The tipping point of the iceberg

Could climate change run away with itself? **Gabrielle Walker** looks at the balance of evidence.

"Be worried," *Time* magazine advised those looking at its 3 April cover showing a forlorn polar bear surrounded by puddles of melted ice. "Be very worried." Immediately below came the occasion for such alarming counsel: "Earth at the tipping point."

The idea that passing some hidden threshold will drastically worsen man-made climate change has been around for decades, normally couched in technical terms such as 'nonlinearity', 'positive feedback' and 'hysteresis'. Now it has gained new prominence under a new name. In 2004, 45 newspaper articles mentioned a 'tipping point' in connection with climate change; in the first five months of this year, 234 such articles were published. "Warming hits tipping point," one UK newspaper recently warned on its front page; "Climate nears point of no return," asserted another. The idea is spreading like a contagion.

The infectious analogy is appropriate. When the writer Malcolm Gladwell unleashed the idea of tipping points on the popular imagination in his book of the same name[1], he was comparing the way aspects of life suddenly shift from obscurity to ubiquity to effects normally studied in epidemiology. Gladwell's tipping points were manifestations of the catchiness of behaviours and ideas. The notion that climate change is getting out of control is catchy, and it has caught on in academic papers and political debates as well as headlines. But is the climate really on the point of tipping over into a radically different state? And if so, what are the implications?

A tipping point usually means the moment at which internal dynamics start to propel a change previously driven by external forces. The idea raises two questions. First, when will that moment be reached? Second, after it has been passed, is the system now destined to run its course regardless of what goes on elsewhere — is a tipping point a point of no return?

Although there's no strong evidence that the climate as a whole has a point beyond which it switches neatly into a new pattern, individual parts of the system could be in danger of changing state quickly, and perhaps irretrievably. And perhaps the most striking of these vulnerable components are in the Arctic. Farthest north is the carapace of sea ice over the Arctic Ocean. South of that is the vast ice sheet that covers Greenland. And then there is the ocean conveyor belt, which originates in a small region of the Nordic seas and carries heat and salt around the world.

On thin ice

All three seem to have inbuilt danger zones that may deserve to be called tipping points. And the outside forces pushing them towards those points are gathering. "There is near-universal agreement that we are now seeing a greenhouse effect in the Arctic," says Mark Serreze from the US National Snow and Ice Data Center in Boulder, Colorado.

Serreze studies sea ice, the member of the arctic triumvirate that has had most recent attention. In the winter, sea ice more or less covers the Arctic Ocean basin. Summer sun nibbles at the pack ice, shrinking it at the edges and creating patches of open water within. Open water reflects much less sunlight than ice — it has what is known as a lower albedo — so the greater the area of dark open water, the more summer warmth the ocean stores. More stored heat means thinner ice in the next winter, which is more vulnerable to melting the next summer — meaning yet more warmth being stored in the open water in the following year, a cycle known as the 'ice–albedo feedback'. "Once you start melting and receding, you can't go back," says Serreze.

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It seems that some of this process is under way. Serreze and his colleagues have found that the summer sea ice has shrunk by an average of 8% a decade over the past thirty years[2]. The past four years have seen record lows

Pointing tip: an iceberg off the coast of Greenland, shed from the edge of the island's icepack.

in the extent of September sea ice, and in 2005 there was 20% less ice cover than the 1979–2000 average, a loss of about 1.3 million square kilometres, which is more than the area of France, Germany and the United Kingdom combined. It was this finding that triggered a raft of alarming headlines.

The ice's volume, rather than its extent, would be a more useful figure, but this is hard to estimate. Radar measurements showing how proud the ice sits with respect to nearby water would help, but the European Cryosat mission intended to provide these data was lost on launch in October 2005. A reflight is planned, but at present the only way to determine the pack thickness is from below. In 2003 Andrew Rothrock and Jinlun Zhang of the University of Washington in Seattle analysed results from a series of submarine cruises from 1987–97 and concluded that the ice thinned by about one metre during that period[3].

Flaming January

A natural swing in wind and weather known as the Arctic Oscillation may have played a key role in the decline. In 1989, this index began to approach its positive mode, in which a ring of strong winds circles the pole. Zhang and his colleague Roger Lindsay, also at the University of Washington, believe these winds flushed large amounts of thick ice out of the Arctic through the Fram Strait, east of Greenland. Last year, they published a model suggesting that because the replacement ice was thinner and more vulnerable to the ice–albedo feedback, this extra loss pushed the Arctic over the edge. Their paper's title: "The thinning of Arctic Sea Ice, 1988–2003: Have We Passed a Tipping Point?"[4].

But given that sea ice was disappearing even before the Arctic Oscillation lurched into its positive state, it is unlikely to have been the sole trigger. "The Arctic Oscillation was a strong kick in the pants," says Serreze, "but if we hadn't had it we would still have seen the ice loss."

