i.e. the micronekton.

The MTL component of the ocean ecosystem is one of the less known despite its critical position. Recent developments in coupled general ocean circulation and biogeochemical models, that incorporate satellite-derived and *in situ* observations, appear to capture the global carbon cycle in pelagic areas, resulting in a realistic basin-scale prediction of lower trophic levels, especially primary production. However, existing modelling approaches to describe the basin-scale spatiotemporal dynamics of MTL are still rare and are at an early stage of development. These models still need to be improved and calibrated with existing *in situ* data.

Hydroacoustic sensors offers unique possibilities for remote sensing of marine life on various scales, extending from basin scales observations at low frequencies (100s of Hz) (Makris et al., 2006) to small scale-high-frequency (mHz) acoustics for detailed observations (mm scale). The sensor could be mounted on various platforms (Handegard et al., 2009) and combined with several other sensors (Claustre et al., 2009), often optical sensors (Holliday et al., 2009). With the development of calibrated echo sounders (Foote, 2009) and modern post-processing systems (Foote et al., 1991), the technology is today a mature technology for observing fish and micronekton for traditional fisheries management purposes. However, the temporal resolution for conventional ship based surveys is low, and may not capture important dynamics of the ecosystem. Ship time is expensive and full coverage in the high sea is unrealistic. As a response, hydroacoustic sensors have been mounted on various platforms. Presently applied systems (Godø et al., 2005; Doksæter et al., 2009; Trevorrow, 2005) are large and expensive, need connection to shore and/or routinely tend.

A hydroacoustic sensor itself does not give direct information of species composition etc. Auxiliary data is usually required. Net samples are the most common method for conventional ship based systems, but there are also other methods to obtain information on species composition. Different species has different frequency dependent acoustic properties, and either using multiple discrete frequencies (Korneliussen and Ona, 2003) or broad

band acoustics (Stanton et al., 1998), these properties may be utilized for species identification. Based on proven methodologies and technologies basin scale coverage with echosounders is possible based on calibrated fishing vessels (Kloser et al., 2009). These data provide a temporal snapshot of the vertical and horizontal distribution and abundance of the dominant acoustic species at large spatial scales. Spatial patterns in the vertical and horizontal distribution can be used to estimate the diurnal vertical energetic transfer of the dominant acoustic scatterers.

The objective of this paper is to a) present two relevant ecosystem models, b) two possible acoustic observation system (stationary and vessels of opportunity), and provide c) a first step in which these models and observations may be combined. Finally, we d) discuss the potential for this approach.

2 The Ecosystem models

2.1 APECOSM

APECOSM (Apex Predators ECOSystem Model) represents the basin wide spatialized dynamics of open ocean pelagic ecosystems from zooplankton up to fishing with a special emphasis on top predators (Maury et al., 2007). The model deals with the flow of energy through the ecosystem with a size-resolved structure in both 3D space and time. The uptake and use of energy for growth, maintenance and reproduction by the organisms are modelled according to the dynamic-energy-budget theory (Kooijman, 2000) and the size-structured nature of predation is explicit.

The pelagic community is divided into epipelagic and mesopelagic groups, the latter being subdivided into vertically migrant and non-migrant species. The model is mass-conservative. Energy is provided at the basis of the model through primary production and transferred through 3D spatially explicit size-spectra. Focus species (tunas at present but it could be any kind of consumer species) are "extracted" from the global size-spectra without losing mass balance and represented with more physiological and behavioural details. The biomasses of the various communities and focus species emerge from opportunistic size-based trophic interactions controlled by the environmentally driven vertical and horizontal distribution of organisms. The forcing effects of temperature, currents, light, oxygen, primary production and fishing are explicitly taken into account.

The size-based approach used in APECOSM is a practical way to obtain a realistic representation of both the non target organisms and the focus species while keeping the functional complexity limited. It is used to analyse the response of global pelagic ecosystems and tuna species to climate change and fisheries pressure. Long term simulations (1958-2001) based on a NEMO-PISCES run forced by the ERA40 reanalysis are currently available.

2.2 SEAPODYM

The Spatial Ecosystem And POPulation DYnamics Model (SEAPODYM) includes a spatial age-structured population dynamics model of large oceanic predators with a MTL sub-model (Lehodey et al., 2008). The SEAPODYM-MTL is also based on an advection-diffusion-reaction system of equations as in APECOSM but rather than a size spectrum, it describes six different MTL functional groups following a temperature-linked time development relationship (Lehodey et al., accepted). This model is used for different application to tuna fisheries in the Pacific Ocean (Lehodey and Senina, 2009).

The functional groups in SEAPODYM-MTL are based on the occurrence of diel migration between the epipelagic, mesopelagic and bathypelagic layers, or the lack of thereof (Figure 1b). Recruitment, ageing, mortality and passive transport with horizontal currents are modelled by a system of advection-diffusion-reaction equations, taking into account the vertical behaviour of organisms. Since the dynamics is represented by the established relationship of temperature-linked time development, there are only six parameters in the model that have to be estimated. The first one (E) defines the total energy transfer between primary production and all the MTL groups. The others are the relative coefficients (E'_n) redistributing this energy through the different components (the sum being 1). The parameterization of E requires absolute biomass estimates of MTL, while the matrix of (E'_n) coefficients can be estimated simply using relative day and night values integrated in the three vertical layers of the model. While the predator model parameterization can be optimized in SEAPODYM by data assimilation techniques using fishing data (Senina et al., 2008), the parameters of the MTL sub-model are currently tuned according to limited information from the literature (Lehodey et al., accepted).

