Climate Change

The changing climate is pushing many Earth systems towards critical thresholds that will alter regional and global environmental balances and threaten stability at multiple scales. Alarmingly, we may have already passed tipping points that are irreversible within the time span of our current civilization.

A storm front passes over Bribie Island, Queensland, Australia.

Source: Barbara Burkhardt

INTRODUCTION

Climate change has long since ceased to be a scientific curiosity, and is no longer just one of many environmental and regulatory concerns. It is the major, overriding environmental issue of our time, and the single greatest challenge facing decisionmakers at many levels (Ban 2008). It is a growing crisis with economic, health and safety, food production, security, and other dimensions. Shifting weather patterns threaten food production through increased unreliability of precipitation, rising sea levels contaminate coastal freshwater reserves and increase the risk of catastrophic flooding, and a warming atmosphere aids the pole-ward spread of pests and diseases once limited to the tropics.

The news to date is bad and getting worse. Ice-loss from glaciers and ice sheets has continued, leading to the second straight year with an ice-free passage through Canada’s Arctic islands and accelerating rates of ice-loss from ice sheets in Greenland and Antarctica. Combined with thermal expansion—warm water occupies more volume than cold—the melting of glaciers and ice sheets from the equator to the poles is contributing to rates and an ultimate extent of sea-level rise that could far outstrip those anticipated in the most recent global scientific assessment (IPCC 2007).

There is alarming evidence that important tipping points, leading to irreversible changes in major Earth systems and ecosystems, may already have been reached or passed. Ecosystems as diverse as the Amazon rainforest and the Arctic tundra may be approaching thresholds of dramatic change through warming and drying. Mountain glaciers are in alarming retreat and the downstream effects of reduced water supply in the driest months will have repercussions that transcend generations. Climate feedback systems and environmental cumulative effects are building across Earth systems, demonstrating behaviours we cannot anticipate.

The potential for runaway greenhouse warming is real and has never been more clear. The most dangerous climate changes may still be avoided if we transform our hydrocarbon-based energy systems to renewable energy systems and if we initiate rational and adequately-financed adaptation programmes to forestall disasters and migrations at unprecedented scales. The tools are available but they must be applied immediately and aggressively.

DETECTION, OBSERVATION, ATTRIBUTION

The Intergovernmental Panel on Climate Change publishes its comprehensive assessment reports on climate change science every five or six years (IPCC 2007). But scarcely a week passes without new research appearing in peer-reviewed literature and news reports that adds to the story. For instance, the IPCC was unable to formally attribute to human influence the climate changes observed in Polar regions because of the regions' natural variability and the insufficient coverage. In 2008 researchers using place-specific gridded data sets and simulations from four different climate models found that changes in Arctic and Antarctic temperatures are not consistent with natural variability and are directly attributable to human influence (Gillett and others 2008). They conclude that human activities have already caused significant warming in both Polar regions with likely consequences for indigenous communities, biological systems, ice-sheet mass balance, and global sea levels.

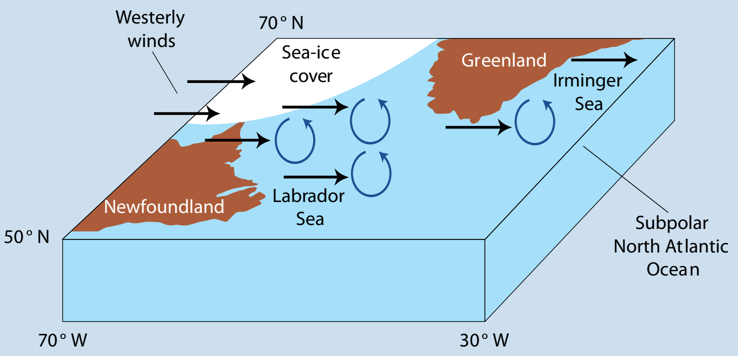
Arctic ice loss

Evidence grew in 2008 that the areal extent of Arctic sea ice is declining more rapidly than previously expected in response to higher air and ocean temperatures. The USA's National Snow and Ice Data Center reported that the year's minimum sea-ice cover occurred on 12 September, when it extended over 4.52 million square kilometres of the Arctic Ocean (NSIDC 2008). This is the second lowest figure for the area of ice surviving the summer thaw since satellite monitoring began in 1979. While 2008 saw 10 per cent more ice cover than in 2007, the lowest figure on record, it was still more than 30 per cent below the average for the past three decades. Taken together, the two summers have no parallel.

For the second year in a row, there was an ice-free channel in the Northwest Passage through the islands of northern Canada. But this year also saw the opening of the Northern Sea Route along the Arctic Siberian coast. The two passages have probably not been open simultaneously since before the last ice age, some 100 000 years ago (NERSC 2008). Theoretically, in 2008 the Arctic ice cap could have been circumnavigated.

A possible unanticipated consequence of sea-ice loss in the Arctic is the apparent return of strong ocean convection in gyres of the sub-polar North Atlantic. This is where surface water sinks to depth as a distinct mass, driving circulation patterns in the Atlantic Ocean (**Figure 1**). The strong mixing documented in the Irminger Sea to the east of Greenland's southern tip and in the Labrador Sea to the southwest is attributed to cold air arriving from Canada that initiated a heat transfer from the ocean to the air, with a sinking mass of cold water as the consequence. In recent winters the cold air from the west has been warmed by higher temperatures of water flowing south through the Davis Strait. However, in the winter of 2007 to 2008, the surface water flowing south was sea-ice melt, colder and fresher than usual, so with winter it froze quickly over Davis Strait. The cold air from the west stayed chilly until it reached the relatively warm water off Greenland, where the subsequent energy exchange triggered the gyres' renewal (Vage and others 2008).

Figure 1: Deep convection in the subpolar ocean



An extensive sea ice cover insulated the strong, cold westerly winds from the warmer ocean until they reached the central basin of the Labrador Sea in winter 2007–08. There, these unusually cold winds rapidly cooled the surface water, leading to mixing of the water column to depths that had not been reached in the last 15 years.

Source: Lozier 2009

The overall declining trend of sea-ice in the Arctic has now lasted at least three decades. The loss is greatest in summer, but is also evident in winter ice packs—in the thickness of the ice. With less ice surviving the summer, the amount of thick ice that has built up over several years is decreasing. This leaves the whole sea-ice system more vulnerable to future warming and brings closer the prospect of an ice-free Arctic (Kay and others 2008, NSIDC 2008).

In the Arctic the atmosphere is warming twice as fast as in most other regions of the world. In the far north warming is amplified by a decrease in the reflectivity of the Earth's surface as ice and snow melt. Ice and snow reflect solar energy back into space, while darker surfaces like bare tundra and open ocean absorb more solar energy and then radiate it to heat the air above. So as the reflective surfaces disappear, the darker surfaces release heat into the immediate environment that results in more melt.

However, there may be other factors contibuting to accelerated warming in the Arctic Ocean. In 2007, there was an especially large loss of ice in the Beaufort Sea, north of Canada and Alaska. This was due to incursions of warm water from the south that melted the ice from beneath (Perovich and others 2008). Also local atmospheric conditions amplified ice loss. 2007's clear sunny skies increased melting in the 24-hour sun, and strong winds during the early part of the summer drove ice into seasonal packs, creating enlarged patches of open ocean (Kay and others 2008). In 2008, winds dispersed the ice that resulted in a larger ice area, but of thinner ice (NSIDC 2008).

Evidence for the role of more systematic natural variability in the Arctic also grew during 2008. New research showed that the region's normal variability, dominated by the Arctic Oscillation and the North Atlantic Oscillation, presents warm and cold phases that alternate—with each phase persisting through several years (Keenlyside and others 2008, Semenov 2008). The phases are triggered by changing patterns of ocean currents that allow more or less warm water into the Arctic which alters air movements (Graversen and others 2008). In recent years, the region has been in a warm phase, accentuating the effects of global warming. While phase changes in the Arctic Oscillation and the North Atlantic Oscillation may mask incremental climate change trends, some scientists are asking how climate change affects these oscillations and others, such as the El Niño Southern Oscillation (Goodkin and others 2008, Goelzer and others 2008).

