2 Positive Feedbacks, Dynamic Ice Sheets, and the Recarbonization of the Global Fuel Supply: The New Sense of Urgency about Global Warming

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I am delighted to be here to talk about my understanding of the current state of climate science. I should start by saying that I am not trained as a climate scientist, although I have been working in the area and reading the literature on climate science for twenty years, since my PhD studies at MIT. I have written articles with climate scientists, and I am deeply interested in the social and technological implications of climate change.

I think I have my finger on the pulse of the climate science community at the moment, and what I've noticed in the last several years is a shift in the perspective of leading scientists regarding the seriousness of the climate situation. A few years ago they regarded global warming as a matter of serious concern; now most appear to think that it's a matter of grave urgency – that we may be literally running out of time. The recent IPCC (Intergovernmental Panel on Climate Change) reports are increasingly viewed as out of date. Leading scientists perceive these reports as underestimating the degree and rapidity of climate change and the severity of its consequences.

We have to keep in mind that – around mid-2005 – the IPCC process brought a guillotine down on the scientific findings that were to be incorporated in the reports. These reports therefore do not reflect almost two years of extraordinarily important findings from multiple streams of scientific research. Indeed, immediately after the Working Group 1 report was released (in February 2007),[1] many climate scientists and geophysicists working on ice-sheet dynamics argued that it significantly underestimated potential sea-level rise this century. More recently, we've seen much higher carbon dioxide emissions than were anticipated by the IPCC, while the absorptive capacity of ocean and land-based carbon sinks appears to be decreasing more rapidly than anticipated.

Scientists working in this area are principally concerned about three issues: one concerns an underlying mechanism of climate change; another concerns key consequences of climate change; and the final issue concerns the nature of human energy systems. I'll talk about each of these issues today, and they're highlighted in the title of my presentation.

The first is destabilizing or 'positive' climate feedback. A positive feedback is a causal cycle – essentially a vicious circle – in which warming causes a series of changes that reinforce warming. There are two main kinds of positive feedback: the kind that operates more or less directly on temperature and the kind that operates on the carbon cycle. The feedbacks that operate on temperature are reasonably well incorporated into contemporary climate models. Those that operate on the carbon cycle are not, and it's becoming increasingly clear that they're the ones that could literally be deal-breakers for humanity. We may be quite close to creating circumstances in which the biosphere releases enormous quantities of carbon into the atmosphere. At that point, global warming could become its own cause, and it wouldn't really matter what we do in terms of mitigating our emissions of carbon dioxide – the global ecosystem would take over.

The next issue concerns ice-sheet dynamics: the nature of melting ice sheets, especially the Greenland ice sheet, and the rate at which they're melting. I'll talk more about this subject in a minute.

Finally there is the issue of the recarbonization of the global fuel supply. We have recently seen a reversal of a very important trend that had prevailed for about two hundred years – a progressive decarbonization of fuel supplies around the world. This trend meant that we released, over time, less and less carbon into the atmosphere for every unit of energy we produced. In the past five years, that trend has reversed, with potentially staggering implications for climate change.

Now, before going into these issues in more detail, I want to say a little bit about what I think is the decisive defeat of three main arguments that have been introduced over the years by climate sceptics. These are the arguments firstly about long-term temperature change, secondly about satellite data on tropospheric warming, and thirdly about radiation from the sun. I will make only brief remarks about each one of these sceptical arguments, because I think they have been pretty well demolished and shown to be invalid by careful research. The defeat of these arguments has great consequence for the larger debate about the policy implications of climate change.

The first argument concerns the long-term trend of Earth's average surface temperature. In 1999, Mann, Bradley, and Hughes released a paper that estimated average global temperature for the last millennium. This work was subsequently updated by Mann and Jones in 2003 to provide a temperature record from the years 200 to 2000 AD.[2] These researchers combined a number of different paleoclimatological records – like tree rings and coral growth rates – that are 'proxy' measures of atmospheric temperature during various historical epochs. They cobbled these proxy measures together to get a long-term record of the planet's temperature. Their graph famously showed a sharp uptick over the last half-century, which is why it was widely labelled the 'hockey stick' graph. It has been one of the most contentious pieces of evidence used to support the claim that we are experiencing an abnormally warm period.

You are probably familiar with this debate; it has been covered in the pages of the *Globe and Mail*. In response to criticism of the statistical methodology used to cobble these records together, the National Academy of Sciences in the United States created a panel to examine the Mann et al. methodology. The panel released its results last year, saying that, overall, while some questions remained about the methodology, the original study's conclusions were largely correct: the warming of the last 40 years very likely made Earth hotter than anytime in the last 1000 years, and it certainly made Earth hotter than anytime in the last 400 years. I think the National Academy of Sciences report dealt with the hockey stick issue; it's off the table now, except for some – and I use this word deliberately – crazies out there.[3]

The second argument concerns satellite data. There has been an enormous debate about an apparent discrepancy between data from satellites that show no warming in the troposphere and data from ground-level instruments that show warming. The argument was originally made by John Christy of the University of Alabama in Huntsville. But recent studies have looked very carefully at this apparent discrepancy between satellite and ground-level data and have shown that Christy and his colleagues made a number of methodological and statistical errors. Once these errors are corrected, the discrepancy disappears.[4] The satellite record actually shows tropospheric warming – in fact, it shows both tropospheric warming and, as we would expect from global warming theory, stratospheric cooling.

