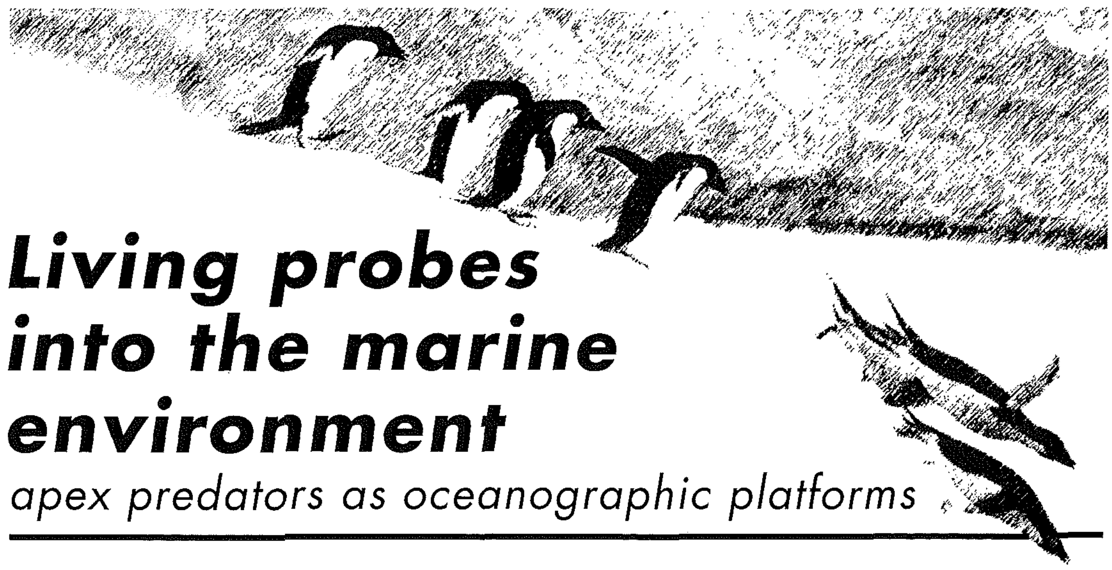


Living probes into the marine environment

apex predators as oceanographic platforms

Sascha K. Hooker, Ian L. Boyd, Mark A. Brandon, Elizabeth J. Hawker

The primary obstacles to the collection of oceanographic data are the limitations of sampling in time and in three-dimensional space. Ship-board surveys are well designed for detailed sampling at depth, but are constrained in horizontal space and limited in time by high costs. Satellite monitoring can produce time-series of data over large horizontal spatial scales, but has only limited ability to obtain data concerning parameters at depth, and can also be constrained by the necessity for calibration and 'ground-truthing' of data. In contrast, fixed platforms can provide high-resolution data over long time periods, but only within limited three-dimensional space. So what is the answer?

The optimal data-gatherer

If we were to design the optimal oceanographic data-gatherer to overcome the obstacles of conventional sampling in space and time, we might come up with an autonomous instrument that could cruise the oceans assimilating information about its surroundings. This hypothetical instrument could examine the whole ocean surface and descend to depths of over 1000 m. It would have an operational time-span from a few days to over 50 years (depending on how we chose to use it), minimal running costs, and would return (with data) to a predictable location at a predictable time. When confronted by the scientific challenge of marine systems, most biological and physical oceanographers would find good use for such an instrument. But it would be unbelievably complicated, and would go far beyond the potential of even projects such as *Autosub,** which is limited by energy requirements and the complexity of programming needed to enable it to avoid obstacles.

In many ways, this instrument sounds like one of those unworldly theoretical concepts dreamt up by mathematicians or science fiction writers. However, the reality of this vision is much closer than one might think. Why should our instrument not be a living organism within the marine environment? Attaching oceanographic sensors to living apex predators would relinquish the user's control over fine-scale selection of samples, but could provide potentially limitless data; and if predators were chosen strategically, it could give detailed information for selected regions of interest (Table 1, overleaf).