Greenland and Antarctica ice sheet loss

The largest mass of ice in the Arctic covers the island of Greenland. In places, the ice sheet is three kilometres thick. If it melts, it will raise sea levels by an estimated six metres. Until recently, glaciologists presumed that the ice would thaw slowly over millennia, as warming at the surface of the ice sheet permeates downward and gradually melts the ice. That thinking is reflected in the IPCC fourth assessment report (IPCC 2007).

But the ice sheet is currently losing mass much faster than would be expected if melting alone was to blame. Current losses are more than 100 cubic kilometres a year. New findings in 2008 revealed that the flow into the ocean of the Jakobshavn Isbrae glacier in western Greenland, one of the most important routes for ice loss, has doubled since 1997 (Holland and others 2008).

It appears that physical processes are destroying the integrity of parts of the Greenland ice sheet. The precise mechanisms remain disputed but two possibilities are being discussed. One is that warm ocean waters are destabilising the mouths of major glaciers like the Jakobshavn Isbrae, speeding their flow. A second arises from the discovery that meltwater forming at the surface of the sheet is draining down crevasses and moulins to the bottom of the ice sheet. This meltwater lubricates the previously frozen contact between the ice and underlying bedrock, again causing glacier flow to accelerate. In 2008, researchers reported on one of the thousands of melt-water lakes that now form on Greenland each summer (Joughin and others 2008, Das and others 2008). The four-kilometre-wide expanse of water that formed in 2006 completely drained into the icy depths in 90 minutes, at a flow rate greater than Niagara Falls.

Scientists walk along the edge of a large canyon carved out by over a decade of meltwater flow across the surface of the Greenland ice sheet.

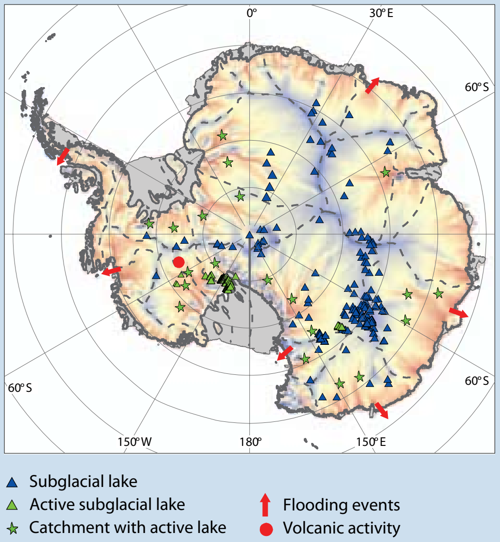
Source: Sarah Das/ Woods Hole Oceanographic Institution

But the significance of this process for ice loss remains unclear. There has long been discussion about the extent and the effects of subglacial water drainage and how those influences vary with the size and the temperature of the ice mass (Bell 2008, O'Cofaigh and Stokes 2008). Some researchers argued that the subglacial rivers formed by moulin drainage in Greenland are ephemeral, that the water swiftly disperses and the flowing ice grinds to a halt against the bedrock. According to this argument, such events may only be responsible for 15 per cent of the annual iceberg formation from Greenland (Van der Waal and others 2008). But the evidence is based on only a handful of sites. And even if Greenland's subglacial water proves less important than some believe, this leaves open the question of why the great ice sheet is losing mass so rapidly.

Whatever the processes involved, it is now clear that Greenland can lose ice at rates much faster than previously supposed and has done so frequently in the past. A new analysis of historical data on the extent of the Greenland ice sheet shows that total meltdown is quite possible as a result of warming on the scale that is being forecast for the next few decades (Charbit and others 2008).

Antarctica is losing ice, too, particularly from the West Antarctic ice sheet. This sheet contains enough ice to raise sea levels by about five metres. It sits like a wrecked ship with a frozen weld to submerged mountains and has always been considered potentially unstable—particularly because warmer ocean waters could melt the frozen link between ice and rock. Researchers estimated in 2008 that loss of ice from the West Antarctic ice sheet increased by 60 per cent in the decade to 2006 (Rignot and others 2008). Ice loss from the Antarctic Peninsula, which extends from West Antarctica towards South America, increased by 140 per cent.

Box 1: Subglacial drainage in Antarctica



The International Polar Year, which started in March 2007 and will draw to a close in March of 2009, is a scientific programme that focuses on changing Arctic and Antarctic conditions. Some of the most exciting work studies the dynamics of ice sheet water drainage. New data showing the existence of large scale water drainage systems beneath the polar ice sheets have renewed concern about ice sheet stability.

Beneath the Antarctic ice sheets over 150 subglacial lakes evolve, including Lake Vostok, a basin the size of Lake Ontario. High-resolution imaging of the ice sheet surface has allowed scientists to monitor the movement of water through previously unrecognized interconnected hydrologic systems that include large lakes and rivers. While the extent and degree of interconnection are unknown, the potential drainage system in Antarctica is larger than that of the Mississippi River basin.

In the coming decades, significant changes in the polar regions will increase the contribution of ice sheets to global sea level rise. Under the ice streams and outlet glaciers that deliver ice to the oceans, water and deformable wet sediments lubricate the base, facilitating rapid ice flow. In Antarctica, subglacial lakes have the capacity to modify velocities in ice streams and outlet glaciers and to provide sources of lubrication for new ice-flow tributaries.

Subglacial fluvial systems of Greenland and Antarctica provide a valuable modern analogue for former ice sheet dynamics. Prehistoric glacial lake outbursts sculpted the topography of vast regions in North America, Europe, and Asia. These floods also delivered enormous quantities of sediment and freshwater to deltas and to the oceans—possibly contributing to temporary disturbances in oceanic thermohaline circulation.

Sources: Allison and others 2007, Bell 2008, Shaw 2002, Toggweiler and Russell 2008

The processes affecting the peninsula involve accelerating glacier flows caused by both warmer air and higher ocean temperatures (Rignot and others 2008) (**Box 1**).

An additional factor in Antarctica that could undermine the integrity of the great ice sheets is the recent disappearance of a number of ice shelves. These shelves float on the ocean but are attached to the ice sheets indirectly. The shelves often act like corks in a bottle, holding back glaciers on land whose loss will raise sea levels.

