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Article abstract

Climate change is the most pressing societal issue of our time. The Canadian geological community is deeply divided as to whether or not anthropogenic carbon dioxide is the principal driver of the global warming that we see around us. As geologists, we have the scientific understanding to be effective stewards of Planet Earth and thus have a critical role to play in the climate change debate. Many of the basic scientific principles in this debate, however, are more a matter of atmospheric physics than classical geology: this may be one reason why so much uncertainty continues in the geological community. Also, we have a professional responsibility to inform ourselves and our colleagues beyond the level of knowledge of the general public. We must apply the precautionary principle in assessing the response of the Earth to human activity. We should learn from the engineering and medical communities that our students should be well educated in fundamental principles and that a balanced assessment of issues should be presented to the public and decision-makers. The scientific debate over climate change should be carried on at mainstream meetings and in the peer-reviewed literature.

GAC PRESIDENTIAL ADDRESS

Greenhouse Gases and Global Change: A Challenge for Canadian Geoscience

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SUMMARY
Climate change is the most pressing societal issue of our time. The Canadian geological community is deeply divided as to whether or not anthropogenic carbon dioxide is the principal driver of the global warming that we see around us. As geologists, we have the scientific understanding to be effective stewards of Planet Earth and thus have a critical role to play in the climate change debate. Many of the basic scientific principles in this debate, however, are more a matter of atmospheric physics than classical geology: this may be one reason why so much uncertainty continues in the geological community. Also, we have a professional responsibility to inform ourselves and our colleagues beyond the level of knowledge of the general public. We must apply the precautionary principle in assessing the response of the Earth to human activity. We should learn from the engineering and medical communities that our students should be well educated in fundamental principles and that a balanced assessment of issues should be presented to the public and decision-makers. The scientific debate over climate change should be carried on at mainstream meetings and in the peer-reviewed literature.

SOMMAIRE
Les changements climatiques constituent l'enjeu le plus pressant du moment. Le milieu géologique canadien est profondément divisé sur la question du dioxyde de carbone, en tant que cause principale du réchauffement climatique dont on peut voir les effets autour de nous. En tant que géologues, nous disposons de la connaissance scientifique nous permettant d'être des intendants efficaces de la planète Terre, et à ce titre, nous avons un rôle de premier plan à jouer dans le débat sur les changements climatiques. Cela dit, nombre des principes scientifiques qui sous-tendent ce débat, relèvent davantage du domaine de la physique de l'atmosphère que de la géologie classique; ce qui serait une des raisons qui expliquerait que tant d'incertitudes demeurent dans le milieu géologique. Aussi, il est de notre devoir professionnel de nous tenir bien informés et de nous assurer que nos collègues disposent d'un niveau de connaissances supérieur à celui du grand public. En mesurant les répercussions de l'activité des humains sur la Terre, nous devons appliquer le principe de précaution. Nous devrions tirer profit de l'expérience des milieux médicaux et du génie et réaliser qu'il est essentiel de bien informer nos étudiants des principes fondamentaux et de présenter une évaluation équilibrée, tant au grand public qu'aux décideurs.

INTRODUCTION
Climate change resulting from anthropogenic increases in the abundance of greenhouse gases in the atmosphere is the most important Earth Science issue facing the planet. Yet from personal experience, I know that there are many in the Canadian geoscience community who are either uncertain about, sceptical of, or firmly opposed to the concept that atmospheric carbon dioxide will result in significant climatic change over the next century. This scepticism is rooted in our experience as geologists of other causes of climate change, some rapid, in the past. Rigorous scepticism is a pillar of both the scientific method and of a democratic society. However, much of the scepticism of the Earth Science community does not appear to be thorough or well-informed. Furthermore, our dealings with the public and policy makers should be governed by different rules than those of legitimate scientific debate within the geological community.

In this paper, I want to examine possible reasons for the scepticism among geologists, which I believe to be damaging to the standing of the Earth Science community. I will suggest some possible causes for this scepticism and offer some solutions for reducing this scepticism. I will review the important role that Earth Science plays in the climate change debate and suggest ways in which we should respond to the intense societal interest in the debate.