The predicted epipelagic micronekton from the Atlantic is presented in Figure 2. The model predictions for the mid-point of each month m , each class c , at the location of the buoy system, is exported resulting in $\tilde{x} = f(m, c)$. This will be used to compare with the observations from the Mid-Atlantic-ridge buoy.

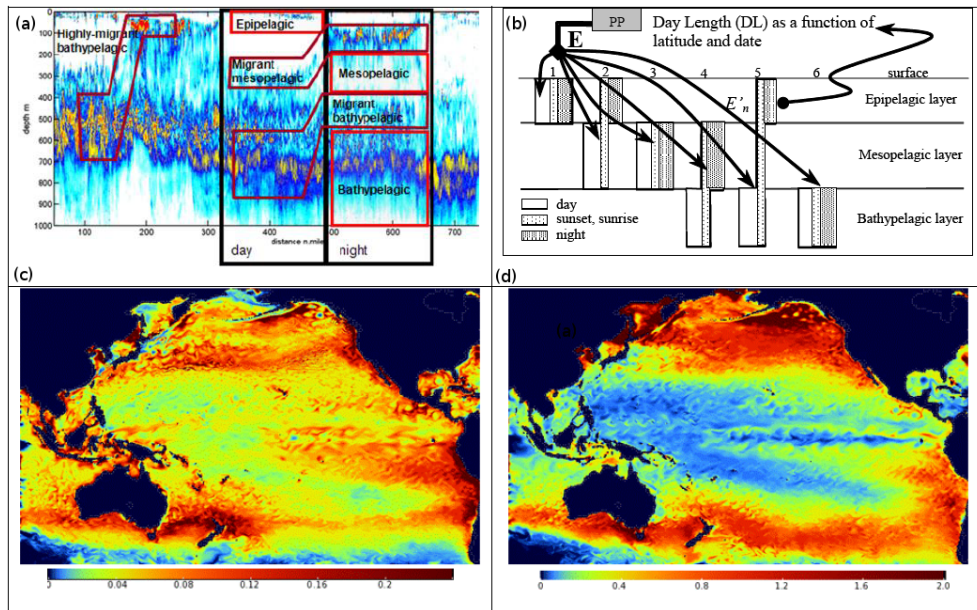


Figure 1: Mid-trophic functional groups. (a) identification of MTL functional groups on acoustic echogram from the vessel transects. (b) The conceptual model of the 3-layer 6-mid-trophic functional groups 1: epipelagic, 2: migrant mesopelagic, 3: mesopelagic, 4: migrant bathypelagic, 5: highly-migrant bathypelagic, 6: bathypelagic. (from Lehodey et al., accepted). Comparison between (c) the predicted production ($gm^{-2}d^{-1}$) and (d) the biomass (gm^{-2}) of the epi-pelagic mid-trophic functional group at resolution $1/4^\circ$ in the Pacific.

