



A huge elephant seal slides into the kelp on subantarctic Marion Island. C. Fraser

periods) come and go over the course of thousands and millions of years, more or less in a regular fashion.

Some of these glacial periods are relatively minor, with not much more ice at the poles than we have now, while others can be extreme, with ice covering vast areas of the planet. Right now we are in an interglacial period, meaning there is comparatively little ice on Earth and the climate is generally quite warm.

The most recent glacial period is thought to have peaked around 20,000 years ago at a time known as the Last Glacial Maximum. Sea level was more than 120 metres lower than at present as water moved out of the oceans and into the great ice sheets covering much of the land. Sea-ice extended further out into the ocean near the poles.

Along with more ice and lower temperatures came changes in ocean and wind circulation patterns. In short, the world was quite a different, colder place.

How do plants and animals cope with such severe climate changes? Many species would have needed to move towards the Equator as the higher latitudes became colder or covered in ice. Some may even have become extinct, with nowhere suitable to live.

As the ice melted, and glaciers receded, plants and animals could return to the areas their ancestors had left thousands of years before. Those that got there first would have found plenty of new space to spread out in, but those that were slow in returning would have found much of the land (or ocean) already occupied by the early arrivals – very much a “first in, best dressed” scenario.

Using modern molecular techniques we can look for signs of these migrations in the genes of organisms living today. DNA is built from four nucleotide bases – adenine, thymine, cytosine and guanine (A, T, C and G). DNA mutates over the generations, leading to small differences

An ICIER Ice Age

BY CERIDWEN FRASER

New evidence from seaweed genes reveals that the last ice age might have been colder than previously thought.

Anyone visiting the South Island of New Zealand will probably notice beds of very large kelp growing along its rocky coasts. Southern bull kelp (*Durvillaea antarctica*) is one of the world's largest seaweeds – a single plant can be more than 10 metres in length.

All around southern New Zealand, seals, sea lions and penguins frolic in the giant spaghetti-like strands of kelp tossed about in the rough surf. Indigenous Maori people even built boats (*waka*) out

of this enormous floating seaweed, and used its hollowed-out fronds as bags to store food.

While its size is impressive, the invisible molecules of DNA hidden in its cells hold the key to something bigger: ancient sea-ice.

Variations in the Earth's orbital pattern over time (e.g. changes to its axial tilt) are thought to be the main causes of natural climate change. These “Milankovitch” climate cycles, as they are known, mean that ice ages (glacial



Long strands of bull kelp fronds streamline as a wave washes in. The tough, buoyant fronds float at the surface of the water and move freely with the motion of the waves. C. Fraser

in the genetic make-up of individuals.

For example, if part of the DNA sequence of an animal reads TACAG, a chance mutation when it reproduces might alter the sequence of its offspring to TACTG. If this mutation does not affect the functioning of the animal in any negative way, the change might be kept and spread throughout the population in later generations.

We can usually tell if populations of a particular species have been separated for a long time by looking for differences like these. If there has not been much gene flow, or interbreeding, among populations they are likely to have very different DNA sequences.

Bull kelp, the large seaweed that grows around New Zealand, is also found in South America (in Chile), as well as on many of the small islands surrounding Antarctica. Recently I set out with Jon Waters, Raisa Nikula and Hamish Spencer of the University of Otago to see how genetically connected these populations are.

We know that there are millions of pieces of kelp floating around the ocean. At any one time it is thought that there could be as many as 70 million rafts of this particular bull kelp drifting at sea.

We also know that there is a strong current circling Antarctica – the aptly named Antarctic Circumpolar Current (also known as the West Wind Drift), which is driven by westerly winds howling around the icy southern continent. Any kelp raft caught in this current could potentially travel across an

entire ocean and wash up on a far shore.

How often does this happen? Does it allow gene flow between distant populations?

I spent an exciting year travelling around the Southern Hemisphere, wading into heavy surf to snip off small pieces of kelp wherever I went. With the help of icebreaker ships and helicopters, I travelled to subantarctic islands and scaled down rocky cliffs to reach the elusive seaweed in the churning seas below, watched on by king penguins, albatrosses, elephant seals and killer whales.

Back in the lab I began to extract and sequence fragments of the kelp's DNA. As the results came in we realised that

we had found something quite unexpected.

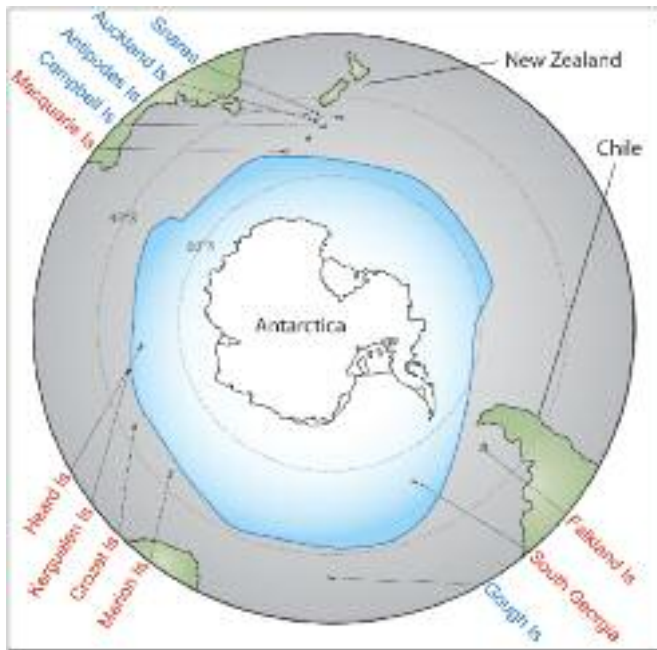
If the kelp could indeed travel around effectively we would expect there to be strong similarities in the genetic structure of different populations. Instead, along the coasts of mainland New Zealand and Chile, almost every site had different haplotypes – that is, different unique sequences of DNA fragments. There were even differences between sites that were just a few kilometres apart. Clearly, kelp populations around New Zealand and along the coast of Chile have not interbred much.