My remarks are based on my personal impressions of the thinking of the geoscience community. I have carried out unscientific straw polls of various groups on various occasions over the past year. There are currently at least two rigorous social science surveys underway in Canada on attitudes towards global change and I eagerly await these results. I do assume some underlying causes of current attitudes, but much of my analysis will still be valid even if future research shows some of those causes to be incorrect.

I will declare my bias up front. I am not one of the sceptics but I hope I have an open mind. Like many marine

Quaternary geologists, I work with colleagues whose science has informed the assessments of scientific literature made by the Intergovernmental Panel on Climate Change (IPCC). As with the plate tectonics debate of the late 1960s, I find the science compelling.

WHAT IS THE CONTROVERSY ABOUT?

Most geoscientists know that the Earth's climate has changed profoundly in the past. In their professional work, many are aware of the consequences of Quaternary glaciation. The scientific questions that I most often hear from geoscientists include:

- Is global warming really happening on a scale beyond that of pre-industrial climate change?
- We know that many factors caused climate change in the past. Why are we not talking about the importance of volcanoes, or astronomic forcing, when we look at the climate today?
- Is variation in solar insolation responsible for the most recent phase of warming, as it has been responsible for climatic change in the past?
- If global warming is due to anthropogenic greenhouse gases, is the key gas methane, carbon dioxide or water vapour?
- Is carbon dioxide a consequence, rather than a driver, of global warming?
- If climate models are so bad at hindcasting, how can they possibly forecast?

We are also influenced by our political, cultural and social environment. It is well known that the view of global warming is different in Alberta than in Quebec. I have heard the following non-scientific points:

- There is a herd instinct. On matters on which we are not experts, do we just pick up factoids from our colleagues?
- If Greenpeace and the Sierra Club believe that carbon dioxide induces global warming, it must be treated with scepticism, given that so much else that they claim is unbalanced.
- IPCC is not a scientific organization; it is a collection of geopoliticians interested in the continuity of their grant funding.
- Geologists are used to the concept that change, including rapid change, is natural. As a discipline, much effort over the past two centuries has gone to refuting those who prefer religious explanations to natural change.

These non-scientific points clearly need further rigorous investigation by social scientists. I draw no conclusions from them, but offer them as one clue to the way in which the Earth Science community is thinking.

WHAT ARE THE SCIENTIFIC ISSUES?

As geologists, we know that there are many causes of climate change through geological time (Fig. 1). We also know that these causes operate on different time scales and that atmospheric climate involves complex feedback effects with the hydrosphere, the biosphere and the lithosphere.

The fundamental scientific question, however, is not what processes may force climate change. The question we have to address is *what is the magnitude of the climatic effect of global increases in the concentration of greenhouse gases*? This is a relatively simple question of atmospheric physics. Radiation from the sun is balanced by energy radiated back from Earth to space (Fig. 2). The Earth's atmosphere, and particularly high clouds and a variety of so-called greenhouse gases, reduce the amount of energy radiated back into space. These greenhouse gases include water vapour, with a mean residence time of about 10 days in the atmosphere, carbon dioxide (50-200 years), methane (12 years) and nitrous oxide (120 years). Excess carbon dioxide is eventually taken up, largely by the ocean. However, the current rate of production of anthropogenic carbon dioxide is much greater than can be removed by the oceans and the amount of carbon dioxide in the atmosphere has increased from 280 ppm in 1750 to 380 ppm today (Fig. 3). The relative importance of greenhouse gases since 1750 compared with other sources of radiative forcing in creating disequilibrium in the Earth's radiation balance has been evaluated by IPCC (2001) and is summarized in Figure 4. The disequilibrium in the radiation balance caused by the increase in greenhouse gases inevitably results in global warming, just as cloud cover at night results in local warming compared with clear sky conditions. Rapid increases in greenhouse gases will inevitably lead to global warming: this is a consequence of basic physics. Warm climates cannot be maintained without greenhouse gases to block outgoing

