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Chris Pyle

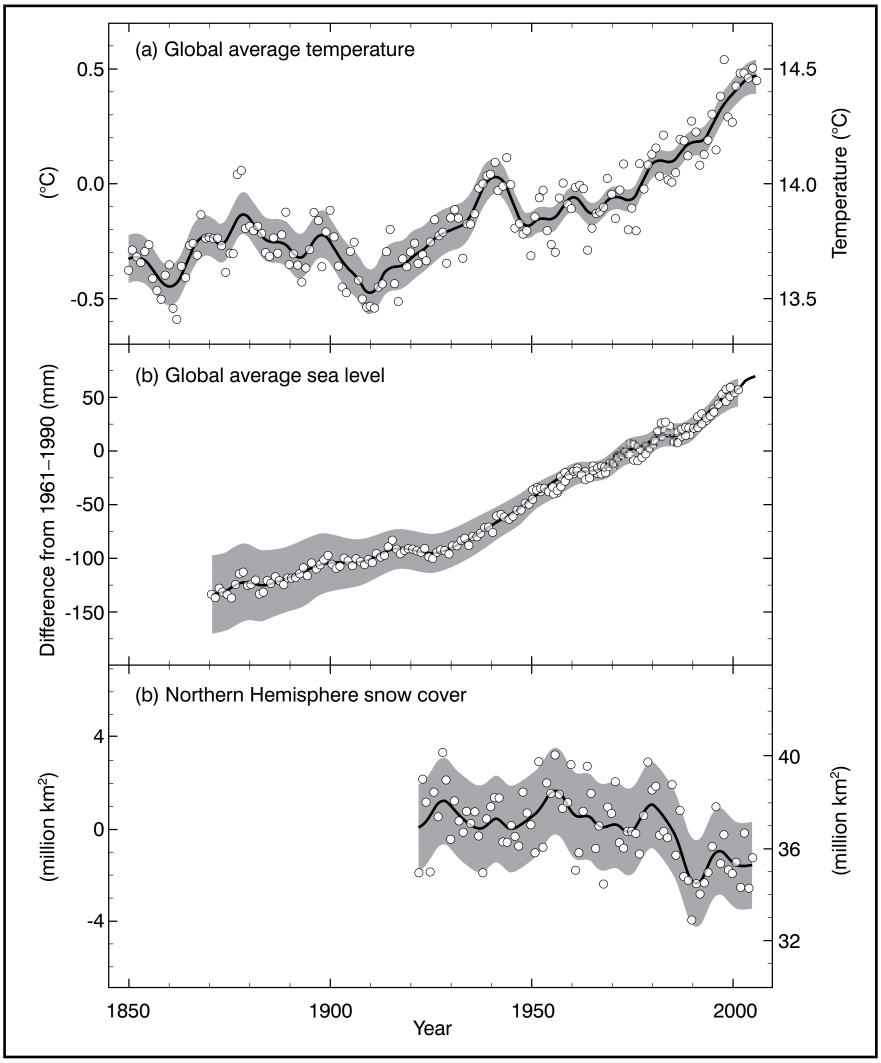
# The Concept of a 'Tipping Point' in Climate Change

There is broad scientific consensus that the rising concentration of atmospheric greenhouse gases is causing global temperatures to increase (Figure 1). Carbon dioxide is the principal greenhouse gas, and its atmospheric concentration has risen from a pre-industrial value of 280 parts per million to around 390 ppm today. Human activity has also added to other greenhouse gases, including methane and nitrous oxides.

The Intergovernmental Panel on Climate Change (2007) estimates that global average temperatures are currently increasing by around 0.2°C per decade. Future projections depend on industrial and governmental policies, but a mid-range estimate is that by the end of the 21st century, global temperatures may increase by 1.4 to 3.8°C, and that sea levels may rise by 0.21 to 0.48m.

