

What air bubbles trapped in Antarctic ice tell us



Sliced ice, ready for analysis.

As the carbon dioxide content of the atmosphere rises inexorably, concern about possible effects on the earth's climate is increasing. Will a general temperature increase turn the American wheat belt to desert and melt polar ice?

Fortunately, any effects are being delayed by the fact that only about half the carbon dioxide emitted by burning coal, oil, and natural gas remains in the atmosphere. If it all accumulated there, the carbon dioxide concentration would double from its present 340 parts per million in the next 45 years.

Instead, the best estimates suggest this will take until the middle of next century. Over the last few decades the oceans appear to have absorbed some 43% of carbon dioxide emitted from fossil fuel burning.

Confident predictions of how future carbon dioxide emissions will affect the

concentration in the atmosphere rely on an accurate model of carbon dioxide pools and their interactions.

A number of important parameters must be included in such a model. The first two are the rate at which the gas is released into the air from the burning of fossil fuel (easily calculated for past and current use, but difficult to forecast) and the rate at which the concentration of the gas is rising in the atmosphere (measured at a number of monitoring stations around the world, including the one at Cape Grim, Tasmania).

Next come estimates of the flux of carbon between the biosphere, ocean, and atmos-

phere. Measurements of the abundance of the isotopes carbon-13 and carbon-14 are very useful here. (Plants discriminate against the stable carbon-13 isotope, so changes in its abundance in the air relative to that of carbon-12 provide an indication of changes in the size of the biomass pool; nuclear testing in the '50s and early '60s created a burst of radioactive carbon-14 that acts as a marker for the turnover of carbon dioxide in the oceans.)

Another important parameter is the extent to which the biosphere has been depleted due to deforestation and agricultural expansion, and how much carbon from these processes has been released into the atmosphere.

It seems that carbon dioxide released today in the destruction of forest almost matches uptake by the remaining vegetation.

Thus, for accurate modelling, we need to know the carbon dioxide concentration prior to 1850, when industrialization began apace and broad-acre farming felled much forest.

Trapped air bubbles

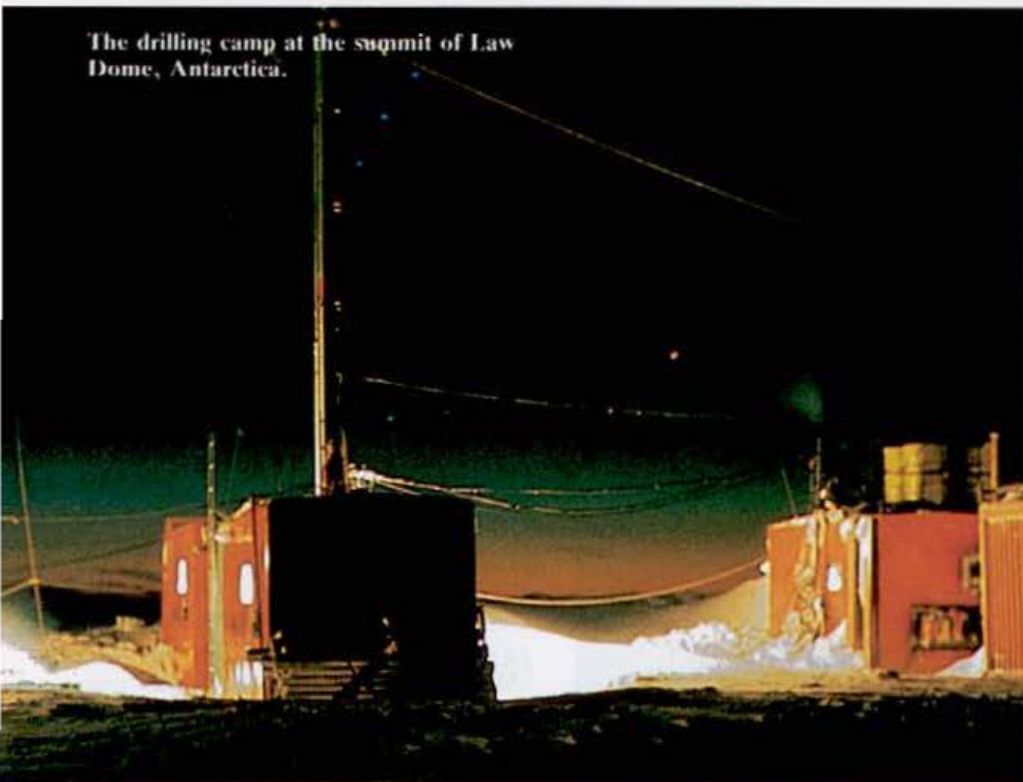
Air bubbles trapped in polar ice are now giving scientists the missing information — and providing a few extra surprises as well. Recently, a Swiss group from the University of Bern published data on carbon dioxide concentrations extending back 1000 years, and a team from the CSIRO Division of Atmospheric Research and the Antarctic Division of the Department of Science presented similar data going back to the 17th century.

