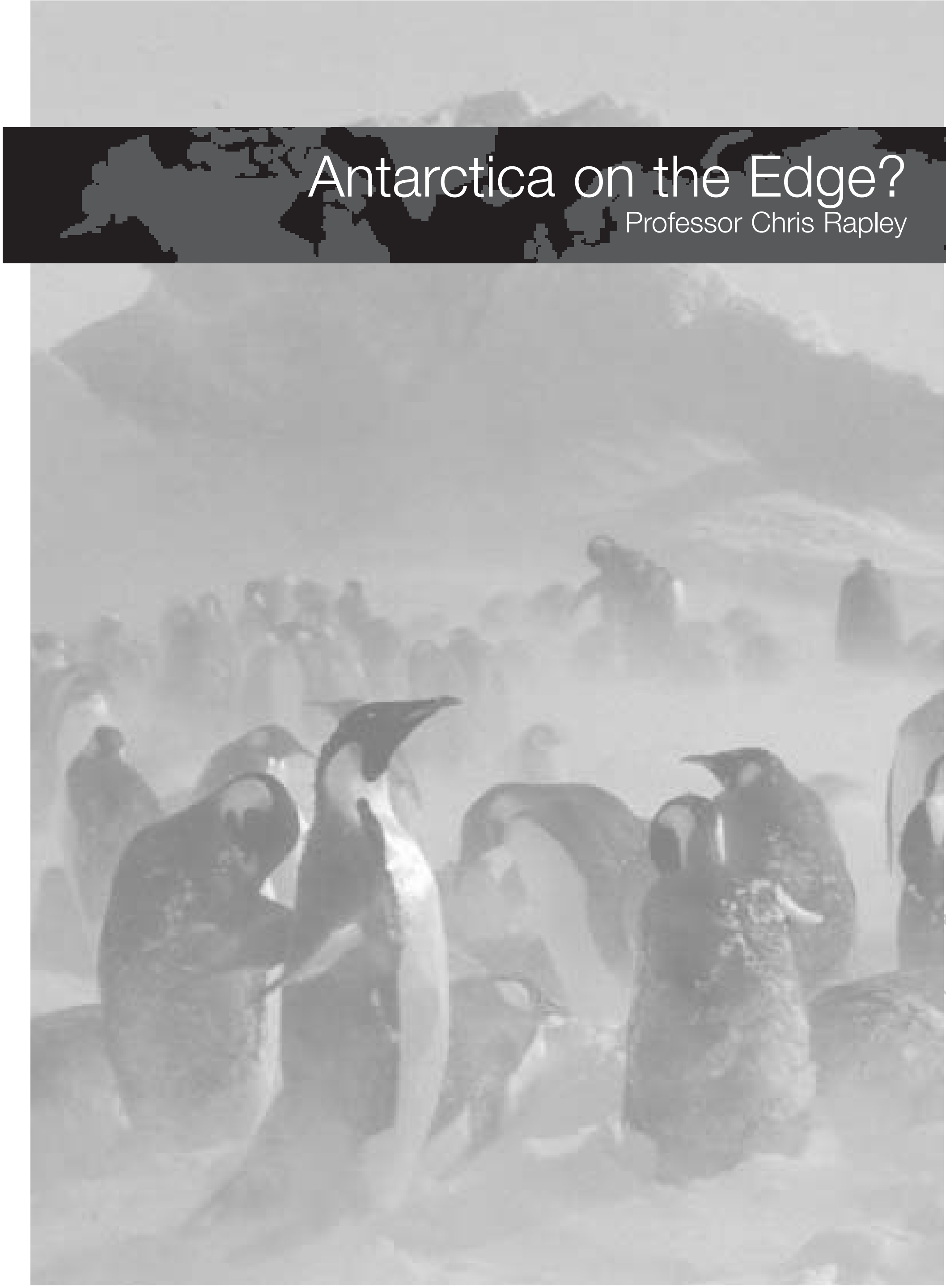
Antarctica on the Edge?