The third argument concerns radiation from the sun. The most common argument now put forward by climate sceptics is that the recent warming is a result of changes in the intensity of the sun's radiation. But a major review article last year in the journal *Nature* showed that it's virtually impossible to explain the warming we've seen in the last 40 years through changes in solar radiation.[5] This research is pretty well definitive, too.

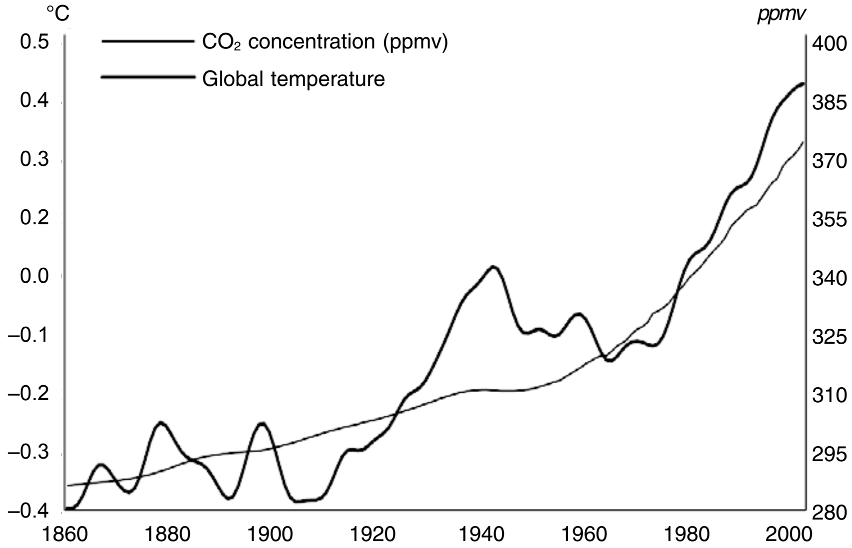
So, these three arguments used by sceptics have been largely put to rest. We are now down to a hard core of climate change deniers who are essentially impervious to any evidence – and they write me all the time. Sometimes I engage in an amusing exercise just to see how detached from reality they can actually be. I send them scientific papers and reports on the latest climate research, and invariably the evidence in these reports makes absolutely no difference to their point of view.

This kind of psychological resistance points to something I think we need to confront directly: a process of denial of evidence that is quite powerful in some parts of our society and in some individuals. I think there are three stages of denial, which I talk about in my latest book.[6] The first is *existential* denial, where one denies the actual existence of the phenomenon. But existential denial is hard to sustain when the evidence becomes overwhelming, as is now the case with climate change. So, people tend to move away from existential denial and start engaging in what I call *consequential* denial, in which they deny that the consequences of the problem are going to be particularly serious. This is essentially the position taken by a lot of climate change sceptics now. They're saying, 'okay, there's climate change, but we can deal with it. It's basically a pollution problem that is not so serious. We can adapt as necessary.'

The evidence is also increasing, of course, that we won't be able to adapt adequately to the magnitude of the climate change that's likely even this century – or that the economic and social consequences of this change will be so great that, if we try to adapt, we'll still need to aggressively mitigate our output of carbon dioxide. So the final position, once it becomes impossible to support even consequential denial, is what I call *fatalistic* denial: one basically accepts that the problem is real and that it's going to hurt a lot, but then one simply says, 'there's nothing we can do about it.' In my future research I want to explore the larger social consequences of widespread fatalistic denial. I think they could be astonishingly bad.

Let me go on to quickly give you a sense of the three issues that I

Figure 2.1. Average global temperature increase



talked about before: positive feedback, ice-sheet dynamics, and recarbonization of the fuel system. Let's talk first about what the recent IPCC Working Group I report said about global warming to date – that the 'warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.' Figure 2.1 shows CO_2 concentration, which is the thinner line, and global temperature, which is the darker line. The period of particular interest to scientists is in the past 40 years when there appears to be, prima facie, quite a close correlation between CO_2 concentrations and global temperature.

From November 2006 through February 2007, large parts of Canada experienced warming in the neighbourhood of 2°C to 4°C. I'll give you a sense of the magnitude of that change: prior to this recent bout of warming over the last 40 years, Earth's average temperature had increased only about 5°C from the coldest period of the last ice age 15,000 years ago. Last winter's warming was most pronounced in the northern part of the planet – in the neighbourhood of 6°C – a fact that I'll return to shortly.