Whatever the precise mechanisms, the decrease in ice seems to be warming the atmosphere, as heat pours from the open water into the air above it. Springtime temperatures began rising throughout the Arctic basin in the 1990s[5]. This year, the Arctic archipelago of Svalbard experienced a remarkable heatwave. January was warmer than any previously recorded April, and April was more than 12 °C warmer than the long-term average.

Lindsay and Zhang suggest that the ice–albedo effect has indeed passed a tipping point, with the internal dynamics more important than external factors. But neither observations nor models suggest that the effect will now run away without outside help. According to climate modeller Jason Lowe of the UK Met Office in Exeter, the relationship between sea ice and temperature is reassuringly linear. "When you plot sea ice against temperature rise, whether from observations or models, it forms a remarkably straight line," he says. "It's not a runaway effect over the sorts of temperature ranges that we're predicting here." Lowe says that although the planet will almost certainly lose more ice, it does not have to lose it all. But if current trends in greenhouse-gas emissions and global warming continue, a planet that used to have two permanent polar caps will have only one.

Losing the sea ice would be bad news not only for polar bears and other charismatic megafauna, but also for some of the Arctic's smaller inhabitants. Photosynthetic plankton that live in pores and channels within the ice are the foundation of the area's food supply, and are not well adapted to ice-free life. Open-ocean plankton might benefit, but the Arctic is so poor in nutrients that this would probably not be much compensation[6].

Change of winds

Compared with the overall scale of human-induced climate change, the additional warming expected if the ice–albedo feedback goes all the way would not be immense. The 4.5% of the Earth's surface above the Arctic Circle is simply too small to make a radical difference to the planet's energy balance. There are, however, some hints that the loss of sea ice may have more far-reaching effects beyond the simple number of watts absorbed per square metre. Tim Lenton, an Earth-systems scientist at the University of East Anglia in Norwich, UK, points out that our current, relatively stable pattern of winds, which is caused by three circulatory air systems in each hemisphere, depends in part on a white and cold North Pole.

Sinking air in the Arctic is an integral part of an air system called a Hadley cell; there is another Hadley cell over the tropics. Between these two cells are the fierce westerlies and the high-altitude jet streams that drive storms around the middle latitudes. "If any part of the current structure broke down, that would be profound," says Lenton. "If the system starts to switch seasonally between three cells and a less stable structure, you change the position of the jet streams, you change everything." Models of this possibility are scarce, but Jacob Sewall and Lisa Sloan of the University of California, Santa Cruz, have shown that an ice-free Arctic could shift winter storm tracks over North America, drying the American west[7].

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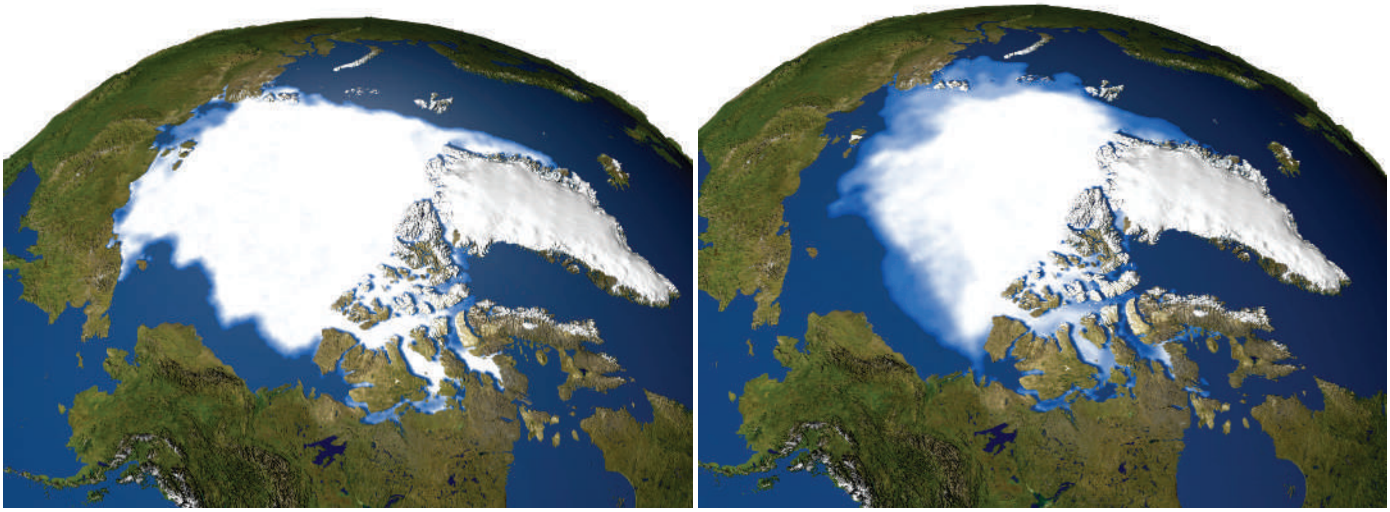
The local warming caused by less sea ice could also affect the second tipping point, the size of the Greenland ice sheet. Here the effects could be dramatic, although delayed by centuries; there is enough ice on Greenland to raise sea levels by seven