This **Geofile** discusses the evidence for the idea that the patterns of future change may not be gradual. Are there nasty surprises lurking in the greenhouse?

*Figure 1: Observed trends in global average temperature, sea level and northern hemisphere snow cover. White circles show yearly values, and the shaded area shows the uncertainty interval of the data*




Source: IPCC (2007) *Fourth assessment report summary for policymakers*, CUP, p.6.

## Tipping points

The term 'tipping point' was popularised by Malcolm Gladwell's best-selling book (2000), which suggested that an accumulation of small and gradual changes may sometimes cause a dramatic transformation. The tipping point is the change that occurs when an object goes beyond its point of balance and falls – the straw that breaks the camel's back.

The tipping point concept is relevant to climate change because **thresholds** in the climate system may lead to abrupt changes in impact. For example, a gradual rise in sea levels may suddenly destabilise a large ice sheet. The human impact may also depend on tipping points, for example if sea level rise suddenly overtops coastal defences for a major coastal city.

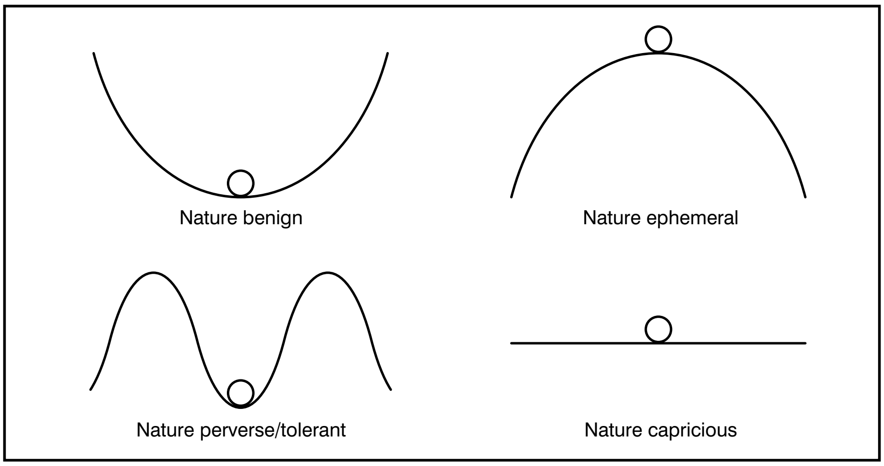
Tipping points also occur when systems contain positive **feedback** loops. Systems that return to equilibrium after disturbance are dominated by negative feedback. For example friction gradually slows a swinging pendulum. However, positive feedback occurs when processes amplify an initial change. For example, a ball rolling downhill gathers momentum and its speed increases. The earth's complex climatic system contains both positive and negative feedback loops.

## How sensitive is the earth's climate system?

Some physical systems are robust and resilient to change. Others are vulnerable and highly sensitive. Figure 2 shows four views of the climate system, conceptualised as a ball on a landscape. Maslin (2008) describes these as 'four myths of nature'.

- Nature benign: in this view, nature is stable. No tipping points exist; no matter how violently it is shaken, the ball will always come to rest in the bottom of the basin.
- Nature ephemeral: nature is precarious and fragile. The slightest human interference is liable to unleash catastrophic collapse.
- Nature perverse/tolerant: within limits the environment can tolerate disturbance, but major excesses will cross tipping points and lead to disaster.
- Nature capricious: nature is unpredictable, and beyond human control.

*Figure 2: 'Four myths of nature'*




Source: M. Maslin (2008, p.37); based on J. Adams (1995) *Risk*, UCL Press, p.34.

Each of the four views will lead to a very different policy response. You may like to consider which of them best fits your own view of the world's environmental systems.

This **Geofile** examines the evidence for tipping points in the Earth's climate system, which may help to show which of the four 'myths of nature' best describes the environment's response to climatic forcing.

## Tipping points in climatic processes

The earth's climate arises from the interaction between a complex set of sub-systems, including the atmosphere, hydrosphere, biosphere and cryosphere (ice).

