
nature
IS GREENLAND MELTING?
Weighing the evidence
QUANTUM COMPUTING
FISH STOCKS IN DECLINE
PERSONALIZED GENOMES

nature

www.nature.com/nature

Vol 452 | Issue no. 7189 | 17 April 2008

All eyes north

The Arctic — particularly Greenland — needs to become a major focus of research for years to come.

Halfway through the International Polar Year (IPY), which actually stretches from March 2007 to March 2009, it is clear that polar research has received exactly the kind of boost that its planners were seeking. As of last month, more than 160 projects were under way with full or partial funding. Some 60 countries are involved, including such unexpected ones as Portugal and Iran.

Public outreach has been particularly successful, with children and students getting involved in polar celebrations, video links to researchers in the field and websites. The ranks of polar artists are swelling with painters, sculptors and even a puppeteer. There are IPY stamps and IPY coins, and Sweden has made toilet paper with the IPY logo on it.

More seriously, several multidisciplinary, multinational projects have now begun. Europe is deep in the throes of planning its icebreaker-cum-drillship, the *Aurora Borealis*, for launch in 2014. Denmark has started its next Greenland ice-core drilling project. In Antarctica, teams have drilled through the ice shelf to the sediment below, and others are planning an assault on the buried Gamburtsev Mountains.

Yet for all this apparent vigour, major problems remain for polar research — chief among them funding. A number of IPY-approved projects struggled to get off the ground last year, as money for them was slow to come from national governments. This includes the US National Science Foundation (NSF), the powerhouse of polar research, which was hamstrung by, among other things, the late approval by Congress of its 2008 budget.

Some money is now flowing. According to IPY managers, around \$400 million in new funds is being distributed across the entire IPY; added to the \$800 million that would normally be spent worldwide on polar research during that time, they argue it's like getting three years' funding in two years.

But that doesn't solve the tougher issue of how resources should be allocated. With its long tradition as the scientific continent, Antarctica has historically drawn the lion's share of funding. The NSF, for instance, spends about \$325 million on the continent annually, largely to maintain its massive research infrastructure there. Arctic sciences, in contrast, get about \$100 million.

Attention needs to shift northwards, and fast. The precise north–south balance can certainly be debated. But consider how surprised researchers have been by the sudden and dramatic shrinking of the Arctic sea ice in recent summers. That fact alone signals that more monitoring and modelling is needed to understand what might happen next.

> "The entire polar-research community needs to come together to monitor Greenland's meltdown on a comprehensive scale."

The most pressing Arctic question concerns the future of the Greenland ice sheet (see page 798). Too little attention is paid to monitoring its ice loss each summer and modelling what that might mean for the future. In total, Greenland's ice could raise the sea level by 7 metres — far less than the 21 metres locked in Antarctica, but far closer to complete meltdown. Yet Greenland gets just \$10.5 million annually of NSF money — \$9 million of which goes on logistics. Denmark pours twice that amount in, but it is still not enough.

Currently, a handful of individually motivated researchers heroically rush to the island each summer to set up monitoring stations. They capture the jerky motions of the massive outlet glaciers that are dumping Greenland's ice into the sea, and videotape the huge meltwater lakes that form on the ice sheet each summer and then drain away into oblivion. They patch together data from a motley collection of remote-sensing satellites, trying to capture the changes in Greenland's ice as they happen.

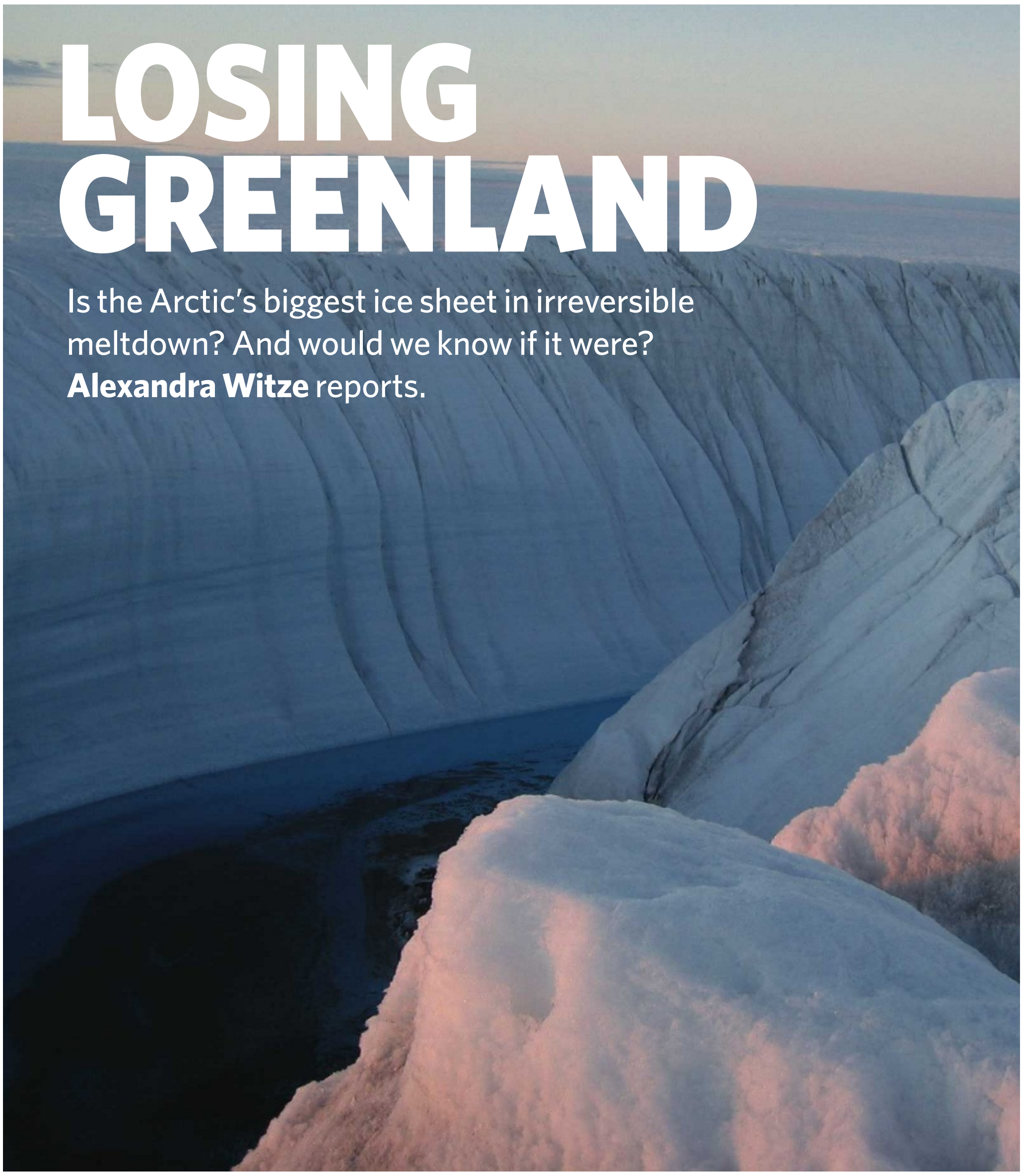
But they can only do so much. The entire polar-research community needs to come together to monitor Greenland's meltdown on a comprehensive scale. In the best of worlds, the IPY would open the eyes of those who control the purse strings to the need for more Arctic monitoring. Members of the US Congress, for one, have been happily signing up for trips to the South Pole and to Summit Station atop Greenland. It remains to be seen whether those visits will make any difference when it comes to Congress voting on money for the NSF — or whether the NSF would even choose to give more money to its Office of Polar Programs given the competing demands on its resources. But it is time to spend more on Greenland, and to think more about Greenland, and to make sure this continues for years to come. ■

A ghost of battles past

The US veterans' administration should go ahead with a much-delayed study of Agent Orange.