Professor Chris Rapley



Environment on the Edge

The question mark at the end of the title – Antarctica on the Edge? – is important, as we will see. But let us start with the most complex object in the universe, and one in which we are rather interested because we live on it: the Earth. From the point of view of scientists interested in systems analysis and the way systems function as a whole, the Earth is the most fascinating object because it is the most complex. The Earth has geology, physics, chemistry, biology – which as far as we know is not prevalent in the universe – and, of course, it has an advanced technological civilization, for which there is also no evidence elsewhere. It is the interaction of all these elements that makes the Earth so interesting to study.

The Earth as a system

We can start by making a few comments about the Earth as a system, a highly complex and interconnected one. We can break it up into the geosphere (the solid part that is most of the Earth), the ocean, the atmosphere, the ice, the life and the humans. That is six interconnected compartments, and because six things can be connected six times five over two ways, we already have 15 interconnections, without even starting to break down the different spheres. This complex Earth functions as an integrated whole, which means that the traditional scientific approach of studying the smaller pieces that make up the whole is not sufficient.

The Earth provides what are known as ecosystem services – freshwater, fresh air, food, shelter, energy – upon which life depends. The Sun provides the primary source of energy that drives everything, the movement of the fluids and the energy supply to the life forms. There is no user manual, there are no spare parts – and human impact is leading us into uncharted waters.

We can look at carbon dioxide trace from the Vostock ice core record drawn from the Antarctic for a period of 450,000 years. It fluctuates periodically, but under the natural control of the planet it tends to limit at a lower level of about 180 parts per million and an upper level of about 280 parts per million, the upper level being during relatively brief warm periods and the lower level being during ice ages. There have been four ice ages during the last 450,000 years, although we have ice core records that run further back. Current carbon dioxide levels are about 370 parts per million, showing that in the past 100 years (measured directly over the past 40 years and taken from bubbles in ice cores for the previous period), human burning of fossil fuels has increased the carbon dioxide content of the atmosphere by as much as the normal change between an ice age and an interglacial, and it has done so at a very, very fast rate – the fastest rate of change the planet has seen for at least millions of years.

Where carbon dioxide levels are going in the future is a moot point, but based on a variety of projections of the continuing growth of human population, human activity and use of carbon-based fuels, levels at the end of this century will end up significantly higher than they have been for the last 500,000 years, and in fact significantly higher than they have been for the past 200 million years. This has consequences. Everyone knows that the Earth's surface is warmer than it would otherwise be because of the presence of greenhouse gases in the atmosphere, mainly water vapour. But carbon dioxide is a factor, and if you enhance the greenhouse effect, which helpfully stops us from freezing over, then you increase surface temperatures unless there are feedbacks to prevent it.

There are other consequences of increasing the carbon dioxide content of the atmosphere. It makes the oceans more acidic, as we are already measuring. It has a big impact on marine ecosystems. It fertilizes the land biosphere. So it is important not to become obsessed solely with the enhanced greenhouse effect. These effects begin to interact and cascade, so that although the land biosphere is taking more carbon dioxide at present because it is being fertilized, when it gets warmer respiration will increase, and at some point the land biosphere will become a source of carbon rather than a sink.

There is a whole community of people trying to predict what the future impact of carbon dioxide increase will be on climate, and a great deal of uncertainty. Prevalent among them are the numerical modellers, many of whom have come from the world of meteorology, where they have been very successful. They are trying to build simulations, or numerical models, of the Earth. Then there is another community of people who say that if climate did change, and temperatures did increase, and acidification of the oceans did happen, how serious would it be? What would be the impacts? The question everyone is interested in – because it was set at the 1992 Earth Summit in Brazil where Article 2 said, to paraphrase, that humans should not affect the climate in a dangerous way – is: what do we mean by dangerous, and what does that mean in terms of climate change and carbon emissions and the trajectory we need to take into the future? Is a change of 4°C, 3°C, 2°C, or 1°C dangerous? That is the question that Sir David King posed, with the support of the UK prime minister, to the Exeter conference "Avoiding Dangerous Climate Change" in February 2005: What constitutes dangerous climate change?