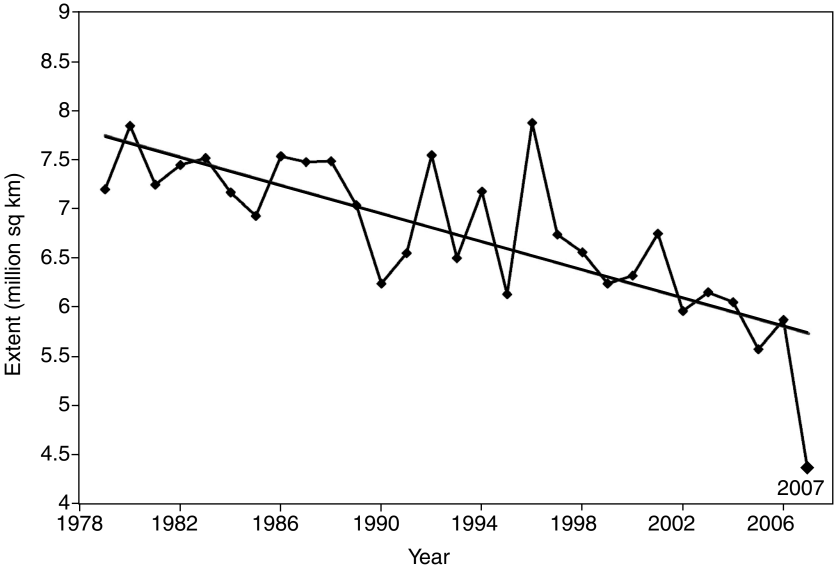
Using a range of scenarios with different configurations of technology, energy consumption, population growth, and trade relations between North and South, Working Group 1 estimated that warming in 2100 would fall between 1.1°C and 6.4°C, with the best estimate around 3°C. The scenario that I think represents the most likely modified 'business-as-usual' future is A1B, which predicts about 3°C by 2100. The Working Group also projected that 'climate sensitivity' – the amount of warming a doubling of pre-industrial levels of CO_2 (i.e., from 280 ppm to 560 ppm) will produce – will also be about 3°C, with a range from 2°C to 4.5°C. But they additionally said something very important that has not been widely reported – that values significantly higher than 4.5°C cannot be excluded. Computer models of the climate tend to break down at this upper range, but nonetheless substantial evidence now suggests we may see such extreme warming.

In the A1B scenario, by 2020 to 2029 Canada will warm between 1.5°C and 2.5°C; by 2090 to 2099, Canada will warm in the neighbourhood of 6°C to 7°C. Some people say that Canada is going to benefit from climate change. Well, let me challenge that assertion: we may have lower heating bills in the winter for a few years, but because we're a polar country, warming here will be twice as fast and the ultimate magnitude will be twice as great as the average warming for the planet. Optimistic comments about benefits to Canada neglect warming's staggering consequences for our flora and fauna, for our forests that can't adapt and will die en masse, for Canada's central grain-growing regions that could easily turn to desert, for the Great Lakes as their water levels fall, for transportation in the St Lawrence Seaway, and for northern permafrost that will melt. In actual fact, climate change may ultimately affect Canada as harshly as any country in the world.

Why are we warming more rapidly in the planet's northern reaches? The basic reason is the ice-albedo feedback. The sea ice floating on the surface of the Arctic Ocean is white, so it reflects a large proportion of the sun's radiation back into space. As this sea ice melts from global warming, it leaves behind open ocean water that absorbs about 80 per cent more of the sun's radiation. The ocean water becomes warmer. Then, after the summer passes in the north and fall comes, the water releases its heat back into the atmosphere, which impedes the refreezing of ice. So winter generates thinner ice, and this ice melts more easily the following summer. This is a positive feedback, a vicious circle.

Figure 2.2 was produced by the National Snow and Ice Data Center in Boulder, Colorado. It shows the minimum extent of Arctic sea ice

Figure 2.2. Minimum Arctic sea ice cover



each year going back to 1978. The Arctic ice cap melts somewhat every summer – it always has and still does. Sea ice extent reaches its minimum sometime around the middle of September, and then as the days get shorter and cooler the ice starts to recover. A regression line has been plotted through the points up to 2006, showing a steady decline in ice extent, year by year. Notice that the melting in 2007 was much more severe and showed a sharp downward divergence from the trend. By 16 September 2007, we had lost about a third of the Arctic ice cap compared to the 1979–2000 average, and about 50 per cent compared to the 1950s average. The current expectation among scientists is that we will see a completely ice-free Arctic ocean in summer by the end of the next decade – perhaps even as early as 2013. I want to say a couple of words about the implications of this extraordinary change.

The last thing we should be worrying about or thinking about, I believe, is whether we're going to be able to run a lot of ships through the Arctic, or whether we'll be able to explore for oil and gas there as the ice vanishes. The area above the Arctic Circle makes up about nine per cent of the total surface area of Earth above the equator. The loss of ice will change the reflectivity of much of the polar region and therefore alter the energy balance of the northern half of the planet. We can't fully predict the consequences of this change, but they may be severe.

