Climate Change and the Antarctic: What Next?

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Chris Rapley

President of SCAR
Member of the International Polar Year 2007-2008 Joint Committee
Director British Antarctic Survey

British Antarctic Survey
High Cross
Madingley Road
Cambridge CB3 0ET
United Kingdom
Tel 44 (0) 1223 221524
Fax 44 (0) 1223 350456
Email c.rapley@bas.ac.uk

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1. The Earth seen from space (courtesy of the Apollo 17 astronauts) reveals a small blue orb in the inky darkness of the cosmos. The image was taken with the Sun directly behind the camera and well out of the Earth's equatorial plane, and so reveals the Antarctic continent and its snow and ice in all their summertime glory. Also evident is the thin envelope of fluids – atmosphere and ocean – surrounding the planet, and the signature of life – the green colouration over central Africa. The photograph itself is proof positive of the presence of an advanced technological species - us. The planet is unique, as far as we are aware, since its study requires social science, economics and biology in addition to geology, physics, and chemistry.

2. Energy from the Sun is the predominant driver of all activity on Earth, from the motions of the fluids to the rhythm of life, excepting the slow motions of the continents and processes in the planet's interior. Geothermal heat, lunar tides and human energy generation are trivial in comparison (by a factor 1000). The balance between the energy intercepted and the energy radiated into space is almost exact. Small differences cause the planet to warm or cool. The Sun appears very different when observed with specialised cameras, which reveal the violent nature and variability of its upper layers and atmosphere. Solar activity drives changes on Earth as do other astronomical phenomena, from meteorite strikes to gamma ray flashes. The planet itself is hugely complex, with its various components – atmosphere, ocean, ice, biosphere, humans and the solid earth – all interacting, with a myriad of interconnections, some highly nonlinear. There is evidence that an emergent characteristic of the Earth, through the interplay between its physics, chemistry, biology and geology, is a degree of self-regulation, maintaining conditions conducive to life in the face of external and internal changes.

3. Although life may exist elsewhere in the Universe, we only know of its presence on Earth. Our planet is therefore arguably the most complex object in the Universe, and in any case a considerable scientific challenge to understand. Scientific progress through "reductionism" – the study of the component parts – is a necessary but insufficient part of the approach. Essential is a "systems" view, in which the planet is also considered as a whole. This has been a challenge to the science community, who have had to learn how to eliminate disciplinary "silos" and work together to an unprecedented degree. Good progress has been made but more is required. A further challenge is the sheer enormity of the object of study, and the vast spread of spatial and temporal scales which need to be addressed. These range from the microscopic to the planetary (13 factors of ten), and from fractions of a second to billions of years (20 factors of ten). Even by aggregating the entire world's resources of researchers and their equipment, coverage is thinly spread, and priorities have to be sharply focussed and addressed. International cooperation and coordination are essential. There is no planetary "Users Manual" and the Earth is finite, without spares. And yet all of life relies upon the "ecosystem services" it supplies free of charge. These include clean air, fresh water, food, fibre, shelter and spiritual fulfilment, as well as more esoteric but high value services such as the pollination of crops. In spite of the self-evident need to care for and protect our irreplaceable "Life Support System", the state of the planet is increasingly unhealthy as a result of human activities.

4. The World Wildlife Fund (WWF) "Living Planet" report indicates that the "Human Ecological Footprint" – the area of biologically productive land and water needed to provide the ecological resources and services used by humanity – exceeded the "one planet" threshold in the mid-1980s. The WWF's "Living Planet" index – based on the status of the populations of 1313 vertebrate species worldwide, has declined 30% in 30 years.

5. Until the late eighteenth century human energy use can be characterised as "organic" – exploiting the flows of wind and water and the capabilities of "beasts of burden", including humans, often as slaves.

6. The transition to an energy system based on fossil fuels – which have built up underground over millions of years through a combination of biological and geological processes – has been rapid (even in human terms) and has transformed the human condition incomparably for the better. The availability of concentrated and convenient energy and of scientific and technological advances, especially in medicine, have resulted in an explosive growth in the human population. This, combined with an equally rapid growth in economic activity has reached the point where humans constitute a force at the global scale. Human-induced climate change and stratospheric ozone depletion provide two examples.