Antarctica: a description and history

Now we must move on to Antarctica, an important player in this game. In the 1770s Captain James Cook had been instructed by the Admiralty to find the southern continent. He struggled to do so and was beaten back by the elements. He said: “Should anyone possess the resolution and fortitude to push yet further south than I have done, I shall not envy him the fame of his discovery but I shall make bold to declare that the world will derive no benefit from it.” There is an air of sour grapes about this statement because he did not see the continent. Then he set sail for Tahiti and was killed in Hawaii.

Cook was proved wrong rather quickly because his own journals immediately started off the sealing trade. Many people benefited from exploiting the southern oceans in this way, which of course also led to the whaling trade.

I once had the pleasure of taking four new UK Members of Parliament onto the *James Clark Ross* research vessel in Stanley Harbour in the Falklands, and when we showed them a map it was clear that they did not have a clue about Antarctica. Here are some basic facts. It is the fifth largest continent; it is completely surrounded by ocean; it is the highest, windiest, coldest and driest place on Earth; it is 99.7 per cent ice covered and holds 90 per cent of the world’s ice, although there is a lot elsewhere. The volume of the ice sheet is roughly 30 million cubic kilometres, and it is on average 2.2 kilometres thick – 4.5 kilometres at its maximum. The ice is so heavy, it weighs down the Earth’s crust beneath it by about a kilometre.

Antarctic ice exerts a major influence on southern hemisphere weather, ocean circulation and climate. If we melted it all, which would require much energy and time, then it would raise global mean sea level by 57 metres, which means that Cambridge, for example, would be under water. I am often asked why the United Kingdom should worry about this remote, distant and difficult-to-reach part of the planet. One thread of reasoning says Antarctica is remote but relevant: London needs protection against flooding, and as sea levels inexorably rise – 1.8 millimetres per year – the Thames barrier will ultimately become insufficient. Antarctica will have a role in that sea level rise in future.

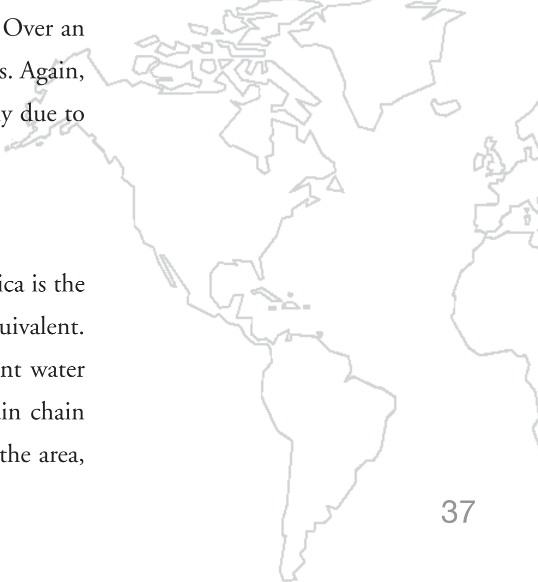
Let’s go back about 200 million years, or 4 per cent of Earth’s history. There is a place called Fossil Bluff, which is one of the four staging posts of the British Antarctic Survey (BAS), where you can find beautiful fossils of ferns and plants. Two hundred million years ago the Antarctic was the hub of the Gondwana supercontinent and Antarctic temperatures were considerably warmer than they are now. About 35 million years ago there was a major cooling and formation of a dynamic ice sheet. About 15 million years ago came the large permanent ice sheet which fluctuates in size, and that cooling is reckoned to be linked to the configuration of continental fragments and the opening of ocean gateways. Today we have a circumpolar ocean with Antarctica set squarely over the south pole with a big ice sheet on it.

When we compare proxi-temperature records with carbon dioxide and methane records, we see that there have been clear fluctuations driven by periodic variations in the Earth's orbit, so there have been subtle changes in the way heat is accumulated onto the Earth before it is radiated into space again. Marine sediments show us there have been 46 cycles in the last 2.5 million years over the ice core record, with 120,000-year cycles over the more recent period. The earlier cycles were shorter with roughly 10°C temperature variations, and are very closely correlated with carbon dioxide and methane variations.