**Autosub* is an unmanned autonomous underwater vehicle for gathering data.

Marine organisms and the environment

Like all organisms, marine animals are, to a degree, products of their environment, partly through genetic adaptation, partly through behavioural responses to variability in the immediate surroundings. Thus by recording observed variation in features of animal behaviour, development and life-histories, we can infer information on environmental variability. For example, at the most basic level, species composition of coastal ecosystems can be used to predict the range of environmental conditions in the area. Secondly, local abundance and growth of certain species can be used to infer additional features of the environment, such as the degree of wave action or exposure to storm damage. Lastly, variations in growth rate or number of offspring may reflect interannual variability in environmental conditions. Of course, it is almost always more satisfactory to carry out direct observations of the environment, but there are circumstances where observation of the underlying physical and biological systems can be difficult and/or prohibitively expensive. In the open ocean we have often relied on the use of inferential data, and it is here that the use of top predators as the vehicle for our instruments would come into its own.

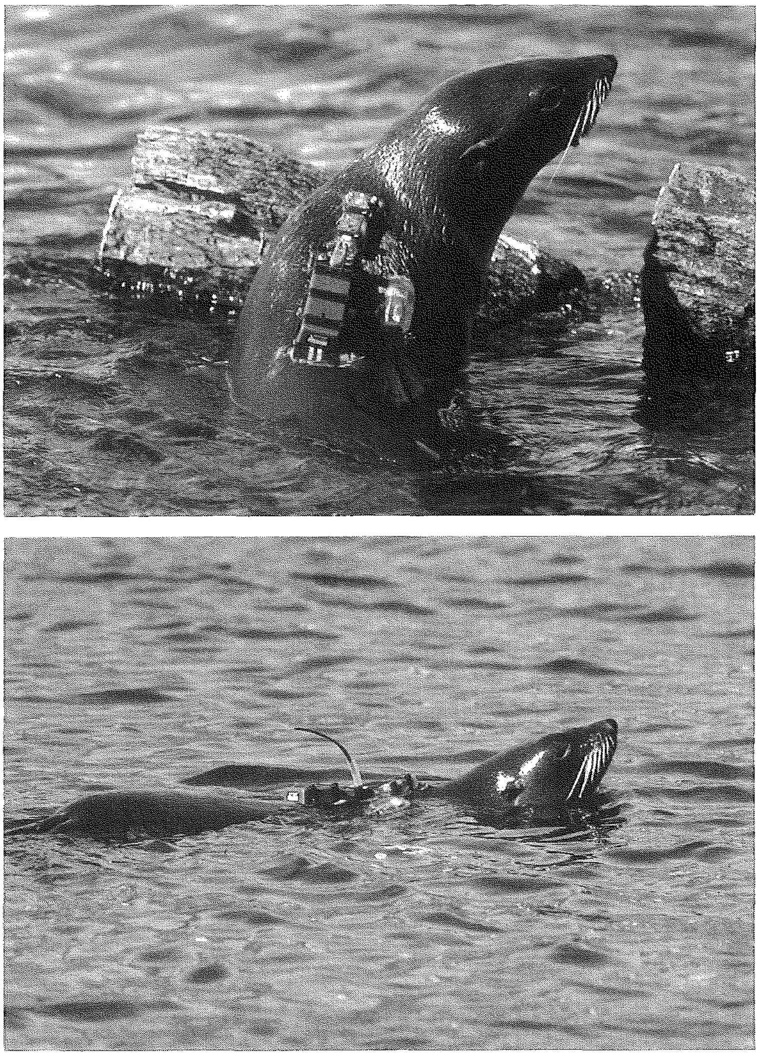


Figure 1 *Various species of marine fauna are tracked using data-logging and radio transmitting systems (VHF or satellite).* ***Upper*** *Antarctic fur seal with data-logger, VHF and satellite transmitters.* ***Lower*** *Swimming Antarctic fur seal, with satellite transmitter antenna showing above the water surface.*
Ian Boyd and other researchers at the British Antarctic Survey have been deploying time–depth recorders and satellite positioning tags on Antarctic fur seals to investigate their foraging ecology around Bird Island, South Georgia.

(Photographs by A.R. Martin.)