7. The energy generated by burning fossil fuels can be regarded as the "fleeting by-product". The real product is an increased loading of carbon (in the form of carbon dioxide) in the atmosphere. Although the terrestrial biosphere

(plants, trees and soils) and the oceans have assisted by absorbing roughly half of the emissions, the atmospheric content has increased rapidly – a thousand times faster than the natural cycles of climate and carbon – and significantly – by more than 35% - a magnitude equivalent to the natural variations between an ice age and an interglacial. Geological processes (rock weathering) by which carbon dioxide is removed from the atmosphere, operate on timescales too long to be relevant. Although human carbon emissions are small compared with the annual "natural" exchanges between the ocean, atmosphere and terrestrial biosphere, they have upset the balance to which the undisturbed system had adjusted.

8. The annual human emissions of carbon have risen from a few million metric tons in 1850 to 7 Gigatons (GtC) today (the CO_2 tonnage is 3.67 times greater). What matters to the atmosphere is the total amount of carbon injected, and this is estimated to be 500GtC, with contributions of 320GtC from carbon fuel burning and cement production, and 180GtC from land use change, mainly deforestation.

9. Direct measurements of the carbon dioxide concentration in the atmosphere made since the 1950s, combined with data from the bubbles trapped in Antarctic ice cores, show the dramatic rise induced by humans, and reveal that the current concentrations are greater than at any time over the past 860k years.

10. The existence of the "Greenhouse Effect" and the means by which it operates have been understood since the mid-nineteenth century. The measured surface temperatures of Mars, Venus and Mercury affirm our ability to calculate its effects. The key issue is the opacity of the atmosphere – mainly due to the presence of water vapour and carbon dioxide – to infra-red (heat) radiation from the Earth's surface, which results in the atmosphere being warmed, and in turn radiating some heat back to the surface. The phenomenon is highly beneficial, since the Earth's surface is 30^{o}C warmer than would otherwise be the case, making "life as we know it" possible. By our emissions of CO_2 humans have enhanced the effect, both directly and because a warmer atmosphere carries more water vapour. The upshot is an estimated current net imbalance between the heat received by the surface and the heat lost of approximately 1.5W/m^2.

11. More than 90% of the heat imbalance is absorbed by the oceans, and this can be seen in the vertical temperature profiles averaged from thousands of measurements over the last 30 years, in which a slowly deepening surface warming corresponds to the predictions of numerical models, and is inconsistent with natural variability.

12. The measured warming of the land surface of some 0.7^{o}C since pre-industrial times can also only be accounted for by a combination of natural (solar induced and internal variability of the system) and human-induced forcings. The geographical distribution is patchy, with parts of the polar regions (Alaska, Siberia, Antarctic Peninsula) showing the strongest increases – up to 5 times the average. This is consistent with the amplification of warming predicted for polar areas as a result of the "ice-albedo" feedback, in which the loss of ice and snow (which reflect approximately 90% of incoming solar radiation) exposes land or ocean (which absorb some 80% of the radiation). In the summertime, this results in further warming and further loss of snow and ice. In the winter, it can also result in an increased release of heat back to the atmosphere, but the net outcome is an amplification of the warming.

13. The Policy-Maker's summary of Working Group I of the Fourth Assessment Report of the UN's Intergovernmental Panel on Climate Change concludes that (i) current atmospheric greenhouse gas concentrations far exceed the levels of at least the last 650k years (the limit of the data analysis at the time the IPCC carried out its review) as a result of human emissions, (ii) warming of the climate system is unequivocal based on a mass of factual evidence, and (iii) the climate forcing is overwhelmingly human. These conclusions are based on an evaluation of thousands of peer-reviewed scientific publications and have been agreed by the politically appointed delegates of 113 nations, including nations whose administrations are "climate sceptic". There indications that the conclusions of the IPCC tend to be conservative.

14. Palaeo comparisons of global temperature and sea level show that whenever the world is warmer, sea levels rise. Any initial growth of the cold, high altitude interiors of the great ice sheets is more than compensated for by losses through melting and sliding around their peripheries.