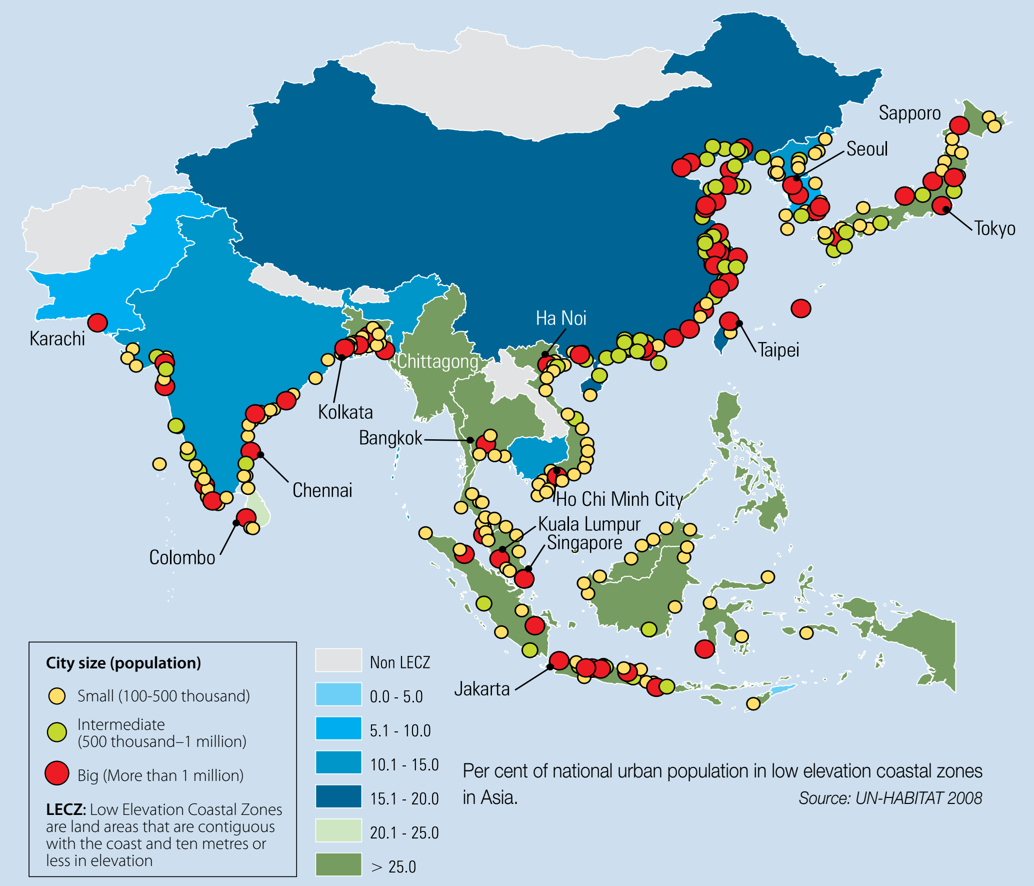
A large part of the Wilkins Ice Shelf collapsed in February 2008 (Braun and others 2008). At that time the British Antarctic Survey said the shelf is in imminent danger of collapse (BAS 2008). As of December 2008, satellite radar imagery shows more cracks within the Wilkins Ice Shelf itself, especially at the head of the ice bridge stabilizing the shelf edge. The ice bridge has diminished in width from 6.0 kilometres to 2.7 kilometres since the February collapse (ESA 2008).

Sea level rise

The last IPCC assessment forecast that global sea levels would rise by between 18 and 59 centimetres in the coming century—just from the thermal expansion of warmer oceans and the melting of mountain glaciers (IPCC 2007). But since the report was completed, many researchers involved in that assessment have predicted that a much larger rise is possible, indeed probable. The new prediction originates in part from reassessments of the potential for physical break-up of the ice sheets of Greenland and Antarctica.

For instance, a study presented at a conference of the European Geosciences Union at Vienna in

Figure 2: Asian cities at risk from sea level rise



Per cent of national urban population in low elevation coastal zones in Asia.

Source: UN-HABITAT 2008

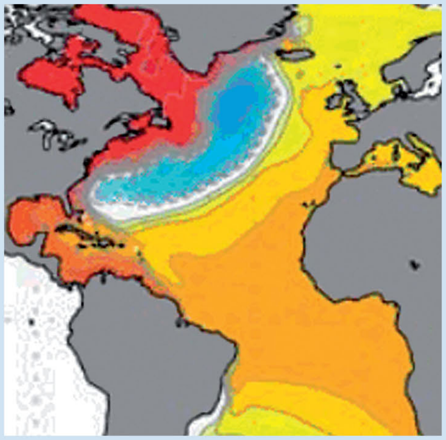
April suggested that a rise of between 0.8 and 1.5 metres was most likely (Schiermeier 2008).

Errata: Another study on the dynamics of glacier and ice sheet loss argued that sea level could rise by as much as two meters in the coming century as a result of outflows from all global land ice sources, with significant contributions from Greenland, Antarctica, and all other glaciers and ice caps (Pfeffer and others 2008)

Such a rise would be far beyond anything seen in the recent past. Sea levels rose 2.0 centimetres in the 18th century, 6.0 centimetres in the 19th century, 19.0 centimetres in the 20th century, and what is projected as an equivalent to 30.0 centimetres for the 21st century based on rates observed in its first few years (Jevrejeva and others 2008). These predictions are not unprecedented: The magnitude of scale for sea level rise now being forecast would be in line with what happened at the end of the last ice age. Then, as ice sheets disintegrated, sea levels rose by between 70.0 and 130 centimetres per century (Carlson and others 2008).

A one-metre rise in sea levels worldwide would displace around 100 million people in Asia, mostly eastern China, Bangladesh, and Vietnam; 14 million in Europe; and 8 million each in Africa and South America (**Figure 2**). However, a new study of how a sudden release of meltwater, or its ice equivalent, from ice sheets into the oceans would influence sea levels shows that, in the first years, the rising waters would not flood with equal speed everywhere. It would take several decades for a pulse of rising sea levels to spread around the world.

Figure 3: Global ocean response to Greenland ice sheet melt



The map shows the response of the ocean over ten years to localized freshwater forcing associated with Greenland ice sheet loss with variance measured in millimetres. The spreading and redistribution of the freshwater in the ocean starts wih an initial boundary wave with associated negative sea surface heights depicted in shades of blue and positive sea surface heights shown in shades of red and orange, moving southward from the Labrador Sea toward the equator. It continues to cross the Atlantic toward the eastern side and further poleward.

Source: Stammer (2008)

From the Greenland ice sheet, most of the melted water would initially stay in the Atlantic (**Figure 3**). Fifty years after release, sea level rise would be thirty times greater in parts of the North Atlantic, including the Gulf of Mexico, than in the Pacific. Similarly, the study found that water from a collapsed Antarctic ice sheet would swamp coastlines in the southern hemisphere, while being barely measurable in the northern hemisphere for at least 50 years (Stammer 2008).

But whatever the detailed modelling may reveal, research in 2008 indicates that sea level rise—from thermal expansion, mountain glacier retreat, and ice sheet melt—is likely to be much greater and to arrive much sooner than believed even two years ago. No matter how quickly climate change is mitigated, sea level will rise. So, efforts to adapt to rising seas are more urgent than ever.

SINKS, SOURCES, AND FEEDBACKS

Future climate change will depend largely on how fast greenhouse gases accumulate in the atmosphere. That in turn will depend on how much we emit into the atmosphere—and also on how much nature is able to absorb.

Since 2000, anthropogenic carbon dioxide emissions have been increasing four times faster than in the previous decade. Most of the emissions came from burning fossil fuels and manufacturing cement (See Resource Efficiency, Chapter Five). These emissions are now 38 per cent above those in 1992, the year governments attending the Earth Summit pledged to prevent dangerous climate change (Global Carbon Project 2008).

At the same time, natural carbon sinks that absorb some of our emissions are unable to perform this function with their former efficiency. The main carbon sinks are the oceans, frozen tracts in the Arctic, and forest ecosystems—all these sinks are losing their absorption capacity. Analysis of a variety of studies suggests that the uptake of carbon by the oceans fell by 10 million tonnes in 2007. It is not yet clear whether this is part of a longer-term trend (CDIAC 2008).

Carbon in the Arctic

The Arctic is warming faster than any other region of the planet. The Arctic also contains very large stores of carbon in the form of methane that may be released as the planet warms. Large-scale methane releases would provide a major positive feedback to global warming and could turn natural ecosystems from carbon sinks to carbon sources, triggering uncontrollable global warming.

The carbon is contained in soils, including frozen permafrost, and beneath the bed of the Arctic Ocean. Two studies in 2008 revised upwards the amount of soil-carbon believed to be held in permafrost. One study of North America concluded there was 60 per cent more than previously supposed (Ping and others 2008). A second international study doubled previous estimates for the carbon inventory of the entire Arctic permafrost (Schuur and others 2008). These findings suggest there is presently twice as much carbon in the northern permafrost as there is in the atmosphere.

Researchers investigating how Arctic sea-ice loss affects temperatures on land predict that future warming in the western Arctic could be 3.5 times greater than the global average. This accelerated warming would be most pronounced in the autumn season and would lead to further rapid degradation of permafrost in northern peatlands (Lawrence and others 2008).