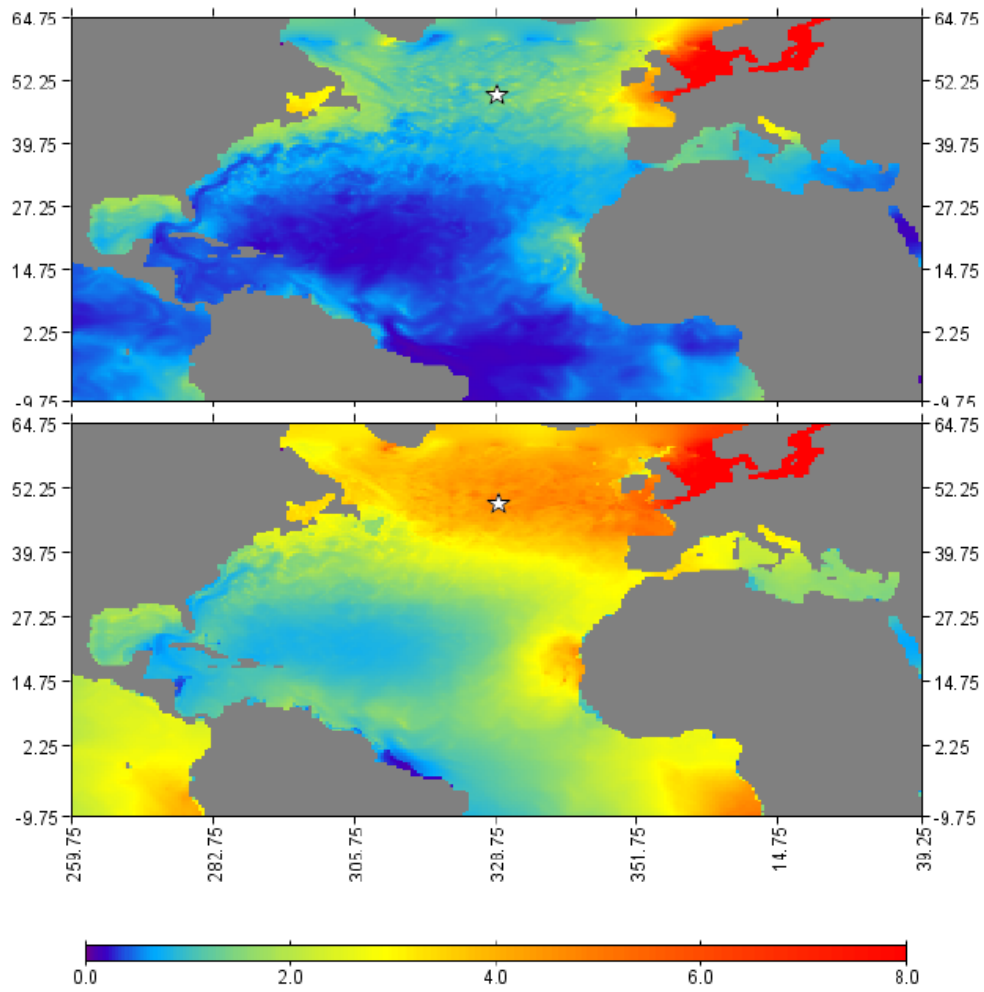


Figure 2: Biomass distribution of micronekton ($gm^{-2}d$) predicted with SEAPODYM-MTL in the north Atlantic during day (top) and night (bottom) in the epipelagic (euphotic) layer. Simulation at $1/2$ deg x month using SODA (Carton et al., 2000) ocean reanalysis and satellite-derived primary production (Behrenfeld and Paul G. Falkowski, 1997). Stars indicate the position of MarEco buoy.

3 The Observations

3.1 The Mid Atlantic Ridge (MAR) observations

A rig designed and built at the Institute of Marine Research was deployed at the Mid-Atlantic Ridge at position N51°31.6′, W30°19.9′, and depth 907 m, during the period 22nd of July 2004 to the 24th of May 2005, c.f. Figure 3. See Godø et al. (2009a) for details. The rig was equipped with a Simrad EK60 echo sounder and a Simrad ES38DD depth stabilized transducer. The transducer is a 38-kHz split beam with a 7-degree circular beamwidth. A sampling scheme was set up to increase operational time, and the rig was equipped with enough battery power to operate for almost one year.

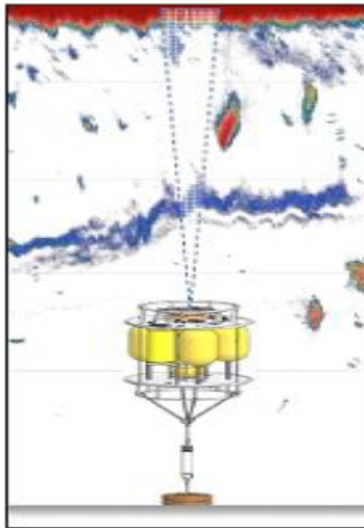


Figure 3: Conceptual overview of the lander deployment.

The data was reduced to a 1 minute time resolution, and a monthly mean diel cycle was produced by taking the mean between the pixels at same depth and time of day over one month (Figure 4). The resulting data set is the monthly mean acoustic volume backscatter (Mac Lennan et al., 2002) for a given time of day and depth, i.e. $s_v = f(t, z, m)$ where t is time of day, z is depth and m is month.

Before calculating the mean values, a threshold of -60dB is applied, efficiently removing stronger signals, e.g. from whales (Doksæter et al., 2009).

3.2 Vessel transects

Basin scale snapshots of the dominant acoustic scatterers using calibrated echo sounders from fishing vessels complement the high resolution stationary observations (Kloser et al. (2009), Figure 1a). These acoustic backscatter

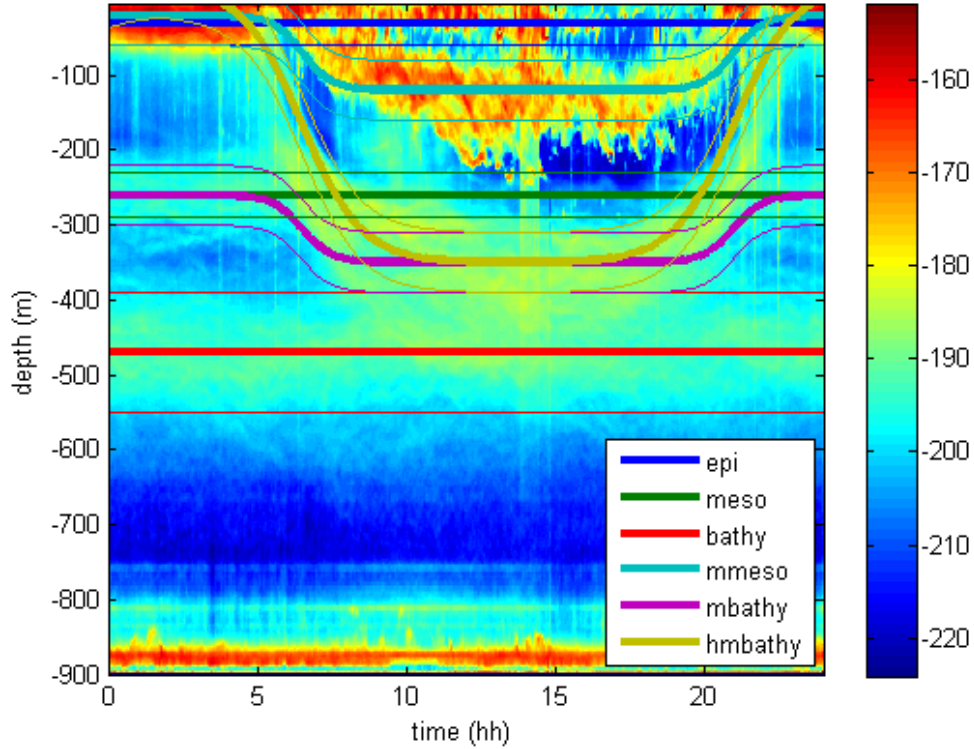


Figure 4: A mean monthly echogram from the MAR buoy from month $m = 11$. The mean and σ depth for the classes 1: epipelagic layer ($c='epi'$), 2: migrant mesopelagic ($c='mmeso'$), 3: mesopelagic ($c='meso'$), 4: migrant bathypelagic ($c='mbathy'$), 5: highly-migrant bathypelagic ($c='hmbathy'$), 6: bathypelagic ($c='bathy'$), respectively.

snapshots at 38 kHz provide the means to extrapolate to the larger scale with appropriate assumptions of the dominant acoustic species.

