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Review

Marine animals as platforms for oceanographic sampling: a "win/win" situation for biology and operational oceanography

Mike Fedak

NERC Sea Mammal Research Unit (SMRU), Gatty Marine Laboratory, School of Biology, University of St. Andrews, Fife KY16 8LB, Scotland (maf3@st-and.ac.uk)

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Abstract: The development and deployment of logging and telemetry equipment on wide ranging marine animals has provided a wealth of data on their movements and behaviour. We can now predict, within reasonable limits, where many species go, which parts of the water column they will visit and when they will go there. But we also need to know more about the environment through which they move in order to understand their biology and the potential risks to their population status. Additionally, there is a need for near real-time monitoring of ocean processes for long-term weather and climate analyses and forecasting. Developments in sampling and data retrieval devices have made it possible to create a synergy between the biological studies of marine vertebrates and oceanographic studies used to describe and predict changes in the ocean atmosphere system. We can use larger marine species as platforms of opportunity to gather detailed oceanographic information. Animals can collect information from logistically difficult areas, at fine temporal and spatial resolution at relatively low cost. I will discuss some technological opportunities that are currently available, the results of ongoing projects and one "proof of concept" study with the hope of stimulating interest across the technical, oceanographic and biological communities for such an approach.

It seems certain that the need for timely, high resolution oceanographic information required for understanding the distribution of marine animals and for the development of increasingly fine resolution physical models will grow more rapidly than the funding available to collect that data. By using animals as platforms, we can close the gap between resources and requirements.

key words: telemetry, foraging, salinity/temperature profiles, modelling, climate change

Introduction

Telemetry and bio-logging devices are returning increasing amounts of information about marine animals from all the major taxa of top predators, including fish, reptiles, birds and mammals. In ever-increasing detail, these devices provide information on where the animals go, how they behave and, to some extent, provide information on their immediate environment. However, understanding the factors that determine the distribution of wide ranging marine animals requires a more general understanding of the physical and biological structure of the oceans than spot samples of environmental parameters can provide. Animal-derived data needs to be integrated with more synoptic oceanographic approaches. But it is often the case that when we look for data on the oceanographic conditions in areas through which the animals move, we find it is incomplete or lacking. This can be because the animals utilize areas of ocean that are poorly known because of their inaccessibility or as the result of other logistic constraints. It is also often the case that we need information on a finer spatial or temporal scale than oceanographic models can provide. This perceived gap between what we as biologists would like to know about ocean structure and the limited information available to describe it appropriately provides motivation for us to supply more environmental data from the tags we apply, using the animals themselves as oceanographic samplers. Oceanographers too are sometimes limited by a lack of data to build and test their models. It is therefore not surprising that the idea of using marine animals as sampling platforms has grown among both biologists and oceanographers alike.

This is not a new idea. The earliest published reference to the approach I have found is from a U.S Navy report written by Evans and Leatherwood in 1972 but I am sure that it occurred to scientists long before that. Indeed, the links between bio-logging devices for use on marine mammals and oceanographic measurement goes back to the very origins of the ideas for monitoring dive behaviour. Gerry Kooyman in his book, *Weddell Seal*: *consummate diver* (1981), recounts how Pers Scholander got the idea for a dive recorder that could be attached to whales from a description written by Lord Kelvin in the 19th Century. Lord Kelvin developed the idea to take soundings from a moving ship based on the compression of air in a capillary tube containing pigment. It was this original oceanographic application that indirectly sparked the ideas for Kooyman's pioneering work developing dive recorders.

But while the idea of using animals as oceanographic platforms is not new, the technological tools to produce effective monitoring equipment have only recently become available, because of the availability of very small, low power microelectronics and computing techniques. Additional impetus is added to this development by ever increasing demands for oceanographic data. These demands are certainly felt by the biologists wanting to understand the distribution of marine animals and how they interact with the marine environment but they are also driven by the data requirements of the oceanographic community itself. The importance of near real-time monitoring of ocean processes for long-term weather and climate analyses and forecasting is increasingly being recognized. Innovative remote samplers such as moorings, buoys, gliders etc. are being developed, each of which can return data on rapid timescales. Ultimately, programs such as the Global Ocean Observation System (GOOS) will enable the assimilation of such near real-time data into state-of-the-art general circulation models. One important purpose of these is to accurately represent and predict climate variability on seasonal and longer timescales. Using larger marine top-predators to carry instruments to collect such data can play a significant role in this effort.

While the opportunities presented by this approach may not yet be widely recognized in the oceanographic community, such recognition is rapidly developing, particularly within multidisciplinary groups brought together by pioneering integrated studies such as TOPP (Tagging Of Pacific Pelagics) as discussed by Barbara Block and Dan Costa at this meeting. This large-scale pilot project has been supported in part by the Census of Marine Life project (CoML) funded by the Sloan Foundation. This foundation initiated the project to provide a stimulus to large scale, cross-disciplinary exploration of the seas. Funding through the US National Oceanographic Partnership Program (NOPP), administered by the Office of Naval Research has helped to advance the technological developments needed to develop equipment and to create the integrated databases required to make the data accessible. Other projects based on this approach are being formulated or have been submitted to other funding agencies (*e.g.* NEO, as presented at this meeting).