Even by government standards, a near 30-year delay in getting a study approved is extreme. But that is essentially what has happened with a proposed large-scale epidemiological study of the possible effects of the defoliant Agent Orange and other combat factors on US veterans of the Vietnam War. This US administration, or the next, would do well to heed the advice issued last month by the National Academy of Sciences that such a study should now proceed.

The academy argues that new data, and advances in geographical information systems (J. M. Stellman *et al. Nature* **422,** 681–687; 2003), could plug a significant gap in earlier epidemiological studies (see page 786). Today, a study should be able to provide key information about when and where troops were exposed to the defoliant, which contained highly toxic compounds called dioxins. And advances in computing and databases mean that the study would cost a fraction of earlier estimates.



LOSING GREENLAND

Is the Arctic's biggest ice sheet in irreversible meltdown? And would we know if it were? **Alexandra Witze** reports.

When people talk about catastrophic climate change, there's a fair chance that Greenland is on their mind. If they use the term 'tipping point', then it is pretty much a sure thing. One-twentieth of the world's ice is locked up atop that island, and if it were to melt completely, global sea levels would rise by seven metres. The collapse of the Greenland ice sheet is in the front rank of potential climate catastrophes.

Melting is already undoubtedly and dramatically underway. Glaciers are spitting icebergs into the ocean and scurrying back up their narrow fjords like rats up drainpipes. Giant lakes are forming on the frozen surface, sending torrents of water plunging through fissures in the ice sheet and thus, perhaps, accelerating its slipping and sliding seawards. Over the past four summers, Greenland has shed an average of between 380 billion tonnes and 490 billion tonnes of ice each year — on average 150 billion tonnes more than it gains in snow in winter.

That's a lot of water. It is not, as yet, a lot of Greenland's ice, which totals 2.9 million cubic kilometres. Such size brings with it an inherent sense of stability. We do not expect things bigger than mountain ranges just to go away. But there's a disturbing sense in which Greenland shouldn't be here in the first place. It is a holdover of the most recent ice age, a creature of conditions that no longer apply. No ice sheet would grow in Greenland if the current one were to vanish — even without human-induced warming, the climate would not allow it. The ice is a relic, stranded out of time. And relics are fragile.

The question is, how fragile? Has the warming the sheet has experienced so far and the further warming already in the pipeline enough to push the ice sheet past a point of no return[1]? If that is not yet the case, how far from that threshold are we? And if the sheet does start to go, how fast will it do so? The sheet will not vanish tomorrow, nor in a century — but assumptions that such processes take millennia are being reexamined on the basis of the changes already seen. The most recent synthesis report from the Intergovernmental Panel on Climate Change notes that the changes seen in Greenland today are not fully factored into the estimates of sea-level rise given in earlier science reports from the panel — a note that those who see Greenland as a potential poster child for catastrophe have made much of.

As yet, these pressing questions simply cannot be answered. They require models and theories not yet fully developed. And that lack of development is in part a lack of data — good data that show clear trends. Even though researchers scatter themselves around the island every summer to try to capture the meltdown's extent and processes, there is no systematic, long-term, broadly based monitoring of the sort needed to produce a truly comprehensive account of what is happening with the ice sheet. "Do we have the data we need to understand what's driving these changes?" asks Ian Howat, a glaciologist at Ohio State University in Columbus. "The answer is definitely no."

The gravity of the situation

To get the best overview of the great Greenland meltdown, you need to go to space and look for gravity. The Gravity Recovery and Climate Experiment (GRACE) is a pair of US–German satellites that orbit Earth 500 kilometres up, one close behind the other. Through constant interchange of microwaves the satellites measure the distance between them very precisely, and that distance changes as massive objects below tug at the leader and the follower in slightly different ways at any given instant. The small discrepancies so produced can be used to calculate a gravity map for the planet. As masses move around, that map will change.

Data from GRACE have revealed how the water flow in the Amazon basin changes with the seasons, and which Asian aquifers are replenished by the monsoons. The mission has also provided new information about the flow of water off the massive ice sheets in Greenland and Antarctica. "When you look at a lot of the insight we have" about Greenland, says

I. JOUGHIN

Konrad Steffen, a glaciologist at the University of Colorado at Boulder, "it's GRACE".

The estimates vary as to how much mass is lost through melting each summer. Isabella Velicogna of the University of California, Irvine, leads a group that takes a large-scale approach[2], averaging the global gravity numbers provided by GRACE for each 30-day period. Her latest estimate suggests that 211 billion tonnes of ice are being lost each year, mainly from southern Greenland. "There is no doubt that things are changing faster than we expected," she says. Meanwhile, Scott Luthcke of NASA's Goddard Space Flight Center in Greenbelt, Maryland, takes a different tack, using the changing distance between the satellites to calculate the pull of smaller mass concentrations on the ground over time[3]. Including the 2007 melt season, he gets preliminary estimates of 154 billion tonnes of ice lost per year. The numbers sound different, but both groups emphasize how close they are, and over time there seems to be some convergence. "These are two vastly different ways of processing data, and they're almost within the error bars," says Luthcke. "Greenland is losing a lot of mass."

GRACE is also providing clues as to how the situation varies from year to year — particularly for the last melt season, when surface temperatures were 4–6 °C higher than average and during which 500 billion tonnes of ice vanished. That's 30% more than the previous year, and 4% more than the previous record, set in 2005. "2007 was a shocking year," says Luthcke. And GRACE's findings are bolstered by observations of dramatic ice losses by other satellites. Radar measurements, for instance, have shown[4] that glaciers in southern Greenland are dumping ice into the ocean ever more quickly. At the American Geophysical Union meeting in San Francisco in December, Velicogna presented results showing that the GRACE estimates are supported by data taken from the Ice, Cloud and Land Elevation Satellite (ICESat), which uses a laser altimeter to measure elevation changes on the ice sheet.

"2007 was a shocking year." — Scott Luthcke

An island rising

One reason why extra information is needed to supplement the data from GRACE is the problem of 'post-glacial rebound'. As big as Greenland's ice sheet is today, in the ice age it was just a part of something far bigger, ice that reached as far south as the Ohio Valley and as far east as the Urals. That vast mass pressed the crust beneath it down into the denser mantle below. Although most of the ice has long since disappeared, large parts of the high-latitude crust have yet to recover from this repressed position. Scandinavia, for instance, rises 9 millimetres higher every year as the denser mantle pushes the lighter crust back up. This ongoing bounceback makes analysing the GRACE data harder.