In the northern hemisphere, there are three important cycles of atmospheric circulation between the equatorial region and the pole. They are called Hadley cells. In each cell, warm air rises at the southern end of the cycle and flows northward at high altitude. Then, when the air cools, it descends to the surface and flows southward back to the starting point. There is a cell in the equatorial region, another at mid-latitude, and another over the Arctic. Some climate scientists think that loss of the Arctic sea ice could cause the Hadley cell in that region to break down, which would have consequences for the paths of jet streams further south. Jet streams influence storm tracks and precipitation patterns, which can in turn intimately affect our ability to grow food.

Let me now say a little bit more about some other feedbacks. This is one of the punch lines of my presentation today. I mentioned earlier that there are two general kinds of feedback: those that operate more-or-less directly on temperature, such as the ice-albedo feedback, and those that operate on Earth's carbon cycle, where warming produces a change in the amount of carbon in the atmosphere. We have a fairly good understanding of the former and not such a good understanding of the latter. One carbon feedback that worries scientists involves the melting of the permafrost in Siberia, Alaska, and Northern Canada. As the permafrost melts it releases large quantities of methane – a very powerful greenhouse gas that, in turn, causes more warming. Scientists are also concerned about the potential release of more carbon dioxide from forests: just yesterday researchers reported evidence that, as the climate has warmed, the Canadian boreal forest has gone from being a carbon sink to a slight carbon emitter.

And then there's the matter of pine bark beetles. As you likely know, we've lost wide swaths of pine forest in British Columbia and Alaska – huge areas of trees – to bark-beetle infestation. As the climate warms, bark-beetle populations reproduce through two generations during the summer, and beetle mortality is lower during the winter. Both these changes mean that beetle populations become much larger overall. If these larger populations cross the Rockies and get into the boreal forest that stretches from Alberta to Newfoundland, and if they kill that forest, the forest will be susceptible to fire that could release astounding quantities of carbon dioxide. I asked Stephen Schneider, a leading climate scientist at Stanford, about the implications of such a development. He just shrugged and said, 'well, we're talking about billions of tonnes of carbon.'

Other potentially destabilizing carbon-cycle feedbacks include the drying of the Amazon and the possibility that if it dries it will burn; the drying of peat bogs in Indonesia, which have already been susceptible to wide-spread burning; and the saturation of ocean carbon sinks. The Southern Ocean around Antarctica is no longer absorbing carbon dioxide to the extent it did in the past. Warming has produced much more vigorous winds closer to Antarctica. These winds have churned up the sea and brought to the surface deep carbon-rich water, which absorbs less carbon from the atmosphere. Also, higher levels of carbon dioxide in the atmosphere are acidifying the oceans, a change could reduce populations of molluscs and phytoplankton that absorb carbon into the calcium carbonate of their shells.

Our climate has both positive and negative feedbacks. The positive ones are self-reinforcing, and the negative ones equilibrate the climate and counteract the tendency towards self-reinforcing climate change. The big question for climate scientists then is: What is the balance is between the positive and negative feedbacks? A consensus has emerged over the last two years – a consensus again not reflected in the recent IPCC reports – that the positive feedbacks in the climate system are much stronger and more numerous than the negative feedbacks.

In a paper published last year in *Geophysical Research Letters*, Scheffer, Brovkin, and Cox carried out a comprehensive assessment of the feedback situation.[7] They wrote, '[we] produce an independent estimate of the potential implications of the positive feedback between global temperatures and greenhouse gasses.' In other words, these researchers focused specifically on carbon cycle feedbacks. They went on, 'we suggest that feedback of global temperature and atmosphere CO_2 will promote warming by an extra 15% to 78% on a century scale over and above the IPCC estimates.'

Let's turn to the issue of dynamic ice sheets. The Greenland ice sheet is the second largest mass of ice in the world, after that in Antarctica. If we melt Greenland entirely, we get seven metres of sea-level rise. If we melt the West Antarctic ice sheet, we get another five metres. If we melt the rest of Antarctica, we get an additional fifty or so metres. The Greenland ice sheet will probably be the first to melt, because it's the most vulnerable. During the last interglacial period 125,000 years ago, when temperatures were roughly what they're going to be at the end of this century, much of Greenland melted, and sea levels were four to six metres higher than they are right now.

We are probably already committed to temperatures in that range with the industrialization processes that are underway on the planet, especially in China and India. The estimate of the sea-level rise for this century that the IPCC produced was twenty to sixty centimetres – or somewhere around half a metre. Two independent studies of Greenland in the last two years, neither reflected in the IPCC reports, suggest that the ice sheet is now melting at the rate of 200 to 250 cubic kilometres a year, which is about 200 times the amount of water that Los Angeles consumes each year. According to the most recent study, that rate has doubled in the last ten years. That study used satellites to measure slight variations in the gravitational field around the planet; and based on these variations, the researchers estimated change in the mass of the Greenland ice sheet.[8] The two studies used very different methodologies, but their results correspond closely. So we can be confident that we're already seeing the Greenland ice-sheet disappear quite quickly.