The Arctic region stores very large amounts of methane in the form of hydrates locked in ice lattices in permafrost or beneath the bed of the Arctic Ocean. During 2008 there has been growing interest in tapping offshore methane in hydrates as a source of energy. But climate scientists are concerned that methane hydrates could escape into the atmosphere either as permafrost melts or as warmer waters destabilize frozen offshore deposits (Bohannon 2008).

In 2008, marine researchers discovered more than 250 plumes of methane bubbling up along the edge of the continental shelf northwest of Svalbard (Connor 2008). The International Siberian Shelf Study reported elevated methane concentrations offshore from the Lena River delta (Semiletov 2008). Meanwhile, researchers showed that, once under way, thawing of east Siberian permafrost—thought to contain 500 billion tonnes of carbon—would be irreversible: 250 billion tonnes could be released in a century (Khvorostyanov and others 2008).

Northern peatland soils that are not frozen also contain large amounts of carbon and are vulnerable to warming. The peat's ability to store carbon is highly dependent on its moisture content. Warming will dry out the peat, lowering water tables. A new modelling study showed that this would lead to massive loss of organic carbon in the soil. In northern Manitoba, Canada, a 4.0° Celsius warming would release 86 per cent of the carbon sequestered in deep peat (Ise and others 2008).

In 2007 and 2008, methane concentrations in the atmosphere began to show an upward trend after nearly a decade of stability. At first researchers assumed that the higher concentrations would be limited to the northern hemisphere and could be attributed to peatland degassing. But similar findings were detected in the southern hemisphere also to reveal a global increase (Rigby and others 2008). Scientists await more data before they can determine whether the reading is a blip, a spike, or the beginning of a worrisome new trend.

Forest sequestration

One reason for fears about the ability of forests to soak up carbon dioxide is that forest cover itself is declining and contributing to emissions—1.5 billion tonnes of carbon a year enter the atmosphere from changes in land use, almost entirely from deforestation in the tropics (Global Carbon Project 2008, Canadell and Raupach 2008). Another reason is that even intact forests may be in trouble: The ability of forests to store carbon may have peaked and rising temperatures may already be decreasing carbon uptake by vegetation in the northern hemisphere. Higher temperatures impose significant stress on trees during the summer season and photosynthesis halts sooner. Once the photosynthesis comes to a halt, carbon is no longer sequestered. And stressed forests are vulnerable to damage from pollution, pests, and disease that can turn them into carbon sources (Piao and others 2008) (See Ecosystem Management, Chapter One).

Amazon on the edge

The Amazon rainforest, which covers 5 million square kilometres and contains a quarter of the world's species, could be on a climatic edge. In 2008, one of the world's leading climate models, run by the Hadley Centre at Britain's Meteorological Office, predicted that the Amazon may be close to a crucial tipping point. Beyond that point, the almost daily rainfall that sustains the jungle will become less dependable, soils will dry out, and much of the forest will die (Harris and others 2008) (**Box 2**).

Box 2: A river runs through it

The pivotal role of the Amazon region in global climate was underlined in a study of the impact of outflows of the Amazon River into the Atlantic on the ocean's carbon cycle. The Amazon, the world's largest river, carries about a fifth of all the world's river water. It sends a muddy freshwater flow for thousands of kilometres into the Atlantic, taking rainforest nutrients like nitrogen with it. Microbes contained in the flow feed off the nutrients and fertilize the ocean, increasing plankton growth that results in the oceans absorbing carbon dioxide from the atmosphere.

The findings provide a new perspective on the ability of the overall ocean system to soak up man-made emissions. But they also underline how the ocean carbon sink could be vulnerable to changes on land, such as deforestation and drought. Drought in the Amazon would both damage the rainforest and reduce the river flow, cutting the flow of nutrients and reducing the ocean's ability to capture carbon dioxide from the air.

Source: Subramaniam and others 2008

The Amazon River delivers a plume of sediment to the Atlantic Ocean. *Source: NASA*

One reason for the Amazon rainforest's vulnerability is that its rainfall is critically dependent on a pattern of tropical ocean temperatures that is threatened by climate change. When this pattern is disrupted by a warmer eastern Pacific and a tropical North Atlantic that warms faster than the South Atlantic, these new conditions are known to cause drier conditions in Brazil. For instance, a major drought in the Amazon in 2005 was in 2008 diagnosed as being the result of unusually warm temperatures in the North Atlantic (Harris and others 2008). A doubling of carbon dioxide levels in the atmosphere could warm the oceans sufficiently to decrease rainfall in the Amazon basin by 40 per cent. Such a decline in rainfall would reduce the rate of growth of rainforest vegetation by 30 per cent. This would be in addition to the predicted decrease in growth of 23 per cent directly attributable to the higher air temperatures (Harris and others 2008).

According to this scenario, the combination of heating and drying in the Amazon basin would initiate a runaway loss of forest. Forest loss would raise temperatures, doubling local warming this century from an anticipated 3.3 to 8.0° Celsius. Even if temperatures did fall to former levels, the rains would not return because there would be no forest to process them through evapotranspiration. Finally, soils would have dried out when exposed to sunlight and be more susceptible to erosion, accentuating the drought conditions (Betts and others 2008, Malhi and others 2008).

Black carbon and other feedbacks

There are other important anthropogenic influences on climate besides greenhouse gases. Evidence is mounting for significant consequences to climate variability from soot, aerosols of black carbon that originate from fires on the landscape. Global emissions of black carbon are rising fast and Chinese emissions may have doubled since 2000. The warming influence of black carbon could be three times greater than estimates from the IPCC's latest report, making it the second most importance climatic agent after carbon dioxide (Ramanathan and Carmichael 2008).

These findings remain controversial—not least because black soot can cool as well as warm. But when black carbon falls onto ice it darkens the surface, absorbing more of the sun's energy which leads to local warming and melting. Soot may be a contributor to the disappearance of glaciers in some regions and could even explain the accelerated rates of melt in the Himalaya-Hindu Kush (Ramanathan and Carmichael 2008) (**Box 3**). But soot released from the increasing number of wild fires in North America and Siberia is also shading the Arctic from direct sunlight, causing cooling (Stone and others 2008).

Another air pollutant with known cooling properties was reassessed in 2008. Sulphate aerosols, often the main component of acid rain, cool the atmosphere by scattering sunlight back into space. The new studies suggest that efforts to curb acid rain by cutting sulphate emissions, particularly since 1980, have contributed substantially to the very rapid warming over Europe and the North Atlantic since 1980 (Ruckstuhl and others 2008, Van Oldenborgh and others 2008).

In another unexpected finding, increasing fallout of acid sulphates in China has been suppressing natural methane production from bacteria in rice paddies, slightly reducing global warming (Gauci and others 2008). These feedbacks in no way undermine the argument that man-made pollution is warming the planet, but they remain significant uncertainties. Most importantly, they demonstrate the complexities inherent in Earth systems, as well as the intricate balances of cumulative effects under varying circumstances and at multiple scales.

IMPACTS AND VULNERABILITIES

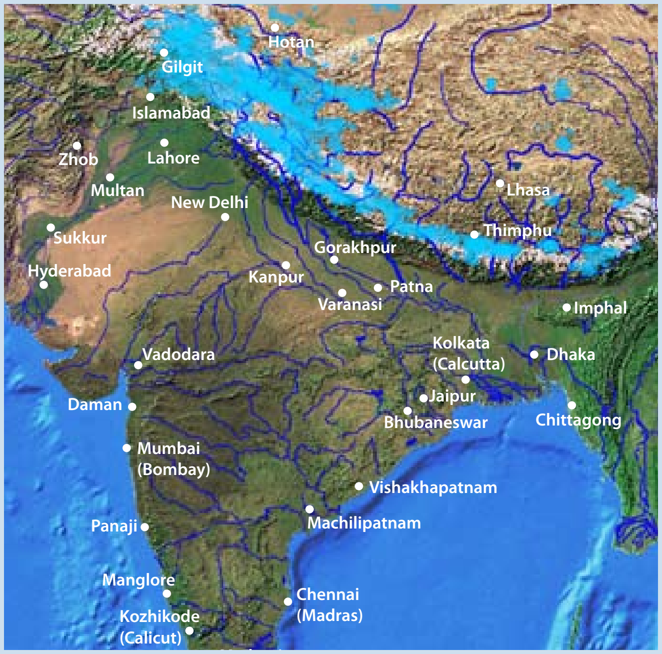
New research demonstrated that winds in the strongest cyclones have become more intense in all oceans (Elsner and others 2008). The increase has been greatest in relatively cool ocean basins that have seen the largest increases in sea temperatures, notably the North Atlantic, but also the eastern North Pacific and southern Indian oceans.