Help may soon come from a system of global-positioning receivers that have just been installed around Greenland to measure how the bedrock is rising over time. Last summer, a team of researchers from the United States, Denmark and Luxembourg put 24 stations around the rocky, ice-free edges of the island — tripling Greenland's global positioning system (GPS) infrastructure in one field season, according to Michael Bevis, the project leader at Ohio State University. The Greenland GPS Network (GNET) is one of the northern components of a two-pole effort called POLENET to measure post-glacial rebound and other phenomena; there will eventually be around 50 GNET stations in Greenland. "We need much improved models of post-glacial rebound, otherwise GRACE measurements will have very limited value in Greenland and Antarctica," says Bevis. "If we can pull this off, GRACE will become the most powerful system ever devised for measuring ice mass change."

The GNET stations are strung along the rocky margin of Greenland, mainly in remote areas (see map, page 800). They require a lot of battery capacity to continue operating throughout the winter months, and links to five of the stations installed last summer have already gone down. The team is planning to retrieve the data manually and fix the stations this summer.

All this makes GNET a fairly expensive proposition. The last field season consumed about US$1 million, and flat budgets, rising fuel costs and the weak dollar are making things even tighter this year. The rest of the GNET stations will have to go in over the next two summers instead of all in 2008, as originally planned.

The GNET receivers are expensive, highly precise, heavy and, in principle, durable. Another monitoring strategy takes the opposite tack; it uses GPS equipment cheap enough to lose, embedded at the calving fronts of some of Greenland's most active 'outlet glaciers'. These are the thick streams of ice that flow through narrow fjords into the oceans surrounding Greenland. A decade ago, researchers thought that these outlet glaciers moved slowly, creeping downward from the high centre of the ice sheet. In recent years, though, the glaciers have been doing a veritable hokey-cokey on their approach to the ocean, first advancing rapidly, then pulling back.

It started more than a decade ago with the biggest outlet glacier of all, Jakobshavn Isbræ on the west coast, which among its claims to fame is the most likely source of the iceberg that sank the *Titanic*. Between 1992 and 2003, Jakobshavn Isbræ accelerated from 5.7 kilometres per year to 12.6 kilometres per year[5]. "That was incredibly dramatic," says Ian Joughin, a glaciologist at the University of Washington's Applied Physics Laboratory in Seattle. "A decade ago, nobody would have anticipated one of Greenland's biggest outlet glaciers doubling its speed." Faster glacier movement means more ice dumped into the ocean, and a thinning of the central ice sheet from which the glaciers feed.

Over on the east coast, the island's other two big outlet glaciers also started speeding up[6]: Helheim in 2002, and Kangerdlugssuaq in 2005. The process didn't go smoothly.

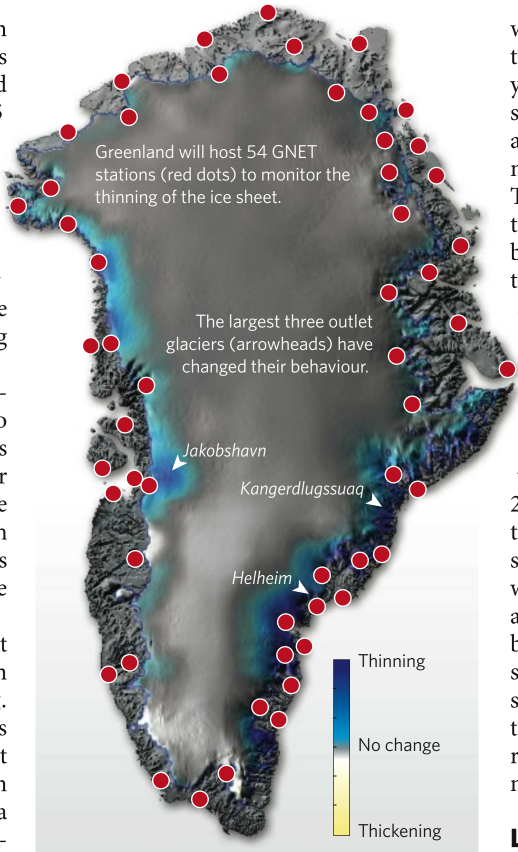
NASA/GSFC VISUALISATION STUDIO

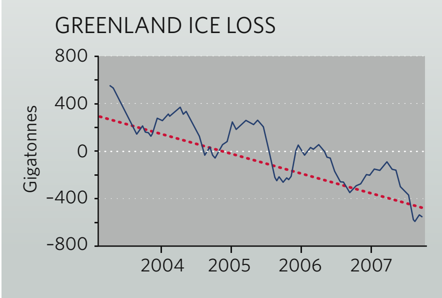
Helheim, for instance, retreated more than 3 kilometres between 2001 and 2003 as its front melted away faster than new ice flowed down to make up the difference. Then in 2005 it began advancing again as flow took over. This back-and-forth is captured most dramatically in remote-sensing images from satellites such as NASA's Terra and Aqua. "There is a lot of variability, and the important thing to remember is we only have a few good years of observations," says Joughin. "We don't know if we are looking at the beginning of a longer-term trend."

Joughin and others suspect that the back-and-forth of the outlet glaciers has a lot to do with the geometry of the fjords the ice squeezes through. The glaciers inch forward until their ends finally break off, calving icebergs into the ocean. This relieves stress on the glacier, which begins to surge, much as removing a buttress holding up a rickety old house will cause the house to collapse.

But the scenario is not as clear-cut as it might seem. In the past, glaciers advanced and then calved off icebergs when they got too long. Now, the calving happens while the glacier is advancing. What this means is unclear, but it does suggest that the glaciers are behaving in a fundamentally different manner than just a few years earlier. "This is what we cannot predict," says Steffen.

But the unpredictable is not necessarily unprecedented. During the 1920s, Greenland experienced a rapid warm-up; average annual temperatures rose more than 2 °C over the decade. At Ohio State, meteorologist Jason Box and student Adam Herrington have been looking for records of what happened to the Big Three outlet glaciers back then, to see whether there are lessons about what to expect in the future. Among their finds





SOURCE: S. LUTHCKE

was a series of maps showing the snout of the Kangerdlugssuaq glacier. Over just a few years in the early 1930s, the glacier retreated some 10 kilometres upstream — having lost an area up to 70 square kilometres in what may have been a single large calving event. The break-up, says Box, was "exceptional" in that the ice would have taken years to grow back to its previous state. And it suggests that the sort of rapid response to warming seen in recent years is the glaciers' expected response to warming.

One emerging area of research is the effect that ocean temperatures — as opposed to air temperatures — have on the outlet glaciers. Howat says, for instance, that warm ocean temperatures in the summer of 2003 coincided with a time when several of the outlet glaciers feeding into that warmer sea began speeding up dramatically. But little work has been done to correlate ocean temperatures with the glacier retreats. The ocean has been "a total blank spot on the map," Howat says. "You have a big ice sheet with a lot of it sitting in the water — you'd think you'd want to know what's happening in the water." Some researchers are starting to target this as their next area of interest.

Lakes on ice

The water that surrounds Greenland has been there forever. More novel is the increasing amount of water which, in summer, sits on top of it. What starts out in the winter as cold white snow ends up in the summer as a landscape of blue water, as more than 1,000 shallow melt lakes up to 5 kilometres across form on the ice. It is like Minnesota — but white.