I believe all of the communities involved are increasingly recognizing the value of such integrated approaches. Biologists realize that without such integration, they will not understand how ocean processes shape the life histories of the beasts they study and how they affect the status of their populations. Ecosystem managers, environmental policy makers and conservationists know that without integration of the biological and oceanographic information, they can not make sensible decisions about management regimes. Furthermore, as the demands of operational oceanography increase, oceanographers will search for new cost effective, innovative technologies to fill the gap between data requirements and the resources provided to collect that data. Therefore, I am convinced that using marine animals to collect oceanographic information, while not a new idea, is an idea whose time has come. I believe that with further development, the approach could have an impact on the study of the "Earth System" nearly as significant as did the development of satellite remote sensing.

Two different approaches to collecting information about the behaviour and environment of marine animals have developed in parallel, often utilizing similar sensors but differing in how the information is returned; archiving information for subsequent retrieval when animals or instruments are recaptured or recovered versus transmission of information in near-real time. While the two approaches are subject to differing constraints, both have proved useful in appropriate circumstances (see Boehlert *et al*., 2001; Guinet *et al*., 1997; Koudil *et al*., 2000; Hooker and Boyd, 2003 as examples of the archival approach). In this brief review, I will discuss the approach taken by a group of biologists and engineers at the Sea Mammal Research Unit (SMRU) to enable the use of marine mammals and other large marine animals to collect and process oceanographic information and to relay this information in near real time via satellites. I will discuss the general methodological problems that need to be overcome to accomplish this process and provide examples of recent studies by SMRU and others that show the potential of the approach. My fundamental purpose is to demonstrate the potential of the technique in order to raise its profile within the oceanographic community. I also hope to encourage increased cross-disciplinary collaboration between biologists studying marine animals, engineers and oceanographers and highlight the synergies made possible by the approach.

Methodology

There are a number of constraints that must be overcome to realize the potential of animal-borne oceanographic sampling devices. Some are common to all forms of telemetry and data logging while some are specific to oceanographic sampling from animals. My intention is to review these in a very general way and to give examples of how instruments designed and built by the Sea Mammal Research Unit and others (SMRU) have attempted to overcome them.

General constraints of telemetry and bio-logging

I suggest that the most fundamental constraint to the use of animals as platforms is the size of the instrumentation package that they can carry. For systems that relay information *via* telemetry, the battery is often the single largest component in any device. This is because sizes of electronic and (with developments in nano-technology) even mechanical components have become relatively small. Therefore the energy requirement of the devices emerges as the most important "ultimate" constraint *via* its influence on battery size (Fedak *et al.*, 2002). Because every bit of information that is sent uses up some of the energy contained in the battery, minimizing size requires that any information that is sent is informative and important.

SMRU began to develop bio-logging devices, termed Satellite Relayed Data Loggers or SRDLs, that used UHF radio to relay data via the Argos satellite system almost two decades ago, when this technology was still in its infancy. We realized at the outset that it was important to use the data transfer facility that the Argos system provided because inevitably, as soon as we could locate animals at sea, we would want to learn about their behaviour and how they were exploiting marine resources. Because of bandwidth constraints imposed by Argos and the small percentage of time air-breathing marine animals remain at the surface, the amount on information that could be sent was extremely limited. Energy constraints operated in parallel with the limitations imposed both animal behaviour and Argos (note that these sets of limitations are not additive; actions that overcome one set of constrains also