How the Australians gathered the ice samples, and analysed the air bubbles in them for carbon dioxide, is explained in the box. Their results are summarized in the graph on page 26.

The most significant finding of both the Swiss and Australian scientists is the essentially constant carbon dioxide concentration of about 280 p.p.m. before 1800.

The main implication of this result is that it restrains the contribution from the biosphere since then to quite small values (assuming that the oceans' role has not changed during that time). If we calculate the amount of carbon dioxide that needs to be released to raise atmospheric concentrations from 280 p.p.m. to today's 340

The drilling camp at the summit of Law Dome, Antarctica.



p.p.m., the result tallies quite closely with the amount released from the burning of fossil fuels.

Despite prevalent injury to her forests, the earth's biosphere can only have been diminished by something less than 50 thousand million tonnes (50 Gt) of carbon — less than one-third of the total amount so far released as a result of fossil fuel burning. (Other figures for comparison are

the 700 Gt estimated to reside in standing forest, and the 1500 Gt in soil.) Furthermore, to maintain consistency with models of carbon dioxide movement, that 50 Gt must have been released mostly between 1850 and 1900.

In other words, it seems that carbon dioxide released today in the destruction of forest is being matched by an almost equivalent amount taken up by the remain-



Retrieving the long-hidden ice core from its Antarctic resting place.

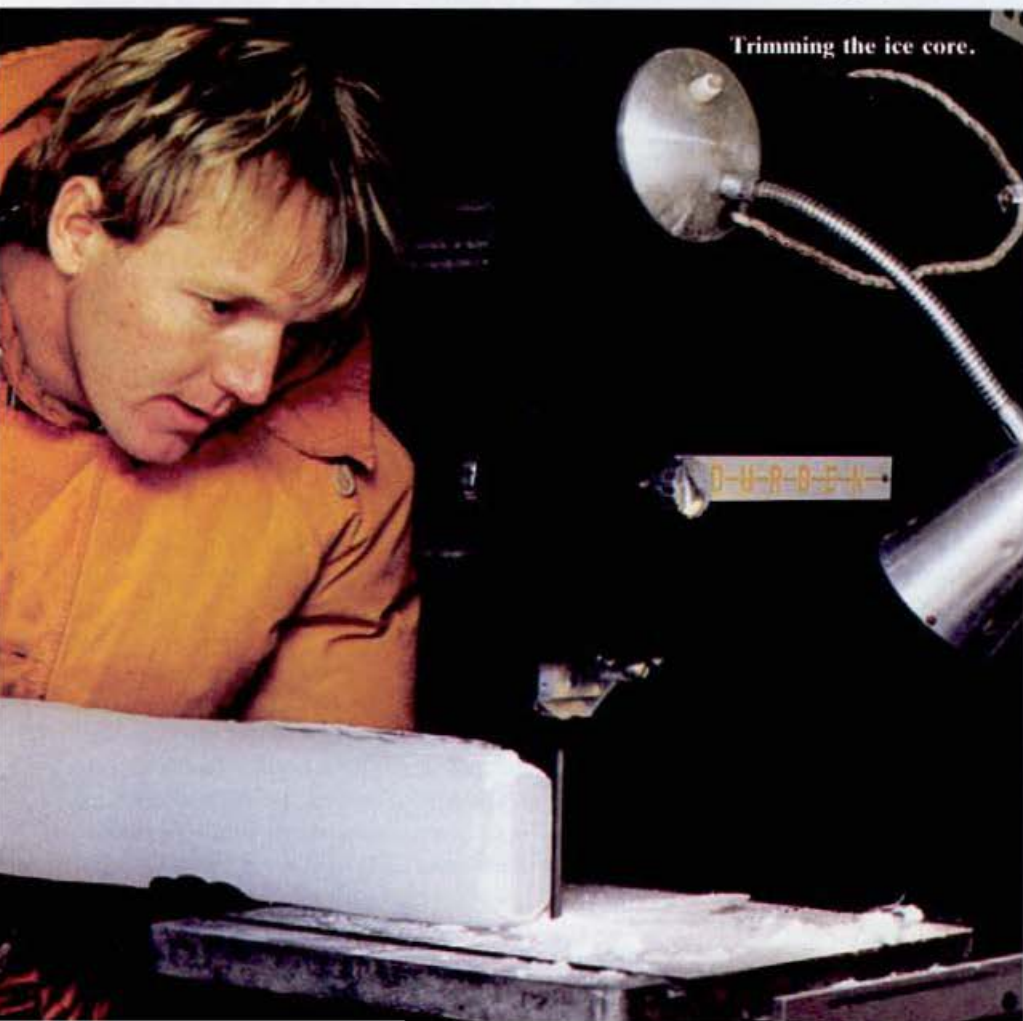
ing vegetation. That means that very powerful compensatory mechanisms are operating. Measuring the relative abundance of the stable carbon isotopes carbon-12 and carbon-13 in air trapped in ice cores would, as explained earlier, confirm this equivalence, and both groups of scientists are planning to do this.