The following sections outline the thresholds and feedback loops in five key physical processes, each of which illustrates the interactions between different parts of the climate system. The processes described include the ice-albedo effect; release of methane stored in permafrost; meltwater and glacier flow; sea level rise and ice sheet instability; and the possibility of changing ocean currents.

## Albedo feedbacks in snow and sea-ice cover

Albedo is the technical term for the reflectivity or 'whiteness' of a surface. Pale surfaces have a high albedo, and reflect a large proportion of incoming solar radiation; dark surfaces absorb a higher proportion of the incoming solar radiation, causing their temperature to rise.

Fresh snow has an albedo as high as 0.9 (meaning that 90% of all incoming radiation is reflected back into space), whereas bare rock may typically have an albedo of around 0.3. Sea-ice has an albedo of around 0.6, while the albedo of the ocean surface can be less than 0.1.

This albedo difference causes a positive feedback loop, which can quickly accelerate snow and ice retreat once melting has begun. As larger areas of soil and rock are exposed, or as pale sea-ice melts to expose the dark ocean water beneath, the surface albedo falls dramatically and the temperature of the surface rises, which brings on faster melting nearby.

As well as the reduction in snow cover shown in Figure 1, there is strong evidence for large changes in Arctic sea-ice cover over recent decades. One study showed that September sea-ice cover in the Arctic Ocean fell by 7.8% per decade from 1953 to 2006. This may in part be the ice-albedo effect in action.

At the onset of a glacial period, the opposite positive feedback will occur: once snow covers a large area of the earth's surface, it will reflect such a large proportion of the incoming solar radiation into space that the area will remain cold, allowing the snow to remain and the process to persist. (The ultimate example of this is the 'snowball earth' theory, that runaway cooling would leave a white, snow-covered planet permanently frozen.)

## Methane stored in permafrost

The ice-albedo effect has a further significance in some tundra regions, where the removal of surface ice reveals dark peat beneath. Sub-arctic Western Siberia contains around a million sq km of frozen peat bogs, parts of which have begun to thaw.

An estimated 70 billion tonnes of methane are trapped in the frozen peat, formed from slow decomposition of the waterlogged organic matter. As the Siberian permafrost begins to melt, this powerful greenhouse gas is able to escape into the atmosphere. This permafrost zone also extends offshore, and the loss of Arctic sea-ice cover may release methane from frozen sea bed sediments in a similar way. This is an area of considerable current research activity.

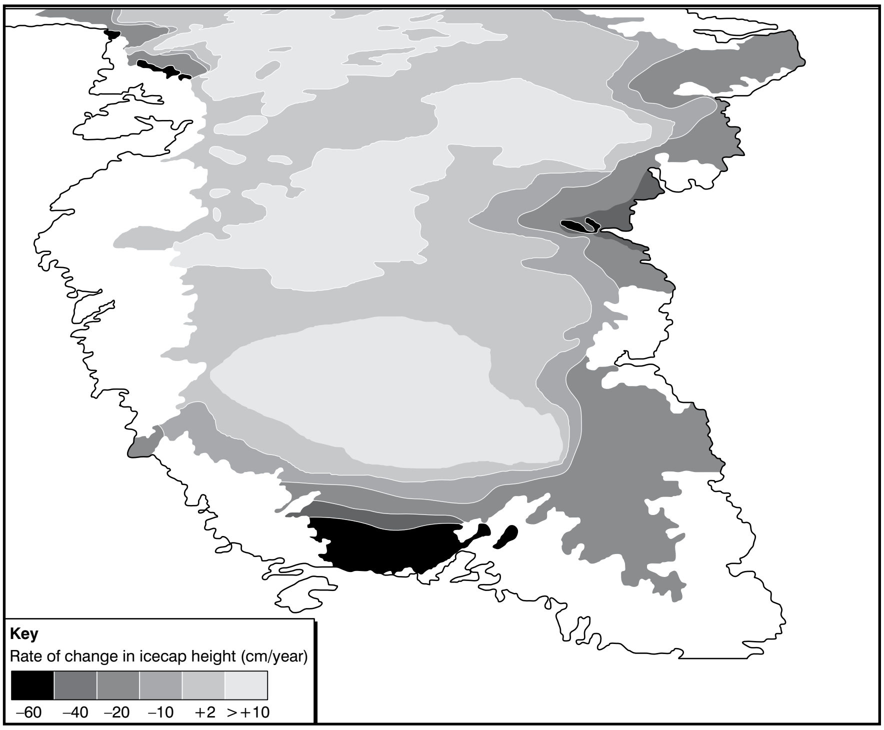
Even under the most pessimistic scenario it would take many decades for the Siberian permafrost to melt. However, the gradual thaw that releases methane to the atmosphere represents a positive feedback with the significant potential to accelerate rates of atmospheric warming. It is estimated that if the Siberian permafrost were to thaw over a hundred-year period, the annual methane emissions would be equivalent to the current methane flux from all the world's wetlands and agriculture.