This is an important point because in many comparisons of temperature and carbon dioxide, climate temperatures change and carbon dioxide does not. There are reasons for this: for example, the input from the Sun varies slightly, or the atmosphere can be upset by volcanic eruptions. But there is no place in the record where carbon dioxide moves and temperature does not, and that is an important fact to use in the argument with sceptics about the impacts of carbon dioxide change today. Over an even shorter period, the last 18,000 years, sea levels around the world have risen by 120 metres. Again, the current rate is about 1.8 millimetres per year, but past rates were ten times greater, largely due to loss of the northern ice sheets but also due to change in the southern ice sheets.

Recent changes in ice sheet

To familiarize ourselves further, we can divide Antarctica into three broad areas. East Antarctica is the ice sheet bedrock, mainly above mean sea level, with the bulk of the ice 52 metres sea level equivalent. West Antarctica sits on bedrock up to 2 kilometres below sea level, with a smaller equivalent water mass, 5 metres global sea level equivalent. Then there is the Antarctic Peninsula, a mountain chain extending towards South America joining the tip of the Andes, which is only 7 per cent of the area,



and only 0.3 metre sea level equivalent, but an important area, where BAS does much of its work for logistical reasons.

We will first look at the input side of the ice sheet, the snow coming in. Most of the snow is dumped by the moist marine air around the coast, while the large central area of the continent has low snowfall and is technically a desert. It is the peninsula and the area slightly to the west of it that gets the highest annual snowfall. Total accumulation is equivalent to a significant 6 millimetres of sea level per year, and in the peninsula it is about 0.4 millimetres of sea level equivalent.

On the output side, ice deforms and flows under its own weight downhill, forming fast-moving ice streams. The velocity of ice movement depends on the thickness and the friction at the base. If there is water at the base, ice slides, but if it is frozen it deforms. There are 33 major drainage basins, and the ice creeps like porridge. It is the ice streams that transport the bulk of the ice towards the coast, like a network of tributaries. The flow rates are 10 metres per year or less in the interior, reaching 1 or 2 kilometres per year at the coast. Where a lot of the ice extrudes over the ocean, it lifts off and starts floating; the thickness of these ice shelves ranges from hundreds of metres to tens of metres. There are two particular areas where this happens, each larger than the area of France: the Ronne Filchner ice shelf and the Ross ice shelf. As Archimedes could have told us, the transition from grounded ice to floating ice is where it displaces its own weight of water, raising sea level.

Ninety per cent of ice loss from Antarctica is through these ice shelves; the rest is blown off the continent by the winds. The loss is either by iceberg calving at the edge, when they float off north, break up and melt, or by basal melting in which the ocean erodes the underside of the ice shelf and carries water away. The first process is very sensitive to air surface temperature and the second to ocean temperature.

Humans have been active on the Antarctic continent for only 100 years, and active scientifically, in respect of monitoring what is going on, only for the past 50 years. Even these monitoring data are very sparse and intermittent. There are temperature data from a number of places around the continent, most of which do not show a statistically significant signal. The only strong signal is one of a warming over the Antarctic Peninsula of the order of 2.5°C in 50 years. That is five times the global mean change over the same period. Is this human induced, the fingerprint of human beings? We are

not completely sure, but the evidence is growing that the answer is yes. There is a strong association with the intensified flow of westerly winds around the Antarctic, which, when they hit the peninsula, move more warm air south. The intensified westerlies appear to result from the regional effect on sea ice of greenhouse warming – which results from human activities. Although we realize there are strong connections between the polar part of the southern hemisphere and the equatorial parts of the Earth through the atmosphere and through the ocean, they are only now being unravelled.

The impact of the warming has been very evident, and there has been much recent media interest in a comprehensive study by BAS of the behaviour of 244 glaciers over the last 50 years. This study, involving thousands of aerial photographs and satellite images, has shown that 87 per cent of glaciers have retreated over the last 50 years, even though at the beginning of that period they were not retreating. It is clear that this phenomenon has built up over 50 years, and that it has swept further south as the period progressed.