2007 was a particularly good year to study this surface melting, because there was a great deal of it. High-pressure weather systems

A GPS station, part of a network for measuring crustal movement.

M. BEVIS

throughout much of the summer kept storms away, allowed the Sun to beat down on the ice almost without cease. The melt season lasted 25–30 days longer than average, and 19,000 square kilometres turned from ice to water, says Marco Tedesco of Goddard — that is roughly the area of Wales. The effect was particularly noticeable at higher elevations; as warm air swept ever higher, the area that melted at 2,000 metres or greater was 150% larger than normal.

Even in a normal May to August field season, researchers have to make sure that their instruments stay anchored on the ice sheet, planting their poles 2–3 metres deep to make sure they can withstand the melt. It's not just the water that makes things difficult — it's the unpredictability. Melt lakes have been known to drain away tens of millions of cubic metres of water in the space of a day, swirling down some unknown drain channel in the ice. Huge waterfalls appear and then disappear overnight. How exactly the water gets from the top of the ice to its bowels isn't known, but understanding the plumbing could help illuminate a crucial question — does the water that reaches the bottom of the ice sheet lubricate it in a way that encourages movement and collapse[7]? This has become a commonplace speculation among Greenland catastrophists, but the degree to which it is actually happening, how well it explains the ice loss measured by GRACE and to what extent it may change the shorelines of the world is not yet clear.

Back to the Eemian

The suddenly apparent pace of change has led some to question previous, rather staid models of ice-sheet dynamics, which suggest that even fast changes take several centuries. "It has only been in the past five years that we have realized that hey, the ice sheet is falling apart, these changes are happening, our models are way off," says Howat. But predicting how far off they actually are — and some believe they may not be as soon as catastrophists predict — is not easy. Anecdotes of this or that particular, however momentous, are no match for thorough, consistent monitoring. If you want models of the future you can rely on, you have to monitor the process you model. "The modelling has not happened because there are just not enough data," says Philippe Huybrechts, an ice-sheet modeller at the Free University in Brussels. Researchers on the ice might see moulins forming, or outlet glaciers calving, but "it is just in one place and for one season, or for a few weeks", he says. "To generalize from that over a whole ice sheet in a way that you can predict things, it's just not possible."

> "You have a big ice sheet with a lot of it sitting in the water — you'd think you'd want to know what's happening in the water." — Jason Box

At the moment, the best Greenland modellers are stretched by trying to explain what has already happened, without even thinking about what is to come. They are responsive, not predictive. But some are trying to change that. At the University of Kansas, Cornelis Van der Veen is helping to lead an effort to improve ice-sheet models; he and others are planning a major conference to be held in July in St Petersburg, Russia. The idea is to identify the big unknowns and figure out how to tackle them, one by one. "One outlet glacier speeding up isn't really the end of the world," he notes. "But if they are doing that all over the place then that is an indication that something is going on that we really do not understand. It is not something that can be solved within a couple of months."

"It's very difficult to model a new process, such as why glaciers accelerate, before you have an understanding of why it is happening," says Dorthe Dahl-Jensen of the University of Copenhagen. "One thing is to observe it. The next step is to understand it. The third is to put it into the model and predict the future. We are at step two, struggling to understand the process."

One route to understanding may be through palaeoclimate studies. Dahl-Jensen is leading a team that aims to drill a core 2,500 metres into the ice of northwestern Greenland over the next couple of summers. This core — the North Greenland Eemian Ice Drilling — would complement the pioneering climate records cored out of Greenland's ice over the past couple of decades. None of the earlier cores was able to extract an unbroken record of the Eemian stage, some 120,000 years ago and the last time that Earth was in a warm 'interglacial' period. Understanding what Greenland was like then could help scientists understand how the ice sheet might respond in a warmed future, says Dahl-Jensen. Temperatures in Greenland were roughly 5 °C higher during the Eemian than they are today. Yet sea level was only one or two metres higher, and every ice core that has ever been drilled deep enough on the island has included some ice from the Eemian. "A major part of the Greenland ice sheet survived," says Dahl-Jensen — and argues that more sampling of this period might help to pinpoint the factors that could allow ice to stick around when temperatures are higher than today.

But this is not necessarily the encouraging

J. BALOG/AURORA PHOTOS

The calving rate of some Greenland glaciers has increased.

news it might seem. Because global warming is amplified near the poles, 5 °C of warming in Greenland might be achieved with just 2.5 °C of average global warming — which is quite plausible. And an important regional factor here might be the dramatic recent reductions seen in the sea ice to the island's north. The extent to which the cold, reflective ice on the sea keeps Greenland cool is simply not known.

The long view needed

More sampling of the past, together with that of the present, may help us to unravel the future of the Greenland ice sheet. For now, though, things seem to be getting more ravelled, not less. Every year brings a new set of data, a new insight into the behaviour of Greenland's interlocking ice-sheet dynamics, stream flows and glacial surges. "We are just learning so much," says Leigh Stearns, a glaciologist at the University of Maine at Orono. "Every summer brings something totally different."

But if the learning is copious, it is not systematic. Despite the real risk of a meltdown — and the real benefits to be gained from being able to say something reliable about how long there is to go, and how high the seas might rise — the investigation of the ice's every nook and cranny is far from over. One idea is to use unmanned aerial vehicles (UAVs) to fly across the ice sheet gathering data such as the depths of melt lakes. But this is easier said than done; John Adler, a PhD student at the University of Colorado at Boulder, ran some tests last August in which he took three types of commercially available UAVs to Kangerlussuaq airport and ran flights over the melt lakes for a week. He is still getting the kinks out of the system, but says that UAVs could provide a cheaper and more repeatable way to get local measurements than relying on expensive helicopter flights, as is done today. Even so, the UAVs are labour-intensive and cannot be operated all year round.

> "Every summer brings something totally different."
> — Leigh Stearns

Over the long term, satellites should provide the most coherent record of change. The Terra and Aqua satellites, along with Europe's Envisat and other surface-monitoring satellites, are workhorses that regularly photograph the advance and retreat of outlet glaciers. Despite its glitches, the ICESat altimeter sends back elevation changes that track the thinning of the ice sheet; a successor, ICESat-II, is already in the works. And the European Space Agency is working to launch a successor to the ice-thickness-measuring CryoSat, the first incarnation of which failed after launch in 2005.

Yet major problems remain in acquiring and using Earth-observation data (see *Nature* **450,** 782–785; 2007). Access to data from Canada's Radarsat-1 and Radarsat-2 for instance, is ensnarled in a potential takeover by a US company, a sale that was blocked last week by the Canadian government.

Even with the right satellites, not everything can be done from space. Yet very few researchers have Greenland as the main focus of their scientific work. Decades from now, this could turn out to be one of the most short-sighted allocations of resources that began the twenty-first century. Climate change elsewhere in the Arctic has been swifter than anticipated. The remarkable shrinkage of the sea is "the largest change in Earth's surface that humans have probably ever observed," Howat points out. Trying to get any and every handle on how that affects the poised mass of ice next door must surely be a priority, he says. "This should be a critical thing to study." ■

I. JOUGHIN

Melt water draining into moulins could accelerate the movement of the ice sheet.