## Enhanced glacier flow rates in a warmer world

Rates of ice melt have a strong influence on the speed of glacial movement. This is another positive feedback in the cryosphere system. Many glaciers in summer have a dramatic outwash stream at the glacier snout. This comes from surface meltwater, which has run across the surface of the ice until it has encountered crevasses or moulins which directed the flow of water through tunnels towards the glacier bed. The arrival of pressurised meltwater at the glacier bed lubricates sliding of the glacier along the ice-rock interface. Where glaciers are resting on thick sediments and moraines, the meltwater injection makes the sediments softer and more deformable. The result of surface melting is to increase the rate of glacier motion. This process implies that global warming will lead to increasingly rapid rates of glacial flow, with an impact on ice volume and sea level.

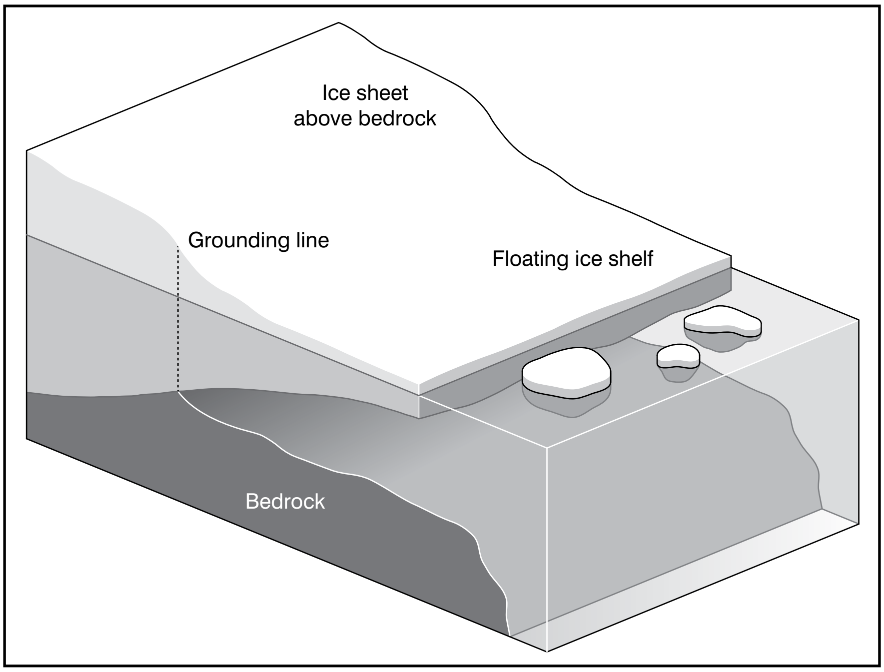
Melt-induced acceleration has been the subject of intensive study by glaciologists in Greenland. Jakobshavn Isbrae is a large ice stream which flows into Baffin Bay on the west coast of Greenland. It is the fastest-flowing glacier on earth: its motion rates have reached over 12 km

*Figure 3: Thinning of the edge of the Greenland icecap*




Source: NASA Earth Observatory (2000). http://earthobservatory.nasa.gov/IOTD/view.php?id=721 accessed March 2011.