At the tip of the peninsula is an island where over the last century the thick ice shelf has disappeared, and ice shelves down both sides of the peninsula have gone. The discovery that some huge ice shelves have just shattered and disappeared in a matter of days has been quite a shock. There is a current of strong evidence and understanding that these ice shelves become damaged by the presence of significant summer melt waters – surface water which drains down cracks, damages the fabric and causes the ice shelf to be susceptible to breaking up. That line has been steadily moving south.

Once an ice shelf has gone, a ship can go in – which could not happen before – and sample marine sediments underneath. Both BAS and the United States have done this, and what we are finding is that the northern ice shelves went quite naturally 2,000 to 5,000 years ago in a slightly warmer period. It is therefore perfectly possible for ice shelves to disappear through natural fluctuations in regional or global climate without intervention from humans. But the evidence on the last large collapse is that it was not a recent one, and we are now entering areas that have not been opened up for millennia.

At first, the consequences of ice shelf losses were open to speculation because the important point is what happens to the glaciers that feed them when the ice shelves collapse. Using satellite data it has

been found that wherever an ice shelf has gone, the feed glaciers have speeded up and lost significant volume close to the coast. In cases where the ice shelf is still in place but subjected to identical climatic conditions, the glacier is unaffected. This is quite strong evidence for the cork-in-a-bottle analogy: if the cork is removed it causes the glaciers to accelerate, and that does add to the annual increase in global mean sea level. On the other hand, evidence is beginning to emerge that perhaps that acceleration is not being sustained, and that there is a readjustment of those glaciers. We must wait and see how they settle down.

Next let us consider the West Antarctic marine ice sheet, much of which you remember is grounded on bedrock well below mean sea level. It has been suggested for a long time that this is unstable. In particular, it has been suggested that as global mean sea level rises there is a hydrostatic lift that attempts to raise the ice sheet, allowing very high-pressure water at the grounding line to force its way underneath. Once there is wet water under the ice sheet, the ice can slide much faster than when it is frozen to the bedrock, and hence the suggestion of a positive feedback that could make the ice sheet unstable. This has been proposed as a possible explanation for global mean sea levels appearing to be 5 metres higher at the last interglacial, which was also a couple of degrees warmer than it currently is.

Using expensive pieces of radar equipment which bounce signals off the surface of the planet – and these work particularly well with ice-sheet surfaces that are flat and featureless – a number of scientists are trying to find out more about the surface of the ice sheet. The impressive fact is that you can measure, from 700 kilometres away, the position of the surface of the ice sheet to an accuracy of a few centimetres.

From these scientists' data, we find some areas where there has been no significant change in ice sheet, while some are going down significantly. From aircraft data and *in situ* work by the United States, it seems the ice streams that feed into the Ross ice shelf are stagnant or growing and have a positive ice balance. Another area is losing ice, and the three drainage basins are losing ice rapidly. The synchronism suggests that the cause is connected with ocean warming, which has removed the buttressing ice shelves and led to an acceleration in ice loss. Certainly the air temperatures in the far south indicate that this is not a surface-melting issue.

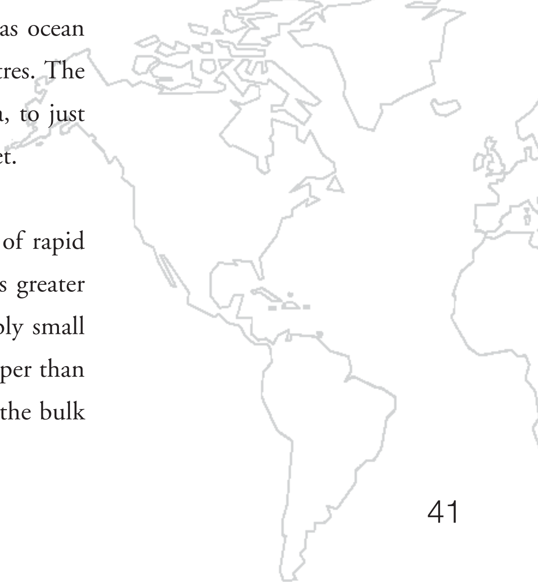
Earlier this year in *Science Express,* an important paper from Kurt Davis and his colleagues in the United States reported the findings from processing hundreds of millions of radar echoes from the Antarctic ice sheet during the period from 1992 to 2004. The West Antarctic ice sheet is losing ice at 1.6 millimetres sea level equivalent per year. The East Antarctic ice sheet is growing, and this is because the warmer atmosphere carries more moisture and the marine air masses penetrating the area are dumping more snow onto the ice sheet. David Vaughan at BAS sets out in an unpublished paper his belief that the peninsula is losing a net amount of ice into the ocean of a similar order. Duncan Wingham at University College London (UCL), too, has an unpublished paper with similar findings.