Even more surprising, however, was the pattern we found in the subantarctic. The kelp at almost all of the more southern islands had nearly identical DNA sequences even though some of the islands are separated by tens of thousands of kilometres of ocean. Identical sequences across such vast distances was in striking contrast to the diversity of sequences we found in more northern areas, such as the coasts of New Zealand and Chile.

What could explain such a contrast?

In the Northern Hemisphere, many plants and animals show similar patterns of low genetic diversity at polar latitudes and high diversity at equatorial latitudes. We know that this is in response to postglacial migration, with species moving back into areas freed by receding glaciers and the first arrivals spreading out quickly to cover the new territory. The genetic make-up of those early migrants ends up dominating the polar areas.

The pattern observed in southern bull kelp looked very much like a postglacial recolonisation. Perhaps sea-ice, which is known to destroy beds of bull kelp, had wiped kelp off the



This map shows the previous estimate of the extent of Southern Hemisphere sea-ice at the Last Glacial Maximum. The subantarctic islands labelled in red are those that seem to have been only recently recolonised by bull kelp.

islands during the last glacial period.

But there is a problem with this hypothesis. Sea-ice was not thought to extend as far north as some of the islands that appeared to have been affected.

We tried to think of other explanations to explain the pattern we had found. Nothing seemed to fit. The subantarctic kelp had clearly only been on the islands for a very short time – perhaps a few thousand years. Any longer and it would surely have shown differences in DNA sequences among populations. Could something other than ice have knocked it off the islands?

Naturally, water temperatures were lower at the Last Glacial Maximum but we know that this species of kelp can survive in very cold water. Today it grows on some sheltered parts of Heard Island and South Georgia, both of which are partially glaciated and have water temperatures near 0°C. It seems unlikely that the subantarctic kelp populations were destroyed by cold water.

Sea levels dropped in the last glacial period. Perhaps when sea level dropped it exposed very sandy shores in some places, making it unsuitable for kelp to grow on. But many of these islands are steep volcanoes, and even with lower sea levels they would have had abundant rocky shores on which kelp could attach.

It seemed the only sensible explanation was sea-ice. Could the previous estimates of sea-ice at the Last Glacial Maximum have been wrong?

Most estimates of ancient sea-ice in the Southern Hemisphere have been made by taking sediment cores of the sea

floor. The upper layers of oceans are filled with drifting microscopic algae (in a sense, very small seaweed) known as diatoms. There are many species of diatoms, and each has a unique shape, with a delicate frustule (“shell”) made of silica. Different species live in different parts of the ocean, and there are some species that are particularly common in sea-ice.

When diatoms die, the frustule sinks to the ocean floor and can be fossilised in the sediment. By dating sediment cores, and looking at the fossil diatom composition at each time period, scientists can estimate whether or not much sea-ice was above that particular part of the ocean.

Naturally it takes a lot of these sediment cores to piece together a complete map of ancient sea-ice. In some parts of the ocean no sediment cores have been taken at all. Interestingly, the parts of the Southern Ocean that most lack diatom data for sea-ice are around those very islands where we found evidence for ice.

Could the ice have indeed extended further north than previously thought? It seems likely. Based on the evidence of the extent of the ice from the bull kelp genes, and the lack of evidence contradicting this from diatom fossils, there could well have been more sea-ice in the Southern Hemisphere during the last glacial period.

We published our results in *Proceedings of the National Academy of Sciences, USA*, and turned our thoughts to other projects, but the story cannot end there. If sea-ice was more extensive at the Last Glacial Maximum than we thought, the implications for our understanding of past and future climate change are enormous.

Sea-ice interacts with all sorts of other climate systems. More sea-ice means more of the Sun’s radiation will be reflected back into the Earth’s atmosphere, and the amount of sea-ice can also affect ocean and wind circulation patterns. If there was more sea-ice it is likely that the warming of the Earth after the last glacial period may have been more rapid than we thought. All of these things have to be taken into account when we make models to predict how much, and how quickly, the Earth’s climate might change in the future.

This sort of study can also tell us a lot about how plants and animals will respond to climate change. With human-induced global warming a major threat, we need to understand as much as we can about how the Earth’s climate interacts with the planet’s ecosystems.

Kelp DNA has given us a clue that previous sea-ice estimates might be inaccurate. However, it doesn’t tell us exactly where the edge of the sea-ice was.

Clearly we need more studies – using a variety of scientific approaches – to discover the truth.

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