*Figure 4: Large parts of the West Antarctic ice sheet are grounded below sea level. A rise in sea level has the potential to destabilise ice shelves which buttress the grounded ice sheet*




Source: P. Huybrechts (2009), *Nature* 458: 295-6.

per year, and it has been estimated to produce 35 billion tonnes of icebergs per year. Scientists have observed large meltwater lakes draining rapidly into crevasses and towards the glacier bed. It is likely that this meltwater is linked to the ice stream's rapid flow. There is also evidence that the dramatic rates of melting and movement at Jakobshavn Isbrae may be driven by rising sea water temperatures. The warmer ocean melts and destabilises the glacier front. This allows the mass of ice upstream to flow more rapidly towards the ocean.

Figure 3 shows how the fringe of the Greenland ice sheet is thinning. This is due to enhanced melting and ice loss via glaciers such as Jakobshavn Isbrae.

## Sea level rise and ice sheet instability

On an even larger scale, rising sea levels have the potential to drive another positive feedback of glacial retreat. Because ice is less dense than water, an increase in sea levels has the potential to float the edge of some glaciers and ice sheets which are currently grounded, leading to their disintegration.

Most of the West Antarctic ice sheet is grounded below sea level (Figure 4), and so it has a long-term vulnerability to destabilisation by rising sea levels. The sea water would also cause basal melting. This would generate a strong positive feedback of oceanic undercutting and glacial retreat.

There is evidence that the West Antarctic ice sheet has disappeared at least once in the recent geological past, possibly during the last interglacial, when global temperatures were a little higher than today. The West Antarctic ice sheet contains over 2 million cubic km of ice; if the entire ice sheet collapsed, sea levels might rise by 3 metres across the whole world's oceans. This is an area of considerable uncertainty, but probably involves a timescale of centuries or millennia.

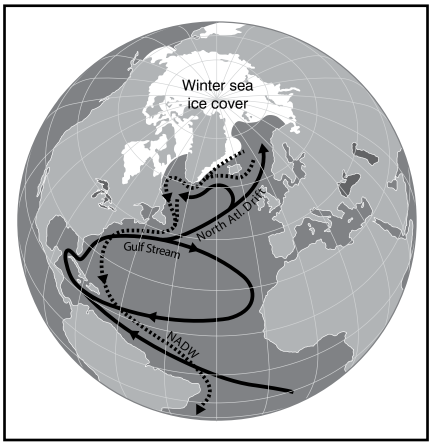
## Deep water and the Gulf Stream

Another area in which climate scientists see the possibility of a future tipping point is in the world's ocean currents.

The Gulf Stream and its extension the North Atlantic Drift flow from the tropics and bring large quantities of heat to western Europe. These currents are the surface flows of a giant conveyor belt, which returns deep below the surface in the cold, saline current known as North Atlantic Deep Water (Figure 5). This deep water current is driven by density: areas of warm surface water cool and evaporate in the far North Atlantic, sink towards the ocean floor, then flow southwards. The process releases large amounts of heat energy to the atmosphere.

We know from the chemistry of sea floor sediments that the flow of North Atlantic Deep Water is not constant. During the last ice age, sea ice halted the North Atlantic Deep Water. Warm surface waters did not flow northwards to the North Atlantic, and the heat

*Figure 5: The warm surface waters of the Gulf Stream and North Atlantic Drift and the cold North Atlantic Deep Water (NADW). Changes in the flow of these ocean currents affected world climates during the ice ages*




Source: S. Rahmstorf (1997), *Nature* 338: 825-6.

from deep water production was not released to the atmosphere.

