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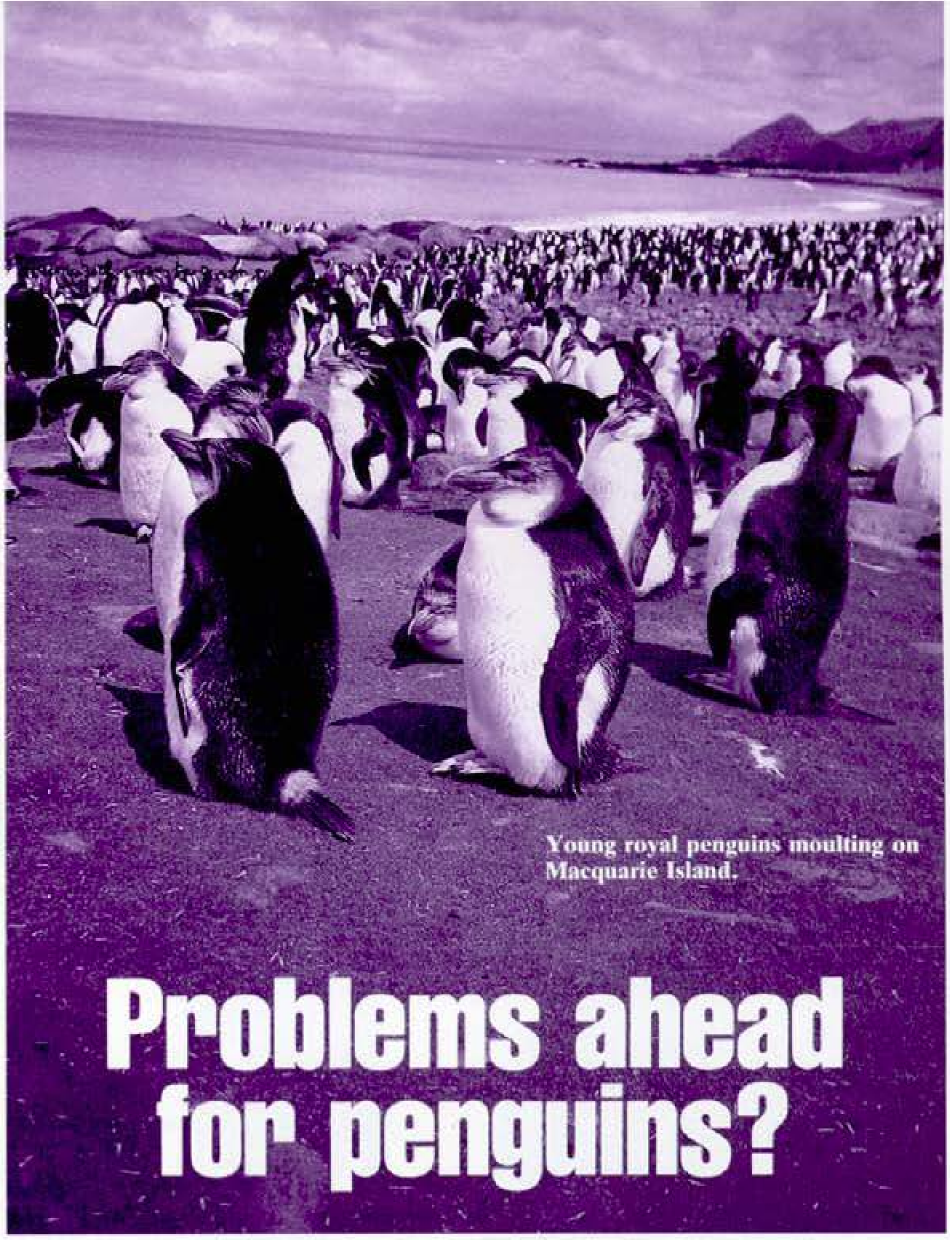


Young royal penguins moulting on Macquarie Island.

Problems ahead for penguins?

When we think of our native animals, penguins are not usually the first creatures to spring to mind. They don't fit the image of a hot and dry continent.

And yet we have several areas around mainland Australia and Tasmania where little penguins (previously called fairy penguins) live in some abundance. Four other penguin species occur on Macquarie and Heard Islands in the Southern Ocean; and in the Australian sector of Antarctica, the Adelie and emperor penguins hold sway.

There can be little doubt that penguins are popular with the public. Australian and overseas tourists flock to one of the country's most visited attractions — the penguin parade at Philip Island near Melbourne. Penguins don't live in the Northern Hemisphere and so, like kangaroos and koalas, are unusual creatures to many of our international visitors.