(Continued opposite)

Table 1 *Costs and benefits of different oceanographic sampling protocols.*

Sampling method	Costs	Benefits
Ship-board monitoring	Expensive Limited in time and space	High-resolution data
Satellite monitoring	Expensive Weather-dependent Little depth penetration	Large horizontal scale Potentially long time-series
Fixed platform	Minimal 3D spatial resolution	Cheap Potentially long time-series
Autosub	Expensive Requires mother-ship	High-resolution data Large horizontal scale Potentially long time-series
Living platform	No fine-scale spatial control	Cheap High-resolution data Large horizontal scale Potentially long time-series

At the simplest level, marine predators are often the most easily observed element of the marine ecosystem. Species vary in tractability, and those that are constrained by the need to return to land – seabirds and seals – are generally the most accessible to researchers. They therefore present highly visible and accessible platforms for carrying oceanographic data-loggers. Admittedly, using animals solves only the vehicle part of the design problems for our oceanographic data-gatherer. The data-loggers still need to be designed, programmed, deployed and perhaps retrieved, and the data downloaded. However, this approach removes many of the complications involved in attempting to design instruments for independent deployment.

Different marine mammal and bird species cover almost all areas of the globe and show a wide range of variation in depth penetration. Species such as elephant seals regularly dive to depths of over 500 m, and at times to depths of over 1000 m, and are known to travel 2 500 km on a 70-day foraging trip. Individual animals carrying appropriate instrumentation thus have the potential to provide information broadly equivalent to that of an undulating oceanographic recorder, but over many thousands of kilometres, and for periods of more than six months at a time. Although we cannot control where these animals go, research suggests that they often travel to, and disperse along, oceanographic features of interest, such as the South Polar Frontal Zone. Researchers could thus essentially 'pick and mix' species, populations, and even individuals, to obtain data about areas and depths of interest. For example, Table 2 (overleaf) shows some of the basic parameters relating to the horizontal and vertical scope of marine predators that have previously been used for instrument-attachment in the area of South Georgia.

However, oceanic predators can offer us far more than just vehicles to carry instruments. Their sensory capabilities, used to hunt for prey in the most efficient way possible, are far beyond those of any instruments we might design to be carried by them. The distribution and abundance of predators will inevitably be influenced by the distribution and abundance of prey. In the oceanic environ-

Figure 1 (cont.) ***Above*** *Dall's porpoise with radio-transmitter attached to the dorsal fin. Brad Hanson of the National Marine Mammal Laboratory, USA, is investigating the movements of Dall's porpoises in the waters around the San Juan Islands, Washington.* ***Right*** *Killer whale with time–depth recorder and radio-transmitter attached by suction cup. The subsurface behaviour of killer whales around the San Juan Islands is being investigated by Robin Baird of Dalhousie University, Canada.* ***Below*** *Macaroni penguin with satellite transmitter. Kate Barlow of the British Antarctic Survey is using satellite transmitters, taped to the feathers of macaroni penguins, to reveal the foraging locations of these predators around Bird Island, South Georgia.*

(Photos by R.W. Baird, S.K. Hooker and K.E. Barlow)

ment these prey will, in turn, be influenced by the distribution and abundance of their food, together with ocean currents and other physical variables. This interdependence continues through the food chain until we are left with the physical factors determining levels of primary production. Thus the deployment of oceanographic recorders on predators can ensure the collection of data in regions of particular interest, while data collected during travel to and from these sites can provide background information.

Seabirds and seals experience the marine environment across a wide range of spatial and temporal scales (Table 2, overleaf). At the small scale (e.g. tens of metres, and minutes) the details of their behaviour have the potential to provide an indication of the distribution of prey (for example, krill, fish or squid species). They may also reveal small-scale variability in the structure of the water mass, as the predators themselves may target certain physical characteristics within the water column in order to locate prey (cf. Figure 2, overleaf). Similar variability may be reflected at progressively larger scales, through the number of offspring produced or the time taken for individual seabirds or seals to return to feed their young with a parcel of energy of a particular size. When viewed over a number of years, changes in such parameters can provide insights into interannual oceanic variability and, since different species forage across different spatial scales, this information can be viewed

The size of the study animal and the required duration of data-gathering (which is in turn related to the frequency of sampling and the memory limitations of the data-logger) both influence the method of sensor-attachment

in terms of regional, shelf-zone or ocean basin variability, depending on the species and/or time-scale chosen.