In Tasman Sea waters the dominant scatterers are small fish with gas bladders (e.g. myctophids) and estimates of basin scale density can be inferred from these snapshots to initialise (Kloser et al., 2009). Based on fine scale acoustic and net sampling water column biomass estimates vary considerably by a factor of 10 to 18 between acoustics ($16-29 \text{ gm}^{-2}$) and nets (1.6 gm^{-2}). The vertical movement of dominant acoustic scatterers can be further segmented into depth layers (epi, meso and bathy) and the energetic exchange between layers calculated based on fine scale acoustic, optical and net sampling of the depth and day/night stratified dominant acoustic group target strengths. This requires depth stratified net and acoustic sampling for day and night time estimates of mean weight and target strength (Kloser, manuscript in preparation).

With a vessel based dataset Opdal et al. (2008) observed the same system as the MAR buoy. Appearance of the scatters combined with their behaviour over time decided their belonging to the specified groups. Six layers were identified from surface to bottom:

- Layer 1 Epipelagic zooplankton with low target strength often confounded by acoustic noise (air bubbles etc from vessel or wind/waves). No or limited migration.
- Layer 2 Migration upper layer between epi- and meso-pelagic layers, probably dominated by *Maurolicus muelleri* and *Benthosema glaciale* as indicated by trawl catches.
- Layer 3 Migrating layer between mesopelagic and lower epi-pelagic layers. Likely contributors are *B. Glaciale*
- Layer 4 Migrating mesopelagic layer migrating from about 500m at day towards surface at night. Important contributors to acoustic backscattering *Notoscopelus kroyeri* and *N. bolini*.
- Layer 5 Non-migrating layer of mesopelagic fish 500-1000m. Important contributors to acoustic backscattering *Scopelogadus beanie* and *Serrivomer beanie*.
- Layer 6 Near bottom traces of benthopelagic fish

These observations are used to discuss the allocations of acoustic backscatter to the functional groups in our comparison between the SEAPODYM model and MAR buoy.

4 Combining the MAR observation and the SEAPODYM model

We have tried to utilize the depth distribution of the different groups in the SEAPODYM model on the MAR data.

The depth distribution for each model group c ('epi', 'meso', 'bathy', 'mmeso', 'mbathy', 'hmbathy'), c.f. Figure 1(b), is described using a mean depth and a standard deviation around the mean depth, as a function of time of day. The mean depth of the diurnal variation for each functional group is modelled using a logistic function. For each month m and group c , let

$$\bar{w}(t; m, c) = \frac{D \exp \{\alpha(t' - \beta)\}}{1 + \exp \{\alpha(t' - \beta)\}} - D \frac{\exp \{\alpha(12 - \beta)\}}{1 + \exp \{\alpha(12 - \beta)\}}, \quad (1)$$

where $\beta = 12 - \frac{1}{2}(\beta_2 - \beta_1)$ for $t' \in [0, 12)$, β_1 is the time of the morning downward migration, β_2 the time of afternoon upward migration, D is the amplitude of the migration, and α is the "speed" of the transition and z_0 is the mean depth at midnight. For $t' \in [12, 24)$ the curve is mirrored around $t' = 12$. Further $t' = t + \{12 - \frac{1}{2}(\beta_1 + \beta_2)\}$ is the shifted time variable, where t is the time of day (0-24), resulting in a curve symmetric around the time point in between β_1 and β_2 . The parameters are invariant with time t within a diel cycle, but they are different between classes c and months m .

The extent of each of the layer around the mean depth $\bar{w}(t; m, c)$ is modelled by the parameter $\sigma(m, c)$, and the weight for each class as a function of the position in the echogram is given by

$$w(t, z; m, c) = \frac{1}{2\pi\sigma} \exp \left\{ \frac{-(z - \bar{w})^2}{2\sigma^2} \right\}, \quad (2)$$

see Figure 5.