Tropical cyclones only form when ocean temperatures exceed about 26° Celsius. Therefore it is likely that warmer oceans will generate more tropical cyclones. But things may not turn out so simply. Most potential storms never turn into tropical cyclones even above that temperature, because other atmospheric conditions exert significant influences.

A major new modelling study forecast that a further warming of the North Atlantic could in fact discourage formation of hurricanes, the regional name for tropical cyclones. The study forecast an 18 per cent decline in the annual hurricane count by later this century. It commanded attention because the same team had previously produced a remarkably accurate 'hindcast' of hurricane numbers over the past 30 years (Knutson and others 2008).

The paper argued that, along with ocean temperature itself, what matters most for hurricane formation is the temperature difference between the surface of the ocean and the top of the troposphere, the region where hurricanes reach their greatest height. The authors argued that the recent increase in North Atlantic hurricanes arose because of unusual warming in the tropical North Atlantic with normal temperatures in the troposphere, probably due to short-term natural fluctuations. If this combination proves anomalous,

Box 3: Meltdown in the mountains



One of the most explicit signs of the Earth's warming is the near-universal retreat and thinning of mountain galciers in temperate and tropical regions, as well as in Polar latitudes. New data from the World Glacier Monitoring Service at the University of Zurich tracked 30 reference glaciers in nine mountain ranges and underlined the extent of this phenomenon. The reference glaciers were in equilibrium in the early 1980s, accumulating the same amount in precipitation each year as they lost during melt season. But in the past two decades, they have been losing ice rapidly.

This loss is accelerating. From 2005 to 2006, the most recent collated data set, the reference glaciers showed an average thinning of 1.4 metres, almost five times the annual loss in the 1980s and 1990s. Among those glaciers dissipating the most, Norway's Breidalblikkbrae thinned by more than 3.0 metres in the year, France's Ossoue glacier thinned by almost 3 metres, and Spain's Maladeta glacier thinned by nearly 2 metres. Of the 30 reference glaciers, only one thickened, Echaurren Norte in Chile. The report concludes that up to 750 million people could be seriously affected as Himalayan glaciers disappear and the rivers they feed become seasonal, especially in northern India.

Hazardous substances—transported through the atmosphere, condensed with water molecules, deposited on ice surfaces, and encased within glaciers—are now being released back into the environment as glaciers melt. Currently restricted-use DDT is turning up in unanticipated amounts in Adélie penguin populations that occupy parts of the Antarctic coast. Organic pollutants such as insecticides have been well documented as they melt out of glaciers in North America's Rocky Mountains and polychlorinated biphenyls, or PCBs, can be found downstream of European glaciers. As temperate mountain glaciers disappear they will deliver unwelcome chemicals to ecosystems and communities struggling to cope with expected floods and then, eventually, droughts (See Harmful Substances and Hazardous Wastes, Chapter Two).

In South Asia alone, nearly a billion people depend on glacier melt water from the Himalaya/HinduKush mountain system.

Sources: WGMS 2008a, WGMS 2008b, Geisz and others 2008, Blais and others 2001, Schindler and Parker 2002, Branan 2008 then the recent rising trend in strong hurricanes may cease.

The study was controversial, however. Some reviewers pointed out that the model could not reproduce the strongest hurricanes—the ones people care about the most and that have become more frequent. Others pointed out that the findings were restricted to the North Atlantic. Apparently, different rules will apply in the Pacific and other basins, where global warming is still expected to produce more, and more dangerous, cyclones.

The year 2008 saw a series of other significant predictions for future extreme weather as researchers attempt to deliver relevant insights at regional and subregional scales. One such finding predicts that daily high temperature extremes are set to rise twice as fast as average temperatures (Brown and others 2008). Another suggests that there are likely to be many more extremely intense rainfall events in a warmer Europe (Lenderin and van Meijgaard 2008).

Growing concern about world water shortages highlight new findings on the possible impacts that climate change will have on the hydrologic cycle, including rainfall, soil evaporation, and loss of glacial meltwater flows in rivers. New findings predict empty reservoirs in the Mediterranean and American midwest, dry rivers in China and the Middle East, and less predictable river flows chracterized by flash floods in a glacier-free South Asia (Barnett and Pierce 2008).

Several researchers warned during the year about the dangers of communicating what are likely over-precise predictions of local climate change, especially rainfall and river flows. Uncertainty about some aspects of climate change has to be accepted. But unpredictability is no reason to delay taking action on climate change. Far from it. Its unpredictability is part of what it makes it so dangerous (Smith 2008).

TIPPING POINTS

With possibilities of collapsing ice sheets, methane bubbling out of permafrost, desiccated rainforest ecosystems, and sporadic ocean circulation patterns, concern is growing that Earth's life-support systems are approaching thresholds that contain tipping points. Such fears are reinforced by growing evidence that it has happened before. Past climatic shifts, such as the end of an ice age, have happened abruptly. Studying these past changes could help predict whether anthropogenic climate change is about to precipitate irreversible changes.

In early 2008, a team of scientists published the first detailed investigation of vulnerable Earth systems that could contain tipping points. The team introduced the term 'tipping element' for these vulnerable systems and accepted a definition for tipping point as "...a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system..." (Lenton and others 2008).

The team examined nine of these elements and assigned transition times to emphasize policy relevance. They also suggested average global temperature increase that approaches a critical value within each tipping element.

The elements they considered as policy relevant include the Asian monsoon, the West African monsoon, Arctic sea ice, Amazon dieback, boreal forest loss, thermohaline circulation, El Niño Southern Oscillation, collapse of the Greenland ice sheet, and loss of the West Antarctica ice sheet (**Box 4**) (See Environmental Governance, Chapter Six). The study warned against a false sense of security delivered by projections of smooth transitions of climate change. Instead, too many critical thresholds could be crossed within this century because of the changing climate. Scientists hope to establish early warning systems to detect when these suggested tipping elements become unstable (Lenton and others 2008).

The goal of early warning may be complicated by the cumulative effects the different Earth

Hurricane hitting Cuba in 2008.

Source: Associated Press/ Eduardo Verdugo

Box 4: Tipping point in Africa?

Debate continues about whether the Sahel, one of the world's regions most vulnerable to climate variability, is about to pass a tipping point. Some studies suggest that the Sahel region of West Africa could see a sudden revival of rains if global warming and changes in ocean temperatures in the North Atlantic combine to trigger a strengthening of the West African monsoon. This tipping point has been crossed in the past: From 7000 to 3000 before the common era (BCE) large parts of the Sahel were verdant after an exceptionally dry period around 8500 BCE. Evidence published in 2008 suggested that even if this revival occurs it may not be as abrupt as some suggest. A study of pollen and lake sediments in the Sahara investigated how the Sahel went from wet to dry conditions over a one thousand year period that began six thousand years ago. Other studies suggest this shift happened within a few decades. The search for a reliable means of predicting future precipitation patterns in the Sahel region of Africa continues, with one study suggesting that links to sea surface temperatures that held in the 20th century might not apply in the 21st century. However, even if the Sahel did become a lush landscape, only good governance could promise that it would not be a source of conflict and mismanagement (See Ecosystem Management, Chapter One; See Disasters and Conflicts, Chapter Four).