Instrument development

Technological advances over the past decade have enabled us to obtain detailed data from animals at sea. The attachment of VHF and satellite radio transmitters to marine mammals and birds can provide us with details of their surface locations a number of times a day (Figure 1). Similar technology is used to track marine fish using acoustic transmitters. Attached tags record behavioural and environmental data, which can either be stored within the unit for later recovery, or be transmitted to a satellite. To date, most effort aimed at improving these instruments has been focussed on the technical difficulties involved in miniaturizing transmitters, battery packs and data-loggers into packages weighing as little as 25 g for deployment on flying seabirds. The need for such miniaturization arises from concerns that the attachment of instruments to the study animals may adversely affect their behaviour and welfare. In general, it has been found that terrestrial animals are largely unaffected by attached instruments weighing less than 5% of the body weight of the study animal. Among marine species, the size and shape of the instrument package is also an important consideration because of the need to minimize hydrodynamic drag. In general, the impact of increasing drag does not appear to be overly detrimental to the study animals for tags of the sizes and attachment durations currently used.

However, problems in reducing both the size and the weight of the oceanographic sensors currently in use may present the greatest obstacle to their inclusion into packages for deployment on marine animals. Since oceanographic equipment is generally deployed from large research vessels, until now there has not been nearly so much pressure for miniaturization of sensors or equipment.

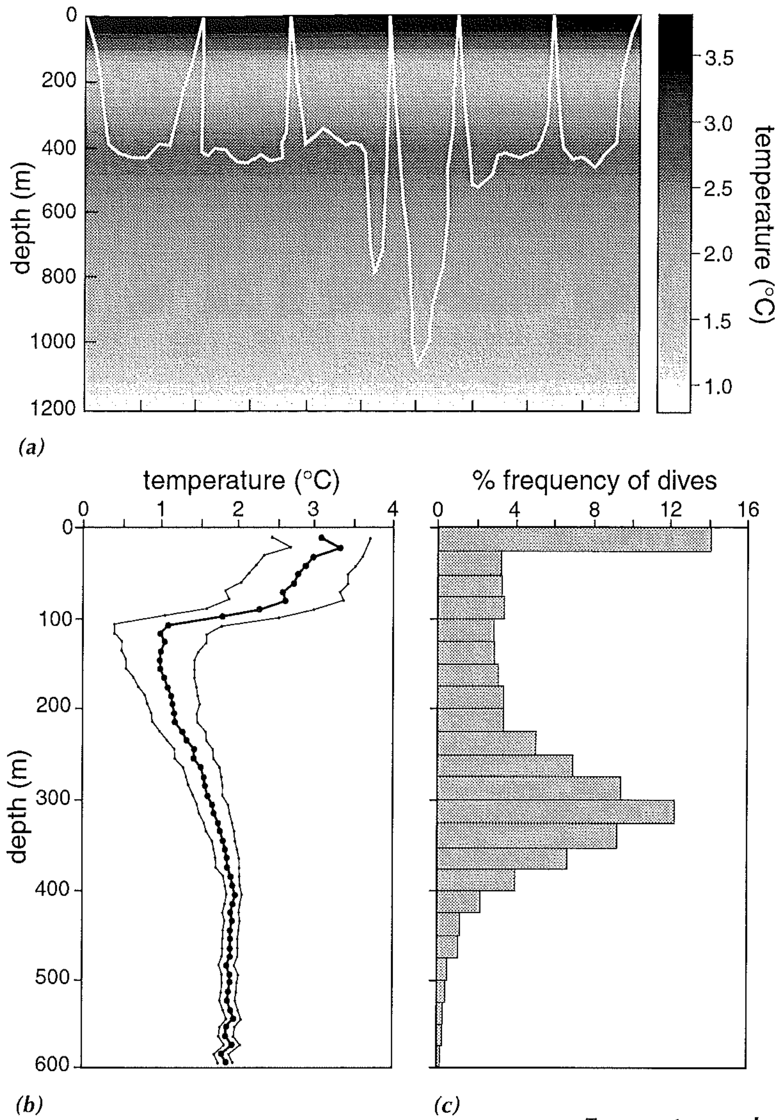
The data-logging tags which have been developed to date are now beginning to help us answer important biological questions about foraging patterns in seabirds and seals. The tags used on marine animals were originally designed to record the depth of the study animal at predefined time intervals. Gradually these tags have been developed to include several other biological and environmental sensors. Many tags now also incorporate measurement of temperature and light level. The light sensor included in the tag has primarily been used to locate the position of