Climate scientists now recognize that the models of ice sheet melting that the IPCC reports relied upon to estimate sea-level rise were radically inadequate. These models were 'static,' in that they assumed that atmospheric warming melts the ice, and the resulting water then runs off the surface of the ice sheet and down into the ocean. Scientists now know that these ice sheets have cracks in them. Water runs down the cracks, and as the ice melts the cracks can sometimes expand into gaps 10 to 15 metres across, with millions of tonnes of water flowing downwards. This flow creates pools underneath the ice sheets that lubricate the movement of glaciers and increase the speed of glacial movement into the ocean. Rates of movement are much higher than the IPCC reports expected. This phenomenon has truly scared scientists close to the subject.

Let me read some quotations of Robert Corell, chairman of the Arctic Climate Impact Assessment, the principle synthetic report on the state of the Arctic climate. Commenting on the Ilulissat glacier in northwest Greenland just a few weeks ago, he said 'we have seen a massive acceleration of the speed with which these glaciers are moving into the sea. The ice is moving at 2 meters an hour on a front 5 km long and 1,500 metres deep. That means that this one glacier puts enough fresh water into the sea in one year to provide drinking water for a city the size of London for a year.' He had flown over the glacier and seen 'gigantic holes in it through which swirling masses of melt water were falling. I first looked at this glacier in the 1960s and there were no holes. These so-called moulins, 10 to 15 meters across, have opened up all over the place. There are hundreds of them.'[9] The glacier is moving at 15 km a year into the sea, although it sometimes surges forward much faster. He measured one surge at 5 km in 90 minutes.

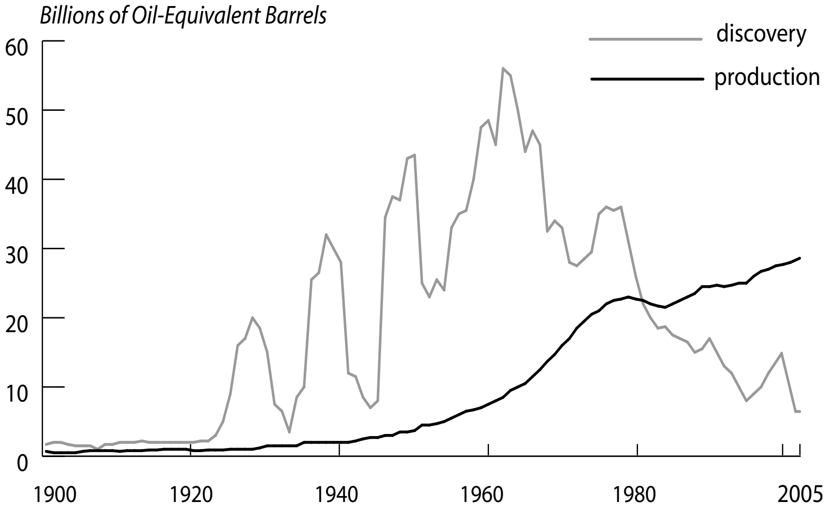
Big things are happening in Greenland – things that will affect sea level. The consensus emerging now among climate scientists is that we're going to see oceans rise by a metre this century and that we may even see two metres. A change of this magnitude would have enormous effects on coastal areas of Canada – on residential areas in Victoria and Vancouver (especially on the municipalities of Delta and Richmond in the Lower Mainland) and on the ports of Vancouver, St John's, and Halifax. With a two metre rise, concerns about rebuilding infrastructure and moving populations inland will – in a few decades – become real, even urgent.

With regards to global warming, changes are generally happening much faster than anticipated even a few years ago by the best scientific consensus as reflected in the IPCC reports. Faster change raises the issue of the relative balance – in terms of our policy response – between mitigation and adaptation. Some observers argue, myself among them, that we need to shift some of our policy resources to adaptation. We're going to see significant warming, with sometimes severe consequences, and we need to get ready for these consequences at the urban, municipal, and national levels. Of course, we can't neglect efforts to reduce carbon dioxide output. But in some respects the mitigation challenge we face is almost impossibly hard.

I'll give you an indication of what we're up against. Very soon humankind must cap and then ramp down global carbon emissions. We have very little room to warm: the estimated maximum safe warming from pre-industrial temperatures is around 2°C; beyond that point we get into a world where the positive feedbacks I've just discussed may develop great force. The warming to date has been about 0.8°C, and the warming in the pipeline – even if all emissions cease right now – is about 0.6°C. This leaves us with around 0.6°C room to warm.