To ensure our penguins are safely conserved, we need to know more about their feeding requirements throughout the year, and where they forage for their food — mainly fish, squid, and krill — when in the wild. Then we can assess what impact commercial fishing may have on them — for human fisheries and penguins may sometimes compete for resources. Too much fishing — especially if in the 'wrong' places and during the 'wrong' season — and the penguin populations can suddenly crash, as happened in the Falkland Islands in 1986.

In the Southern Ocean, penguins account for 80% of the biomass of all sea birds, and birds are the major predators on marine creatures in the surface layers of the ocean. So, if we are to regulate fishing down there — to ensure sustainable yields — and conserve our penguins, we need to know how much the penguins are harvesting from the system, and at what times of the year they need the most food.

The study of how much food an animal needs, and how it spends the energy so gained, is called energetics. Dr Brian

Green of CSIRO's Division of Wildlife and Ecology specialises in this field. Currently, one of his projects involves a study of the energetics of penguins in Australia, Antarctica, and the Southern Ocean. He is assisted by Mr Keith Newgrain, with collaboration from Ms Rosemary Gales and Mr David Pemberton, of the University of Tasmania, as well as researchers in the Antarctic Division.

Life in the wild

Until recently, scientists could only estimate the water and energy needs of animals in the wild by using results derived from laboratory experiments. In the case of penguins, life in a metabolic chamber, where energy use is deduced from measurements of oxygen consumption, is a far cry from hunting fish in the foaming swell of the Southern Ocean. Estimates of the energy costs of an animal catching its own food and dealing with the vagaries of life in the wild were largely guesses.

But in the last 10 years or so, techniques that make use of isotopes of various elements have allowed scientists to determine energy consumption rates and water intake without keeping an animal in the laboratory.

Varieties of 'heavy' water — either with a normal hydrogen atom replaced with deuterium or tritium, or containing the isotope oxygen-18 — allow the researchers to calculate not only the total quantity and rate of replacement of water within an animal but its metabolic rate — and hence energy consumption — as well. We can distinguish isotopes from the 'normal' molecules by their difference in mass or their emission of radiation (if, like tritium, they are unstable).

Put simply, the technique of metabolic measurement with isotopes works like this: out in the field, Dr Green and his colleagues inject penguins with known small quantities of isotopes, which disperse evenly around the body within about 3 hours.

Following that 3-hour 'equilibration period' — during which the penguin must not eat or drink — the scientists take a small blood sample, mark the animal, and then release it. (The operation can only be done when the penguins are based on land in colonies — as many species are during the breeding season. Little penguins remain in their colonies throughout the year, and this has enabled Ms Gales to study their energetics during the winter as well.)

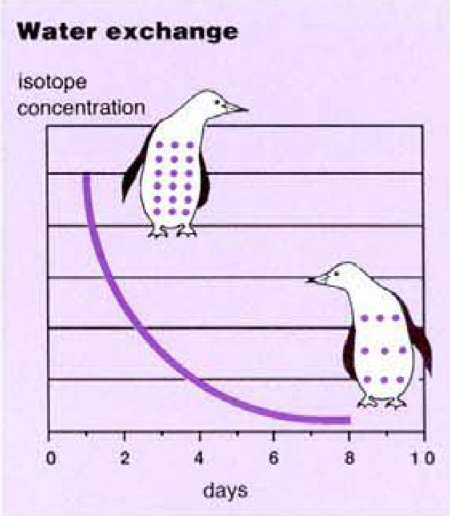
The quantity of isotope in the sample tells us by how much the labelled molecules have been diluted and so, as we know the injected volume, we can calculate the total quantity of water in the animal. This marks the start of the experimental period.

After a few days in the wild, the scientists need to recapture the marked penguin and take another blood sample. The second sample will contain considerably fewer molecules of isotope than the first, as the animal has been busy eating, drinking, and excreting and thus exchanging water with its environment. The level of isotopes in the body falls logarithmically with time, reaching almost nothing by about 7 or 8 days (see the graph).