Sources: IPCC 2007, Kropelin and others 2008, Brovkin and Claussen 2008, Cook 2008

Source: Mike Hettwer

Cast from the archaelogical site of Gobero, Niger on the shoreline of Mega Lake Chad, hundreds of kilometres from the current lake shore. These remains of a mother and two children date to about 3300 years before the common era.

systems have on each other, given the complexities at multiple scales and under various circumstances. In 2008 such complexities were demonstrated when early warning efforts resulted in observations of unexpected enhanced thermohaline circulation in the Labrador and Irminger Seas (Vage and others 2008). Another new study found links among El Niño, the Asian monsoon, and the south equatorial Atlantic's sea surface temperature. These teleconnection clues hold out the prospect of more accurate seasonal forecasts of the Asian monsoon, including its possible failure (Kucharski and others 2008).

CONCLUSION

Uncertainties remain in climate change science, especially regarding the operation and interaction of Earth systems over various timeframes and how subsystems react to feedbacks. In particular, more work is required to understand the nature of possible tipping points in systems operating at various scales. For now, the evidence suggests that we may be within a few years of crossing tipping points with potential to disrupt seasonal weather patterns that support the agricultural activities of half the human population, diminish carbon sinks in the oceans and on land, and destabilize major ice sheets that could introduce unanticipated rates of sea level rise within the 21st century (Lenton and others 2008, Schellnhuber 2008).

The basic scientific building blocks behind forecasts of widespread and damaging climate change are irrefutable (IPCC 2007). Unless action is taken soon to stabilize and then decrease concentrations of greenhouse gases in the atmosphere, these changes will cause widespread damage to ecosystems, natural resources, human populations, and their fragile economic activities. Such damages could certainly end prosperity in developed countries and threaten basic human livelihoods in developing countries (**Box 5**).

Box 5: Managing the unavoidable

Until very recently, technology transfer to address climate change has dwelled on mitigation issues. Given that the overwhelming majority of global greenhouse gas emissions are from the energy sector, energy alternatives became the dominant focus for technology transfer. Since energy technologies have been promoted as centralized and infrastructure dependent, it has been a priority on the part of developing country decision makers to emulate developed country models by promoting infrastructure development, modernizing energy delivery, and stimulating private sector investment in large scale installations. So technology transfer in the climate context has come to focus squarely on flows of experience, know-how, and equipment installation arrangements between countries, especially from developed to developing countries, and less on deployment and dissemination within countries (See Resource Efficiency, Chapter Five).

Now that the question of technology for adaptation has moved towards centre stage, some of the ideas about technology transfer for mitigation have been carried forward into the adaptation domain. However, this approach will likely not work.

First, adaptation is not new in the way that modern energy infrastructures are new. Second, the sectors that need technology for adaptation are ubiquitous—not dominated by one sector like energy. Third, many technologies for adaptation, and techniques for adaptation that foster shifts of behaviour and approach, are already available in developing countries. And fourth, the most needed technologies and techniques for adaptation are unlikely to be as capital intensive as those for mitigation, meaning there will not be huge short-term profits to be made by corporate interests.

The selection of technologies for adaptation can be a delicate matter: Caution must be exercised in the introduction of some technologies to avoid possible unintended side effects. The development and application of suitable criteria, motivated by the immediacy of the adaptation challenge, will help to avoid some of these problems.

There are three essential criteria—efficiency, equity, and effectiveness. First, any chosen technology should be subject to some efficiency criterion. Before adopting any specific adaptation measure or set of measures it is important that the benefits exceed the costs, especially at the local level. Second, it is important that the choice of technology for adaptation is equitable in its distribution. In choosing among alternatives, decisonmakers may wish to consider which segments of the population will particularly benefit and where and upon whom the full costs will be incurred. Third, although they may be efficient and equitable, some adaptation options may be politically, socially, or legally unacceptable and lead to negative effects. Perhaps a simple change of an existing regulation may be sufficient to facilitate needed effects. Too often, alterations in cultural values and attitudes are involved: These can be much harder to change. But if approached with respect and rationality, social and cultural obstacles can be negotiated, especially when community leaders can be convinced of the advantages emerging from effective adaptation techniques and technologies.

Five sectors require particular emphasis for adaptation planning. They present challenges, but also offer some lessons learned that could be considered:

In many coastal locations technology has been instrumental in reducing society's vulnerability to perennial weather related hazards. Traditional and recently developed techniques and technologies that have proven to be effective in reducing vulnerability to weather-related hazards will also be important as technologies for adaptation to climate change.

For water resources, climate change induced variability in the hydrologic cycle imposes additional challenges on planning and management. The development of appropriate adaptation strategies to cope with this added uncertainty requires a broad, integrative approach given the multidimensional roles that water plays in sustaining human life, society, and the ecosystems on which they depend.

For agriculture, it is important to consider a diverse toolkit for adaptation because there are a number of uncertainties regarding the range of impacts associated with climate variability and climate change. This is essential to retain the flexibility to transfer and adopt appropriate site-specific techniques and technologies.

Source: Strait Crossing Bridge Ltd.

The Confederation Bridge links the Canadian provinces of New Brunswick and Prince Edward Island. Along its 13 kilometre length the piers and road surface were built a metre higher than required to accommodate for expected sea level rise and associated variable ice conditions over its one hundred year lifespan.

There is along history of dealing with the impacts of climate variability in the sector of public health. Incorporating consideration of where, when, and how extensively climate change could affect future disease burdens is important for increasing resilience. In facing climate change health issues it is especially important to design interventions in collaboration with practitioners addressing the full spectrum of public health challenges.

Finally, an integrated and exhaustive governance structure is central to the success of adaptations, particularly in infrastructure projects and in urban settings. The broader the scope of the adaptation intervention, the greater the need for good governance to ensure efficiency, equity, and effectiveness. Awareness-building and involvement of community groups is essential, as is honest involvement of public and private sector interests, in the successful transfer of technologies for adapting infrastructure systems to the changing climate.

Source: Klein and others 2006

REFERENCES

AGU (2008). Proceeding of the American Geophysical Union Fall Meeting 2008 December. American Geophysical Union. http://www.agu.org/meetings/fm08.old/index.php/Program/SessionSearch/?show=detail&sessid=381 [Accessed 14 December 2008]

Allison, I., Béland, M., Alverson, K., Bell, R., Carlson, D., Danell, K., Ellis-Evans, C., Fahrbach, E., Fanta, E., Fujii, Y., Glaser, G., Goldfarb, L., Hovelsrud, G., Huber, J., Kotlyakov, V., Krupnik, I., Lopez-Martinez, J., Mohr, T., Qin, D., Rachold, V., Rapley, C., Rogne, O., Sarukhanian, E., Summerhayes, C. and Xiao, C. (2007). The scope of science for the International Polar Year 2007–08. Produced by the ICSU/ World Meteorological Organization, Geneva

Ban, K.M. (2008). Statement by United Nations Secretary-General Ban-Ki moon at the opening of the High-Level Segment of COP 14 in Pozna, December11, 2008 http://unfccc.int/2860.php

Barnett, T.P. and Pierce, D.W. (2008). When will Lake Mead go dry? *Water Resources Research*, 44, W03201, doi:10.1029/2007WR006704

BAS (2008). *Antarctic ice shelf 'hangs by a thread'*. British Antarctic Survey http://www.antarctica.ac.uk/press/press_releases/press_release.php?id=376

Bell, R.E. (2008). The role of subglacial water in ice-sheet mass balance. *Nature Geoscience* 1(5), 297-304

Betts, R., Sanderson, M. and Woodward, S. (2008). Effects of large-scale Amazon forest degradation on climate and air quality through fluxes of carbon dioxide, water, energy, mineral dust and isoprene. *Philosophical Transactions of the Royal Society B*, 363(1498), 1873-1880