The constant level of atmospheric carbon dioxide over the years preceding human influence is a significant finding by itself. For if it fluctuated all over the place, that would mean we couldn't relate today's observed changes to any particular release of the gas — there would be no firm link between cause and effect.

Past millennia

So much is clear. But differences of scientific opinion start to appear when we push the ice-core record back thousands of years. Recently, collaborating Russian and French scientists have analysed a 2083-m Antarctic ice core, which they date as spanning 150 000 years.

The Swiss group has worked on extracting a reliable 40 000-year record of atmospheric carbon dioxide, and the Australians have plans to retrieve an ice core going back 30 000 years. Ocean sediments have also been analysed for carbon-13, giving an indirect measure of carbon dioxide concentrations in ages past — up to 170 000 years ago. (The sediments contain remains of



Trimming the ice core.

surface-dwelling plankton, and the ratio of carbon-13 to carbon-12 in them relates to the atmospheric levels of carbon dioxide prevalent in their day.)

The Australians have plans to retrieve an ice core going back 30 000 years.

The message coming from these analyses is that carbon dioxide concentrations have fluctuated widely on these larger time scales. The ocean sediment record is reproduced on page 26, and it indicates that concentrations of the gas have varied from a minimum of 180 p.p.m. about 65 000 years ago to a maximum of 330 p.p.m. (equivalent to modern-day levels) some 125 000 years ago.

Furthermore, these variations parallel the variations in the earth's temperature, as inferred from the oxygen-18 content of the polar ice cores (also shown). (Water contains a small proportion of oxygen-18, as well as the normal oxygen-16; the proportion of isotopes that evaporate and



become bound in polar ice depends on the temperature.)

For instance, 20 000 years ago, during the coldest part of the last glacial period (from which we are still emerging), the concentration of carbon dioxide was 40–100 p.p.m. lower than the pre-industrial value. About 16 000 years ago, as the great ice

Trapped air bubbles, about to be released by crushing the ice under vacuum. They will divulge what past carbon dioxide levels have been. The colours come from illumination by polarized light, and show the crystal structure of the ice.

sheets began to melt, carbon dioxide began a geologically rapid increase that only stopped a few thousand years ago.

Unlocking ice-bound secrets

Slowly the hot metal ring melts its way down through the virgin Antarctic ice. Expeditioners from Casey station pack the 100-mm-diameter core from borehole D into insulated containers for refrigerated transport back to Australia.

Borehole D, 473 metres deep, was drilled in 1977 at the summit of Law Dome, where snow has been accumulating for thousands of years. Pressure compacts the snow into ice, and each 65 cm of ice represents 1 year's contribution.

The drill advances at about 2 m per hour, and periodically it needs to be winched to the surface to recover the core. A team of four Antarctic workers reckon on retrieving an average of 1 m of core an hour on a good day. They cannot go much deeper than about 500 m with a thermal drill because the pressure at such depth is so great that the ice begins to flow inwards as soon as they hoist up the drill to retrieve a section of core.