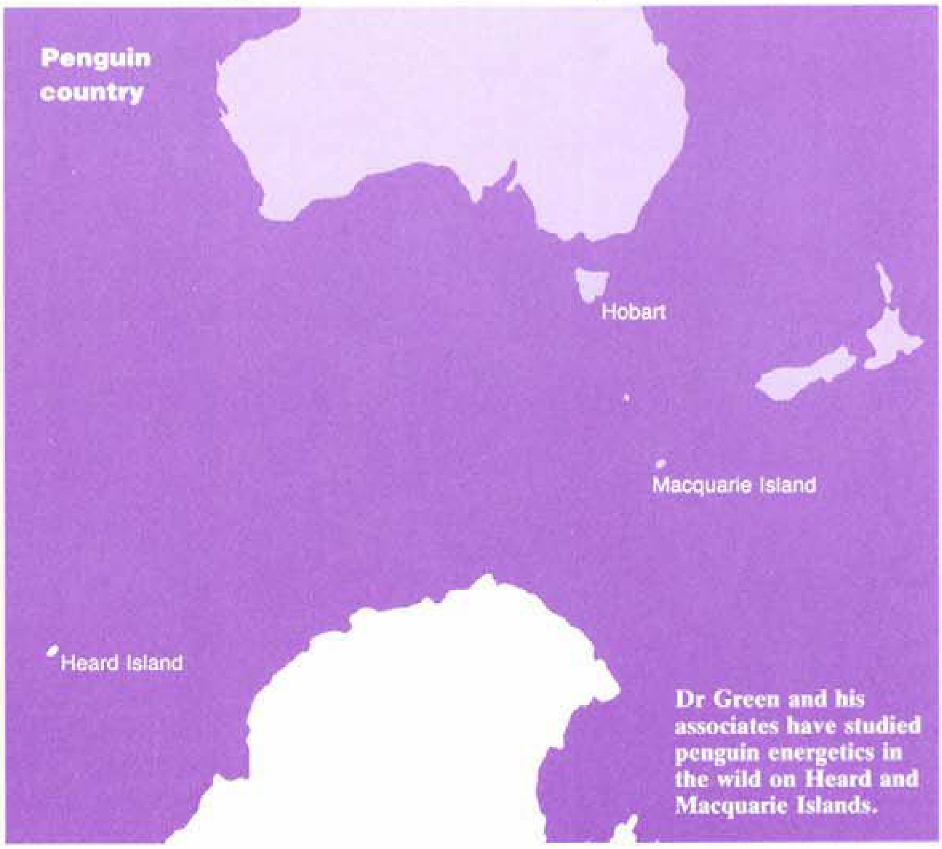
Knowing the original volume injected, the total quantity of water in the animal at the beginning, and the isotope concentration when it is recaptured, we can calculate how much water has passed in and out of the body between measurements. In its logical basis, the technique is very similar to the 'mark–release–recapture' method used by ecologists to estimate the size of a population and described on page 16 in *Ecos* 54. But instead of using a known number of labelled animals, we use labelled molecules.

Now, if penguins don't drink, then all the water that they take in must come from their food, and if we know the proportion of water in their food items, we can estimate how much they ate during the course of the experiment. Actually penguins do drink — at least, they take in sea water when they feed, and some actively drink out of rock pools. Conveniently, sea water contains a fairly precise concentration of salt, or sodium chloride. So Dr Green has used an isotope of sodium to determine what fraction of the water influx is due to the ingestion of sea water.

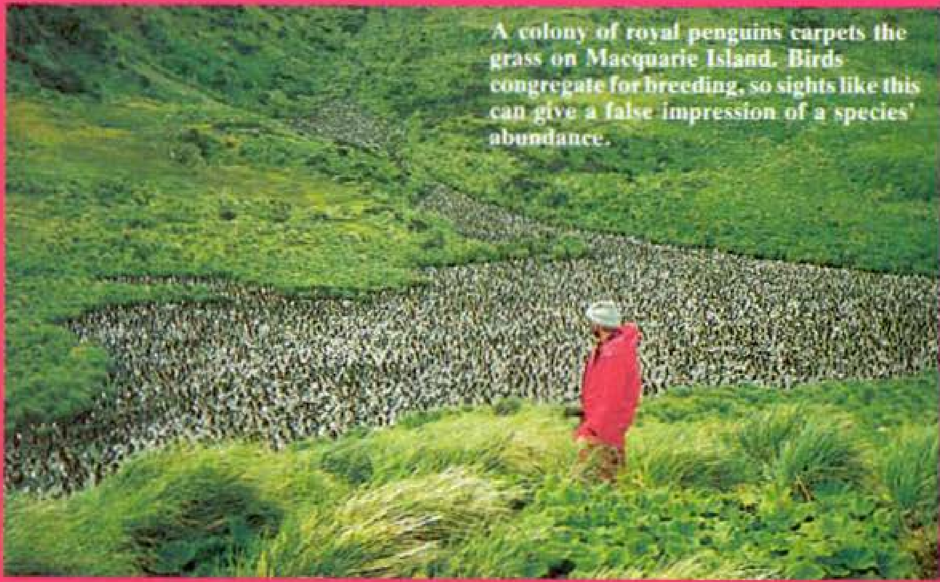
Knowing the total water flux, and the proportion contributed by sea water, he now can work out how much water comes from their food. Then, provided he knows the food's water content, he can determine how much food they are eating. This ability to estimate is very important when dealing with penguins because, unlike land animals, we cannot easily observe them feeding in the wild, as they swim and dive so quickly, and are shy of boats.