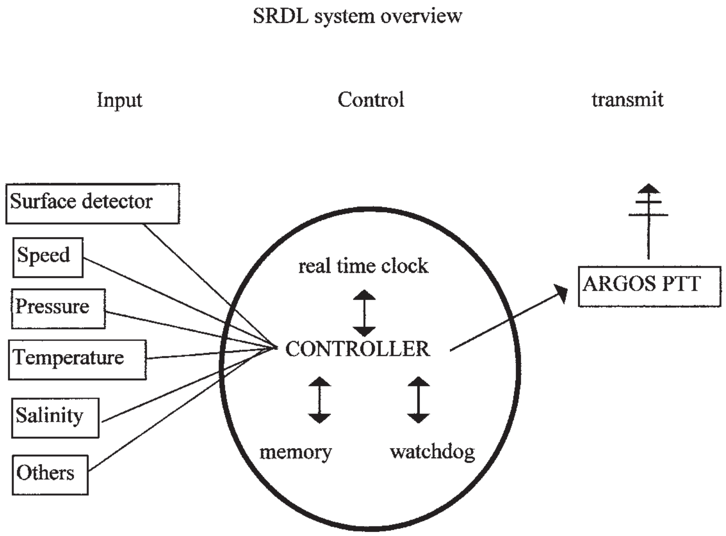

Fig. 1. Schematic diagram of components in SMRU SRDLs. The SRDLs consist of a central micro-controller that monitors inputs from a range of sensors and a real time clock and controls the performance of a UHF transmitter that relays messages *via* the Argos System. It has access to a relatively large memory and can sample at variable rates, up to > 10 times/s, storing data collected at this high resolution in memory for processing and subsequent transmission. The controller runs a complex program that determines the sampling schedule of sensors and timing of transmissions. Because of severe bandwidth constraints that result from the limited time spent at the surface by most air-breathing marine vertebrates, limitations imposed by Argos and limits to battery power, the controller uses a range of data compression techniques to promote energy-efficient data transfer as well as effective power management. By this means, the SRDL can provide data on relatively changing and complex phenomena in the narrow bandwidth available without loss of meaningful resolution (see test and Fedak *et al.*, 2002 for details). The SRDL can send 85000 transmissions spread over periods greater than one year on a single lithium D-cell battery.

work to overcome the others). So we designed SRDLs that incorporated a micro-controller (Fig. 1), with the ability to run complex, flexible software to control data collection, process and compress data while managing the energy budget of the tags. The key tactics involved firstly collecting data at full resolution, then creating effective models to structure the data, applying data compaction techniques, optimising transmission scheduling and having the tag monitor its behaviour to control data delivery, energy costs and tag lifetime. The tag's software contains a simple model of the animal's behaviour. This allows data to be organized and structured to minimize the number of bits of information that needed to be sent to describe complicated behaviours. The tag's software uses a variety of levels of abstraction to provide both detailed information and more synoptic summary information (see Fedak *et al.*, 2002 for a summary of the approach). We linked the output of the tags, as relayed by Argos, to automated decoding software and data base systems in order to make the data available locally as soon as possible after it was received from Argos. Finally, we created a data visualization system to allow the multi-dimensional data provided by the tags to be combined with environmental data from other sources and viewed in an easily accessible visual format on a computer workstation. This visualization system (MAMVIS, Fedak *et al.*, 1996) allowed biologists not familiar with the details of the technology to use a simple GUI interface to explore their data through a time-linked 3-D presentation that incorporated oceanographic data from remote sensing and models.

In a sense this approach was "pre-adapted" for the collection of environmental information. The capability for sophisticated software control of all of the tags functions, based on flexible high level software written in "C", meant that the tags could be easily programmed for a wide range of different animals and data collection tasks. The software meant that we could optimise performance in order to fit as much useful information as possible into the narrow bandwidth available, leaving room for both behavioural information and other data. With the inclusion of suitable sensors, we realized that we had an opportunity to have the tags collect detailed local environmental information that was useful to us in describing the animal's immediate environment. In addition, by using appropriate sensors, we could insure that the information collected was compatible with that collected by more conventional oceanographic approaches. This would make the information of interest to oceanographers, who would then help us place the animals in a broader oceanographic perspective. To this end, we connected a commercially available oceanographic sensor (see below) for salinity/temperature measurements to our SRDL units.

Constraints on oceanographic sampling from animal platforms

Salinity/temperature/depth (CTD) information collected as vertical profiles over a range of depths arguably provide the most fundamental information required by physical oceanographers. Typically, salinity is calculated from highly accurate and precise simultaneous measurement of temperature and conductivity. Temperature is an extremely influential factor in this calculation and so must be estimated, typically to > 0.01°C. Conductivity is usually estimated from inductive or, less often, conductive effects and such sensors are subject to disturbance from fouling. Another difficulty with some sensors is that the field generated by the sensors is perturbed by the device's surroundings. Whereas for instruments located in a frame of fixed geometry, these effects can be taken into account. Correction is not straightforward where instruments are attached to animals, which can change their posture or modify their immediate environment (see below for a particular example where bubbles released by fur seals produced erratic results (Hooker and Boyd, 2003)). Furthermore, the measured temperature must be taken of precisely the same water "sample" for which conductivity is estimated.

Quantification of the accuracy and precision of the sensors that provide this data is critical if data are to be acceptable to oceanographers and assimilated by data consortia into databases such as GOOS, BODC, AEDC, WOD, etc.

This is a particular difficulty for the unsupervised, extended deployments possible with animal-born instruments. Additionally, there is only a small likelihood for recovery of instruments for post-sampling calibration. This puts a premium on sensor stability, preliminary testing, calibration and the development of methods for assessing instrument drift. While depth and temperature sensors are relatively stable and thus are amenable to a priori assessment, approaches for the measurement of conductivity for the calculation of salinity present greater challenges. As in the case of drifter buoys, sensor fouling is a problem, although maybe less so because of the animals' continuous movement through the water. Nevertheless, it remains a formidable challenge to avoid fouling of sensors. Other approaches to monitoring salinity may be possible in the near future but fouling over time is likely to remain a problem. Additional difficulties with inductive approaches involve near field effects caused by the presence of the animal or of other tag components. Careful shaping of the geometry of the sensors and inductive coils is required to prevent perturbations from affecting readings. These problems are common to almost any instrument whether it is deployed on a buoy, AUV (Autonomous Underwater Vehicle) or animal platform. The size constraints imposed by attachment to animals compound such difficulties.