Thin on top: between 1979 (left) and 2005, the minimum extent of Arctic sea ice shrank by about 20%.

metres. "After hurricane Katrina, the deepest water in New Orleans was six metres," says glaciologist Richard Alley from Penn State University. "Greenland is more than that for all the coasts of the world. Do you move cities, do you build seven-metre walls and hope they stay, or what?"

Until recently, nobody had painted a convincing portrait of how Greenland is responding to Arctic warming. A glacier here may recede while one over there grows; ice may be accumulating inland and eroding near the coast. But in the past couple of years, almost all of the indicators have started to point in the same direction. Greenland is melting.

Cracking up

Although satellite measurements of Greenland's interior suggest that snow has recently been accumulating there, the margins are receding[8]. Laser measurements taken from planes suggest that this coastal melting is probably enough to outweigh the build-up of snow inland[9]. Also, Greenland's glaciers seem to have been speeding up. A few months ago, Eric Rignot of NASA's Jet Propulsion Laboratory in Pasadena and Pannir Kanagaratnam of the University of Kansas, Lawrence, published satellite evidence that between 1996 and 2000, Greenland's more southerly glaciers had begun to accelerate, and that by 2005 the northerly ones had followed suit[10]. They estimate that over the past decade this lurching has more than doubled Greenland's annual loss of ice, from 90 to 220 cubic kilometres per year.

"In the past decade there has been a lot of warming," says Alley. "There's plenty of room to argue whether that's a natural fluctuation or not, but there's a clear relation between Greenland getting warmer and Greenland getting smaller."

Modelling by Jonathan Gregory from the University of Reading and his colleagues suggests that it would require an average warming worldwide of 3.1 °C to drive this shrinking to its ultimate conclusion of an ice-free Greenland[11]. This climatic point of no return is around the middle of the range foreseen by the Intergovernmental Panel on Climate Change, but is higher than a previous estimate made by the same group[12]. Their revision is a measure of how quickly the field is changing. "It's not just Greenland that is going fast," says Alley. "The rate of publications, the rate of new papers, and the rate of disagreement have multiplied amazingly."

But these models do not take into account the dynamism of Greenland's glaciers. In 2002 Jay Zwally from NASA's Goddard Space Flight Center in Greenbelt, Maryland, found that as soon as summer meltwater appeared on the surface of west-central Greenland, the ice began to slip more quickly[13]. This is surprising, as slip rates should depend on processes at the base of the ice rather than at its surface. But Zwally points out that the great lakes of water produced by the melting could slip down conduits in the ice and be delivered directly to the bed.

This result doesn't necessarily make a big difference to the fate of Greenland, as the increase in the ice's speed was relatively small. But it points to a new way in which the ice sheet could react to climate change quicker than anyone had realized. "In places inland where the ice is frozen to its bedrock, if you warm the surface and wait for heat to get conducted to the bottom it takes 10,000 years," says Alley. "But if you send water down through a crack it takes maybe 10 minutes, maybe 10 seconds." If this process started to move inland, even the interior of Greenland's ice sheet could be vulnerable to warmer air. That could point to the sort of self-sustaining feedback that tipping points are made of.

Getting fresh

The models don't incorporate this mechanism, because they can't. The cliff fronts of many Greenland glaciers are shot through with bright blue conduits, but nobody knows how widespread these veins are inside the ice. Still, the responsiveness of Greenland's glaciers makes that point-of-no-return figure of 3.1 °C even less comforting. What's more, a lot of damage can be done without losing all of the ice. The ice sheet did not vanish during the last interglacial, around 130,000 years ago, when temperatures in the north were a few degrees higher than they are today. And yet the latest analyses suggest that meltwater from Greenland increased the sea level by between two and three metres. The only good thing about such an increase is that it would take centuries.

As with the melting of Arctic sea ice, the melting of the Greenland ice sheet has implications for its neighbours. The third tipping point is the origin of the great oceanic conveyor belt, or thermohaline circulation. Thanks to its cold temperatures and high salinity, water in the Nordic seas between Greenland and Scandinavia is unusually dense and sinks. Surface water is drawn northwards to replenish this. One result of this flow is that Britain is warmer than its latitude would seem to deserve.