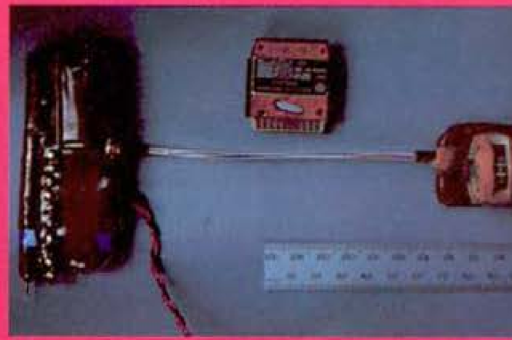


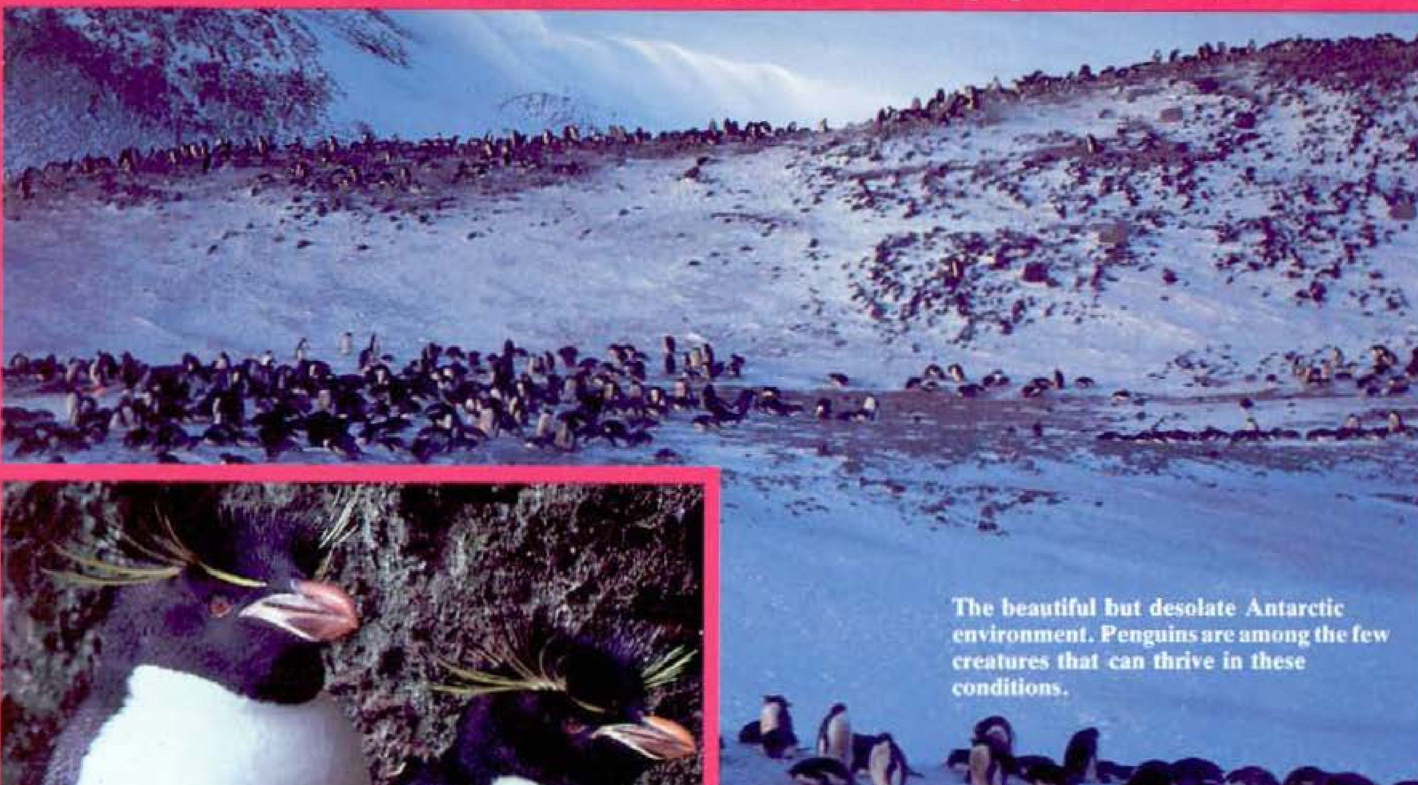
How the concentration of isotopes in penguins' body fluids decreases with time as the penguins exchange water with their environment.



Dr Green and his associates have studied penguin energetics in the wild on Heard and Macquarie Islands.


A colony of royal penguins carpets the grass on Macquarie Island. Birds congregate for breeding, so sights like this can give a false impression of a species' abundance.