Table 2 *Approximate horizontal and vertical spatial scales of journeys made by marine predators during the breeding season at South Georgia. Trip-length is included to illustrate the potential time-scales for potential data-logging, and body mass to show the variation in the size of data-logger required, given that the logger should weigh less than 5% of the body mass.*

Species	Approximate horizontal range	Approximate modal dive-depth	Trip length	Body mass
Antarctic fur seal, *Arctocephalus gazella*	100s of km	50 m (max. 150 m)	4–5 days	40 kg (female) 200 kg (male)
Southern elephant seal, *Mirounga leonina*	1000s of km	400–500 m (max. 1500 m)	3–9 months	600 kg (female) 4000 kg (male)
Macaroni penguin, *Eudyptes chrysolophus*	20–40 km	20–35 m (max. 115 m)	18 hr	4.5 kg
Gentoo penguin, *Pygoscelis papua*	10 km	80 m (max. 150 m)	12 hr	6 kg
Chinstrap penguin, *Pygoscelis antarctica*	10s of km	50 m (max. 120 m)	1.5–2 days	4 kg
King penguin *Aptenodytes patagonicus*	100s of km	150–200 m (max. 300 m)	10–20 days	12–14 kg
Grey-headed albatross, *Diomedea chrysostoma*	1000s of km	3 m (max. 6 m)	1–6 days	3.7 kg
Black-browed albatross, *Diomedea melanophris*	1000s of km	2.5 m (max. 4.5 m)	1–6 days	3.7 kg
Wandering albatross, *Diomedea exulans*	1000s of km	0.3 m (max. 1 m)	1–15 days	8.7 kg
White-chinned petrels, *Procellaria aequinoctialis*	1000 km	2 m (max. 12 m)	2–6 days	1.4 kg
Blue-eyed shag, *Phalacrocorax atriceps*	10 km	80–90 m (max. 115 m)	12 hr	2.5–3 kg

Figure 2 *(a) Illustration of the diving behaviour of a southern elephant seal in relation to depth and measured water temperature, over the course of 2 hr 30 min (the tick marks are at 15 min intervals).* ***(b)*** *Mean sea temperature (points to either side show the standard deviation) measured in relation to depth.* ***(c)*** *Percent frequency of depths (over 552 dives in total) showing the predominance of time spent at the thermal discontinuity between the cold mid-water and deeper warmer water.*

(Redrawn from Boyd and Arnbom, 1991)



the tagged animal using the times of sunrise and sunset. Biological sensors including speed, heart rate, stomach temperature, and the measurement of ambient and internal sound (using an external or contact hydrophone, respectively) have in the past been incorporated into this basic design. Recent developments in camera-attachment also allow a truly bird's-eye view into the marine ecosystem. As far as additional oceanographic parameters are concerned, it may also be possible to extract information on light attenuation at depth from the light sensor, but this has yet to be fully explored. The potential for incorporation of several other sensors, such as conductivity (salinity) and fluorimetry (chlorophyll), is enormous, and simply awaits the necessary reduction in size of these sensors.