When more classes overlap, we define the relative weights between the classes by

$$p(t, z; m, c) = \frac{w(t, z; m, c)}{\sum_c w(t, z; m, c)}, \quad (3)$$

c.f. Figure 6. All the parameters are manually set based on scrutinizing

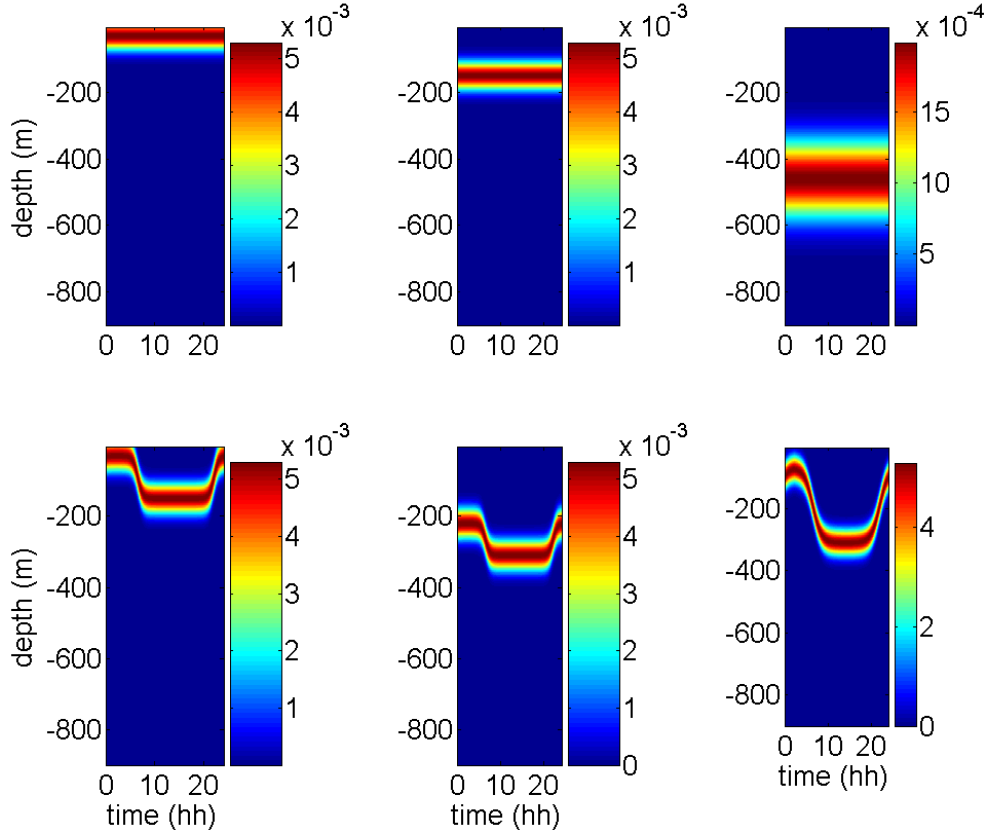


Figure 5: The weights w used to allocate acoustic energy to the functional classes. Each subplot show the weight for each functional class c as a function of time and depth, for the classes ('epi', 'meso', 'bathy', 'mmeso', 'mbathy', 'hmbathy'), from top left to lower right, respectively. The data presented here is the weights for month 11.

the mean monthly echograms by tweaking the parameters so that curves fits the echograms Figure 4.

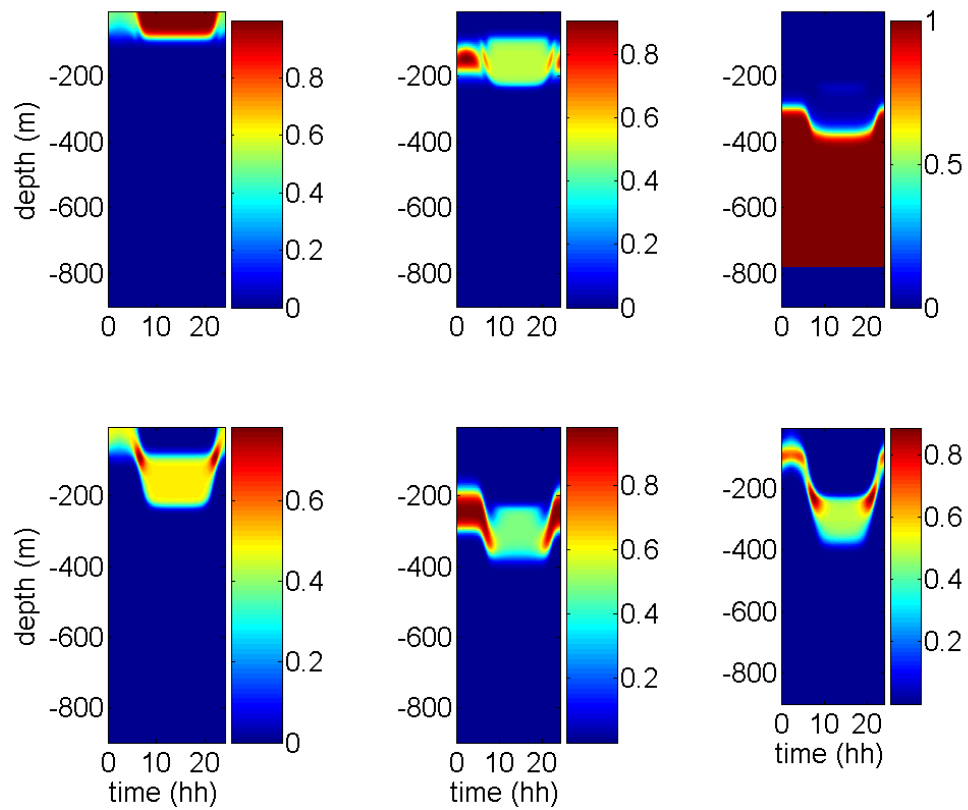


Figure 6: The fractions p for each functional class c as a function of time and depth, for the classes ('epi', 'meso', 'bathy', 'mmeso', 'mbathy', 'hmbathy'), from top left to lower right, respectively. The data presented here is the fractions for month 11.

For each month m and each class c , the monthly mean acoustic backscatter (s_v) is multiplied with p and integrated over the water column:

$$s_a(t, m, c) = \int_z p(t, z, m, c) s_v(t, z, m) dz, \quad (4)$$

see Figure 7.

