
IGOR LEHNHERR

CLIMATE CHANGE

A planet in flux

How is life on Earth reacting to climate change?

BY JOHN P. SMOL

Human activities have added billions of tonnes of carbon dioxide to Earth's atmosphere, causing global temperatures to rise. We are beginning to see how warmer temperatures are altering climates all over the planet and to understand the effects they are having on animals, agriculture and people. What will Earth look like in the year 2100? How will climate change have altered the planet's biology?

A CHANGING WORLD

Fly over the high Arctic in summer and you will see a landscape speckled with shallow ponds, some ringed by mossy wetlands. Frozen for most of the year, these ponds melt for a few months and become biodiversity hotspots teeming with plants, animals and microorganisms. The Arctic's isolation and extreme environment have made it difficult to gather observational data on the region's ecological changes, and existing records are sparse and incomplete. Fortunately, the ponds and lakes in this region can help scientists build a picture of the high Arctic's environmental conditions going back thousands of years.

The sediments of these remote ponds reveal their history. They contain pollen grains, dead algae and invertebrate fossils, as well as other biological, chemical and physical information. Their accumulation at the bottom of the ponds, one layer on top of the next, produces a vertically arranged historic timeline. Rather like tree rings, which reflect the growing conditions of years past, sediment records provide a glimpse of earlier climates and environmental disturbances. We can think of them as being like an aircraft's 'black box', only for the ecosystem.

In 1983, my lab began studying about 40 of these freshwater ponds on the east–central side of Ellesmere Island, the most northerly island in the Canadian archipelago. We chose shallow ponds because their small size means they are highly susceptible to change. Each year we return to the Arctic to collect water samples and sediment deposits from these ponds and other northern regions for comparison.

At first we knew very little about these aquatic environments or the microorganisms they contain. We began by studying the fossils of diatoms, miniscule jewel-like algae found in almost every pond and lake. My earlier work in other parts of Canada had shown how environmental change alters these diatom communities over time. Each diatom species requires a specific set of environmental conditions to survive and reproduce. By knowing which species live in which environments, we can use the past occurrences of diatoms to understand the environmental conditions at the time. Initially, I planned to track these subtle

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variations to learn more about how the region had changed over thousands of years.

In 1994, we discovered some unexpected changes in the diatom collections of these Arctic ponds. At one site, we sank a hollow tube about 100 cm into the pond bottom, extracted a sediment core and sliced it into sections. By using dating techniques based on the radioisotopes carbon-14 and lead-210, we knew that this particular core stretched back about 6,500 years. For most of that time, the same three or four diatom species had dominated the pond. But around the mid- to late-nineteenth century, the diatom community changed dramatically: it became more diverse and complex, a sign that the ice cover had declined[1]. We hypothesized that a warmer climate could have brought on the sudden shift. Other scientists were already proposing that humans might be altering the climate, but our study suggested that this warming had started about a century earlier in the high Arctic.

There were soon other dramatic signs of climate change in our study area. During the 1990s, the Arctic ponds became saltier and their water levels dropped, evidence that they were evaporating rather than losing water by other means. We speculated that if the warming continued, the ponds might disappear within the next century.

When we returned in July 2006, however, we found that some ponds were bone dry and others were mere puddles[2]. Cracked mud had replaced the waters we had once waded into. The surrounding wetland was so dry that we could set it on fire with a cigarette lighter. We were stunned. Ponds that had been permanent water bodies for thousands of years were now ephemeral, filling in the spring with the melting snow and evaporating by July. Mainland temperatures in the Arctic for the first seven months of 2006 shot up by 3.5°C above the 30-year average, and it was the warmest summer on record. The warming had pushed the ponds past their tipping point and into an entirely different state that couldn't support a wetland. Losing the ponds altered an ancient ecosystem inhabited by aquatic organisms such as algae and invertebrates, and used by waterfowl for breeding and by Arctic foxes that prey on the birds and their eggs.

The demise of the Arctic ponds is a sign of climate change, a long-term shift in the Arctic climate measured by changes in temperature, precipitation and other indicators. Climate change has moved faster here than at lower latitudes. The change we have seen in the Arctic is the bellwether for global climate changes that are already under way. But what is causing Earth's warming? If we know that, we may be able to stop it.