Data-collection and transmission

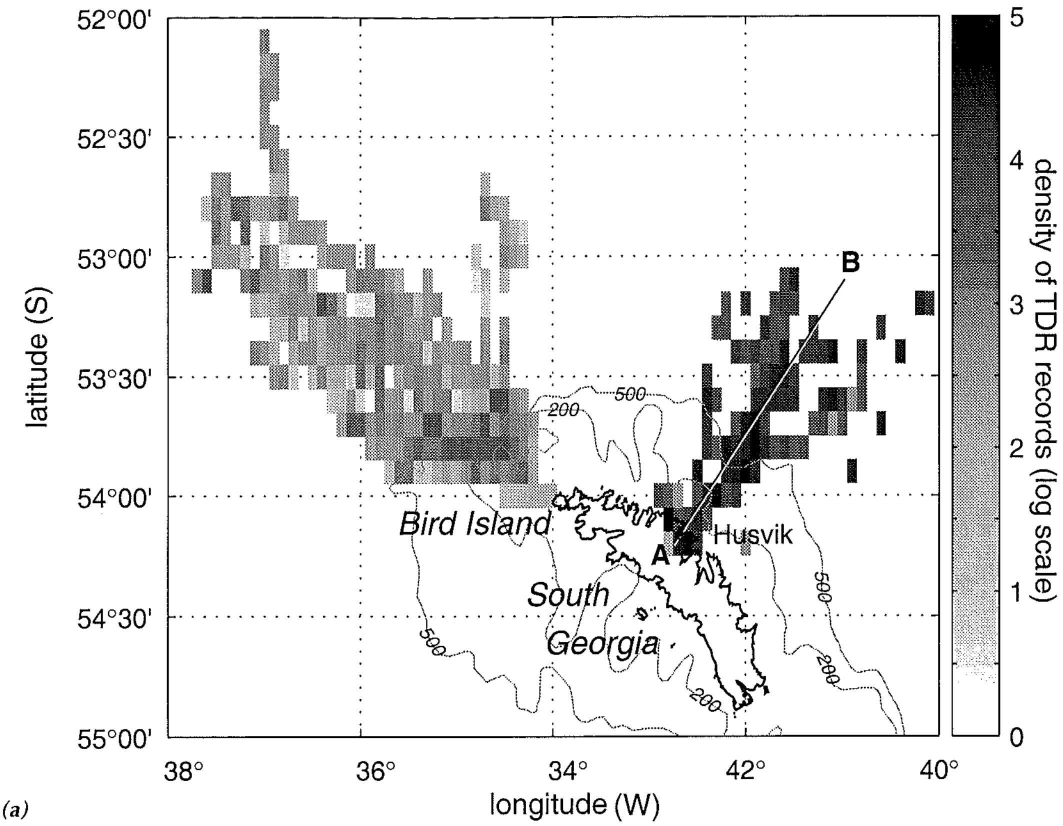
In the long run, the use of many different species will allow the investigation of oceanographic features at different scales of measurement, defined by the behaviour of the carrier. However, further obstacles in tag-attachment and data-retrieval may restrict our initial attempts to the more accessible near-shore species. Even then, for reliable tag-recovery, researchers need to be certain where and when the tag may be recovered. Thus, tags are primarily deployed on animals that show reasonable site-fidelity.

Currently, tags used on marine mammals tend either to store data onboard for downloading at a later date, or to transmit data remotely via satellite. However, both of these methods have their limitations. Onboard data-logging is restricted by the memory capacity of the tag, so that over extended time-scales there will be a trade-off between frequency and duration of sampling. However, one of the benefits of data-logging tags is that for short-duration deployments (days), data can be collected at high resolution. These tags need to be recovered in order to retrieve the data, but this also means that they can be re-used relatively easily.