When the last ice age came to an end, around 15,000 years ago, deep water production re-started and the return of the North Atlantic Drift warm water to western Europe contributed to the rapid warming of the continent.

Around 12,900 years ago, however, post-glacial warming was interrupted by a dramatic climatic reversal, which lasted about 1400 years. Glaciers reappeared in the British Isles, and the landscape returned to tundra. This phase is known as the Younger Dryas episode, named after an arctic flower whose pollen is found in abundance from this time.

The most likely explanation for this sudden cooling event is the disruption of North Atlantic Deep Water by huge meltwater inputs from the surrounding landmasses. With the conveyor switched off, the North Atlantic Drift no longer brought warm surface waters to the edge of Europe.

The Younger Dryas episode gives an unsettling picture of sudden step-changes in the earth's climate system.

In a warming world, climate models suggest that an increased flow of fresh water into the surface waters of the North Atlantic from glacial melting or increased precipitation could weaken the flow and formation of deep water. There is at least the possibility that greenhouse warming could be interrupted by an episode similar to the Younger Dryas.

## Negative feedback effects

The focus of this **Geofile** has been on the possible tipping points, thresholds and positive feedbacks of climate change. There are also negative feedback effects in the climate system, which may tend to dampen climate change. You might like to carry out some internet research into the likelihood and importance of the following three:

- An enriched carbon dioxide atmosphere may promote plant growth. Faster biomass accumulation might then in turn remove more carbon dioxide from the air.
- The height, density and albedo of clouds may change. It is possible that in a warmer world, higher evaporation rates might increase cloud cover, which would then reflect more of the sun's energy into space.
- **Global dimming** refers to the possible effect of airborne particles in preventing incoming solar radiation from reaching the earth's surface. Desertification caused by global warming may create more atmospheric dust from wind-blown soils.

## Tipping points in areas of the world

Some areas of the world are particularly vulnerable to tipping points and climate change. A major report by the World Wide Fund for Nature identified four such areas of the world (Lenton et al, 2009).

1. There are 136 coastal mega-cities which are increasingly vulnerable to sea level rises. Many of these cities are also growing in size due to rural-urban migration. WWF identify the ports of Asia and the United States as especially vulnerable to higher sea levels and storm surges.
2. More than 60% of the cropped area of India depends solely on monsoon rainfall. The impact of greenhouse warming on the Indian summer monsoon is a major area of uncertainty in current climate change models. In addition, the hydrological regime of South Asia will gradually alter as the Himalayan snowfields and glaciers decrease in size. These currently supply up to 85% of the dry season flow of the great rivers of north India.
3. Like the Indian monsoon, rainfall over the Amazon basin is linked to the El Niño climatic oscillation, which is thought to be sensitive to climate change. There is thought to be a risk of Amazon drought and forest die-back in an enhanced greenhouse environment.
4. Sub-tropical areas are also vulnerable to increased aridity, including Southern Europe and the Middle East. Mexico in particular faces a future of declining water resources, while south-west North America may face multiyear droughts similar to those of the Dustbowl era of the 1930s.

## Conclusion

Intensive research will assist scientists to predict the possible future climate change scenarios and their impacts on human populations. Some of the tipping points discussed in this **Geofile** may well be reached, but the timing remains uncertain, as do the overall results of interactions between positive and negative feedback loops.

## References

Gladwell, M. (2000) *The tipping point: How little things can make a big difference*. Little, Brown and Co.
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## Focus Questions

1 Which of Maslin's 'myths of nature' (Figure 2) most closely describes your view of our planet's likely response to climate change?

2 In your opinion, which of the possible tipping points should be the main focus of resources and research by governments and climate scientists? Give your reasons.

3 Identify the groups of people and areas of the world are most vulnerable to the tipping points of climate change. Discuss the likely impacts.