The electronic activity recorder (EAR), designed and built by Mr Kit Williams. The larger part fits on the penguin's back, and consists of the depth transducer, batteries, and memory. The small unit, worn on the front of the bird, contains the speed transducer. They are connected by the attachment ribbon that wraps around the penguin.


The beautiful but desolate Antarctic environment. Penguins are among the few creatures that can thrive in these conditions.


Rockhopper penguins.


Penguins are at their most efficient and elegant when swimming, as this underwater shot shows. (Photo by Rudie Kuiter.)

We know what their food items are from observing what they feed to their chicks on land, from analysis of the adults' stomach contents, and by sampling the fish species in the areas where penguins forage. Back in the laboratory, Dr Green and his assistants can determine the composition of typical food items and establish their levels of water and salt.

Energy

Scientists can use water labelled with oxygen-18 at the same time as water labelled with hydrogen isotopes to determine the metabolic rate of a penguin. By the method outlined above, they can calculate how much oxygen-18 is lost from the body during the experimental period. Some of this will have been lost in its original state as water, but some would have entered into the body's biochemical reactions and eventually have been released as carbon dioxide.

Knowing the level of ^{18}O-labelled water in the animal's total water at the beginning, and knowing the total water lost from measurements of the labelled-hydrogen water, the scientists can then deduce how much heavy oxygen was lost as water. The remainder of the disappeared isotope must have escaped in the form of CO_2. From this they can estimate the total quantity of CO_2 released during the experimental period.

Obviously, the greater the metabolic rate, the greater is the quantity of CO_2 breathed out and energy used. (For example, when we start running, we consume energy more rapidly and, by breathing faster, release more CO_2.) However, the volume of carbon dioxide an animal produces does not bear a simple relationship to the amount of energy being used. It depends rather on what type of foodstuff is being metabolised to provide the energy.

To calculate the number of kilojoules of energy an animal is using from the volume of CO_2 released, we need to know the approximate composition of its diet. If a penguin is burning only fat, then we know that every litre of CO_2 breathed out is equivalent to 28 kilojoules (kJ) of energy. The value falls, however, if the bird is metabolising protein or carbohydrate. Analysis of fat and protein (their prey contains very little carbohydrate) in representative penguin diets has enabled Dr Green and his colleagues to assign aggregate figures for various penguin species — ranging from 25 kJ to 26 kJ per L of CO_2 produced.

When the birds are moulting, these figures are a little different. Moulting is a difficult time for adults, because while their ragged old feathers are falling out they lack insulation and streamlining and so cannot enter the water. Therefore, for about 2–3 weeks they stand around on land, unable to feed. During this time, their energy source comprises only body fat, which they accumulated in advance, and so researchers then use a figure of 28 kJ per litre of CO_2 lost.

Once we know the energy expenditure of an animal in the wild, we can also use it to estimate the amount of food required to provide that energy, as long as we know the composition and 'energy density' of the food. This gives us a check on estimates of food consumption derived from water intake, although it is more expensive as it uses costly oxygen-18. So, given a figure for energy expenditure for a penguin species and deducing what creatures it ate from where it foraged, scientists can calculate the quantity of food consumed.

Facts and figures

After years of work, Dr Green and Ms Gales have established that an 'average' little (or fairy) penguin, weighing 1·1 kg, shows a water flux of about 210 mL per day in the wild, of which 10% comes from sea water. This leaves 189 mL per day derived from food, which, from analysis of dietary items, represents 222 g of food per day. That means that each of these small creatures needs 88 kg of prey per year as a minimum, and a greater amount when breeding and raising chicks.

On Macquarie Island, Dr Green, assisted by Mr Newgrain and in collaboration with Mr Graham Robertson of the Antarctic Division, studied the much larger gentoo penguins. The scientists found that the chicks, which increase their weight on average by 80 g per day, each need a total of 60 kg of food from the time they hatch until they fledge. The study took place during the summer breeding season in 1984, when about 4000 chicks fledged from 4700 breeding pairs of gentoos on the island. Therefore the chicks alone, in a single breeding season, consumed a staggering 240 tonnes.

Unfortunately, this time, when penguins need the most food, also coincides with the brief summer when commercial fishing operates in Antarctic waters.

While the penguins are based on land, how far do they go to find food to take back to the chicks? This is not an easy question to answer, but Ms Gales has been working on it, using data-loggers. She straps one around a penguin, and retrieves it (with luck!) a few hours or days later. (Ms Gales need only keep watch at the point of departure, as the devoted penguin parent will always go straight to its nest when it comes out of the water.)

The ingenious data-logger, designed and built by Mr Kit Williams, also of the University of Tasmania, takes a reading of depth and speed of movement at pre-programmed intervals — for example, every 9 seconds for 24 hours. The machine — incorporating a micro-computer — stores the information, which Ms Gales transfers to a lap-top computer in the field, and then analyses later back at the laboratory.