Limited room to warm implies, in turn, that we have very little room to emit. The estimated carbon dioxide concentration that's likely to produce at least 2°C warming is about 450 ppm. (This is actually a conservative estimate; some people would put the threshold for carbon dioxide much lower. Notice, for instance, that I am talking about atmospheric carbon dioxide and not 'carbon dioxide equivalent.' In other words, these 450 ppm do not include chlorofluorocarbons, nitrous oxide, and a number of other powerful greenhouse gases. If they did, the actual limit for CO_2 itself would be much lower than 450 ppm.) The current concentration of CO_2 is about 380 ppm, so the room to emit, therefore, is about 70 ppm. The incremental annual increase is currently about 2 ppm and rising, so we have about 30 years left until we reach

Figure 2.3. Peak oil

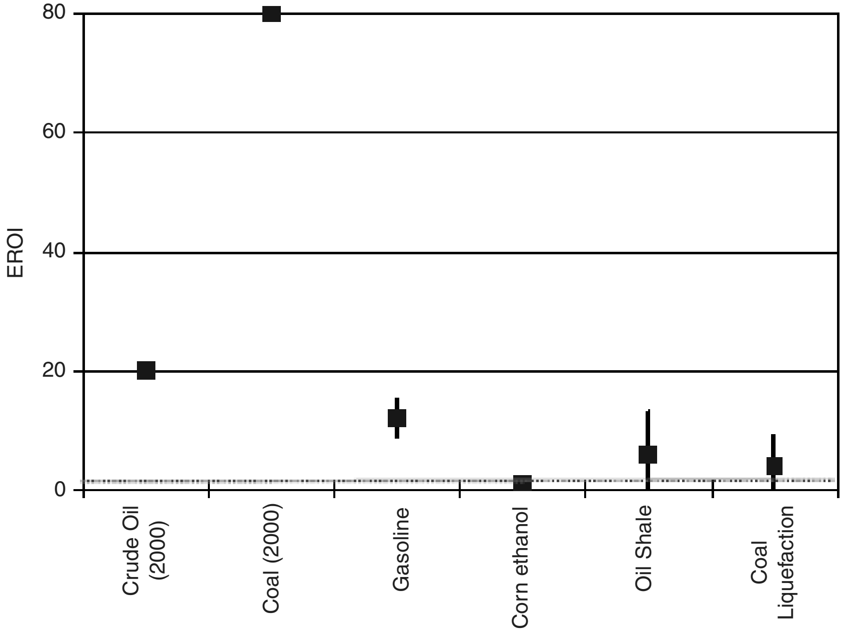


450 ppm. That doesn't mean we have 30 years before we have to start worrying about this problem: it means that in 30 years we'd better be heading south on carbon emissions really fast.

Indeed, we need to be heading towards an 80 to 90 per cent cut in carbon emissions by 2050. Scientists are talking about that kind of reduction, as are environmental activists, but in Canada it isn't even on the policy radar screen at the moment (notably, a number of U.S. Democratic and Republican presidential candidates have committed themselves to such reductions).

My last few comments concern the recarbonization of the global fuel supply. Figure 2.3 is a chart of world oil production and discovery. The lighter line is oil discovery and the darker line is oil production from 1900 and to 2000. We are very close to – if we aren't already at – a peak in the world's conventional oil production. Oil provides 40 per cent of the world's commercial energy and 98 per cent of its transportation energy. It's the stuff that the global economy literally runs on. And it's going to become more expensive, in terms of the energy cost of energy production. As we pass the mid-point of the amount of oil that's ultimately available on the planet, oil companies are finding that they have to go further and deeper into more hostile environments to find smaller pools of lower quality oil. This trend means that – at least when it

Figure 2.4. Energy return on investment (EROI) of various fuels

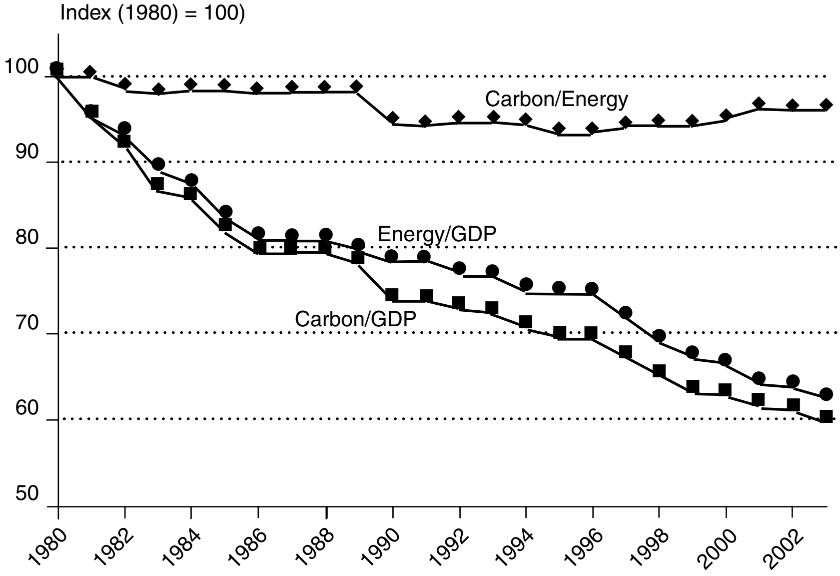


comes to conventional oil – we have to use a lot more energy to get energy. In the 1930s in Texas, drillers were rewarded with a return of about 100 barrels of oil for every barrel of oil of energy they invested to drill down into the ground and pump oil out. In the United States now, this energy return on investment (or *EROI*, as the concept is known among energy analysts) is around 17 to one. The Alberta tar sands give you an EROI of four to one. As we slide down the slope from 100 to one, past 17 to one, towards one to one, we're using a larger and larger fraction of the wealth and capital of our society simply to produce energy, and we've got less left over for everything else we want to do.