HEATING ELEMENTS

Understanding climate change requires knowledge of the gases in the air. More than 99% of the air is nitrogen and oxygen, and the remaining 1% is a mixture of other gases, including carbon dioxide. For every million molecules in the air, there are fewer than 400 carbon dioxide molecules, stated as 400 parts per million (p.p.m.). Yet carbon dioxide has garnered a great deal of attention from scientists studying climate change because it is a 'greenhouse gas'. Greenhouse gases absorb the heat emitted by Earth, warming the atmosphere and the planet.

Methane, ozone, nitrous oxide and chlorofluorocarbons are also greenhouse gases. They are less abundant than carbon dioxide but some are even more powerful. Methane, which is emitted by industry, bogs, rice paddies and belching cows, makes up just 1.8 p.p.m. of the atmosphere but is about 20 times more powerful as a greenhouse gas than carbon dioxide.

Despite their small contribution to the composition of the atmosphere, greenhouse gases have a huge effect on climate. Without them, the average temperature on Earth would be around −18 °C instead of a comfortable 14 °C. Because of their power, even slight changes in their concentration can have large effects on temperature.

"Scientists are still learning, making it difficult to make detailed climate-change predictions."

In the 1950s, the scientific debate around carbon dioxide focused on whether or not it was accumulating in the atmosphere. Globally, cars, factories and other activities that burn fossil fuels emitted more than a billion tonnes of carbon into the atmosphere annually in the 1950s, but many scientists believed that oceans and plants soaked up nearly all of it.

Against the backdrop of this debate, David Keeling, a chemist at Scripps Institute of Oceanography in La Jolla, California, sought to find out. In 1957, Keeling set up an array of newly developed gas analysers on the summit of Hawaii's Mauna Loa volcano to measure atmospheric levels of carbon dioxide. He chose the site because of its isolation and elevation (about 3,400 metres), which avoided local sources of carbon dioxide that might amplify the readings if the observatory were lower or in an industrial or urban setting. At the beginning of the experiment, the average monthly value was 315 p.p.m. Keeling saw the values drop from May to September and then rise again into the next year. The cycle continued, down and up, down and up, decreasing in summer when plants soak up carbon dioxide and grow, and rising again in autumn and winter. Looking at this pattern was like watching the planet breathe.

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After a few years, Keeling spotted another trend: carbon dioxide levels were rising from one year to the next. Industry, transport and other activities were adding more carbon dioxide to the atmosphere every year, but the oceans couldn't keep up. We now know that, over the long term, about half the carbon dioxide we add to the atmosphere stays there; the oceans absorb about 25% and plants soak up the remainder. By June 2011, the atmospheric carbon dioxide concentration had risen to 394 p.p.m.

The current carbon dioxide level far exceeds its natural fluctuation (180–300 p.p.m.) over the past 800,000 years. Scientists know what the historical range was from studying the planet's natural archives, such as tree rings, the sediments of lakes and oceans, and ice cores. These archives are known as proxy records.

The ice cores extracted from the ice sheets of Greenland and Antarctica provide scientists with climate data going back more than 800,000 years. As snow accumulates on the ground, it traps air bubbles, volcanic ash, dust and other substances in chronological order. The air bubbles provide a record of what gases were in the atmosphere at different points in time.

Scientists can also estimate the air temperature when the snow fell by measuring the ratio of two oxygen isotopes, oxygen-18 and oxygen-16. Generally, ice containing a lot of oxygen-18 was formed in warmer temperatures, with higher oxygen-16 levels indicating colder temperatures. Plotting a graph of temperature versus carbon dioxide concentration reveals a correlation between the two.

The same proxy records show that human activities have influenced the climate for more than a century. Researchers use the term 'anthropogenic climate change' to describe climate change caused by human actions. Temperature records show that the planet warmed throughout the twentieth century. In 2010, the global average surface temperature was the second warmest on record, registering 0.96 °C above the twentieth-century average.

One degree may not seem like a lot, but this increase is a global average and the warming is not uniformly distributed across the planet; it is higher in some areas, including the polar regions. Small temperature changes in the Arctic are amplified through a system of positive feedbacks so a small increase in temperature leads to further warming in the Arctic.