Beyond the problems related to the sensors themselves, animal samplers present additional challenges, but also new opportunities. They do not sample randomly; nor do they perform pre-set transect coverages like those that can be accomplished with ships or AUVs. Thus, the exact locations of data collection cannot be pre-determined. This apparent disadvantage itself could make the approach complementary to others, providing samples at unforeseen locations to test and validate models. But clearly developments in analytical methodologies are required to integrate data collected by animals with that collected by more conventional means. Animals always have their own agenda in relation to their particular life history requirements. We now have enough information on many species to predict where they will go within reasonable limits (see Gillespie, 2001; Stevik *et al.*, 2002 for non-exhaustive reviews). Appropriate choice of study species can therefore allow us to pre-define the timing and spatial extent of sampling. We know enough about diving habits to predict the depth excursions that animals will perform and the frequency with which these occur. Unlike drifting buoys, animals often move relatively rapidly in a directed fashion and can deliver transects of nearly contemporaneous data. Their tracks often cut across frontal regions as they travel between breeding, foraging and resting locations. They can direct sampling effort to particularly interesting and productive regions as they adaptively sample their environment based on previous experience. They provide a relatively cheap approach when compared to ships and more elaborate drifting and moored buoys, which can allow for larger deployment numbers. Some species penetrate deeply into Polar Regions in ice-covered areas where cloud cover can limit the applicability of remote sensing, and where profiling floats and ships cannot operate. All these characteristics present problems but can also be advantageous in many instances if used in a complimentary way with other approaches.

Indeed, because of the "adaptive" nature of the way animals sample their environment, it will always be necessary to incorporate data from them into broader, more general coverages provided by remote sensing, ship-born data collection and models. The approach will always be most valuable when used in conjunction with these more conventional approaches, just as is data from drift buoys and ships of opportunity etc. It also seems likely that animal born packages will never provide data of the quality of the best ship-born instruments. But if appropriate specifications of accuracy and precision are provided, the constraints involved in developing and using this approach can be overcome and that animal born oceanographic sensors will provide an extremely valuable complement to other approaches.

Results of past deployments

CTD-SRDLs on beluga whales

Belugas or white whales (*Delphinapterus leucas*) are a high Arctic whale species that is

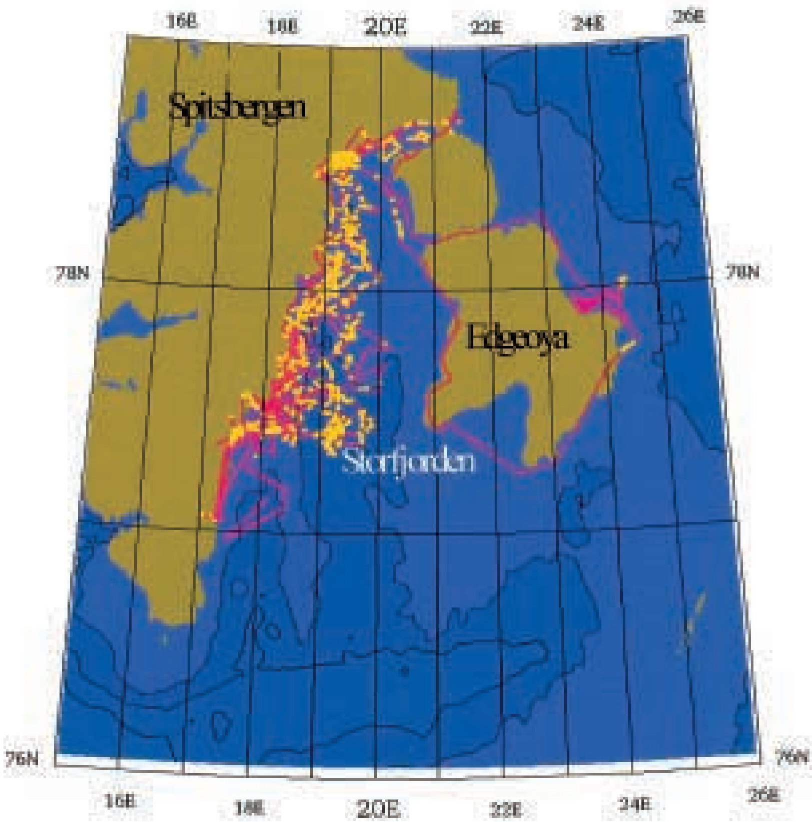

Fig. 2. Map of distribution of CTD-casts performed by a white whale during the Autumn freeze-up in Storfjorden, Svalbard, 7–24 November 2001. The bands of blue colour represent depth contours at 100–500 m (and greater). The red line connects Argos locations in the temporal sequence in which they were computed. Each yellow dot (N=540) represents the location of a CTD profile upcast collected by the CTD-SRDL. Data from Lydersen *et al*. (2002).

circumpolar in distribution (Smith and Martin, 1994) and that frequents waters that are often ice covered and inaccessible to ships and other oceanographic data collection approaches. We deployed novel satellite-linked conductivity-temperature-depth loggers (CTD-SRDLs) attached to the dorsal ridge of wild beluga whales to study the oceanographic structure of an Arctic fjord (Storfjorden; see Fig. 2) in Svalbard (Lydersen *et al.*, 2002). The purpose built instruments incorporated salinity/temperature/depth sensors into purpose built satellite relay data loggers (SRDLs) built by SMRU.