I believe the rising energy cost of energy is a very powerful binding constraint on economic development on the planet. We're entering a transition from a regime of abundant high-quality, and high-EROI energy to one of abundant, mixed quality, and often low-EROI energy.

Figure 2.4 compares the EROIs of various fuel systems. Crude oil has an EROI of around twenty to one, while corn ethanol and biofuel stand at about one to one – in other words, when it comes to ethanol we put in

Figure 2.5. Decarbonization trends



Intensity Ratios: Carbon/GDP, Carbon/Energy, and Energy/GDP

Source: Culter Cleveland, Boston University

about as much energy as we get out. Oil shale and tar sands have an EROI of around four to one or five to one. Creating diesel fuel from coal gives an EROI of about two to one or three to one. But coal by itself provides a very high EROI. In terms of an energy kick, it's great stuff.

The problem is that using more coal takes us in the wrong direction. In fact, it takes humankind in a direction that's radically different from the historical trend. In the last couple of centuries we've seen a steady decarbonization of our fuel supplies. We have moved from wood to coal to oil to natural gas as our main energy source, and with each of these transitions we have released less carbon into the atmosphere for each unit of energy produced. We're now seeing a reversal of this trend.

Figure 2.5 shows trends in three intensity ratios: from top to bottom, they are trendlines for carbon released per unit of energy, energy use per dollar of GDP, and carbon released per dollar of GDP, for the years from 1980 to 2002 in the United States. Although during this period the United States saw a decline of carbon output per unit of GDP, there was actually very little change in carbon released per unit energy. If the U.S.

situation is representative of the situation in wealthy countries, and on this issue it largely is, we actually haven't decarbonized our energy sources at all in the last 20 years. Almost all the gain in the decarbonization of GDP has been a product of increasing energy efficiency. That's an enormously important, and often overlooked, fact.

Since 2002, we've turned the corner. Decarbonization has stopped, and recarbonization has begun. Measurements of atmospheric carbon dioxide concentration taken at the Jubany station in Antarctica – a place where the atmosphere is very well mixed – show that from 1994 to 2001, the average annual addition to the atmosphere's carbon dioxide was about 1.64 ppm. Then from 2002 to 2006, the average jumped to about 2.1 ppm. The trend is heading upwards quickly towards 3 ppm annually. A significant component of this increase in the *rate* of increase (or what mathematicians call the second derivative) is a result of the higher carbon content of fuels. Basically, as oil has become more expensive, companies and economies have begun switching to more carbon-intensive fuel such as coal and oil derived from tar sands. Coal production, especially in China, is rising incredibly fast. China has doubled coal production from one tonne per person to two tonnes per person in the last six years, or from 1.3 to 2.7 billion tonnes of coal for the country as a whole. China is now a major driver of the increasing CO_2 concentration of the atmosphere.

A paper released last week in the *Proceedings of the National Academy of Sciences* provided a groundbreaking analysis of these trends. It looked at the acceleration in the magnitude of the annual addition of carbon dioxide to the atmosphere. The paper's authors break this acceleration into three parts. Sixty-five per cent is due to increasing global economic activity, in particular in India and China, and 17 per cent is due to increasing carbon intensity of the global economy, arising mainly from fuel switching to more carbon-intensive fuels like tar sands and coal. Together, these two factors explain a stark fact: global carbon emissions were increasing by about 1.3 per cent a year throughout the 1990s, but between 2000 and 2006 the rate rose to 3.3 per cent.

The third factor explaining the acceleration in the size of the annual increment of CO_2 in the atmosphere – explaining, in fact, the remaining 18 per cent of that acceleration – is an increase in the 'airborne fraction.' Normally, oceans and forests absorb about half of the carbon dioxide we emit, but that fraction seems to be declining, and the amount staying in the atmosphere – the airborne fraction – is now rising. The researchers note that the drop in carbon absorption, especially in the Southern

Ocean, is likely the result of global warming, which means we're starting to see positive feedbacks in the carbon cycle. The increase in airborne fraction is consistent with results of climate carbon cycle models, they continue, but 'the magnitude of the observed signal appears larger than that estimated by models.' All of these changes, they conclude, 'characterize a carbon cycle that has generated a stronger than expected and sooner than expected climate forcing.'[10]

I think we might actually be very close to self-reinforcing climate change – the situation where warming becomes its own cause. It is hard to say exactly when we will cross that threshold, but it could be closer than most experts anticipated even a few years ago, and certainly closer than implied by the IPCC reports.