ICE, ICE, MAYBE

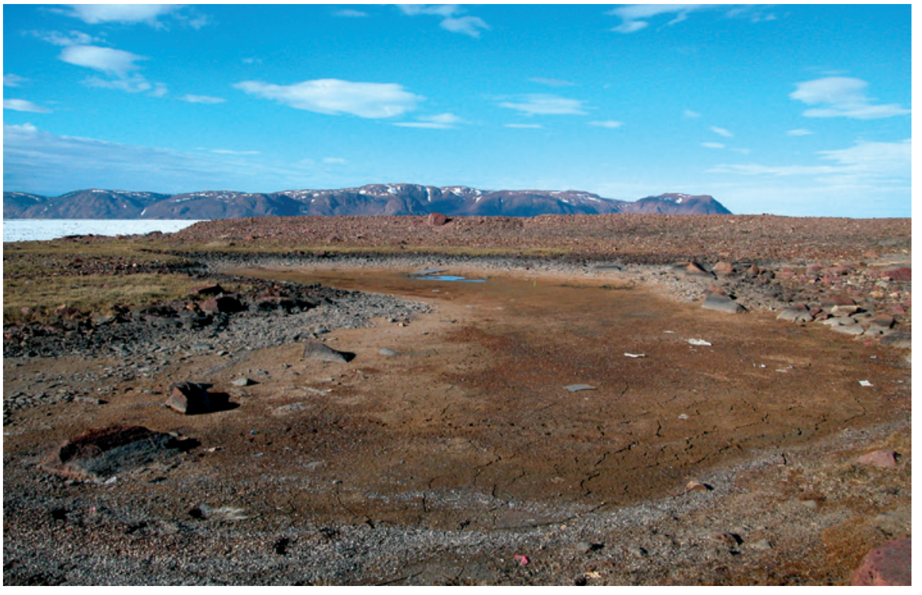
One reason the Arctic is bearing the brunt of climate change lies in a process called ice–albedo feedback. The albedo describes the fraction of incoming energy from the Sun (short-wave radiation) that Earth reflects back into space (as long-wave radiation). Snow and ice have high albedos and reflect 60% to 90% of the Sun's energy. Land, vegetation and open ocean, being darker, have low albedos because they absorb most of the energy. Think about two plastic chairs on a hot summer day, one white and one black. The white one will be much more comfortable to sit on; the black one, having absorbed more of the Sun's energy, may be too hot.

Warmer temperatures can trigger a warming cycle in the Arctic. As the air temperature increases, the ice melts and reveals darker ocean and land, which absorb solar energy during summers when the Sun never sets. These surfaces, which once reflected solar energy, now absorb it. They become warmer and cause more melting, an amplification that explains why the Arctic has warmed at about twice the rate of the global average since 1980.

Just about every climate simulation model shows that the Arctic will lose its multiyear summer sea ice (the ice that has survived previous summer melts) by 2100, but scientists are not yet sure exactly when it will happen. Satellite measurements show that the multiyear ice — ice that has survived one or more summers — covering the Arctic Ocean has been shrinking and thinning for 30 years. In 2007, the Arctic sea ice extent — defined as the area of ocean with more than 15% sea ice per square kilometre — hit a record low of 4.13 million km², roughly 40% below the average from 1979 to 2000.

In 2009, Muyin Wang of the University of Washington and James Overland from the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory projected that the Arctic's first ice-free summer might come decades earlier than previous predictions. They performed computer simulations that used the 2007 and 2008 summer minimum as a starting point. Instead of the sea ice retreating at a constant rate year after year, their calculations showed several abrupt decreases of summer Arctic sea ice, leading to the Arctic being nearly free of sea ice by 2035.

The fate of the sea ice in the Arctic is important because it helps moderate the planet's climate. If the sea ice goes, the planet loses its air conditioning. It is also tied to the well-being of the Inuit and other people in the north who hunt and travel on the ice, and to the mammals and other marine organisms that rely on it to survive. The Inuit often travel long distances over ice-covered water and frozen tundra. Thin ice, late freeze-ups and early break-ups send their sleds and snowmobiles into icy waters and make travel treacherous. One potentially positive outcome of ice melt is that shipping shortcuts are opening up through the Northwest Passage and the Northern Sea Route. Of course, this could also increase the likelihood of negative events, such as oil spills in the Arctic Ocean or the introduction of exotic species.



TOP: JP SMOL. BOTTOM: BELOW: MSV DOUGLAS.

Climate bellwethers: Camp Pond in the Canadian Arctic had been a permanent body of water for millennia (top image taken in July 1996), it now dries during the summer (above image taken in July 2006).