15. A current very dramatic example of retreat within the cryosphere, is the reduction in summer sea ice extent in the Arctic by 25% over 30 years. The continued loss will have major impact on the Arctic ecosystem, including its charismatic megafauna such as polar bears.

16. Although the major contributors to the 20cm global sea level rise of the last hundred years have been the thermal expansion of sea water and the melting of mountain glaciers and minor ice caps, the sea level rise potential of the ice sheets on Greenland (7m) and the Antarctic (57m) dwarf the 0.5m contribution from the remaining lesser components of the cryosphere.

17, 18, 19. The temperature warming of 2.5ºC observed in the Antarctic Peninsula over the last 40 years has been the largest surface warming on the planet. In response, nearly 90% of the glaciers are in retreat, and there has been a succession of ice shelf disintegrations. The key to the latter appears to be surface melting, which causes water to pour down through cracks and damage the structural integrity of the ice shelf, leaving it vulnerable to collapse. Those that have collapsed lie north of the limit of significant summer surface melting. The ice shelves are generally several hundred meters thick at the ice front, where they terminate, and since they are floating, most of that lies below the water level. So whilst they are in place, it is only possible to explore what is underneath by sending in submarines or drilling holes from above. Once they have collapsed, it is possible to get a ship in to the area and extract samples of the underlying marine sediments. These tell us about the history of the ice shelf. In this way, we have found that the northern shelves were absent about 3000-5000 years ago when there was a "natural" (not human-induced) warm period. But the collapse of Larsen B revealed that it had been in place for at least 10,000 years, so we sometimes refer to the present warming as the "Heineken" event since it is "reaching parts that other warmings have not reached"!

20. A recent key publication has shown that the increased incidence of warm air flows over and around the Peninsula, which have led to the ice shelf collapses, can be attributed to a combination of human-induced global warming, which has resulted in an intensification of the Westerly winds blowing around the Southern Ocean, and the human-induced Antarctic ozone hole. This is an important example of an attribution of significant contemporary regional change to humans.

21. The collapse of the Larsen B ice shelf resulted in a sustained increase in the flows of feed glaciers no longer buttressed, whilst glaciers feeding the area still intact showed no change. This resolved a long-standing debate about whether fringing ice shelves exert a significant back pressure on interior flows – the conclusion being that they do.

22, 23. The result is very important as it provides insight into the likely mechanism for the major ice discharge being observed in the Amundsen Sea Embayment (ASE) of the West Antarctic Ice Sheet (WAIS). This has been detected by spaceborne and airborne altimeters and lidars, and by spaceborne imagery and gravity instruments. It seems that a slight (~ tenth of a degree C) warming of the ocean may have caused the collapse of the fringing ice shelves, resulting in the observed discharge. Other drainage basins of the WAIS are "blocked" by huge ice shelves which remain intact. The stability of the WAIS has been a subject of speculation since the 1970s since the bulk of it lies on bedrock well below sea level – as deep as 2.5km in some places – and so experiences an "Archimedian" hydrostatic uplift. The concern is that a retreat of the grounding line (where the ice lifts off and begins to float) may experience a positive feedback and result in a complete discharge of the basin being drained. The "trillion dollar questions" are "How Much?" and "How Quickly?"

24. These are difficult issues to address since the ASE is an especially remote and challenging region to access. There are no research bases in this sector, and so airborne survey and field operations require a heavy lift capability to put in the necessary fuel depots. In the 2005 summer season this was achieved courtesy of the US National Science Foundation, enabling the British Antarctic Survey and the University of Texas to deploy their Twin Otter aircraft equipped with ice penetrating radars to survey the catchments of the Pine Island and Thwaites glaciers. In a seven week period the two aircraft flew 100,000km of flight lines to produce survey the topography of the rock surface beneath.