Blais, J.M., Schindler, D.W., Muir, D.C.G., Sharp, M., Donald, D., Lafrenière, M., Braekevelt, E. and Strachan W.M.J. (2001). *Melting Glaciers: A Major Source of Persistent Organochlorines to Subalpine Bow Lake in Banff National Park, Canada*. http://ambio.allenpress.com/perlserv/?request=get-document&doi=10.1639%2F0044-7447(2001)030[0410%3AMGAMSO]2.0.CO%3B2&ct=1

Bohannon, J. (2008). Weighing the climate risks of an untapped fossil fuel. *Science*, 319(5871), 1753

Branan, N. (2008). *Chemicals melt out of glaciers*. http://www.geotimes.org/aug08/article.html?id=nn_glaciers.html [Accessed 21 November 2008]

Braun, M., Humbert, A. and Moll, A. (2008). Changes of Wilkins ice shelf over the past 15 years and inferences on its stability. *The Cryosphere Discussions* 2(3), 341-382

Brovkin, V. and Claussen, M. (2008). Climate-Driven Ecosystem Succession in the Sahara: The Past 6000 Years. Science, 322: 1326 DOI: 10.1126/science.1163381 [Accessed 28 November 2008]

Brown, S.J., Caesar, J. and Ferro, C.A.T. (2008). Global changes in extreme daily temperature since 1950. *Journal of Geophysical Research*, 113, D05115, doi:10.1029/2006JD008091

Canadell, J.G. and Raupach, M.R. (2008), Managing forest for climate change mitigation. *Science*, 320(5882), 1456-1457

Carlson, A.E., LeGrande, A.N., Oppo, D.W., Came, R.E., Schmidt, G.A., Anslow, F.S. Licciardi, J.M. and Obbink, E.A. (2008). Rapid early Holocene deglaciation of the Laurentide ice sheet. *Nature Geoscience*, 1(9), 620–624

CDIAC (2008). Carbon Dioxide Information Analysis Center. http://cdiac.ornl.gov

Charbit, S., Paillard, D. and Ramstein, G. (2008). Amount of CO2 emissions irreversibly leading to the total of melting of Greenland. *Geophysical Research Letter*, 35, L12503, doi:10.1029/2008GL033472

Connor, S. (2008). Hundreds of methane 'plumes' discovered. *The Independent*, 25 September 2008.

Cook, K.H. (2008). The mysteries of Sahel droughts. *Nature Geoscience*, 1(10), 647-648

Cox, P.M., Harris, P.P., Huntingford, C., Betts, R.A., Collins, M., Jones, C.D., Jupp, T.E., Marengo, J.A. and Nobre, C.A. (2008). Increasing risk of Amazonian drought due to decreasing aerosol pollution, *Nature*, 453(7192), 212-215

Das, S.B., Joughin, I., Behn, M.D., Howat, I.M., King, M.A., Kizarralde, D. and Bhatia. M.P. (2008). Fracture propagation to the base of the Greenland ice sheet during supraglacial lake drainage, *Science*, 320(5877), 778–781

Elsner, J.B., Kossin, J.P. and Jagger, T.H. (2008). The increasing intensity of the strongest tropical cyclones. *Nature*, 455(7209), 92-94

ESA (2008). Wilkins Ice Shelf under threat. European Space Agency. http://www.esa.int/esaCP/SEMXK5AWYNF_index_1.html [Accessed 10 November 2008]

Gauci, V., Dise, N.B., Howell, G. and Jenkins, M.E. (2008). Suppression of rice methane emission by sulfate deposition in simulated acid rain. *Journal of Geophysical Research*, 113, G00A07, doi:10.1029/2007JG000501

Geisz, H.N., Dickhut, R.M., Cochran, M.A., Fraser, W.R. and Ducklow, H.W. (2008). Melting glaciers: a probable source of DDT to the Antarctic marine ecosystem. *Environmental Science and Technology*, 42(11), 3958-3962

Gillett, N.P. Stone, D.A, Stott, P., Nozawa, T., Karpechko, A.Y., Hegerl, G.C., Wehner, M.F., and Jones, P.D. (2008), Attribution of polar warming to human influence. *Nature Geoscience*, 1, 750-754.

Global Carbon Project (2008). *An annual update of the global carbon budget and trends*. Carbon Budget 2007. http://www.globalcarbonproject.org/carbontrends/index_new.htm

Goelzer, H., Levermann A., Rahmstorf, S. (2008). Long-term transient response of ENSO to climate change in a coupled model of intermediate complexity. *Geophysical Research Abstracts*, 10, 1607-7962

Goodkin, N.F., Hughen, K.A., Doney, S.C. and Curry, W.B. (2008). Increased multidecadal variability of the North Atlantic Oscillation since 1781. *Nature Geoscience*, 1, 844-848 doi: 10.1038/ngeo352

Graversen, R.G., Mauritsen, T., Tjernstrom, M., Kallen, E. and Svensson, G. (2008). Vertical structure of recent Arctic warming. *Nature*, 451(7174), 53-56

Harris, P.P., Huntingford, C. and Cox, P.M. (2008). Amazon Basin climate under global warming: the role of sea surface temperature. *Philosophical Transactions of the Royal Society B*, 363(1498), 1753-1759

Holland, D.M., Thomas, R.H., de Young, B., Ribergaard, M.H. and Lyberth, B. (2008). Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience*, 1(10), 659-664

IPCC (2007). Climate Change 2007: The physical science basis: contribution of working group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, New York

Ise, T., Dunn, A.L., Wofsy, S.C. and Moorcroft, P.R. (2008). High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience*, doi: 10.1038/ngeo331

Jevrejeva, S., Moore, J.C., Grinsted, A. and Woodworth, P.L. (2008). Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letter*, 35, L08715, doi:10.1029/2008GL033611

Joughin, I., Das, S.B., King, M.A., Smith, B.E., Howat, I.M. and Moon, T (2008). Seasonal Speedup Along the Western Flank of the Greenland Ice Sheet. *Science*, 320(5877), 781-783

Kay, J., l'Ecuyer, T., Gettelman, A., Stephens, G. and O'Dell, C. (2008). The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum. *Geophysical Research Letter*, 35, L08503, doi:10.1029/2008GL033451

Keenlyside, N.S., Latif, M., Jungclaus, J., Kornblueh, L. and Roeckner, E. (2008). Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, 453(7191), 84-87

Khvorostyanov, D.V., Ciais, P., Krinner, G. and Zimov, S.A. (2008). Vulnerability of east Siberia's frozen carbon stores to future warming. *Geophysical Research Letter*, 35, L10703, doi:10.1029/2008GL033639

Klein, R.J.T., Alam, M., Burton, I., Dougherty, W.W., Ebi, K.L., Fernandes, M., Huber-Lee, A., Rahman, A.A. and Swartz, C. (2006). Application of Environmentally Sound Technologies for Adaptation to Climate Change. Technical Paper FCCC/TP/2006/2, United Nations Framework Convention on Climate Change Secretariat, Bonn, Germany, 107 pp

Knutson, T.R., Sirutis, J.J., Garner, S.T., Vecchi, G.A. and Held, I.M. (2008). Simulated reduction in Atlantic hurricane frequency under twenty-first century warming conditions. *Nature Geoscience*, 1(6), 359-364

Kropelin, S., Verschuren, D, Lezine, A-M., Eggermont, H., Cocquyt, C., Francus, P., Cazet, J-P., Fagot, M., Rumes, B., Russel, J.M., Darius, F., Conley, D.J., Schuster, M., von Suchodoletz, H., and Engstrong, D.R. (2008), Climate-driven ecosystem succession in the Sahara: the past 6000 years. *Science*, 320(5877), 765-768

Kucharski, F., Yoo, J.H., Bracco, A. and Molteni, F. (2008). Atlantic forced component of the Indian monsoon inter-annual variability. *Geophysical Research Letter*, 35, L04706, doi:10.1029/2007GL033037

Lawrence, D.M., Slater, A.G., Tomas, R.A., Holland, M.M. and Deser, C. (2008). Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. *Geophysical Research Letter*, 35, L11506, doi:10.1029/2008GL033985