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The sinking process sets a global mass of water in motion, transporting vast amounts of heat around the oceans. In the 1980s, models began to suggest that melting ice in the north could weaken this system, by putting a plug of fresh water over the sinkhole. This led to fears of abrupt climate change and snap ice ages in Europe and eastern America. These days most scientists think that the power of this flow to affect European temperatures under current conditions, or in a globally warmed future, has been overestimated[14]. But changes in the system could still have far-reaching implications. And models suggest that the thermohaline circulation has its own tipping point.

Comparing the output from 11 different ocean and climate models, ocean modeller Stefan Rahmstorf from the Potsdam Institute for Climate Impact Research (PIK), Germany, has concluded that it would take between 100,000 and 200,000 cubic metres of fresh water per second to shut down the thermohaline circulation — similar to the outflow from the Amazon River[15]. And once the circulation is stopped, restarting it would take a lot more cooling than just reversing the system into the conditions in which it was previously working.

Dry Asia

The good news is that although the Arctic does seem to be getting fresher, it is nowhere near the danger point. Add together the increased output from disappearing sea ice (which moves fresh water from the point where sea water freezes to the point where the ice melts), the melting of Greenland and increased Arctic river flow and you still have barely a quarter of the lower bound of the model threshold.

However, measurements of flow in the deep ocean suggest that the circulation might be fluctuating in ways not considered by the models[16]. And if the melting of Greenland were to gather pace, the thermohaline circulation would be vulnerable. If the lower bounds of the models turn out to be right, a rate of melting that would get through the ice in 1,000 years would trouble the ocean overturning in centuries. “The fate of the thermohaline circulation will be decided by Greenland,” says Rahmstorf. “If that goes quickly it will be bad news for the deep-water formation. But if Greenland is stable, the risk of shutting down the circulation completely is very small.”

“The fate of the ocean circulation will be decided by Greenland. If that goes quickly it will be bad news.” — Stefan Rahmstorf

Any such shutdown would probably have only a small effect on European temperatures. But thanks to the Coriolis effect, says Rahmstorf, such a large shift in the ocean circulation would redistribute sea water so that the North Atlantic rose by up to a metre[17]. There are also suggestions that Atlantic fisheries could collapse.

But the biggest danger would come farther south. In the past, similar changes in ocean circulation seem to have led to significant shifts in tropical rainfall. “If you switch off the thermohaline circulation, the tropical rainfall belts shift. All the models show this. It’s quite simple robust physics,” says Rahmstorf. General circulation models, which try to simulate the workings of the climate system as a whole, often including the ocean, predict at least some weakening of the thermohaline circulation by the end of the century, with a knock-on effect on tropical rainfall — the system that provides much of Asia with food. And as with Greenland, the change doesn’t have to be complete to have consequences. “Just weakening the system is by no means harmless,” says Rahmstorf. “You’d get the same pattern of effects as for a total shutdown, but just a smaller amplitude.”

What insights do these three examples provide into tipping points more generally? One is that they are hard to predict, because they often depend on phenomena too subtle or small to be captured in climate models — the effect of wind patterns on sea ice, or the flow of water through ice-sheet cracks. And bear in mind that the members of the Arctic triumvirate are in principle pretty simple, in that they depend for the most part on physics alone. Possible tipping points in which biology too plays a role — for example, the potential die-back of the Amazon forests if their area diminishes beyond a certain threshold — are even harder to get a grip on. As a result, few researchers are prepared to put a number on how much warmer we could allow the climate to get without endangering humans.

Human factors

Another insight is that points of no return may not be particularly important. Large-scale melting in Greenland is a serious issue over centuries regardless of whether it goes all the way. And the question of whether sea ice would continue to shrink without global warming is academic. The current level of greenhouse gases ensures that the world will continue to warm over the next decades, and the current structure of the world economy ensures that, over that time, there will be further increases in the greenhouse-gas level. The question is what will be done about it, and how soon. As Alley says: “The human tipping points are probably more important than the natural ones. It’s at what point the situation becomes intolerable to us that matters.”

The message from the Arctic is that there is still time to avert the worst potential consequences of the nonlinearities in our climate system. Although it is probably too late to stop a serious decline in sea ice, the other two more powerful members of the Arctic trinity look to be some way off their danger points. And unlike the thermohaline circulation, and perhaps the Greenland ice sheet, the change in sea ice does seem to be reversible.

If disappearing ice and dying polar bears can tip public opinion over its ‘be very worried’ threshold into the realms of greater action, then further tipping points in the human world might have their own, positive, role to play. Ottmar Edenhofer, an economist at PIK, found that in some economic models of responses to climate change, increasing carbon prices encourages renewable energy. Above a specific threshold, even if the price of carbon drops, the advantages of renewables have become irrevocable and the move away from fossil fuels continues[18]. “Our task is to find a way to kick the economic system into a new equilibrium and we can use the tipping points of the market to achieve that,” says Edenhofer. “Tipping points are part of the problem, but they could also be part of the solution.” ■

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