Alexandra Witze is *Nature*'s chief of correspondents for America.

1. Gregory, J. M., Huybrechts, P. & Raper, S. C. B. *Nature* **428,** 616 (2004).
2. Velicogna, I. & Wahr, J. *Nature* **443,** 329–331 (2006).
3. Luthcke, S. B. *et al. Science* **314,** 1286–1289 (2006).
4. Rignot, E. & Kanagaratnam, P. *Science* **311,** 986–990 (2006).
5. Joughin, I., Abdalati, W. & Fahnestock, M. *Nature* **432,** 608–610 (2004).
6. Joughin, I. *et al. J. Geophys. Res.* **113,** F01004 (2008).
7. Zwally, J. *et al. Science* **297,** 218–222 (2002).

See Editorial, page 781. For a video of a camera being dropped down a moulin on the Greenland ice sheet, see http://tinyurl.com/5dua42.

nature Vol 452|17 April 2008|doi:10.1038/nature06825

LETTERS

Changing boreal methane sources and constant biomass burning during the last termination

Hubertus Fischer[1], Melanie Behrens[1], Michael Bock[1], Ulrike Richter[1], Jochen Schmitt[1], Laetitia Loulergue[2], Jerome Chappellaz[2], Renato Spahni[3], Thomas Blunier[3]†, Markus Leuenberger[3] & Thomas F. Stocker[3]

Past atmospheric methane concentrations show strong fluctuations in parallel to rapid glacial climate changes in the Northern Hemisphere[1,2] superimposed on a glacial–interglacial doubling of methane concentrations[3–5]. The processes driving the observed fluctuations remain uncertain but can be constrained using methane isotopic information from ice cores[6,7]. Here we present an ice core record of carbon isotopic ratios in methane over the entire last glacial–interglacial transition. Our data show that the carbon in atmospheric methane was isotopically much heavier in cold climate periods. With the help of a box model constrained by the present data and previously published results[6,8], we are able to estimate the magnitude of past individual methane emission sources and the atmospheric lifetime of methane. We find that methane emissions due to biomass burning were about 45 Tg methane per year, and that these remained roughly constant throughout the glacial termination. The atmospheric lifetime of methane is reduced during cold climate periods. We also show that boreal wetlands are an important source of methane during warm events, but their methane emissions are essentially shut down during cold climate conditions.

The atmospheric concentration of CH_4, the second most important anthropogenic greenhouse gas, is determined by a balance between natural and anthropogenic CH_4 sources and sinks that is still debated. Photochemically induced oxidation in the troposphere and stratosphere, and uptake by methanotrophic bacteria in aerated soils, represent the most important sinks[9,10]. The dominating natural CH_4 sources comprise tropical and boreal wetlands, ruminants, and biomass burning[10,11]. These sources all differ in their carbon and hydrogen isotopic signature. In addition, a release of CH_4 from marine gas hydrates[12,13] and emissions from plants under aerobic conditions are currently debated[14,15]. Most probably all those sources and sinks were subject to palaeoclimatic changes, as reflected by CH_4 being as low as 360 parts per billion (10^9) by volume (p.p.b.v.) during the Last Glacial Maximum (LGM), compared with up to 725 p.p.b.v. in the preindustrial Holocene epoch[3,16,17]. Throughout the glacial period and during the last transition, CH_4 changed by up to 200 p.p.b.v. (refs 3, 18) in parallel with rapid climate changes. Using the interhemispheric CH_4 gradient in ice cores, an increase of high-latitude CH_4 sources in the Northern Hemisphere was derived for warm periods[3,17]. However, a more detailed quantitative source attribution is still missing.

Such quantitative constraint on the sources can be derived from methane isotopic measurements on ice cores[6,7], making use of the different isotopic signatures of the CH_4 sources and the different isotopic fractionation factors for the individual removal processes (Supplementary Table 1). In Fig. 1 typical isotopic signatures for different CH_4 sources are summarized, spanning a wide range of $\delta^{13}CH_4$ and $\delta D(CH_4)$. This shows that $\delta^{13}CH_4$ strongly constrains the amount of CH_4 released by biomass burning, because pyrogenic CH_4 is the only natural source strongly enriched in ^{13}C. The fractionation caused by the sinks is illustrated by the offset of the isotopic signature in atmospheric CH_4 and the calculated emission averages. This fractionation is very pronounced (~200‰) for $\delta D(CH_4)$ but rather small (5–7‰) for $\delta^{13}CH_4$.

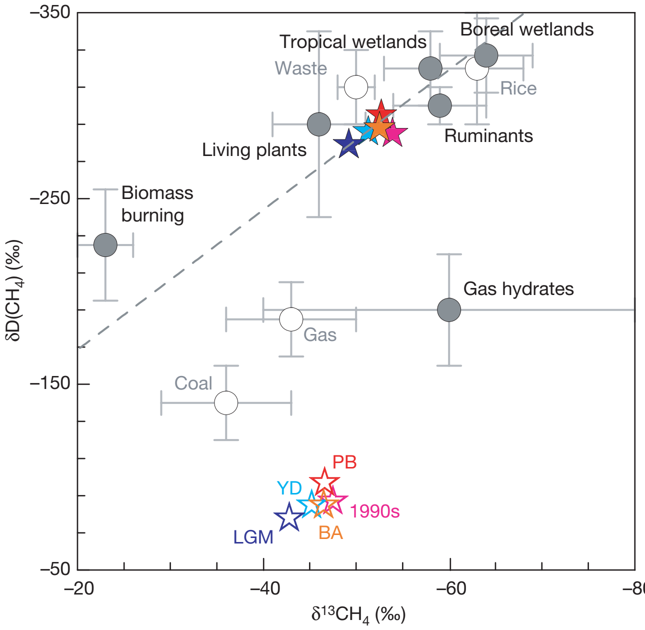


Figure 1 | Typical carbon and hydrogen isotopic signatures of different CH_4 sources used in the Monte Carlo model. Data are from refs 10 and 11 and references therein. Mainly anthropogenic sources are indicated by open circles, mainly natural sources by dark grey dots. The error bars indicate the spread of reported values[10]. No δD values for plant emissions are available so far. We used a value of −290‰, which does not influence our model outcome. Open stars indicate the modelled average atmospheric $\delta^{13}CH_4$ and $\delta D(CH_4)$ for the 1990s, preboreal Holocene (PB), Younger Dryas (YD), Bølling/Allerød (BA) and LGM. Filled stars represent best-guess model estimates for average $\delta^{13}CH_4$ and $\delta D(CH_4)$ emitted, where we limited atmospheric lifetimes to values larger than 5 yr. The dashed line represents a linear fit through these isotopic emission averages. $\delta D = [(D/H)_{sample}/(D/H)_{standard}] - 1$ in ‰, where standard is standard mean ocean water (SMOW); $\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard}] - 1$ in ‰, where standard is VPDB

[1]Alfred Wegener Institute for Polar and Marine Research, Columbusstrasse, 27568 Bremerhaven, Germany. [2]Laboratoire de Glaciologie et Geophysique de l'Environnement, CNRS-UJF, 54 rue Molière, 38400 Grenoble, France. [3]Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland. †Present address: Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen OE, Denmark.