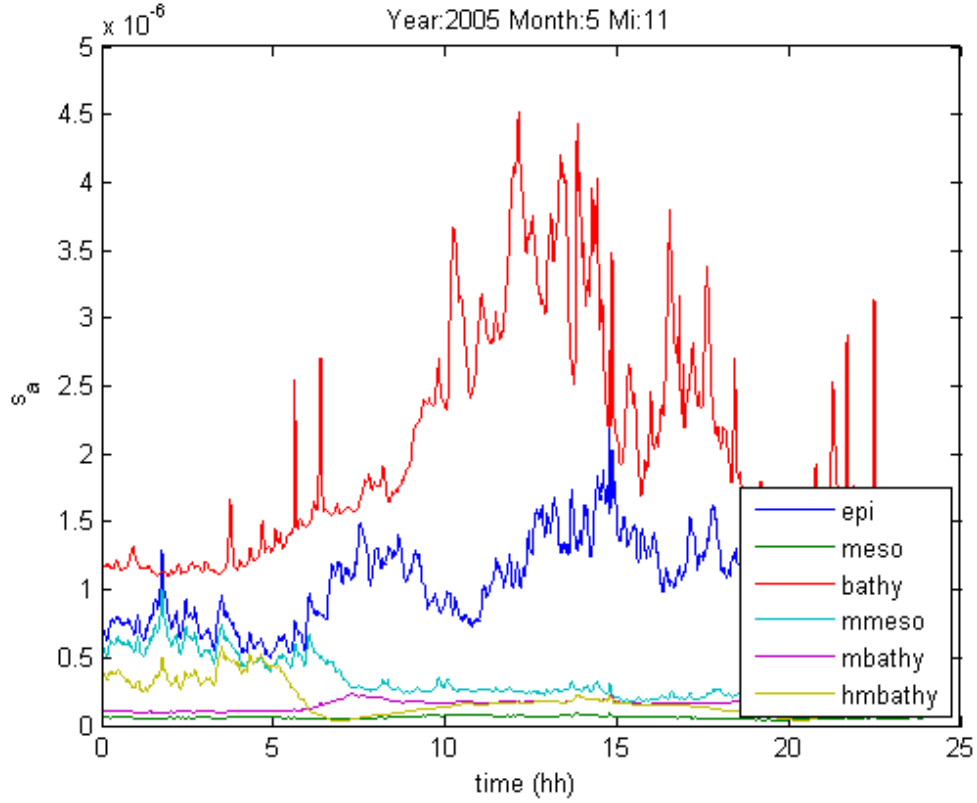


Figure 7: The mean s_a values as function of time of day for each functional class c as a function of time. The data presented here is the s_a values for month 11.

Then we calculate the mean s_a value for each class throughout the diel cycle as a measure to compare with the models:

$$\bar{s}_a(m, c) = \frac{1}{24} \int_{t=0}^{24} s_a(t, m, c) dt, \quad (5)$$

see Figure 8.

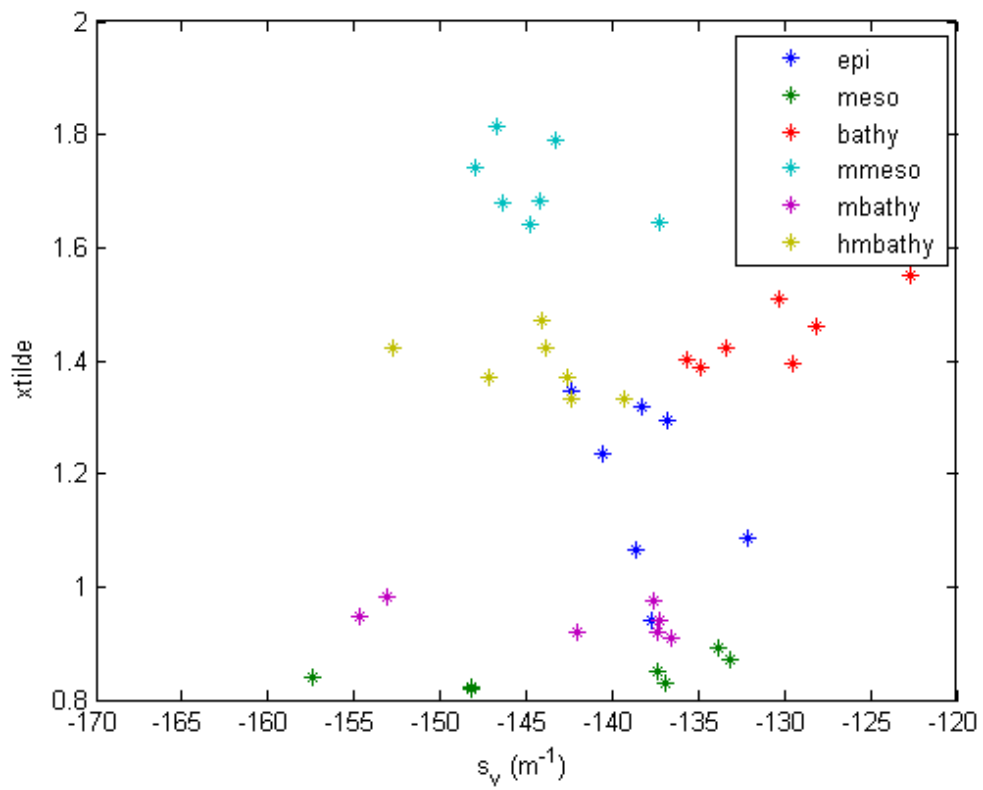


Figure 8: The comparison between classes from model and data, for the different functional groups c for each month m . Ideally, the data should be linearly related. Except for the bathy, there do not seem to be a clear relationship. The causes of these discrepancies are discussed in the discussion.

5 Discussion

This paper presents our initial trials in combining the information from hydroacoustic sensors to the mid-trophic component in an end-to-end ecosystem model.

This initial trial did not show good correspondence with the model predictions and MAR observations, and we need to address this discrepancy. There are several potential causes that may lead to these discrepancies, including the models definition of functional groups, the location of the MAR buoy and model meso scale resolution capabilities. One cause that is not treated in detail is the relatively short duration of the test data; less than one year. Although this represents a great technical improvement over earlier systems, it may be too short validating coupled eco-system models.