Scientists inject an Adelie penguin in Antarctica for studies of energetics in the wild.

A complaint commonly voiced by scientists is that the act of measuring disturbs the very phenomenon under study. Naturally, the data-logger affects the swimming speed of the penguins that wear it.

However, bearing in mind its limitations, it does give us a fair indication of what these diving birds can do. The little penguins that inhabit Australia generally dive for less than one minute and to depths of 20 m or less — on occasion they can go as far as 60 m (this shows how quickly they can submerge and come up). Larger penguins go much deeper and stay down for longer. By examining the recordings of swimming speed, we can also estimate the furthest afield that the animals could go in search of prey, although we don't know their precise direction. (Data-loggers incorporating compasses are being devised.)

During the breeding season, little penguins tend to stay within a radius of about 10 km of their breeding colony, occasionally straying as far as 20 km. Armed with this information, scientists can advise governments on fishing regulations to ensure that no heavy commercial fishing takes place within that radius during the sensitive breeding season. (In fact, little penguins in some parts of Australia — such as in Port Philip Bay — are more likely to be threatened by pests like foxes, or humaninduced disturbance such as pollution and habitat destruction, than by fishing.)

Although the establishment of a fishing-exclusion zone in penguins' foraging areas may help, it doesn't take into account the spawning grounds of prey species, which may be far from the region where penguins eat the adults. In the Southern Ocean we have very little information on the spawning grounds of fish and, as yet, no knowledge of the foraging distances of the four larger species of penguin on Macquarie and Heard Islands. Dr Green is hoping to use data-loggers on them later.

It may seem that a stony beach rendered invisible by a carpet of thousands of penguins is a strong testament to the healthy status of the animal. But Dr Green cautions against believing that. The view during the breeding season gives us a false idea of numbers.

Penguins that spread out through the vast reaches of the southern circumpolar seas for most of the year converge on a handful of small sub-Antarctic islands (and suitable areas of the mainland) for a few months. Ecologists believe that the breeding birds represent about two-thirds of the total population; because the breeding animals are so concentrated in one area, poor food availabilty around the sites for just a few seasons could seriously affect the survival of an entire species.

Although Australian fishing fleets are not involved, the Japanese and Russians have been fishing in the Southern Ocean for many years — mainly for krill (*Euphausia superba*). The Russians have also recently carried out feasibility studies for the establishment of a commercial fishery around Heard Island, which, because it is surrounded by a relatively shallow shelf, is a more productive area for fish than the deep ocean.

The data about penguin energetics and foraging being revealed by the research of Dr Green and others will allow scientists to assess more accurately the role of penguins in the marine environment and the potential competition between the birds and human fishing. It is hoped that these studies will soon give us the necessary information for effective management and conservation of the marine ecosystems of the south, in which these comic and delightful birds have such a prominent role.

Roger Beckmann

More about the topic

Water, sodium and energy turnover in free-living little penguins, *Eudyptula minor*. B. Green, N. Brothers, and R. Gales. *Australian Journal of Zoology*, 1989, **37** (in press).

Estimated feeding rates and energy requirements of gentoo penguins, *Pygoscelis papua*, at Macquarie Island. G. Robertson, B. Green, and K. Newgrain. *Polar Biology*, 1989, **10** (in press).

Some penguin biology

It is hard to imagine a more unusual bird than a penguin. Not only do these creatures look strange, their biological adaptations render them unique. They are therefore classified in a family of their own: Spheniscidae, the flightless sea birds of the Southern Hemisphere that are highly adapted to marine life.