So what is the Antarctic ice sheet contributing by way of global mean sea level rise? Five years ago, the Intergovernmental Panel on Climate Change, which is a consensus process for summarizing the best understanding of system issues, said the following:

- Ice sheet reaction times are thousands of years.
- On a hundred-year time scale, the ice sheet is likely to gather mass because of greater precipitation (and the Davis paper shows that this is true).
- On the basis of really thin evidence, but largely the fact that numerical models could not make it happen, the West Antarctic ice sheet is very unlikely to collapse in the 21st century.

A BAS study came to this last conclusion, too, but based on very little hard evidence. The projected mean sea level rise over the next 100 years – there are many terms in this equation, such as ocean expansion and loss of Alpine glaciers – was estimated as in the order of 11 to 77 centimetres. The Antarctic contribution could range from negative, because of the growth of East Antarctica, to just slightly positive, because of the loss of ice from the peninsula and the West Antarctic ice sheet.

To summarize what we have learned since, there have been some surprising examples of rapid significant regional change. The sensitivity of ice flow down ice streams to ice shelf loss is greater than previously assumed. Another radar-sensing technique allows the detection of incredibly small motions of the ice sheet deep in its interior, and the network of feed streams reaches far deeper than previously thought. This implies that if those accelerate, then they have a greater grasp on the bulk of ice in the interior, and that makes modelling the dynamics difficult.



What is the critical threshold for the West Antarctic ice sheet to collapse? We do not know, but the issue has been reopened by the facts: if you take away the ice shelf, then things start to happen quite quickly. The accumulation over East Antarctica has been confirmed, but over the long term it may not be enough to balance the other losses. The fact is that we have some very large numbers with a wide range of accuracy, and the Antarctic contribution to mean sea level rise now and in the future needs reassessment. Some people have talked of a dangerous climate threshold of 2°C or 4°C, but we believe these are no more than guesses.

Modelling the future

Despite the difficulties in taking measurements, we must try to make the most of our knowledge of the physics, chemistry and biology of the Earth's systems and use computer models to predict what will happen as all these different elements interact with each other. We know world temperature change over the last 50 years, and we have predictions for the next 50 years from data used in what is widely regarded as the best numerical climate model, the Met Office model. But the significant point is that the peninsula warming I mentioned, which is one of the strongest warming features on Earth in the past 50 years, is not represented in this terrific model – so how much can we trust its predictions in the southern hemisphere? Its general predictions may be reasonably accurate, but not so its regional predictions.

What about ice sheet models? There is a mass of information that goes into a numerical ice sheet model, including physics and data, and these are used both to integrate existing sets of data and to project into the future. Ice sheet models also need, of course, to be coupled to general circulation models, which, as I have said, do not work very well in this area. A huge amount of effort has gone into these models, and they are increasingly sophisticated, but not one of them is yet able to represent the deglaciation since the last glacial maximum *and* the observed current variability. You can tune the parameters to make them do it separately, but they cannot do it simultaneously. Although that is no reason for giving up, we are not yet at a point where we have reliable models – either of the atmosphere and ocean in the southern hemisphere or of the ice sheet – to be able to forecast what is going to happen in the future. We need an action plan. More fieldwork in the West Antarctic ice sheet is crucial for understanding what is going on: perhaps the ice loss will stop, or perhaps it will go on for another hundred years, and maybe it will significantly raise global sea level over that time period.