The conventional SMRU SRDLs relay information on the movements (geographic position) and diving behaviour (depth) of marine mammals (Fedak *et al.*, 2002), but for the purposes of this study we integrated onboard oceanographic-quality conductivity-temperature (CT) sensors (Compact CT, Alec Electronics, Ltd; Kobe Japan) in addition to the basic sensors on the tags. The specified accuracies of the CT sensors were ±0.01 mS/cm and ±0.01°C. These values were confirmed by a series of laboratory and field tests using water samples that were calibrated with a Guildline 8400 B salinometer (Guildline Instruments Ltd., Ontario, Canada) and an unmodified Compact CT calibrated by the manufacturer. Depth was measured by the pressure transducer and circuitry onboard the SRDL (KellerPA-7, Keller, Winterthur, Switzerland). The output from the depth transducer was sampled with 16 bit A/D that, after calibration and offset correction, provided each time the tag was clear of the water's surface, provided 20 cm accuracy. Depth and CT sensors sampled data within approximately 10 ms of each other in each sampling interval (*i.e.* virtually simultaneously and at the same location given that the animals change depth at about 1.5 m/s).

The SRDLs were programmed such that the depth and CT sensors sampled once every second during the ascent phase of dives (upcast) on a schedule that was designed to provide data coverage throughout the 24-hour cycle from the deepest dives performed. The day was divided into four 6-h blocks, beginning at midnight, GMT. The SRDL provided information on general dive behaviour at all times. CTD upcasts were performed, starting at the bottom of the first six dives of the 6-hour period that were deeper than 45 m. It then performed additional CTD data collection in any subsequent dives within the 6 h period that were deeper than these first records. System Argos imposes limits on the number of transmissions PTTs can make (maximum 1 transmission/40 s) and the number of bits of information carried in each transmission (currently 248 bits/transmission). Transmission bandwidth constraints, resulting from the interactions of Argos transmission requirements with the limited time spent at the surface by the animals, meant that data on profiles had to be compressed (see above and in Fedak *et al.*, 2001, 2002). Therefore, upon completion of each upcast, a "broken stick" compression algorithm (as used in XBT casts; Rual, 1996) was applied to identify and retain the 12 most important inflection points in the temperature, conductivity and computed salinity profiles. This method first applies a median filter with a 5 m window, followed by a Hamming smoothing filter (11 m window) prior to the broken stick reduction method. At the end of the 6 h period, temperature, salinity and conductivity profiles from the 6 deepest dives of that period were put into a buffer from which they were chosen at random for transmission. The SRDL was programmed to send data for up to 100 days (likely duration of attachment) during which time up to 500 transmissions per day could be sent. However, only a fraction of these were received each day because of satellite availability and transmission interruptions when the antenna of the SRDL is submerged.

During the deployment, the whales routinely dived to the bottom of Storfjorden and occupied areas with up to 90% ice-cover, where deployment of conventional ship-based CTD-casts would have been difficult. During the initial freezing period in the fjord from 7–24 November 2001, CTD-profiles were sent from 540 geographic positions, covering an area of ~8000 km^2. During this period the whale occupied areas that had 4/10th to 9/10th ice-cover. The east-west transect shown in Fig. 3 is from 18 November, while the north-south transect is a composite picture of data collected during the period 10–20 November. A striking feature in both transects is the substantial heat in the water column. The warmest water is found in the deepest parts of the fjord overlaying a layer of cold, more saline water, which was probably a remnant from dense water formed the previous winter. The most probable explanation for the warm tongue of water is that it is an intrusion of warm North Atlantic water (NAW) from the south.

Our oceanographic data, from the white whale's CTD-tag, show that this northward flow of NAW has the potential to have a large influence on the heat content of the water column and therefore also impact ice formation in the Storfjorden polynya area. Previous estimates of brine formation in Storfjorden have assumed the entire water column is near the freezing