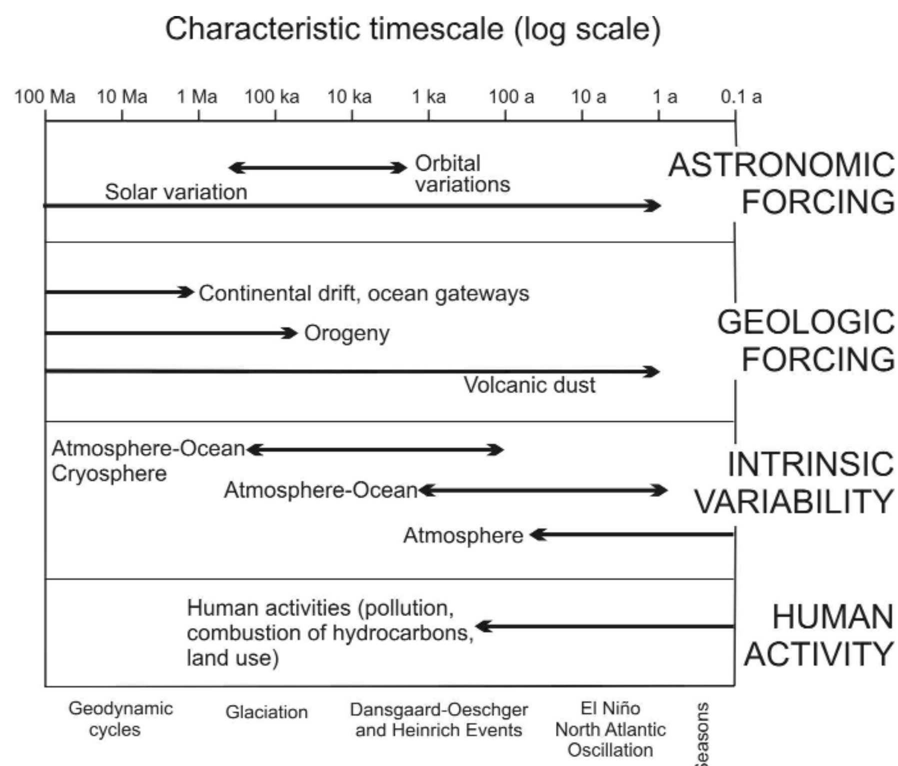

Figure 1. Types of climate forcing and their characteristic timescales (modified from Bard 2006).