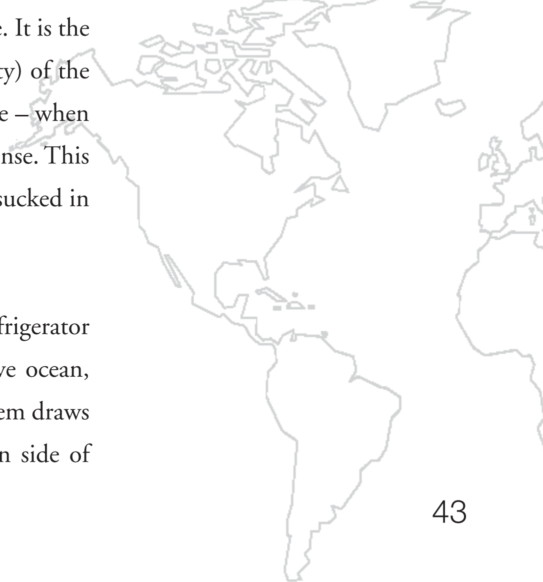
We have precious little data about the atmosphere in the Antarctic and virtually no data at all about its ocean temperatures and circulation. We are just beginning to run submersibles under the ice shelf – the United Kingdom has in fact this year lost one under the ice shelf – and there is a great deal of satellite and aircraft remote sensing going on. Cryosat, which Duncan Wingham and the UCL team have masterminded, will be launched shortly and represents a big step forward from current radar space systems by way of monitoring ice sheet mass balance.

We definitely need more work on the models, and a five-year timescale is essential to make progress. On a positive note, BAS and the University of Texas acquired 100,000 kilometres of radio echo-sounding flight lines in the 2005 season, and these radio echo-sounding data penetrate right inside the West Antarctic ice sheet and cover 30 per cent of it, including the area that is currently active. This large amount of data will reveal a great deal about what is going on, and what we might expect to continue to go on, in this tricky area.

Sea ice

I have concentrated on the ice sheet because it is of the greatest interest. But we have 20 years' worth of satellite data on Antarctic sea ice, showing the shrinkage through the summer and regrowth as the following winter sets in. This is sea ice freezing because it gets dark and very cold indeed, so the top of the ocean freezes because of the radial imbalance but also because of cold winds from the dome shape of the Antarctic continent. This dataset has given us much to think about and be amazed by – huge icebergs spinning round the coast being carried by the very strong ocean currents, for instance. It is the biggest seasonal change on the planet, and it has a huge impact on the albedo (the reflectivity) of the southern hemisphere, as well as being important for other reasons. When you generate sea ice – when you freeze saltwater – you expel the brine, which makes already cold dense water even more dense. This cold dense water rolls off the edge of the continental shelf into the abyss, and warm water is sucked in to replace the cold.

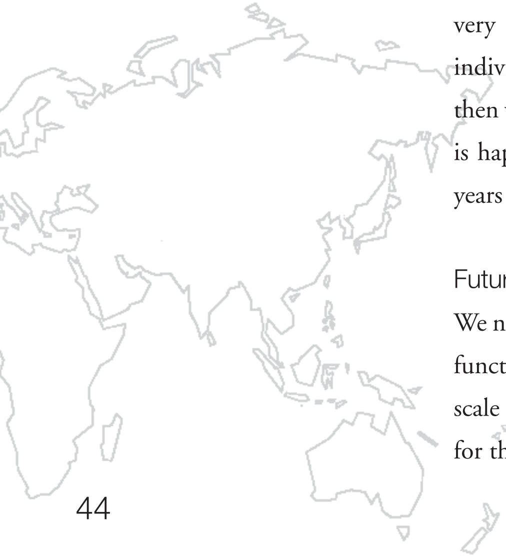
About 40 per cent of the world's oceans are chilled by the Antarctic; the Antarctic is the refrigerator of the world's oceans. The Southern Ocean, which surrounds the Antarctic, is a productive ocean, having a relatively simple food web. The upper parts depend on krill, and that marine ecosystem draws down carbon dioxide from the atmosphere. In the southern Indian Ocean and the eastern side of



South America, the Southern Ocean is very actively absorbing carbon dioxide. The marine ecosystem sits in this conveyor belt being whizzed around the Antarctic in a “jet-stream” current, and the biological and physical dynamics are completely entwined. Krill that are spawned under ice at the tip of the Antarctic Peninsula are carried – and carry out two life cycles on their way – to South Georgia, where seals, penguins and albatrosses are waiting. If anything changes either in the biology or in the physical dynamics, then the waiting creatures starve, and their populations have periodic crashes when something happens in the delivery system. It also, of course, means that the capacity of the Southern Ocean to absorb carbon dioxide varies.