Also, I expect that the first major socio-economic impact of climate change will be on our food supply. We'll see significant production shortfalls because of droughts and storms in major food producing areas. So keep a close eye on grain future prices, which are very high at the moment – the highest prices ever seen for corn and wheat. These high prices are significantly related to a drought-induced decline in grain production in Australia (they're also related to rising demand for grain, in particular corn, from ethanol producers).

My last remarks today concern a topic that – as recently as two years ago – I fervently hoped we would never have to discuss. That topic is geoengineering, the intentional human modification of the planet's climate. Geoengineering would involve, for example, putting sulphates into the atmosphere or putting mirrors into space to try to block a fraction of incoming solar radiation, or it would involve fertilizing the oceans to create plankton blooms to suck carbon out of the atmosphere.

Not only do I now think we have to discuss geoengineering, I believe we will almost certainly have to do it. Next week I'll be attending a meeting on the subject at the American Academy of Arts and Sciences in Cambridge, Massachusetts. Although the topic is at the margins of the public policy dialogue about climate change right now, I expect it will be at the centre of public discussion within four years. In 10 years, we will see demands from the public and many opinion leaders that we carry out geoengineering. And we'll probably start doing it within 20 years, likely when it becomes apparent that the Greenland ice cap is starting to collapse.

We will do it because we will be experiencing really large socio-economic impacts of climate change. We're going to look down the road and wonder about what kind of world we have created for our children and grandchildren. We will recognize that we're facing an emergency unlike anything humankind has ever faced before, and we will demand that our leaders do something, anything, to stop the slide.

I wish it weren't true, but the fact that some of the world's very best climate scientists are coming together to talk about the issue is a clear indication of the new sense of urgency about global warming.

Thanks very much for your time today.

Notes

* This chapter is an edited transcript of an address Professor Thomas Homer-Dixon gave to the conference A Globally Integrated Climate Policy *for* Canada, where the papers in this volume were originally presented. The address reports on the latest climate science, some of which has been published since the cut-off for inclusion in the latest Intergovernmental Panel on Climate Change Report (the fourth assessment report). These findings give added urgency to developing better climate policy and Professor Homer-Dixon places the policy challenge in the wider global context (the Editors).

1 Contribution of Working Group I to the Fourth Assessment Report of the IPCC, *Climate Change 2007 – The Physical Science Basis of Climate Change* (2007) online, http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

2 M. Mann, R. Bradley, and M. Hughes, 'Northern Hemisphere Temperatures during the Past Millennium: Inferences, Uncertainties, and Limitations' (1999) 26(6) Geophysical Research Letters 759; and M. Mann and P. Jones, 'Global Surface Temperatures over the Past Two Millennia' (2003) 30(15) Geophysical Research Letters.

3 Committee on Surface Temperature Reconstructions for the Last 2,000 Years, Board on Atmospheric Sciences and Climate, Division on Earth and Life Sciences, *Surface Temperature Reconstructions for the Last 2,000 Years* (Washington, DC: National Research Council of the National Academies, National Academies Press, 2006).

4 The original argument that satellite data show no warming of the lower atmosphere appeared in R.W. Spencer and J.R. Christy, 'Precise Monitoring of Global Temperature Trends from Satellites' (1990) 247(4950) Science 1558. For decisive evidence to the contrary, see B.D. Santer et al., 'Influence of Satellite Data Uncertainties on the Detection of Externally Forced Climate Change' (23 May 2003) 300(5623) Science 1280; and C. Mears and F. Wentz, 'The Effect of Diurnal Correction on Satellite-Derived Lower Tropo-

spheric Temperature' (2 September 2005) 309(5740) Science at 1548. On errors in interpreting weather balloon data, see S. Sherwood, J. Lazante, and C. Meyer, 'Radiosonde Daytime Biases and Late-20th-Century Warming' (2 September 2005) 309(5740) Science at 1556.

5 P. Foukal et al., 'Variations in Solar Luminosity and Their Effect on the Earth's Climate' (14 September 2006) 443 Nature 161.

6 T. Homer-Dixon, *The Upside of Down: Catastrophe, Creativity, and the Renewal of Civilization* (Toronto: Knopf, 2006) at 131–3.

7 M. Scheffer, V. Brovkin, and P. Cox, 'Positive Feedback between Global Warming and Atmospheric CO_2 Concentration Inferred from Past Climate Change' (2006) 33 *Geophysical Research Letters* L1072.

8 J.L. Chen, C.R. Wilson, and B.C. Tapley, 'Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet' (2006) 313(5795) Science 1958.

9 As quoted in P. Brown, 'Melting Ice Cap Triggering Earthquakes,' *The Guardian*, 8 September 2007.

10 J. Canadell et al., 'Contributions to Accelerating Atmospheric CO_2 Growth from Economic Activity, Carbon Intensity, and Efficiency of Natural Sinks' (October 2007) *Proceedings of the National Academy of Sciences*, Early Edition.