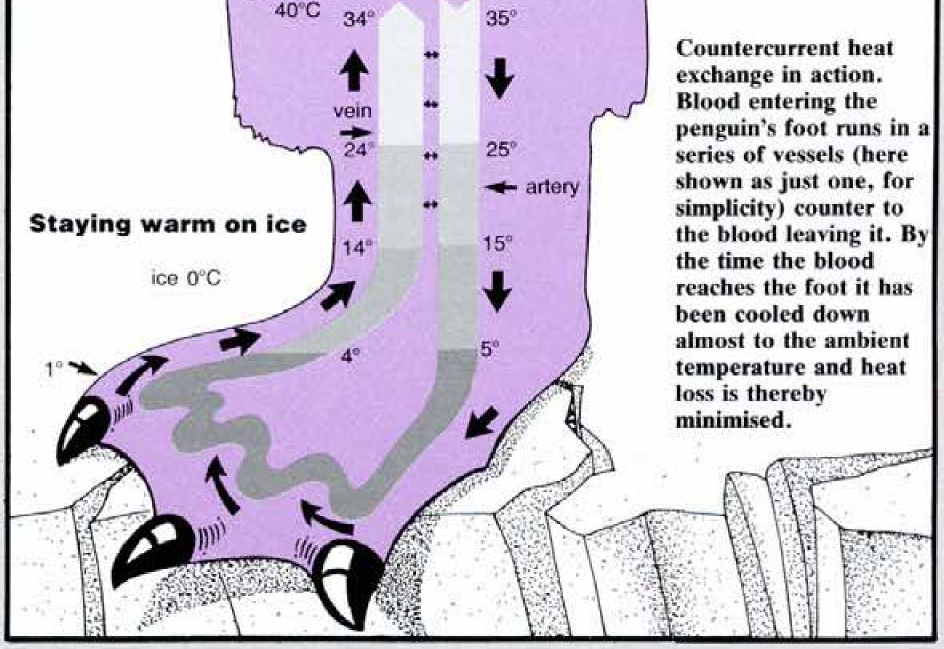
We tend to picture the birds in the windswept Antarctic, sitting for hours on the ice after emerging from an angry sea, without, apparently, noticing the cold. However, penguins do occur in far warmer climes, even in the tropics. The Galapagos Islands, on the Equator, have their own species of penguin, swimming in the cold current that bathes the region, and other species live in warm temperate areas of South America, South Africa, and, of course, Australia and New Zealand.

Scientists disagree on the precise number of species, as they are not certain how to classify some types, but 18 is about right. Of these, nine occur in Australian territory, including Antarctica. They all feed in the water — on fish, squid, and crustaceans. Some spend most of their lives far out in the ocean, only coming to land for a few months each year to breed in large colonies, while others remain based on 'terra firma'.

Of them all, it is the iceberg-dwelling blizzard-bound penguins that most capture our imaginations. How can these little creatures manage to survive in such extremes? The emperor penguin is the species with the most southerly distribution and, as it also chooses to breed in winter, is probably exposed then to the most severe climatic stress of any bird. In some colonies the winds reach 150 km per hour, and the winter temperature averages −20°C, although on occasion the thermometer may drop to −40°C. A male emperor must stand on the ice for 2 months in these conditions, without feeding, in order to incubate the eggs, which he does by placing them on his feet and covering them with his abdomen.

Obviously, good insulation helps. The adults are coated with long, double-layered feathers that overlap like tiles on a roof, and beneath the skin lies a thick layer of blubber.

Physiologists can determine how well an animal is coping with the cold by seeing what happens to its metabolic rate as the outside temperature falls. When the body temperature is in danger of going down, most animals will increase their metabolism to produce heat — often by muscular contractions in the form of shivering. The temperature at which an animal cannot remain at rest indefinitely without doing this represents the lowest end of its comfortable range and varies greatly between species. (It does not show the lower limit for survival, since, provided food is available, increasing the metabolic rate can



Countercurrent heat exchange in action. Blood entering the penguin's foot runs in a series of vessels (here shown as just one, for simplicity) counter to the blood leaving it. By the time the blood reaches the foot it has been cooled down almost to the ambient temperature and heat loss is thereby minimised.

cope with cold, as those who exercise on chilly mornings soon realise.)

For humans — unclothed, of course — this point occurs at about 24°C in still air, a fact that shows our tropical origins. For the emperor penguin it is an amazing −10°C with an 18-km-per-hour wind! Only when conditions get worse than this can we assume that inactive birds start to feel a little nippy. They then reduce their surface area by pulling in their wings, burying their heads, and huddling together.

Cold feet

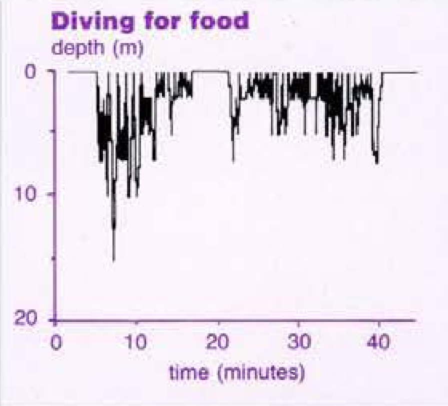
One further useful adaptation allows the uninsulated feet to remain in contact with the ice. The feet, if kept as warm as the rest of the body in these circumstances, would leak away all of the penguin's heat, like a hole in the roof in winter. But most of the heat from the centre of the body does not reach the feet.

In the case of humans, such a cut in heat supply to the body's periphery is sometimes effected in drastic circumstances by simply shutting down the blood flow to the area. The result is that stale, deoxygenated, blue blood accumulates, which explains why, when we are exposed to extreme cold, our skin may go blue. If the situation persists for long enough — many hours — cells in the region will die from oxygen lack. This is frostbite. It is a terrible sacrifice, but at least it helps conserve body heat for the vital internal organs, even if a few toes go black and drop off in the process.