So what has happened to Antarctic sea ice? There is a 20-year trend showing overall growth and strong regional differences associated with the general warming of the atmosphere. Areas of reduced sea ice have, it is believed, led to the observed significant decrease in krill stock in the Weddell Sea area, and this has had an ongoing major impact on the Southern Ocean ecosystem. But the impacts on ocean circulation and the carbon drawdown are simply not known because we do not have the data.

If we move inshore, the shallow-water marine ecosystem around the Antarctic is as rich as a tropical reef. The marine creatures there exist in very low temperatures, and those temperatures have been constant over evolutionary timescales. The organisms that live in warmer waters are capable of handling quite large temperature variations, but those that exist in very cold waters have given up that capability in order to be able to survive there. That is evolutionary adaptation, so they can only tolerate very small temperature excursions. Even a rise of 1°C or 2°C would have major consequences on individuals and therefore on those species, and if there were to be ocean temperature rises of this order then we would see major ecosystem shifts and some mass extinctions. We have some insights as to what is happening and what will happen, and we are concerned, but to predict what will happen in 100 years is impossible.



Future research in Antarctica

We need an enormous range of scales both in distance and time to study and understand how the Earth functions as a system. We have to study microscopic changes and changes right the way through to the scale of the planet, and so we need microscopes and macroscopes, the nice term that has been coined for the satellite instruments that allow little us to see big things in a way we can comprehend. But the world science capability is finite. The United States spends about half the world's investment in understanding how the planet works, perhaps $1-2 billion a year. Europe spends about half that, and the rest of the world together spends the same as Europe.

There is no infinite capability of brainpower or equipment or infrastructure, and so we need to marshal what we have carefully. We need to identify and focus on the key components of this system. When we do, reductionism is not enough; it is no use taking the thing apart and figuring out how the little bits work and putting it together again. It requires unprecedented levels of interdisciplinary research and unprecedented worldwide organization and collaboration, as well as a sense of urgency. Scientists on the whole resist being rushed and move at a pace they think suits the quality of their outputs, but policy makers need some answers quite quickly. The science community therefore needs to be persuaded that it is better to come up with something less than perfect soon, rather than come up with the perfect answer too late.

At the British Antarctic Survey, we have been taking this very seriously in the way that we have developed our new science programme, which we will be carrying out over the next five years. It addresses many of the major issues I have been describing. We have also been working closely with the International Council for Science's Scientific Committee on Antarctic Research. In the past they tended to study lots of little bits, but they are now pursuing five flagship projects, and three address the sort of big questions I have been outlining.

Fifty years on from the International Geophysical Year, we have been very successful in raising worldwide interest in having an International Polar Year – IPY 2007-2008, which will actually take place between March 2007 and March 2009. It will be an intensive burst of international, coordinated, interdisciplinary scientific research and observations focused on the Earth's polar regions, Arctic and Antarctic. It has six themes: current status of the polar regions; change in the polar regions; global linkages; new frontiers; polar regions as vantage points; and, especially for the northern hemisphere, the human dimension. To date we have had 900 expressions of interest worldwide.

I have not been able to give you answers about what constitutes dangerous climate change from the point of view of the Antarctic, but what I hope I have shown is that we are making progress

considering how far away the Antarctic is; how difficult it is to operate in; how remote and challenging it is in many ways; and that we do have the tools to make progress and are marshalling them seriously to do so. I hope, in five years' time, I might be able to tell you more.

Samuel Butler pointed out that "all progress results from the ineluctable desire of every organism to live beyond its means". That is what we are all doing, collectively, and overcoming this will be the real challenge if we are to find a sensible balance between human endeavours, human well-being and the planet.

Professor Chris Rapley CBE is Director of the British Antarctic Survey, and was Chair of the International Planning Group for the IPY 2007-2008.