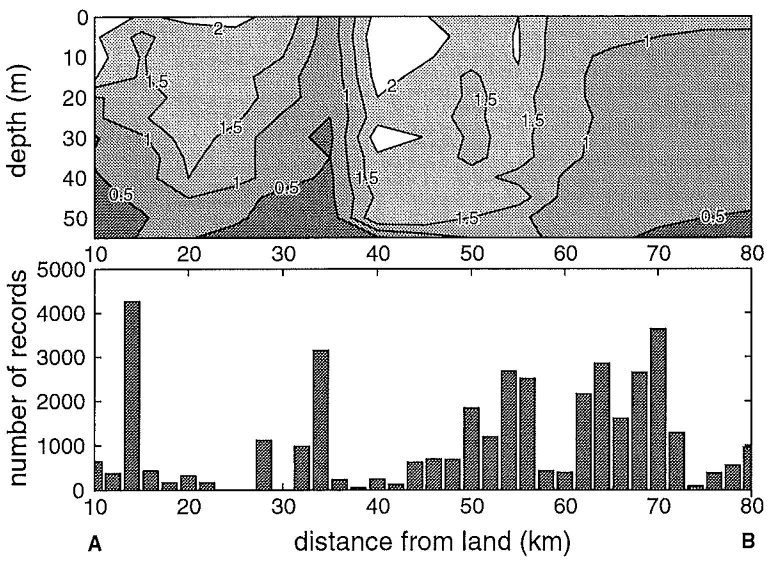
Transmission of data via satellite requires the passage of a satellite overhead, and there are limited numbers of satellite passes daily. For a successful transmission, the satellite transmitter (and thus the animal platform) need to be at the water surface during the period that the satellite is well above the horizon, and the uplink must not be corrupted by wave action or environmental conditions. Furthermore, only a limited amount of data can be sent at each uplink. For the transmission of conductivity, temperature and depth measurements from a dive to 500 m, careful consideration of the optimal transmission strategy will be needed to reduce and compress the dataset for transmission. Satellite transmission of data allows much greater temporal (and thus often spatial) coverage. Its other advantage is that the tag does not have to be recovered in order to obtain the data. However, if tags are *not* recovered, then the costs of this method rapidly exceed those of the data-logging tags.

Of course, the choice of methodology is largely dependent on the study animal and simplicity of tag-attachment. For example, lactating Antarctic fur seals spend 4–5 days foraging at sea (cf. Figure 3(a)), between trips ashore to nurse their pup. Thus a data-logging tag may be deployed prior to this foraging trip and recovered a few days later. In contrast, southern elephant seals spend periods of months at sea, and would thus require a satellite transmitting tag.

Temperature and depth data collected by means of a southern elephant seal highlight the temperature discontinuity between the cold mid-water and deeper warmer water



(a)



(b)

Animals from the breeding sites at Husvik and Bird Island appear to forage in very different locations

Figure 3 ***(a)*** *Plot showing the density of time–depth recorder (TDR) temperature records (log scale) in fur seal foraging areas, from tags deployed at Husvik and Bird Island, South Georgia, during 1998. A–B is the transect line from the Husvik site for which temperature records were examined.* ***(b) Upper*** *Contour plot of temperature data along the transect.* ***Lower*** *Frequency distribution of diving activity along the transect, demonstrating that more time was spent in areas of temperature discontinuities.*

(Redrawn from Boyd et al., *in press)*

Wide-scale oceanic sampling must await improvements in our ability to deploy these tags on cetaceans (whales, dolphins and porpoises). Attachment of tags to pinnipeds (seals, sealions and walruses) or marine birds is usually quite straightforward, since animals can be captured at haul-out or breeding sites, and tags can be glued to the fur or feathers (Figure 1). Attachment of tags to cetaceans is more problematic. Although tags attached by suction-cups (Figure 1) may be deployed from a short distance (5–10 m) onto a variety of cetaceans (usually by pole or crossbow), they only remain attached for periods of hours and so would still require extensive ship support for deployment and recovery of tags. In order to achieve long-term attachment of tags to cetaceans, researchers can either use tags which will penetrate the blubber layer of larger cetaceans, or capture small cetaceans and surgically attach data-loggers to the dorsal fin area (since the blubber layer of small cetaceans is not thick enough for remote deployment of penetrating tags).

Feasibility analysis

Preliminary analysis of the feasibility of using seals to collect oceanographic data has been conducted by researchers at the British Antarctic Survey. Measurement of depth and temperature during diving of a southern elephant seal showed the presence of a distinct temperature discontinuity, with most of the foraging taking place in the transition region between the cold mid-water and deeper warmer water (Figure 2). Deployment of temperature sensors on Antarctic fur seals has allowed collection of data over a wide area (Figure 3). There is a broad correspondence between sea-surface temperature measurements from instrumented seals and data collected from ship-board oceanographic surveys. However, these deployments have highlighted the need for a rapid sensor response, and further modifications of the tags to isolate the temperature sensor from the main body of the tag (and its inherent thermal lag) have gone a long way toward improving this.