To keep the borehole open for future studies, the team fills the hole with liquid, the pressure of which keeps the ice from closing in on itself. (Unfortunately a thermal drill won't work if surrounded with liquid.) Monitoring of the hole's distortion gives glaciologists a clue to the dynamics of the massive Antarctic ice sheets.

The oldest ice the workers have recovered from Law Dome has been there for several millennia, and they have plans to reach bedrock at 1200 m using a mechanical drill that can operate surrounded by liquid.

Other boreholes, at sites where snow deposition is less rapid, have yielded ice as old as 150 000 years. Russian workers have drilled down to more than 2 km, and there is always the challenge of recovering ice nearly twice as deep.

Back in Australia, Antarctic Division scientist Dr Vin Morgan dates the ice by counting the annual layers of oxygen-18 enhancements (snow falling in summer has a higher proportion of this isotope than winter snow).

Interestingly, the enclosed air is deduced to be 67 years younger than its enclosing ice. This is because the ice is formed by packing of dry snow, and decades can elapse before the enclosed air becomes totally isolated from the atmosphere.

Dr Ian Enting of the Division of Atmospheric Research has constructed a model of the trapping process. Together with colleague Dr Jim Mansbridge, he has been investigating the precision with which an age can be assigned to gas recovered from ice cores. The sections of ice core dated as coming from this century show carbon

dioxide concentrations that match the global concentrations as they were known to be about 67 years later.

The analysis of the trapped air bubbles was done in two stages. Extreme care had to be taken throughout to ensure absolutely no contamination of the ancient gas.

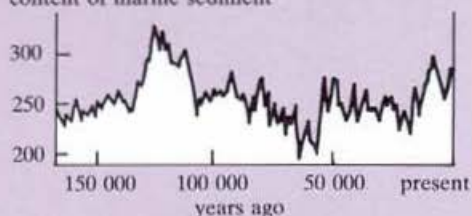
In the first step, Mr David Etheridge of the Antarctic Division crushed about 1 kg of ice under vacuum at -80°C to release about 100 mL of long-imprisoned air. The air was then dried and condensed in a trap cooled by liquid helium, and taken to the CSIRO laboratories. Here, Dr Graeme Pearman, Mr Fred de Silva, and Dr Paul Fraser measured its trace gas content by gas chromatography.

As well as carbon dioxide measurements, the CSIRO workers also determined the abundance of nitrous oxide and methane, two other 'greenhouse' gases. Methane appears to have increased by at least 40% since 1600, and nitrous oxide has increased by 8%. The next step is to measure the abundance of carbon-13 and carbon-14 in the trapped air, and the researchers have plans to do this soon.

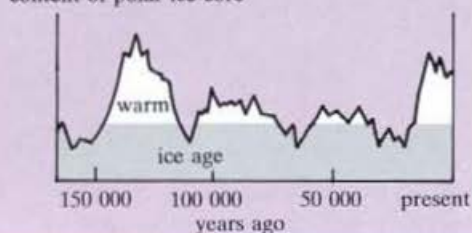
A lattice statistics model for the age distribution of air bubbles in polar ice. I.G. Enting. *Nature*, 1985, **315**, 654–5.

In past millennia

CO₂ concentration (p.p.m.)
inferred from carbon-13
content of marine sediment



global temperature
inferred from oxygen-18
content of polar ice core



Over many thousands of years, carbon dioxide levels appear to have fluctuated significantly. Low levels coincide with ice ages; high ones with warm periods (like now).

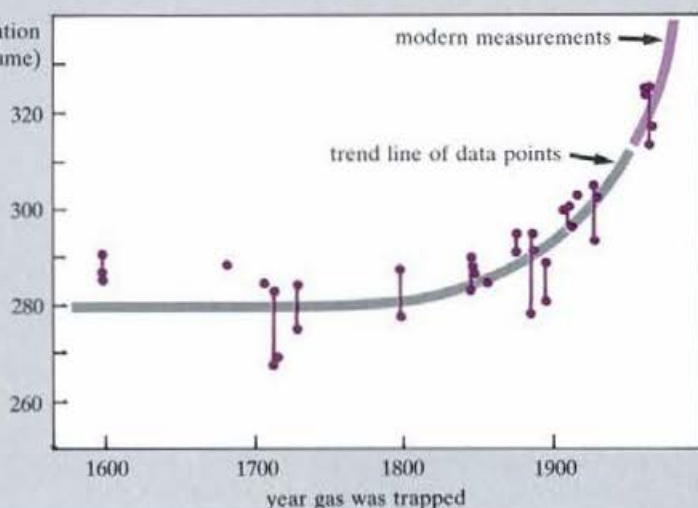
Seeing this close link between climate and carbon dioxide makes one ask: does the changed climate alter the carbon dioxide balance, or does a change in carbon dioxide drive the climate to see-saw to its opposite condition?