25, 26. The resulting map shows that if the current discharge were to continue, an ice volume equivalent to 1-1.5m global sea level rise would be delivered to the ocean. However, humans have not previously observed the collapse of a marine ice sheet, and we do not know enough about the processes involved to say if the discharge will continue or if it will peter out. A comparison of the histories of global mean temperature and sea level over the last half million years shows that during the last interglacial, 120k years ago, the temperatures were a few degrees C warmer than today and sea level was 4-6m higher. It is speculated that about half the additional melt was from the collapse of the Southern ice dome of the Greenland ice sheet, and half from the WAIS. However, the data from yet earlier warm periods suggest that the relationship between temperature and sea level is variable.

27. Satellite observations of the acceleration of Greenland and WAIS glaciers, combined with recording of an increase in the occurrence of Greenland "icequakes", have surprised the glaciological community and caused them to reappraise their views on the speed and strength with which ice sheets react to climatic warming. Associated with this changed view, is the discovery of a complex and apparently highly dynamic network of liquid water drainage beneath the ice sheets, that has a profound effect on glacier flows through its impact on the friction between the ice and underlying rock. It is apparent that the current numerical models, which do not contain "wet" ice dynamics and in any case suffer numerical stability problems at the grounding line, are not capable of predicting the speed or nature of such discharges.

28. The record of sea level rise since the end of the last ice age gives some insight, since it show a sustained rate of sea level rise of 1m/century over a 9k year period. Two bursts at higher rates occurred. Caution must be taken when

drawing an analogy with the present, since the configuration of ice sheets, with a vast Northern ice cover, was very different from today. Nevertheless, it gives an idea of what might be possible, especially if the bursts of sea level rise were associated with the catastrophic collapse of an ice sheet drainage basin and if the WAIS could emulate such a discharge. Sea level rise was stable for the last 3k years, but has increased over the last century, initially to 20cm/ century, but with a contemporary rate of 30cm/century.

29, 30. A major task of the International Polar Year 2007-2008 will be to address the contribution to sea level rise of the major ice sheets, with 11 of the 180 programmes focussing on some aspect of the problem. A synthesis project will be necessary to draw the information together and to arrive at policy-relevant conclusions.

31, 32, 33. Future sea level rise has the potential to affect the lives of millions and to impact trillions of dollars worth of infrastructure. A single flooding of London would alone cost an estimated £30bn, equivalent to 2% of the UK's GDP. Could a flooded London be the future? The unthinkable can happen as we witnessed with New Orleans – for different reasons – in September 2005.

34, 35. Looking ahead, the temperature projections from the IPCC, based on various assumptions about population, economic growth and the extent to which climate change mitigation measures are adopted, project a planet which by the end of the century could be almost unrecognisable. The UN Framework Convention on Climate Change commits nations to avoiding "dangerous" climate change, but what this constitutes can appear very different from the point of view of residents of a Pacific atoll relative to the citizens of western Europe or the USA, for example. Some nations and groups of nations have adopted a 2ºC global mean temperature rise as the "safe" limit, recognising the limitations of such a crude constraint. This corresponds to an atmospheric concentration of greenhouse gases equivalent to a CO_2 concentration of 450ppm. There is evidence that beyond this threshold increasingly undesirable consequences occur, such as the ineluctable collapse of the southern half of the Greenland ice sheet. The objective for humankind must be to "avoid the unmanageable and to manage the unavoidable".

36. It is the case that to stabilise the CO_2 concentration of the atmosphere at a given level, it is necessary once reached to stop adding CO_2! The sustainable level of ongoing emissions is not known; it could be as much as 2GtC per year net, but there is well-founded concern that in a warmer world the terrestrial biosphere and the ocean may become sources rather than sinks of carbon, in which case it would be necessary to draw down the equivalent of their emissions. What matters to the atmosphere is the TOTAL amount of carbon discharged into it. To a first order approximation it seems that humans have a remaining budget of about what we have emitted already (500GtC) before we must achieve these very low or even negative levels of ongoing emissions. Leaving this later rather than sooner makes it harder and potentially much more costly, since the rate of ramp down must be much greater in order to stay within the "allowable" total.