LIFE ADJUSTMENTS

Life has persisted on Earth for billions of years. In response to ancient climate change, the flora and fauna adapted or went extinct. Much of the climate change we are experiencing now is human-made, however, and it is advancing faster because of the steep rise in the concentration of carbon dioxide, methane and nitrous oxide. The effect is greatest in the Arctic but is spreading through the oceans, tropical rainforests and deserts. As regions take on new climatic characteristics — generally warmer temperatures and changes in precipitation and humidity — the plants and animals that live within them need to respond. Some species will thrive in the new climate; others won't adapt quickly enough, and their populations will fragment, shrink and be driven to extinction.

The effects of climate change on flora and fauna are monitored by tracking species of interest over long periods of time. Records are taken of species' phenology: the timing of natural events, such as the annual flowering and bud burst of plants, the return of migratory birds, and the emergence of mammals from hibernation.

Beginning in the late 1990s, scientists began to find changes in the phenology of several species. Generally, these records show long-term trends towards earlier signs of spring. For example, between 1971 and 1995, British birds moved their egg-laying dates forward by almost 9 days, and over a 17-year period, British frogs spawned progressively earlier. In 1999, American robins were returning to the Rocky Mountains in Colorado from lower latitudes 14 days earlier than they did in 1981 (ref. 3). The Inuit have even spotted American robins on some Arctic islands, far from the northern edge of the boreal forest, the traditional limit of their range.

In each of these cases, temperature has played a role. For example, warmer spring temperatures can encourage earlier plant growth, which boosts the availability of insects in early spring. This early availability makes it advantageous for birds and frogs to lay their eggs earlier so their offspring have lots of food. Warmer spring temperatures can also trigger species, like the American robin, to move to higher altitudes. Other factors, such as precipitation, also influence these events.

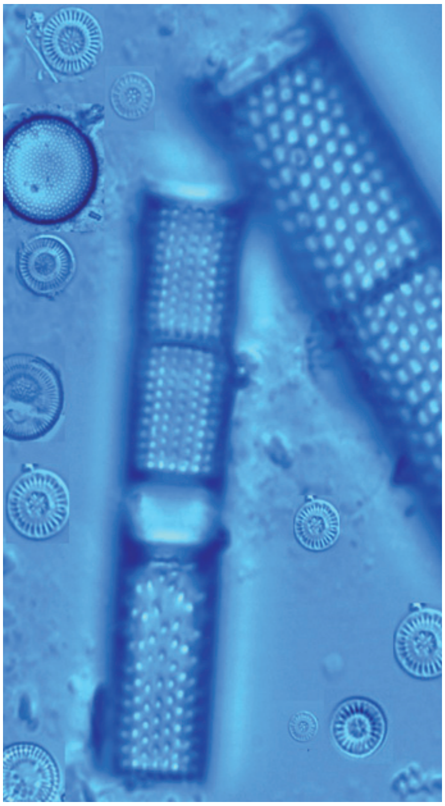
Many species, from beetles to birch trees, are adjusting to climate change by moving outside their usual geographical boundaries, according to several studies. Biologist Camille Parmesan of the University of Texas in Austin was one of the first scientists to document the range shifts of a species in response to climate change. She spent five years locating different populations of the Edith's checkerspot butterfly across the western United States. She then compared the sites with historical population records from museum specimens, private collections and researchers' field notes. She found that the butterfly had moved 124 metres upward and 92 km to the north since the beginning of the twentieth century, which she thought could be in response to warmer temperatures.

When a species alters its phenology or shifts its range, it doesn't do so in isolation. Scientists have documented cases of trophic mismatch when the availability of a food source shifts in response to temperature, taking it out of step with the needs of another species. The springtime growth of a plant or the emergence of insects may be closely tied to local temperatures, but the arrival of another species, such as a migratory songbird, may be cued to changes in day length. If the bird continues to arrive on the same calendar date, its food may already be well past its peak or not available at all.