Using high-precision gas chromatography isotope ratio mass spectrometry (see Supplementary Information) we have been able to derive a high-resolution $\delta^{13}CH_4$ ice-core record over the last glacial–interglacial transition. We carried out carbon isotopic analyses on 34 samples from the EPICA (European Project for Ice Coring in Antarctica) ice core from Dronning Maud Land (EDML)[8]. With its present accumulation rate of 6.4 cm water equivalent per year and an age distribution (width at half maximum) in the air bubbles of 60 yr, this core is especially suited to derive higher-resolution records over the last glacial cycle.

In Fig. 2 our $\delta^{13}CH_4$ record is plotted together with the CH_4 concentrations from the EDML and the Greenland GRIP ice core[3,8]. Clearly, the most conspicuous features of our $\delta^{13}CH_4$ data are the high isotopic values of around −42.8‰ during the LGM followed by a 3.5‰ decrease to about −46.3‰ during the preboreal Holocene. The preboreal value is about 0.8‰ more enriched than values from the Law Dome ice core (Antarctica)[19] for the time interval 1–2 kyr before present (BP) when CH_4 was about 40 p.p.b.v. lower[17]. At the same time the interhemispheric CH_4 gradient[17] and, thus, the boreal methane source strength was comparable. This implies a relatively higher contribution of isotopically light boreal CH_4 emissions to the total CH_4 budget in the late preindustrial Holocene compared with the preboreal Holocene. Alternatively, the lower $\delta^{13}CH_4$ values could be affected by increased rice cultivation and/or livestock in the late Holocene. Whether a significant anthropogenic influence on CH_4 had already started by 5000 yr BP as recently hypothesized[20] cannot be answered at this point.

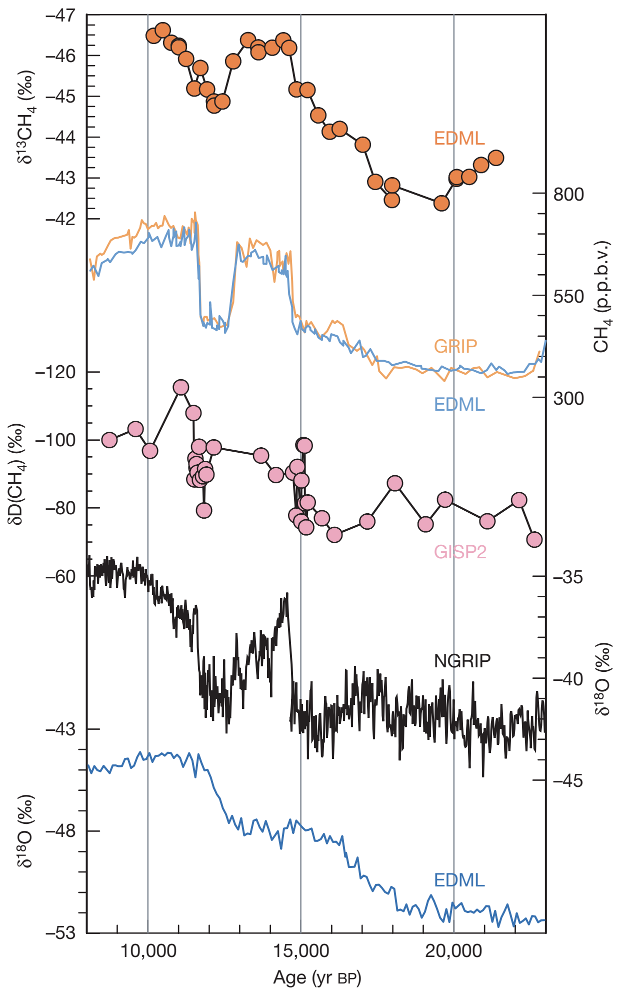


Figure 2 | Glacial/interglacial changes in methane and climate. Carbon isotopic signature of methane (scale reversed) in the EDML ice core together with Greenland (GRIP) and EDML methane concentrations[3,8], δD(CH_4) in the GISP2 ice core[6] (scale reversed) and the temperature proxy $\delta^{18}O$ from EDML[8] and NGRIP[1]. All data sets are given on the GICC05 age scale after CH_4 synchronization[8], except for GISP2 δD(CH_4) data given on their individual methane synchronized age scale[6]. Values of $\delta^{13}CH_4$ were corrected for gravitational enrichment in the firn column (see Supplementary Information) and are referenced against VPDB.

Our $\delta^{13}CH_4$ record shows also significant variations in parallel with the rapid CH_4 changes during the Bølling/Allerød–Younger Dryas oscillation, with $\delta^{13}CH_4$ values during the Bølling/Allerød similar to the preboreal Holocene (about −46.3‰) but with slightly lower CH_4 concentrations. During the Younger Dryas, $\delta^{13}CH_4$ increased to around −45‰. Our data do not support $\delta^{13}CH_4$ values during the Younger Dryas/preboreal transition measured on outcropping ice on the west Greenland margin[7], which generally show isotopically lighter $\delta^{13}CH_4$ values before than after the end of the Younger Dryas. In view of the much higher scatter of those data and the potential of isotopic artefacts occurring in this warm outcropping ice, we think that our high-precision ice-core data reflect more closely the isotopic changes in atmospheric methane.

In principle, changes in the source as well as in the fractionation of the sinks may contribute to the observed changes. The latter effect is small because a global glacial–interglacial temperature increase of 5 °C would decrease the carbon isotope fractionation by only 0.2–0.3‰[21–23] and also changes in lifetime have a negligible effect on $\delta^{13}CH_4$. Accordingly, the $\delta^{13}CH_4$ values indicate mainly a shift to isotopically heavier sources during cold climate periods. Thus, either an isotopically enriched CH_4 source (such as biomass burning) increased, or a depleted source (such as wetlands) decreased. Considering the 50% reduction of atmospheric CH_4 concentrations and the lack of an interhemispheric gradient in the LGM, a reduction of boreal wetland emissions is more likely. To constrain the emission by individual sources, we used a simple model of the CH_4 cycle with two tropospheric and two stratospheric boxes driven by prescribed emission fluxes for time intervals of relatively constant CH_4: the preboreal Holocene, Younger Dryas, Bølling/Allerød and LGM (see Supplementary Information). The model has been validated for recent conditions and reflects CH_4 observations very well. For the last deglaciation our $\delta^{13}CH_4$ data from EDML, together with δD(CH_4) data from Greenland[6] and CH_4 concentrations from both polar regions[3,8,16], provide four constraints for the model. However, with six natural sources and three sink processes, the solution of the model is still underdetermined. To find possible solutions we used a Monte Carlo approach (see Supplementary Information). For many of the sources, the resulting probability distributions are not discriminating, owing to a considerable overlap in the isotopic signatures. However, robust quantitative constraints can be derived for the atmospheric lifetime, biomass burning and boreal wetland emissions.