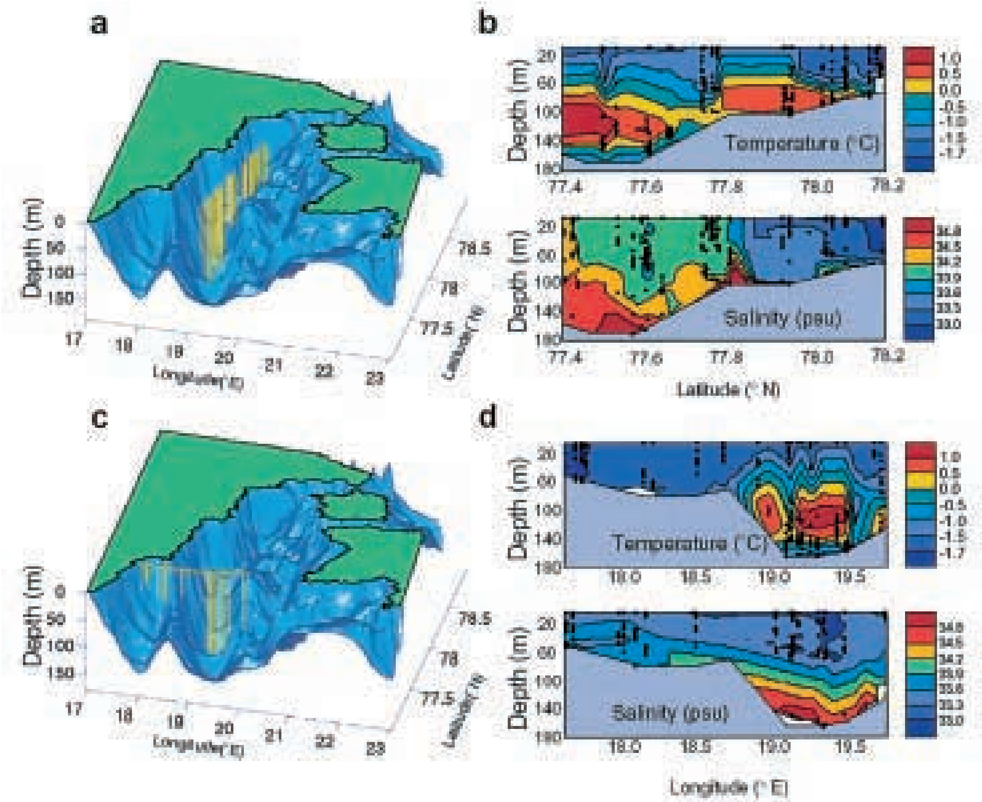

Fig. 3. CTD transects in Storfjorden, Svalbard. The maps show the locations of selected dives performed by a white whale (each yellow spike represents a dive; the length of the spikes represents dive depth) carrying a CTD tag, along a north-south transect (a) and an east-west (c) transect superimposed on a three-dimensional bathymetric map of Storfjorden, Svalbard. CTD-casts produced during these dives are the basis for the temperature and salinity profiles shown in B and D respectively. Each dot in (b) and (d) represents a location where a CTD-measurement was taken. Figure from Lydersen *et al*. (2002).