In penguins, and some other birds such as ducks, the blood reaches these extremities but without carrying much heat away from the centre. The ingenious solution relies on a system called a counter-current heat-exchanger. Blood going to and from the foot is carried in a network of small thin-walled vessels that intermesh. The warm oxygen-carrying blood coming from the centre of the body gives up its heat to the returning blood in the adjacent vessels and arrives cold in the foot.

After delivering its oxygen it returns, picking up heat from the outgoing blood, so it arrives warm back at the core. The end result is that the heat, in effect, cycles around in the exchanger at the top of the leg, but does not warm the foot by more than a few degrees above freezing. However, the blood is still moving and carrying oxygen. (A similar system operates in desert-adapted animals; see the article about camels in this issue.)

Because of the efficiency of these adaptations many penguins — believe it or not — face the problem of how to keep cool much of the time. They constantly produce heat,



Penguin aquatic ability charted: a recording made by Ms Gales of a little penguin's dives (above), and charts showing the frequencies of speeds and depths achieved during two foraging trips (right).

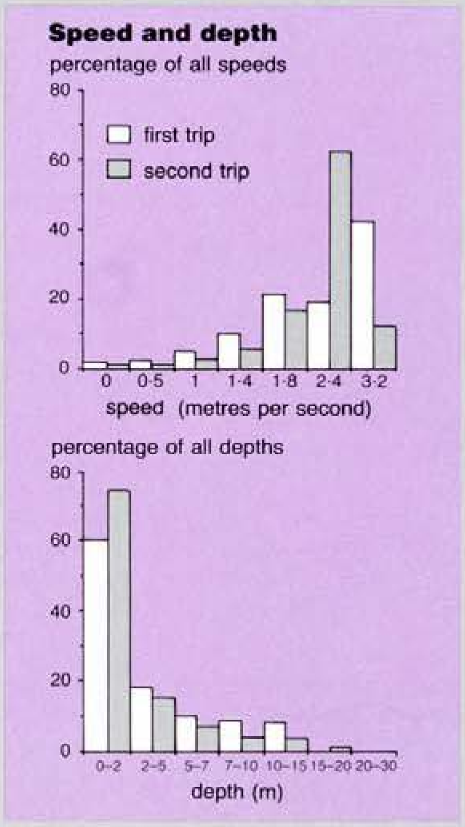
and it has very little means of escaping. When the birds are active, the sun is shining, and the temperature is above freezing, keeping cool is important. They cannot remove their blubber and thick feathers, but instead use the tops of their feet and the insides of their flippers as radiators.

By rearranging the blood flow in their legs they send warm blood to their uninsulated feet. They also open up the capillaries on the inside surface of their flippers (where the blubber is very thin) and stand with flippers extended, hoping to catch some breeze. Species that live in warmer climates have larger flippers, while the emperor penguin has, proportionately, much smaller ones.

Too much fishing, and penguin populations can suddenly crash.

Penguins are adapted to life at sea in many other ways: their diving skills and their ability to drink sea water and excrete the excess salt through special glands near their noses are two of the most noteworthy.

Although not as well adapted as diving mammals, large penguins can remain under water for an average of 2–3 minutes, and small ones for about 1 minute. (Some penguins can dive for longer than the average; dives of 18 minutes have been recorded for emperors.) To keep alive they rely on oxygen already dissolved in their muscles and blood, but they can also make use of anaerobic energy release, which leaves them with an oxygen debt. To repay this, they must take in extra oxygen briefly at the surface, just as happens when we hold our breath. But the penguin is a little



better off than a human underwater swimmer; the bird's heart rate slows significantly during a dive (to 5 or 6 beats a minute compared with a normal pulse of around 100), and the blood supply to inessential organs is reduced, thus saving energy and keeping scarce oxygen for the use of the muscles and nervous system. This reflex response to diving does not exist in adult humans, although it is said to operate slightly in young babies immersed in cold water.

Before diving, penguins breathe out. It seems the very opposite of a sensible idea, but they share this behaviour with other diving animals. Biologists have shown that it prevents the 'bends', a condition well known to human divers and brought about by nitrogen from the air in the lungs forming bubbles of gas in the blood and tissues during quick ascents or repeated dives. By reducing the amount of air they take down with them, penguins minimise this. However, the small birds do not usually dive much deeper than 20–30 metres, while the large go to 70–80 metres. Maximum possible depths are much greater than this — the record observation for emperors is an astounding 270 metres.

Well adapted to life at sea, penguins need only watch out for natural hazards in the form of their predators — various species of sharks, seals, and even killer whales. By comparison, the threat from man-made pollution, such as oil spills and plastic litter, is far more sinister.