In our initial estimate, which is constrained only by ice-core observations (see Supplementary Information), the atmospheric lifetime decreased from the recent value of a little more than 8 yr to around 5.6 yr in the preboreal Holocene and Bølling/Allerød, in good agreement with estimates of preindustrial runs using a three-dimensional model of chemistry and transport[24]. In the Younger Dryas our most likely result indicates a strong lifetime decrease to 4.4 yr and to 3.7 yr in the LGM (Fig. 3a). Although a lifetime decrease is expected from the much lower atmospheric CH_4 concentration and reduced emissions of volatile organic carbon species during the LGM[25,26], this decrease of more than 50% relative to present is much stronger than predicted by current estimates from a three-dimensional chemistry model[26]. However, as also shown in Fig. 3, lifetimes similar to those model estimates also fulfil our data constraints, but are less likely. Such longer lifetimes require a reduction in tropical wetland emissions to explain the lower CH_4 concentrations during the LGM. In summary, data as well as models indicate a shorter CH_4 lifetime during past climate periods in the range of 3–7 yr.

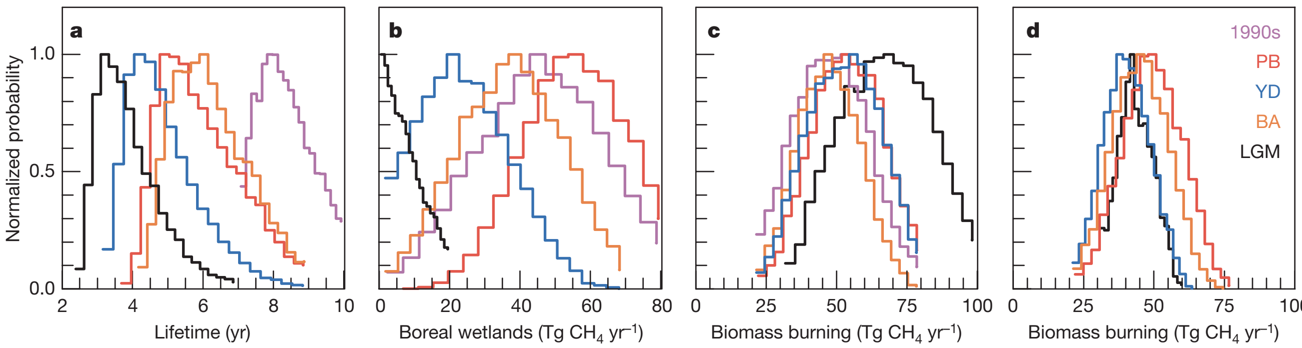


Figure 3 | Methane box model results. Normalized probability functions (NPF) for (**a**) atmospheric lifetime, (**b**) boreal wetland and (**c**) biomass burning emissions for the 1990s (pink), preboreal Holocene (PB, red), Younger Dryas (YD, blue), Bølling/Allerød (BA, orange) and the LGM (black) as derived in our data-constrained Monte Carlo box model. **d**, The biomass burning NPF when we additionally constrain atmospheric lifetimes to be longer than 5 yr. This had no significant effect on the NPF for boreal wetlands. The width of the distribution is a measure of how stringent the estimate is. Note, however, that all model runs in the NPF fulfilled the constraints within the error limits.

The higher atmospheric δCH_4 together with the lack of an interhemispheric CH_4 gradient requires the boreal wetland source in our model to be essentially shut down during the LGM, in line with the extreme cold and vastly expanded continental ice sheets in the high-latitude Northern Hemisphere. Part of the carbon isotope variation observed over the transition may also stem from a shift in the wetland substrate from C4 to C3 plants, following different photosynthetic pathways. However, such a shift cannot explain the size of the observed $\delta^{13}CH_4$ change or the changes in the interhemispheric gradient. A reduction of boreal wetlands connected to a reduced interhemispheric CH_4 gradient and more enriched $\delta^{13}CH_4$ is also supported for the Younger Dryas. In contrast, the $\delta^{13}CH_4$ values derived from outcropping ice on the west Greenland margin[7] show isotopically lighter $\delta^{13}CH_4$ values during the Younger Dryas, which are difficult to reconcile with the interhemispheric gradient indicating a decrease in boreal CH_4 emissions.

Furthermore, quantitative constraints are derived from our $\delta^{13}CH_4$ data for pyrogenic CH_4 emissions. In our initial estimate (allowing for short atmospheric lifetimes) our model suggests somewhat higher biomass burning emissions during the LGM, where significant changes in vegetation cover and aridity occurred[27,28]. When we additionally constrain atmospheric lifetimes in Fig. 3d to longer than 5 yr in line with chemistry models, our best-guess estimate for biomass burning emissions remains close to about 45 Tg CH_4 yr^{-1} throughout the transition, with slightly lower biomass burning during cold periods. Evidence for temporally constant biomass burning emissions is also provided by global vegetation modelling[29], but the modelled biomass burning CH_4 emission is 50% lower than our Monte Carlo estimate.

Secondary trends in $\delta^{13}CH_4$ occurred during the LGM and preboreal Holocene. For instance $\delta^{13}CH_4$ decreased slowly during the preboreal Holocene, when temperatures in Greenland and the CH_4 concentration gradient slightly increased. This may be attributed to expanding boreal sources, for example related to increased thermokarst emissions at that time[30]. During the late glacial (22,000–20,000 yr BP), $\delta^{13}CH_4$ slowly increased by about 1‰ while CH_4 remained constant. A change in the carbon isotopic signature of the biomass fuelling wildfires by 3‰, caused by of a shift from C3- to C4-dominated grasslands, could largely explain this secondary trend in $\delta^{13}CH_4$ despite constant biomass burning emissions. Alternatively, it may represent a slow reduction of wetland emissions compensating a synchronous increase in biomass burning emission.

The result of our steady-state modelling is indicated by the average signatures of CH_4 emissions for past conditions in Fig. 1. These best-guess average emissions lie on a line roughly through the wetland isotopic signature, illustrating the changing influence of boreal wetland emissions on the isotopic CH_4 budget. This clearly shows that a CH_4 contribution from deuterium-enriched marine gas hydrates is not supported by the observed isotope changes. However, quantification of a short CH_4 outburst from marine hydrates will require more high-resolution isotope data around rapid climate warmings together with time-resolved isotope modelling of the atmospheric CH_4 cycle and diffusion effects in the firn column. In summary, our new carbon isotopic constraint is able to determine the change in average CH_4 emissions from boreal wetlands and biomass burning very well, showing that the latter source was surprisingly stable over a wide range of climate conditions. This provides an important test for vegetation models and together with revised atmospheric chemistry models will improve our understanding of the oxidative capacity of the atmosphere in the past.

METHODS

We performed $\delta^{13}CH_4$ measurements on 150–200 g of ice using a purge and trap extraction coupled to a gas chromatography isotope ratio mass spectrometer. We separated CH_4 from other gases using gas chromatography and quantified isotopic ratios on CO_2 after quantitative combustion of CH_4. Absolute standardization is achieved in every run using (i) a pure CO_2 standard (ii) a pure CH_4 standard admitted to the gas chromatography helium stream and (iii) 10 ml (STP) of a synthetic air standard admitted into the extraction vessel. All $\delta^{13}CH_4$ values are referenced against Vienna PeeDee belemnite (VPDB) and corrected for gravitational enrichment. Replicate samples from the EDML ice core have been measured on five depth intervals showing a mean standard deviation of ±0.09‰ with somewhat larger uncertainties for glacial samples with low CH_4 concentration. This is also in line with the reproducibility of the air standards. In summary, we estimate the reproducibility of our measurements to be better than 0.15‰.