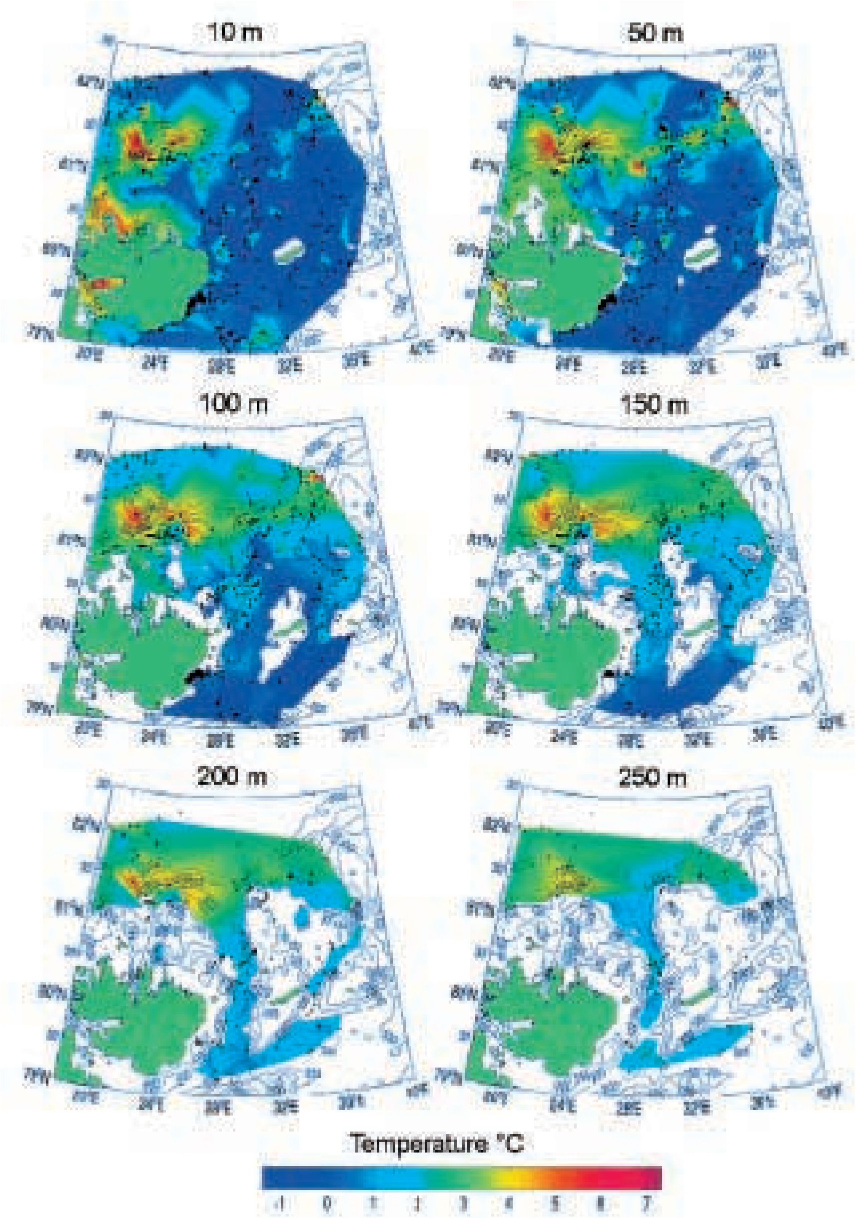

Fig. 4. Temperature distributions at different water depths in northern parts of the Barents Sea based on temperature data collected by ringed seals using standard SMRU SRDLs. Black dots on the map represent locations where a temperature profile was taken (Lydersen *et al*., 2004). The SRDLs on the seals collected data from a large sector of the northern Barents Sea during the autumn and early winter. A total of 2346 temperature profiles were collected over a 4-month period from Norwegian and Russian Arctic waters in areas that were at times 90–100% ice-covered. Temperature distributions at different depths from north-eastern parts of Svalbard, Norway, show warm North Atlantic Water (NAW) flowing along the continental slope and gradually cooling at all depths as it flows eastwards. The data suggests that most of the cooling takes place west of 30°E.

point in the fall and early winter (Haarpaintner *et al*., 2001a), and that the water masses in inner Storfjorden consist mainly of AW (Haarpaintner *et al*., 2001b). This is clearly not the case and future oceanographic models of Storfjorden need to take into account the intrusion of NAW from the south.

We believe that this small-scale pilot study demonstrates the potential utility of collecting oceanographic data from marine animals, both to help us understand their distribution and to gain insight into the oceanographic processes that influence where they live. It is the first report of the use of an animal-born oceanographic CTD biologger.

Another successful deployment has since been reported by Hooker and Boyd (2003) who mounted an ALEC CTD integrated with specially constructed tag on Antarctic fur seals (*Arctocephalus gazella*). These were devices archival tags that stored data during the short feeding trips performed by females that went to sea to forage during lactation. The salinity/temperature profiles obtained from the tags were compared with those obtained from an oceanographic ship operating in the same area. The results were comparable but the authors identified areas where further developments were required. They demonstrated that near-field effects could sometimes perturb readings. They also noted that during the final stage of ascent from depth (from 50–70 m below the surface) bubbles released from the fur of the seals caused the devices to give conspicuously unreliable measures. These problems were observed and documented using cameras attached to the seals that were programmed to record photos during the dive. However, the authors suggested that with careful placement of the tags and calibration, useful CTD profiles could be obtained.

Temperature profiles or sea surface temperatures have been collected by biologgers on both marine mammals and birds (Boehlert *et al*., 2001; Bost *et al*., 2003; Charrassin *et al*., 2002; Guinet *et al*., 1997; Koudil *et al*., 2000). Also, see Wilson *et al*. (2002) for a review on temperature data collected by seabirds. In a paper currently in press Lydersen *et al*. (2004) report the deployment of SMRU SRDLs on ringed seals in the Arctic Ocean around Svalbard. Not only did these animals range widely under heavy ice cover, but they provided coverage without regard to national boundaries, an option not ordinarily available to the Norwegian oceanographers involved in ship-based projects. The data collected by these animals was used to create maps of subsurface temperature structure (Fig. 4) around the north of Svalbard and to provide transects of water temperature from between Svalbard and Franz Josef Land before and after ice formation in the Autumn. At this meeting, Dan Costa reported results from deployments of SRDLs on crabeater seals (*Lobodon carcinophagus*). Temperature profiles were provided from deep within ice covered Antarctic waters as part of the Southern ocean GLOBEC Program (Costa, 2003). In addition, a number of studies presented at this meeting (Bost *et al*., 2003; Charrassin *et al*., 2003; Block, 2003; Daunt *et al*., 2003) reported sea temperature information from animal born platforms. It is clear from these presentations that technological approaches for using biologgers in this way are developing rapidly with issues such as response time and drift being addressed.

All these examples point to the growing realization of the potential of animal-born oceanographic sensors and the acceptance of the approach by the oceanographic community.

Discussion and conclusions

There are clear reasons why biologists will need use animals as oceanographic data collection platforms. Instruments providing detailed, appropriate oceanographic information can collect environmental information at relevant times, locations and scales to help them understand the animal's foraging behaviour and requirements. I emphasize that it beneficial if the information is of the type oceanographers routinely collect so that they also can be brought on board to help with interpretation. If the oceanographers have access to the data so collected, they may be able to improve understanding of local physical oceanographic processes and improve their models to predict conditions experienced by the animals and how these may change. The biologists then can use these better, more detailed models to improve our understanding of foraging distribution and its success.