From the modelling point of view it is necessary to check that the definitions of the vertical layers are consistent between regions. In SEAPODYM, the layers are defined relative to the euphotic depth, and the integrated backscatter in the groups will depend on these definitions. A detailed analysis is necessary to confirm these definitions. If the model groups do not match the site specific groups, the allocation of acoustic energy to groups based on vertical distribution will fail.

In the following we compare the layer interpretation from the MAR buoy with the MAR vessel based estimates. It is important to keep in mind that the vessel observations are limited by an acoustic blind zone at the surface and a noisy observation environment, while the bottom mounted system similarly have a blind zone close to bottom (Totland et al., 2009) and the surface. This is one of the reasons for Opdal et al. (2008) to marginalise and ignore their layer 1. They do not see the whole layer due to its proximity to the surface. We think that this layer is comparable to our epipelagic ($c='epi'$) layer. Their Layer 2 and our migrant mesopelagic ($c='mmeso'$) layer also seem to combine the same behavioural features. Their Layer 4 seem to be comparable to our highly-migrant bathypelagic ($c='hmbathy'$) layer and similarly their Layer 5 and our bathypelagic ($c='bathy'$) layer seems comparable. The main difference seem to be that we define a stationary mesopelagic layer while nothing similar appears in their interpretation, Their Layer 6 is not apparent in our echogram due to the wide blind zone of the system close to bottom (Totland et al., 2009). Another complication in comparison of these two datasets is the difference in acoustic frequency. Opdal et al. (2008) uses data from 18 kHz to enable detection to 2500m. However, due to resonance effects of mesopelagic fish when ensonified at this frequency (Godø et al., 2009b), the appearance of the echograms might differ substantially over the diel cycle. It is encouraging to observe that the layer definition done by two different approaches with two different datasets are so similar, and we consider this as a signal that the community structure in open ocean systems are very stable in time and space.

In general, sub-marine structures provide favourable habitat for marine life (Genin and Boehlert, 1985), and this may cause an increased densities at the location of the MAR buoy. Although Opdal et al. (2008) investigated the population structure around the ridge, their data were too sparse to reach a firm conclusion (their page 55). However, it cannot be ruled out as a cause, and unless the model fully captures these relatively high resolution features, it may be one explanation of the weak fit between the model and the MAR data.

By definition, micronekton organisms can swim. However, due to their small sizes, they are nevertheless strongly impacted by oceanic circulation from large to meso-scales. Since advection is important to set the horizontal but also vertical distribution of the forage biomass, the vertical decomposition in three layers smooth drastically the vertical velocity shear. It could have a strong influence on the results, in particular for equatorial and subtropical regions where vertical velocity shears are strong and counter-currents can occur. Thus, it comes from this that for assimilating acoustic data, the MTL simulations should be as realistic as possible and with meso-scale activity that likely have a strong impact on the concentration of small organisms. Only ocean models using themselves physical data assimilation, especially satellite data, can provide such realistic environmental forcing. Therefore, we are planning to use a recent global ocean physical reanalysis at 1/4 deg x 6 day (MERCATOR:http://www.mercator-ocean.fr/html/mercator/index_en.html) to test the acoustic data assimilation approach in the Mid-Trophic SEAPODYM model.

When defining the weights for the different classes w for allocating echo energy, the weighing do not take into account the numbers and backscattering strengths. If a layer consisting of strong targets merges with a layer of weak targets, the weights associated to the stronger targets should be increased. This was not done in this first step analysis, but needs to be addressed. This may explain some of the variability through the diel cycle for the total echo energy for the different classes.

There is a difference between day and night vertically-integrated signals, and the day backscatter is usually stronger than the night backscatter. This bias needs to be addressed prior to model comparison since the model requires the biomass of a component to be constant throughout the diel cycle. There are several potential causes for this bias (Hjellvik et al., 2004). The most likely one is different behaviour leading to different tilt angle distributions that again causes the mean backscattering coefficient to vary throughout the diel cycle. Also, the fish may concentrate close to the surface, and consequently be unobservable due to the surface blindzone.

Here we have presented our first attempt to couple acoustic observation system to coupled ecosystem models, and we have identified a few key areas to address. A key issue will be to collect a massive dataset of acoustic data from various oceanic regions to assimilate in the ecosystem model. Further

technological advances and reduced costs are expected in the near future that may turn acoustics into a vital source of observations for advanced ecosystem models, and we think that the collaboration between the expertise in modelling and observation methodology is essential to quickly progress and provide new modern tools for the monitoring and management of marine resources and their ecosystems.

6 Recommendations

- 1 Continue deploying observatories using existing platforms, and continue to collect data from ships of opportunity. This will provide important data for further developing the combination techniques for models and observations.
- 2 Further develop the coupling between the models and observations using presently available data from 1.
- 3 Ensure technical development low cost drifters, landers and ship based modules to collect acoustic data, to further support 1 and 2.
- 4 When these objectives are met, a large scaled deployment of hydroacoustic sensors should be conducted, using various platforms (drifters, vessel of opportunities, stationary observatories etc), and finally providing the models with adequate data.

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References

2003. The ecosystem approach to fisheries. Food and agriculture organization of the United Nations. 4 Suppl. 2.
<ftp://ftp.fao.org/docrep/fao/005/y4470e/y4470e00.pdf>
- Behrenfeld, M. J. and Paul G. Falkowski, P. G. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and Oceanography* **42**: 1–20.