Potential source emissions were determined in steady state using a box model of the atmospheric CH_4 cycle. The atmosphere is divided into northern and southern tropospheric and stratospheric boxes with prescribed air mass exchange. Methane emissions into the northern and southern troposphere are prescribed with fixed isotopic signatures (refs 10, 11 and references therein; Supplementary Table 1). The model takes into account oxidation in the troposphere and stratosphere and uptake by aerated soils[10]. To constrain CH_4 emissions in the past the model was run in a Monte Carlo mode, where emissions of each individual source and the lifetime were randomly picked within reasonable limits and compared with the data constraints.

For more details on the analyses and model used, see Supplementary Information.

Received 18 June 2007; accepted 5 February 2008.

1. North Greenland Ice Core Project members. High resolution climate record of the northern hemisphere reaching into the last interglacial period. *Nature* **431,** 147–151 (2004).
2. Johnsen, S. J. *et al.* Irregular glacial interstadials recorded in a new Greenland ice core. *Nature* **359,** 311–313 (1992).
3. Dällenbach, A. *et al.* Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the last glacial and the transition to the Holocene. *Geophys. Res. Lett.* **27,** 1005–1008 (2000).
4. Spahni, R. *et al.* Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* **310,** 1317–1321 (2005).

5. Petit, J. R. *et al.* Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399,** 429–436 (1999).
6. Sowers, T. Late Quaternary atmospheric CH_4 isotope record suggests marine clathrates are stable. *Science* **311,** 838–840 (2006).
7. Schaefer, H. *et al.* Ice record of $\delta^{13}C$ for atmospheric CH_4 across the Younger Dryas–Preboreal transition. *Science* **313,** 1109–1112 (2006).
8. EPICA community members One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature* **444,** 195–198 (2006).
9. Khalil, M. A. K., Shearer, M. J. & Rasmussen, R. A. in *Atmospheric Methane: Sources, Sinks, and Role in Global Change* (ed. Khalil, M. A. K.) 168–179 (Springer, Berlin, 1993).
10. Quay, P., Stutsman, J., Wilbur, D., Dlugokencky, E. & Brown, T. The isotopic composition of atmospheric methane. *Glob. Biogeochem. Cycles* **13,** 445–461 (1999).
11. Whiticar, M. J. in *Atmospheric Methane: Sources, Sinks, and Role in Global Change* (ed. Khalil, M. A. K.) 138–167 (Springer, Berlin, 1993).
12. Kennett, J. P., Cannariato, K. G., Hendy, I. L. & Behl, R. J. Carbon isotopic evidence for methane hydrate instability during Quaternary interstadials. *Science* **288,** 128–133 (2000).
13. Brook, E. J., Harder, S., Severinghaus, J., Steig, E. J. & Sucher, C. M. On the origin and timing of rapid changes in atmospheric methane during the last glacial period. *Glob. Biogeochem. Cycles* **14,** 559–572 (2000).
14. Keppler, F., Hamilton, J. T. G., Braß, M. & Röckmann, T. Methane emissions from terrestrial plants under aerobic conditions. *Nature* **439,** 187–191 (2006).
15. Dueck, T. A. *et al.* No evidence for substantial aerobic methane emission by terrestrial plants: a ^{14}C-labelling approach. *New Phytol.*. doi:10.111/ j.1469–8137.2007.02103.x (2007).
16. Chappellaz, J. *et al.* Synchronous changes in atmospheric CH_4 and Greenland climate between 40 and 8 kyr BP. *Nature* **366,** 443–445 (1993).
17. Chappellaz, J. *et al.* Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the Holocene. *J. Geophys. Res.* **102,** 15987–15997 (1997).
18. Flückiger, J. *et al.* N_2O and CH_4 variations during the last glacial epoch: Insight into global processes. *Glob. Biogeochem. Cycles* **18,** doi:10.1029/2003GB002122 (2004).
19. Ferretti, D. F. *et al.* Unexpected changes to the global methane budget over the past 2000 years. *Science* **309,** 1714–1717 (2005).
20. Ruddiman, W. F. The anthropogenic greenhouse era began thousands of years ago. *Clim. Change* **61,** 261–293 (2003).
21. Cantrell, C. A. *et al.* Carbon kinetic isotope effect in the oxidation of methane by the hydroxyl radical. *J. Geophys. Res.* **95,** 22455–22462 (1990).
22. Tyler, S. C., Crill, P. M. & Brailsford, G. W. $^{13}C/^{12}C$ fractionation of methane during oxidation in a temperate forested soil. *Geochim. Cosmochim. Acta* **58,** 1625–1633 (1994).
23. Saueressig, G., Bergamaschi, P., Crowley, J. N., Fischer, H. & Harris, G. W. Carbon kinetic isotope effect in the reaction of CH_4 with Cl atoms. *Geophys. Res. Lett.* **22,** 1225–1228 (1995).
24. Lelieveld, J., Crutzen, P. & Dentener, F. J. Changing concentration, lifetime and climate forcing of atmospheric methane. *Tellus* **50B,** 128–150 (1998).
25. Kaplan, J. O., Folberth, G. & Hauglustaine, D. A. Role of methane and biogenic volatile organic compound sources in late glacial and Holocene fluctuations of atmospheric methane concentrations. *Glob. Biogeochem. Cycles* **20,** doi:10.1029/ 2005GB002590 (2006).
26. Valdes, P. J., Beerling, D. J. & Johnson, C. E. The ice age methane budget. *Geophys. Res. Lett.* **32,** doi:10.1029/2004GL021004 (2005).
27. Mahowald, N. *et al.* Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments. *J. Geophys. Res.* **104,** 15895–15916 (1999).
28. Kaplan, J. O. Wetlands at the Last Glacial Maximum: Distribution and methane emissions. *Geophys. Res. Lett.* **29,** doi:10.1029/2001GL013366 (2002).
29. Thonicke, K., Prentice, I. C. & Hewitt, C. Modeling glacial-interglacial changes in global forest fire regimes and trace gas emissions. *Glob. Biogeochem. Cycles* **19,** doi:10.1029/2004GB002278 (2005).
30. Walter, K. M., Edwards, M. E., Griosse, G., Zimov, S. A. & Chapin, F. S. III. Thermokarst lakes as a source of atmospheric CH_4 during the last deglaciation. *Science* **318,** 633–636 (2007).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements This work is a contribution to EPICA, a joint European Science Foundation/European Commission scientific programme, funded by the EU and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom. The main logistical support was provided by IPEV and PNRA (at Dome C) and AWI (at Dronning Maud Land). This is EPICA publication no. 190. We thank I. Levin for providing reference air samples and for comments on the manuscript. We thank the logistics team (led by C. Drücker), the drilling team (led by F. Wilhelms) and all helpers in the field at EDML for making the science possible. Financial support for this study has been provided in part by the German Secretary of Education and Research program GEOTECHNOLOGIEN and Deutsche Forschungsgemeinschaft.

Author Information Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to H.F. (hubertus.fischer@awi.de).