The geological record appears to show that earth switches from one stable state — with an abundance of steaming jungles — to the other, an ice age. At the moment we seem to be between stable states.

When the Australian researchers crushed samples of dated ice core, they could measure the carbon dioxide content of the liberated air. Between the years 1600 and 1800, they judge the carbon dioxide level to be 281 ± 7 p.p.m. by volume.

Carbon dioxide levels centuries ago

CO₂ concentration
(p.p.m. by volume)



Nobody can clearly identify any particular factor that, by itself, is powerful enough to turn the earth's climate upside down.

It seems that some small-scale fluctuation acts as a trigger: somehow its effects are amplified, and the climatic balance swings. In other words, Nature's climate system is not so constrained by negative feedback effects that stability is assured. There must be at least one positive feedback influence that, under some circumstance or other, has been — and presumably still can be — brought into play.

Some scientists have looked to changes in the circulation of the deep ocean as the triggering mechanism. At high latitudes we find a close connection between the atmosphere and the vast deep waters that store carbon dioxide. Here, covering less than 4% of the ocean's surface area, the cold conditions allow mixing of deep and surface waters. (If the surface water is warm, it sits stably on top of colder waters underneath.)

This mixing process could perhaps be turned off or on by minor processes. Among the candidates, small changes in the orientation of the earth's axis as it orbits the sun show a correlation with the incidence of ice ages. These 'Milankovitch cycles' — about 100 000, 40 000, and 21 000 years long — are due to regular changes in the combined gravitational pull of the sun, moon, and planets.

Another version of the orbital change theory sees the gas exchange between ocean and air mediated by phytoplankton. The orbit change gives them more light, so they pump more carbon dioxide out of the atmosphere. This effect sets up a sequence of lower temperatures, reduced ocean circulation, and even less carbon dioxide.

Still another version of the orbital perturbation hypothesis has the changed orbit creating more polar ice. This leads to more

reflection of solar energy, and a further cooling, creating more ice, until an ice age has set in.

In all versions, orbital variations have summoned carbon dioxide to amplify their initial tendencies.

A computer model

Mr Barrie Hunt of the CSIRO Division of Atmospheric Research has done an experiment with a 'general circulation' model of the earth's climate, and found that such perturbations are not necessary to explain ice ages. His computer model indicated that the preferred state of the climate, given the present concentration of carbon dioxide, is to exhibit polar ice. Even when the model globe starts out completely ice-free, ice soon builds up. Looked at his way, the problem is more one of explaining the intervening periods of warmth.

His favoured explanation for the onset of a warm period is the appearance of large increases in the blanket of carbon dioxide. Mr Hunt looks to sources of carbon dioxide deep inside the earth. Perhaps volcanic activity is periodically enhanced when tectonic plates collide. In support of this theory, he points to the immense amounts of carbon locked up in limestone sediments and coal deposits. All of this once existed as carbon dioxide in the atmosphere.

It couldn't all have been present in the atmosphere at the one time — no evidence has been found for very high levels there. Rather, it came from periodic volcanic releases from the earth's crust, which led to temporary enhancement in the carbon dioxide blanket and a rise in the planet's temperature.

An advantage of Mr Hunt's line of reasoning is that it can explain the very rapid changes in carbon dioxide that the Swiss group have found in one ice core. Mechanisms involving biological factors would be unable to respond with such speed.

Clearly, more information from ice cores and the like is vital for accurate short-term and long-term models of our globe's precious and intricate life-support system.

Andrew Bell

More about the topic

Evidence of changing concentrations of atmospheric CO₂, N₂O and CH₄ from air bubbles in Antarctic ice. G.I. Pearman, D. Etheridge, F. de Silva, and P.J. Fraser. *Nature*, 1986, **319** (in press).

Polar glaciation and the genesis of ice ages. B.G. Hunt. *Nature*, 1984, **308**, 48–51.

When the air's carbon dioxide doubles. *Ecos* No. 28, 1981, 3–11.