- Claustre, H., Antoine, D., Bohme, L., Boss, E., D’Ortenzio, F., D’Andon, O. F., Gruber, N., Hood, M., Johnson, K., Lampitt, R., LeTraon, P.-Y., Lequ  r  , C., Perry, M.-J., Testor, P., Handegard, N. O., Lewis, M., and Yoder, J. 2009. Expanding and enhancing the system for observing biogeochemical and ecosystem variables in the open ocean: new observations and capabilities in the decade ahead. *In* OceanObs09’ Plenary Community White Paper.
- Doks  ter, L., God  , O. R., Olsen, E., N  ttestad, L., and Patel, R. 2009. Using a bottom mounted lander as a tool for observations and ecological study of marine mammals. *ICES Journal of Marine Science* **66**: 1029–1036.
- Foot  , K. G. 2009. chapter Quantitative Research Surveys of Fish Stocks. *Computers in Fisheries Research*. Springer. second edition. 145–190.
- Foot  , K. G., Knudsen, P., Korneliussen, R. J., Nordb  , P. E., and Roang, K. 1991. Postprocessing system for echo sounder data. *The Journal of the Acoustical Society of America* **90**: 37–47.
- Genin, A. and Boehlert, G. 1985. Dynamics of temperature and chlorophyll structures above a seamount—an oceanic experiment. *Journal of Marine Research* **43**: 907–924.
- God  , O. R., Handegard, N. O., Patel, R., and Torkelsen, T. 2009a. Stationary acoustic systems for monitoring ecosystem dynamics. Manuscript : in prep.
- God  , O. R., Patel, R., and Pedersen, G. 2009b. Diel migration and swim-bladder resonance of small fish: some implications for analyses of multi-frequency echo data. *ICES Journal of Marine Science* **66**: 1143–1148.
- God  , O. R., Patel, R., Torkelsen, T., and Vagle, S. 2005. Observatory technology in fish resources monitoring. *In* International Conference “Underwater Acoustic Measurements: Technologies & Results” Heraklion, Crete, Greece.
- Handegard, N. O., Demer, D., Kloser, R., Lehodey, P., Maury, O., and Simard, Y. 2009. Toward a global ocean ecosystem mid-trophic automatic acoustic sampler (maas). *In* OceanObs09’ Community White Paper.
- Hjellvik, V., God  , O. R., and Tj  stheim, D. 2004. Diurnal variation in acoustic densities: Why do we see less in the dark? *Canadian Journal of Fisheries & Aquatic Sciences* **61**(11): 2237–2254.
- Holliday, D. V., Donaghay, P. L., Greenlaw, C. F., Napp, J. M., and Sullivan, J. M. 2009. High-frequency acoustics and bio-optics in ecosystems research. *ICES Journal of Marine Science* **66**: 974–980.

- 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.
- Kooijman, S. 2000. *Dynamic Energy and Mass Budgets in Biological Systems*. Cambridge University Press.
- Korneliussen, R. J. and Ona, E. 2003. Synthetic echograms generated from the relative frequency response. *ICES Journal of Marine Science* **60**: 636–640.
- Lehodey, P., Murtugudde, R., and Senina, I. accepted. Bridging the gap from ocean models to population dynamics of large marine predators: a model of mid-trophic functional groups. *Progress in Oceanography* Special issue of the EUR-OCEANS conference “Parameterisation of Trophic Interactions in Ecosystem Modelling”, 20-23 March 2007, Cadiz, Spain.
- Lehodey, P. and Senina, I. 2009. An update of recent developments and applications of the seapodym model. *In* 5th regular session of the scientific Committee of the Western Central Pacific Fisheries Commission. Port Vila, Vanuatu. WCPFC-SC5-2009/EB-WP-10. 44 pp.
<http://www.wcpfc.int/meetings/2009/5th-regular-session-0>
- Lehodey, P., Senina, I., and Murtugudde, R. 2008. A spatial ecosystem and populations dynamics model (seapodym) – modeling of tuna and tuna-like populations. *Progress in Oceanography* **78**: 304–318.
- Mac Lennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. *ICES Journal of Marine Science* **59**: 365–369.
- Makris, N. C., Ratilal, P., Symonds, D. T., Jagannathan, S., Lee, S., and Nero, R. W. 2006. Fish population and behavior revealed by instantaneous continental shelf-scale imaging. *Science* **311**: 660–663.
- Maury, O., Faugeras, B., Shin, Y.-J., Poggiale, J.-C., Ari, T. B., and Marsac, F. 2007. Modeling environmental effects on the size-structured energy flow through marine ecosystems. part 1: The model. *Progress in Oceanography* **74**: 479–499.
- Opdal, A., Godø, O., Bergstad, O., and Fiksen, O. 2008. Distribution, identity, and possible processes sustaining meso- and bathypelagic scattering layers on the northern mid-atlantic ridge. *Deep-Sea Research Part II: Topical Studies in Oceanography* **55**: 45–58.
- Senina, I., Sibert, J., and Lehodey, P. 2008. Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: Application to skipjack tuna. *Progress in Oceanography* **78**: 319–335.

- Stanton, T. K., Chu, D., Wiebe, P. H., Martin, L. V., and Eastwood, R. L. 1998. Sound scattering by several zooplankton groups. i. experimental determination of dominant scattering mechanisms. *The Journal of the Acoustical Society of America* **103**: 225–235.
- Totland, A., Johansen, G., Godo, O., Ona, E., and Torkelsen, T. 2009. Quantifying and reducing the surface blind zone and the seabed dead zone using new technology. *ICES Journal of Marine Science* **66**: 1370–1376.
- Trevorrow, M. V. 2005. The use of moored inverted echo sounders for monitoring meso-zooplankton and fish near the ocean surface. *Canadian Journal of Fisheries & Aquatic Sciences* **62**: 1004–1018.