Lenderin, G. and van Meijgaard, E. (2008). Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*, 1(8), 511-514

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J. (2008). Tipping elements in the Earth's climate system. *Proceedings of National Academy of Sciences*, 105(6), 1786-1793

Lozier, S. (2009). Overturning assumptions. Nature Geoscience 2, 12-14 www.nature.com/naturegeoscience [Accessed 20 December 2008]

Malhi, Y., Roberts, J.T., Betts, R.A., Killeen, T.J., Li, W. and Nobre, C.A. (2008). Climate Change, Deforestation, and the Fate of the Amazon. Science, 319(5860): 169-172 DOI:10.1126/science.1146961

NESRC (2008). *No new ice minimum in the Arctic in 2008*. Nansen Environmental and Remote Sensing Center. http://www.nersc.no/main/index2.php?display=moreinfo&news_id=237&displayNews=1

NSIDC (2008). *Arctic sea ice news and analysis*. National Snow and Ice Data Center. http://nsidc.org/arcticseaicenews/

O'Cofaigh, C.Ó. and Stokes, C.R. (2008). Reconstructing ice-sheet dynamics from subglacial sediments and landforms: introduction and overview. Earth Surface Processes and Landforms, 33(4), 495-502

Perovich, D.K., Richter-Menge, J.A., Jones, K.F. and Light, B. (2008). Sunlight, water and ice: extreme Arctic sea ice melt during the summer of 2007. *Geophysical Research Letter*, 35, L11501, doi:10.1029/2008GL034007

Pfeffer, W.T., Harper, J.T. and O'Neel, S. (2008). Kinematic constraints on glacier contributions to 21st century sea-level rise. *Science*, 321(5894), 1340-1343

Piao, S., Ciais, P., Friedlingstein, P., Peylin, P., Reichstein, M., Luyssaert, S., Margolis, H., Hanf, J., Barr, A., Chen, A., Grelle, A., Hollinger, D.Y., Laurila,T., Lindroth, A., Richardson, A.D. and Vesala, T. (2008). Net carbon dioxide losses of northern ecosystems in response to autumn warming. *Nature*, 451(7174), 49-53

Ping, C.L., Michaelson, G.J., Jorgenson, M.T., Kimble, J.M., Epstein, H., Romanovsky, V.E. and Walker, D.A. (2008). High stocks of soil organic carbon in the North American Arctic region. *Nature Geoscience*, 1(9), 615-619

Ramanathan, V. and Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience*, 1(4), 221-226

Rigby, M., Prinn, R. G. Fraser, P. J., Simmonds, P. G., Langenfelds, R. L., Huang, J. , Cunnold, D. M., Steele, L. P., Krummel, P. B., Weiss, R. F., O'Doherty, S., Salameh, P. K., Wang, H. J., Harth, C.M., Mühle, J. and Porter, L. W. (2008). Renewed growth of atmospheric methane, Geophys. Res. Lett., 35, L22805, doi:10.1029/2008GL036037.

Rignot, E., Bamber, J.L., van den Broek, M.R., Davis, C., Li, Y., van deBerg, W.J. and van Meijgaards, E. (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geoscience*, 1(2), 106-110

Ruckstuhl, C., Philipona, R., Behrens, K., Coen, M.C., Durr, B., Heimo, A., Matzler, C., Nyeki, S., Ohmura, A., Vuilleumier, L., Weller, M., Wehrli, C. and Zelenka, A. (2008). Aerosol and cloud effects on solar brightening and the recent rapid warming. *Geophysical Research Letter*, 35, L12708, doi:10.1029/2008GL034228

Schellnhuber, H.J. (2008). Global warming: stop worrying, start panicking? *Proceedings of the National Academy of Sciences*, 105(38), 14239-14240

Schiermeier, Q. (2008). *Sea level rise: Linear or not?* Nature Online. http://blogs.nature.com/news/blog/2008/04/sea_level_rise_linear_or_not.html

Schindler, D.W. and Parker, B.R. (2002). *Water Air Soil Pollution. Focus*, (2)379–397

Schuur, E.A.G., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann, S., Kuhry, P., Lafleur, P.M., Lee, H., Mazhitova, G., Nelson, F.E., Rinke, A., Romanovsky, V.E., Shiklomanov, N., Tarnocal, C., Venevsky, S., Vohel, J.G. and Zimov, S.A. (2008), Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *Bioscience*, 58(8), 701-714

Semenov, V.A. (2008). Influence of the oceanic inflow to the Barents Sea on Arctic climate variability. *Doklady Earth Sciences*, 418(1), 91-94

Semiletov, I. (2008). *International Siberian Shelf Study 2008*. International Arctic Research Center, ISS08-Update, 15 September 2008. http://www.iarc.uaf.edu/expeditions/?cat=8

Shaw, J. (2002). The meltwater hypothesis for subglacial bedforms, *Quaternary International* 90 (2002) 5–22

Smith, L.A. (2008). *Climate modelling is still an abstraction of reality*. The uncertainty in climate modelling: In Roundtable discussion. Bulletin of Atomic Sciences. http://www.thebulletin.org/web-edition/roundtables/the-uncertainty-climate-modeling

Sobel, A.H., Maloney, E.D., Bellon, G. and Frierson, D.M. (2008). The role of surface heat fluxes in tropical intraseasonal oscillations. *Nature Geoscience*, 1(10), 653-656

Stammer, D. (2008). Response of the global ocean to Greenland and Antarctic ice melting. *Journal of Geophysical Research*, 113, C06022, doi:10.1029/2006JC004079

Stone, R.S., Anderson, G.P., Shettle, E.P., Andrews, E., Loukachine, K., Dutton, E.G., Schaaf, C. and Roman III, M.O. (2008). Radiative impact of boreal smoke in the Arctic: Observed and modelled. *Journal of Geophysical Research*, 113, D14S16, doi:10.1029/2007JD009657

Subramaniam, A., Yager, P.L., Carpenter, E.J., Mahaffey, C., Bjorman, K., Cooley, S., Kustka, A.B., Montoya, J.P., Sanudo-Wilhemly, S.A., Shipe, R. and Capone, D.G. (2008). Amazon River enhances diazotrophy and carbon sequestration in the tropical North Atlantic Ocean. *Proceedings of National Academy of Science*, 105(30), 10460-10465

Thompson, A. (2007). Carbon Consumers: Bacteria cause net CO2 uptake in the Amazon River plume, *Nature Geoscience*, 5, 66-67

Toggweiler, J.R. and Russell, J. (2008). Ocean circulation in a warming world. *Nature*, 451, 286-288 doi:10.1038/nature06590

UN-HABITAT (2008). State of the World's Cities 2008/9: Harmonious Cities. London, Earthscan

Våge, K., Pickart, R.S., Thierry, V., Reverdin, G., Lee, C.M., Petrie, B., Agnew, T.A., Wong, A. and Ribergaard, M.H. (2008). Surprising return of deep convection to the subpolar North Atlantic Ocean in winter 2007–08. *Nature Geoscience*, 2, 67–72 doi:10.1038/NGEO382

Van de Wal, R.S.W., Boot, W., van den Broeke, M.R., Smeets, C.J.P.P., Riejmer, C.H., Donker, J.J.A. and Oerlemans, J. (2008). Large and rapid melt-Induced velocity changes in the ablation zone of the Greenland ice sheet. *Science*, 321(5885), 111-113

Van Oldenborgh, G.J., Drijfhout, S., van Ulden, A., Haarsma, R., Sterl, A., Severijns, C., Hazeleger, W. and Dijkstra, H. (2008). Western Europe is warming much faster than expected. *Climate of the Past Discussions*, 4(4), 897-928

WGMS (2008a). *Global glacier changes: facts and figures*. UNEP/World Glacier Monitoring Service, Zurich

WGMS (2008b). *Glacier mass balance data 2005-2006*. UNEP/World Glacier Monitoring Service, Zurich. http://www.geo.unizh.ch/wgms/mbb/mbb9/sum06.html