Similarly, other researchers have used wandering albatrosses to collect sea-surface temperatures over very large areas, and have then used the measurements to validate satellite remote-sensing data. On a smaller scale, sensors attached to penguins have provided detailed information on water temperature within a 200 km^2 bay area and these data have been used to provide an indication of the environmental preferences of prey species. The temperature–depth profiles collected from foraging elephant seals have been used to infer the geographic position of their foraging areas. Similarly, sea-surface temperature records collected from Sub-Antarctic fur seals at Amsterdam Island have been used to estimate their foraging range in relation to the Subtropical Front.

Much of the focus on the data collected from marine predators has been on the analysis of behaviour, and it is only relatively recently that foraging information has been supplemented by oceanographic data. Over the next few years, we plan to incorporate additional oceanographic sensors into the data-loggers deployed on Antarctic fur seals at Bird Island, South Georgia. Our objectives are two-fold: to investigate spatial and temporal oceanographic variation in the South Georgia region, and to investigate how fur seal foraging distributions are affected by this oceanographic structure. These studies will be carried out in parallel with traditional ship-based oceanographic surveys of the region to provide a system of validation for our observations from marine mammals.

Long-term oceanographic variation

The collection of oceanographic information concurrent with predator foraging, and the continued monitoring of the population biology of these predators, should allow more detailed insight into the driving forces that link the physical and biological variability found in the Southern Ocean. The implications of this oceanographic variation can also be examined in light of the resulting life-history consequences for higher predators. Researchers at the British Antarctic Survey have found that the survival and growth of Antarctic fur seal pups at South Georgia show occasional sharp declines (every 4–6 years). These are a direct result of transient reductions in the availability of their main prey, Antarctic krill. Detailed dietary and behavioural studies have suggested that at these times of decline there were fewer krill swarms available, and as a result the fur seals had to travel further to find food. Using these kinds of data over a period of almost two decades, together with data from shipboard sampling during different feeding conditions, we can now begin to understand the physical processes in the Scotia Sea that result in the changing food abundance for fur seals. This is an example of marine variability that would be difficult to detect and monitor over decadal time-scales using simply intermittent shipboard observations or satellites – i.e. without the simple and inexpensive monitoring of predators, which integrate complex physical variability.

The oceanography community has not yet developed a serious interest in using top food chain predators as probes into marine systems. Oceanographers often have to wait for years to obtain enough ship time to test their hypotheses, because of the expense of running modern research vessels. Although the quality of data obtained from marine predators is unlikely to be as good as that obtained from traditional oceanographic methods, this method benefits from the potential to provide synoptic information beyond the reach of satellites, which will augment the value of available ship time. The strategy and analytical techniques used to incorporate these data into oceanographic models will require modification, but the additional information that can be gathered can only be complementary to these models. At the British Antarctic Survey we are taking up the challenge of linking oceanographic and predator research in the arena of the Scotia Sea, particularly around South Georgia. This project is set within a wider international effort to manage the exploitation of the Southern Ocean ecosystem, using these top marine predators as a monitoring tool. Nobody pretends that all the problems of using top predators to monitor and interpret variability in marine systems have been solved. Indeed, a great challenge lies ahead of us, to calibrate the variability in the signals from these top predators in terms of other variability within the marine system. This challenge will occupy us well into the 21st century.

Suggested Further Reading

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For more information on this research, see the British Antarctic Survey website:

http://www.antarctica.ac.uk/Science/Programmes/independent/mibmmo/

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Ian Boyd is the head of the marine ecosystem management programme at the British Antarctic Survey.* He has developed a research programme on Southern Ocean top food chain predators, with primary research interests focussing on the behaviour and ecology of foraging in marine predators and the effects of environmental variability on their populations.

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Elizabeth Hawker** is a physical oceanographer, and is currently pursuing her Ph.D research at the Southampton Oceanographic Centre.

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Mark Brandon has studied the oceanography of the region around South Georgia over the past few years, and is currently lecturing at the Open University.†

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Below *Grey seal with satellite tag, Sable Island, Canada. Don Bowen of the Bedford Institute of Oceanography, Canada, is investigating the foraging behaviour of grey seals in the North Atlantic.*
(Photograph by R.W. Baird)