BEETLE MANIA

Warmer temperatures can increase the abundance of some species, which can have a negative effect on others. The mountain pine beetle is a good example. Since the 1990s, the mountain pine beetle has consumed more than 13 million hectares — an area about the same size as Greece or Louisiana — of lodgepole pine forest in central and northern British Columbia, Canada. Forestry practices throughout the area have also probably exacerbated the beetle outbreak. In the past, its population was controlled in part by early cold snaps and midwinter freezes that killed the beetle. But now, warmer winter temperatures have reduced the beetle's mortality and allowed it to expand its range eastward into Alberta. In its new home, the beetle has started attacking jack pines, a dominant species of the boreal forest. Not only could the beetle move into other provinces, it could also cause Canadian forests to release massive amounts of carbon dioxide into the atmosphere as they die off.

Other species may find they have nowhere to go. The polar bear population in Canada's western Hudson Bay region is falling, partly due to the declining ice. Female polar bears are forced ashore up to two weeks earlier than in the early 1990s because of the early spring ice breakup. Some scientists predict that the population may be in jeopardy if the ice break-up shifts by another six weeks. The problem is that the earlier spring ice breakup shortens their hunting season. Females have difficulty meeting their own energy needs when they are pregnant, and it is even harder to find enough food to feed their cubs. At the same time, grizzly bears are moving north into polar bear territory. There have already been sightings of a grizzly–polar bear hybrid, confirmed by DNA analyses, which is called a pizzly by some and a grolar by others.



K. RÜHLAND

Time capsules: preserved diatoms, a microscopic algae, in sediments divulge data of past environmental changes.

Ocean corals are particularly vulnerable. During the twentieth century, the global oceans' average temperature rose by 0.74 °C. This change may seem small, but corals struggle in water 1–2 °C warmer than its usual summer temperatures. In warm water, corals cast off the symbiotic algae that give them their vibrant colours, a response known as bleaching. Ocean pH is also changing as a result of the increasing carbon dioxide concentration. The carbon dioxide reacts with sea water, making it more acidic and breaking down the molecules that corals depend on to build their skeletons[4]. Both events can lead to coral-reef die-off on a large scale.

> ***"We found some of the ponds were bone dry and other were puddles…we were stunned."***

Climate change also affects human health. Infectious diseases spread by insects can become threats in different places, for example. The cooler climate of the Kenyan highlands has historically kept the incidence of malaria lower than in the warmer lowlands. But warming in the region has pushed the mosquito that carries the parasite to higher elevations, driving up the number of malaria cases. Identifying at-risk areas far in advance of epidemics remains difficult. Scientists are still learning about the biological limits of pathogens and their hosts, making it difficult to make detailed and geographically specific climate-change predictions. As they learn more about the biotic and abiotic factors that influence the spread of disease, they will gain perspective on how climate change will alter infectious disease patterns,

FUTURE UNCERTAINTY

What additional biological changes can we expect to see in the future? The answer depends a lot on what action we take. We have already polluted our atmosphere with high concentrations of greenhouse gases. The planet's population is expected to grow from 7 billion now to 9 billion by 2050, and this is likely to be matched by increasing energy consumption and output of greenhouse gas. Even if we manage to curb emissions, future generations will have to deal with the legacy of these greenhouse gases: temperature extremes, floods, droughts, storms and rising sea-level. We need to find ways to drastically cut emissions, but we must also plan for the future and find ways to adapt. We face some tremendous challenges.

To understand the potential effects of climate change on Earth's flora and fauna, scientists will need to continue tracking and mapping different species. They will look for trends and try to identify the factors that most influence a species' survival or demise, but they must also disentangle the combined consequences of other human effects, including habitat degradation, overfishing, acid rain and toxic compounds.

The complexity of the biosphere gives us the opportunity to ask many questions about our planet, its changing climate, and the species that live on it. Why do some regions of the Arctic warm faster than others, for example? Will we see new biological communities form, while some species are lost and others expand or move their ranges? If so, will these new communities change the way the ecosystem functions? ■

John Smol *is professor in biology and holder of the Canada Research Chair in Environmental Change at Queen's University in Kingston, Ontario, Canada.*
email: smolj@queensu.ca

1. Douglas, M. S. V., Smol, J. P. & Blake, W. Jr *Science* **266**, 416–419 (1994).
2. Smol, J. P. & Douglas, M. S. V. *Proc. Natl Acad. Sci. USA* **104**, 12395–12397 (2007).
3. Inouye, D. W. *et al. Proc. Natl Acad. Sci. USA 97*, 1630–1633 (2000). .
4. Hoegh-Guldberg, O. *et al. Science* **318**, 1737–1742 (2007).