37, 38. A widely acclaimed strategy is to develop multiple means of reducing future human emissions, each seeking a reduction of 1GtC by 2050. Seven such "wedges" would stabilise emissions at current levels and additional wedges would achieve the necessary additional reductions to reduce the net annual gain to within a permitted level. Wedges include improved energy efficiency and conservation, switching to less carbon intensive fuels (gas rather than coal), conversion to bio-fuels, nuclear power, better management of the terrestrial biosphere, especially forests, and CO_2 capture and storage. Al Gore points out that although there is no silver bullet, there is silver "buckshot".

39. Many commercial companies and governments are looking at what could be characterised as "techno-optimist" solutions. An example is given by an impressive study to be found on the Swedish energy company Vattenfall's website.

40. However, the costs of the wedges are hard to discover in the literature. I have attempted some approximate estimates (so treat the figures with care!). The 1GtC wedges from nuclear, wind, and improved efficiency of cars each would require investment in the range $1-4Tn. Since the world annual GDP is currently of order $60Tn, these would seem affordable in principle, and are consistent with the conclusion of the recent Stern report (commissioned by the UK Government) that an ongoing investment of 1% of GDP ($0.6Tn/y) starting now, would avoid a future 20% economic downturn caused by climate change impacts. It is illuminating to compare these figures with the $3-5Tn estimated investment in conventional oil production necessary to satisfy the future projected world oil needs on a "business as usual" basis.

41. A characteristic of the "energy challenge" is that it spans so many domains of human behaviour that solutions tend to be subject to an unhelpful degree of "silo" thinking. Other options include a shift from meat eating to vegetarianism, and a concerted effort to address population growth. The latter offers the prospect of a 1GtC wedge at a cost 1000 times less than the technical approaches. And the collateral benefit is that an absent human has NO footprint.

42. A radical approach to limiting human carbon emissions would be to keep the carbon in the ground by controlling it at source – i.e. by limiting its extraction. It is difficult to imagine carbon being declared an illegal substance, but this is effectively what must happen and sooner rather than later. This was after all the solution adopted to arrest the depletion of stratospheric ozone resulting from human emissions of chlorofluorocarbons, and the approach has worked! The other imperative is to find cost-effective and energy-effective technical means of sequestering carbon during use and of "sucking" carbon back out of the atmosphere. Our ability to achieve this will affect directly the amount of fossil fuel energy future generations will be able to exploit.

43. A worrying fact is that over the last 7 years human carbon emissions have continued on the "Business As Usual" trajectory, which deviates strongly from the path necessary to stabilise at 450ppm. New trajectories can be drawn up, but in the end, if these are not followed, a 450ppm stabilisation level could become impossible to attain.

44. A very significant complicating factor in finding a solution is that the bulk of the projected growth in human carbon emissions is attributed to the developing nations, who arguably have a right to benefit in the way that developed nations have already benefited. The partitioning of the remaining carbon "budget" thus becomes an issue of ethics and equity, as well as sustainability

45. The challenge facing the human race is unprecedented. The evidence for the problem is complex and technical with uncertainties at the detailed level, the impacts of current behaviour are distributed and distant in time and space, "homo urbanus" is insulated from nature, there is inertia in population growth and demography, societal infrastructure and behaviour, strong vested-interests are threatened, there are significant issues of sharing between the developed and developing world, and there is a major mismatch between the jurisdiction, capabilities and motivations of existing institutions relative to what is needed

46. Leadership is required, and although the ingredients are well known in principle, in practice the necessary degree of leadership is currently absent.

47, 48. The "Great Test" confronting humankind in the way it conducts its affairs is to switch from a situation in which aggression and physical strength are rewarded to one in which success will depend on intelligent co-operation for the global common good. The Antarctic Treaty System arguably provides an excellent starting point and example. The issue needs to be addressed with urgency, since climate change and its impacts are already upon us – as are the future generations whose quality of life we will determine.

49. In conclusion, I offer two quotes, one to provide an insight into how to rally concerted action and the second to finish on a note of necessary optimism:

"If the Earth were only a few feet in diameter, floating a few feet above a field somewhere, people would come from everywhere to marvel at it … they would declare it as sacred because it was the only one, and they would protect it so it would not be hurt" (Joe Miller)

"Our problems are Man made, therefore they may be solved by Man" (John F Kennedy)

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