But I believed there are equally clear reasons why oceanographers might benefit from using animals as oceanographic data collection platforms. Animals can provide information from logistically difficult or inconvenient places and times. They can provide data in near real time at relatively low cost. To meet the demands of "operational oceanography", oceanographers and modellers require ever increasing amounts of timely data. Funding is unlikely to increase as quickly as data requirements. New approaches need to be developed to fill the gap. This approach is one such that shows promise.

Table 1 summarizes some of the positive and negative aspects of the approach. I believe that with continued development of both the required hardware and appropriate analytical techniques, most of the negative aspects can be ameliorated. The positive aspects will remain important, even as other "autonomous" approaches are developed. A broad spectrum of oceanographic habitats is used by different species of marine mammal and many have been shown to target oceanographic discontinuities for foraging. They are regarded as 'adaptive samplers', seeking out and spending more time in areas of oceanographic interest. Their knowledge of oceanographic process is an extremely valuable resource that should, and now can be, exploited by oceanographers. Quoting a recent report in the popular press, "These new explorers are actually the real experts on what happens in the ocean—the mammals that live there" (Peter Calamai, Toronto Star, 9 March, 2003). While this is clearly overstatement, these animals do have information of which, we can take advantage and we can use that "expertise" both to ensure their conservation and protect the marine environment. The Oceans are of fundamental importance to the earth's ecosystem because of their resources and their dominant role in determining climate. They are home to populations of marine

Table 1. Pros and cons of animals as platforms for oceanographic sampling.

Pros	Cons
Low cost	Non-random sampling
Near real time data delivery	Limited control of sampling regimes once animals have been tagged and released
Flexibility: Possible to target specific space/time /depth ranges by selecting appropriate species and/or age groups	Variable depth ranges depending on animal behaviour
Transect type as well as directed small-scale sampling	Variable data transmission rate depending on animal behaviour
Access to data sparse areas, *e.g.* within polar ice regions	Fouling, long-term sensor drift
Long term deployments with high spatial and temporal resolution feasible	Inability to re-check calibration after deployment

organisms that are vitally important to mankind and the physical structure and the distribution of resources within the oceans are important to the health of these populations. The cumulative effects of distribution of these resources largely determine the distribution and abundance of marine top predators. Therefore, these larger animals, those on which we can place our equipment, are particularly sensitive indicators of marine resource distribution and abundance and are particularly good indicators of the health of the marine environment. We now can monitor the distribution and behaviour of these animals to understand how they exploit their environment but we need to do more to identify those features that are crucial to the health of their populations. Clearly we require detailed information about their surroundings to enhance this understanding and to learn what features of their environment determine their distribution. Data gathered from the animals themselves will expedite this understanding

Oceans are also increasingly being seen as the key element of man's environment because of their dominant effects on global climate and because of their potential for providing essential resources. Issues of climate change and the consequences of anthropogenic forcing are increasingly dominating international negotiations on environmental management and exploitation and use of the seas. These discussions require new types of oceanographic data that is high resolution yet synoptic in coverage. In the longer term, I expect that this approach will help us to understand the distribution and requirements of marine biota to enable safer stewardship and effective management of marine biological resources. It will make an important contribution to "operational ocean forecasting" to enable safe, effective and sustainable use of the seas and aid the development of higher resolution, near real-time oceanographic models for enhanced understanding of the coupling of oceanic and atmospheric processes. These in tern will enable more robust short, medium and long-term climate forecasting and foster cross-disciplinary cooperation between biologists and physical and biological oceanographers.

Potential ethical issues

At meetings and lectures, individuals have expressed very reasonable ethical concerns related to "using" marine mammals in the service of oceanography and the precedents that this approach may set. It is extremely important, if this approach is to become an effective tool for ocean observation, to make clear why and how it benefits the animals involved. We need to emphasize at the outset, not after the fact, that the idea to have marine animals collect oceanographic information grew from the realization that we have insufficient knowledge of the oceanic environment of most species to allow us to develop an understanding of what features of the ocean are most important to the animals and how variations in those features might influence their reproductive success and population status. Without more detailed information, it will be difficult to reconcile conservation and resource exploitation issues.

But when we develop the means ways to collect oceanographic information at times and at scales relevant to these animals, we immediately become aware of the value of such data to a wider community. As discussed above, many oceanographers also feel that their information requirement will have to increase very rapidly if operational marine forecasting is to progress. With biologists working with the oceanographic community, we can create a "win-win" situation where biologists get the information needed to understand the biology of the animals and to manage the oceans responsibly, while oceanographers get the means help to fill this developing information gap. That improved oceanographic database will in turn generate better models and improve knowledge of oceanographic conditions feeding directly back into improving our understanding of the animals and improving our ability to be better stewards of the marine environment.

So this approach is not about using animals in the service of man. It is first and foremost about the means to collect the data required to protect and manage the marine environment in such a way as to sustain biodiversity. We use the data "in the name of science" but with the strongly held view that the science is done in the service of sustained bio-diversity and environmental protection. The understanding we gain of the "earth system" that is facilitated by this approach can hardly be considered purely "science for its own sake".

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