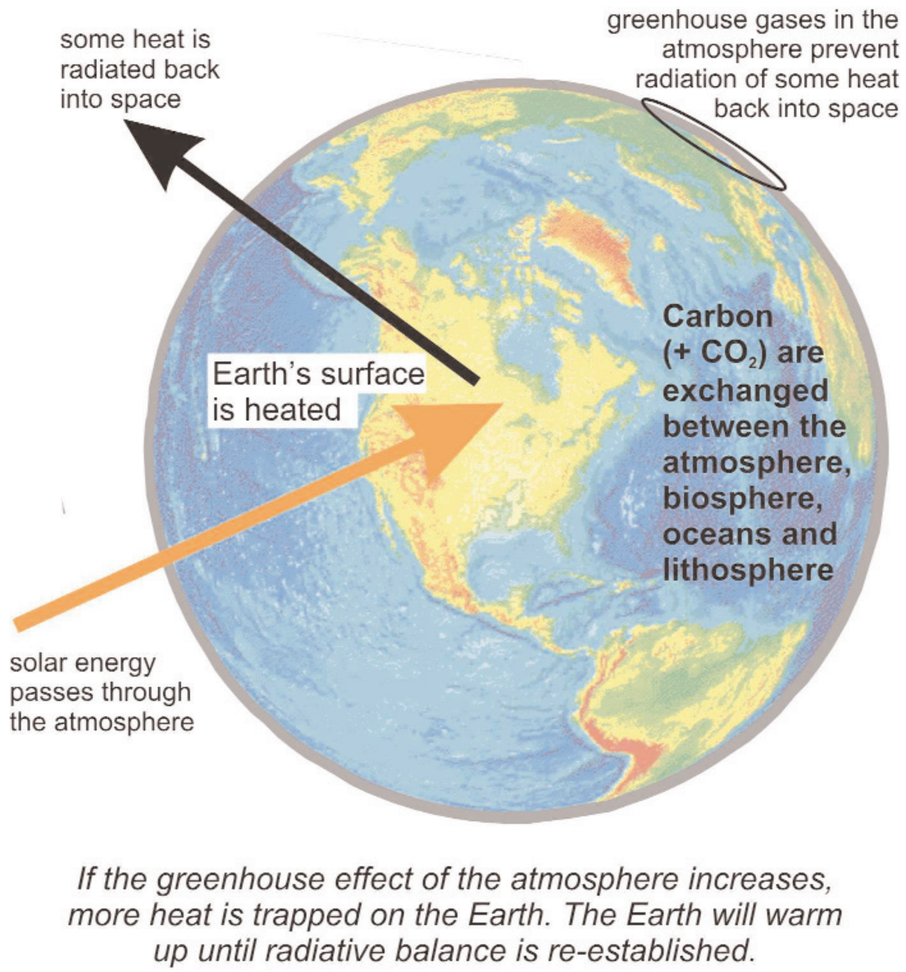

Figure 2. The Earth's radiation balance and the greenhouse effect (modified from Environment Canada [http://www.climatechange.gc.ca/english/climate_change/])

radiation. The thermal effect of increased greenhouse gas is immediate. In many cases, additional indirect effects will lead to processes involving positive feedback that amplify the warming.

The magnitude of the warming effect of current carbon dioxide levels is not trivial. Precise predictions of the magnitude of global warming require coupled atmosphere–ocean global circulation models and assessment of the role of radiative forcing other than by greenhouse gases. There is a robust concensus among those working in the field that warming of at least 1-3°C will take place over the next century.

Significant global warming is an inevitable consequence of the anthropogenic increase in greenhouse gases. It does not matter how climate change has been forced in the geological past. This is the reality of the Earth today. All other scientific questions, including those raised earlier in this paper, are secondary, although some have been turned around by sceptics to be fundamental issues. This paper is not the place to explore the details of these issues (see Weaver 2003, and White 2006, for some responses), but a brief review is provided to identify some of the critical issues that draw on the expertise of geologists. They include:

(1) Is current global warming beyond the range of natural variation in the late Holocene? Expressed in another way, how much of observed variability in weather is forced by anthropogenic greenhouse gases? And specifically, can variation in solar radiation account for current observed global warming?

Present warmth (Fig. 5) is the highest in at least the last millenium. Global climatic models that consider the range of radiative forcing, including solar radiation, sulfur dioxide pollution, and volcanic dust, have been able to simulate temperature variations over the past 50 years (Stott et al. 2000). As argued in an earlier article by Weaver (2003) in Geoscience Canada, the general predictions of climate models match well the observed patterns of late 20th century climate change, including most rapid change in the northern hemisphere and in high latitudes. However, most scientists find variations in solar radiation or cosmic ray flux insufficient to account for significant warming: interested readers can compare Veizer (2005) with the counterarguments by Benestad (2005).

(2) Does the correlation between atmospheric temperature and carbon dioxide in ice cores indicate causality?

As we all know, correlation does not indicate causality. The climatic cycles of the Quaternary show periodicity related to Milankovitch orbital variations, but paleotemperature estimates from Antarctic ice cores show a strong correlation with abundance of carbon dioxide in the cores. During glacial terminations, there is a lag in the increase in carbon dioxide compared with the onset of warming, demonstrating that carbon dioxide cannot be the exclusive

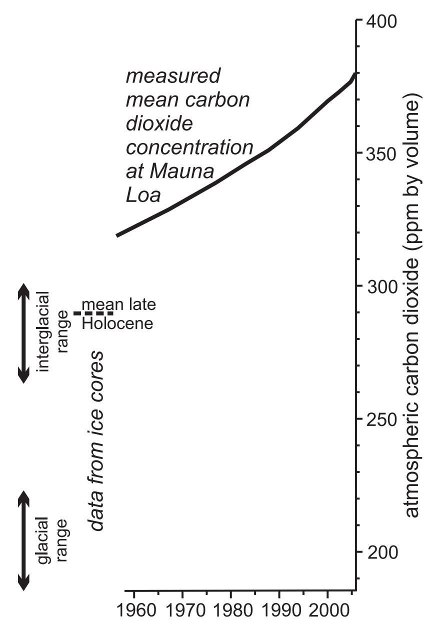

Figure 3. Historical changes in concentration of carbon dioxide in the atmosphere (data from Keeling and Whorf 2005) compared with the Holocene and late Pleistocene record of atmospheric carbon dioxide preserved in ice cores (data from Neftel et al. 1984, and Petit et al. 1999).

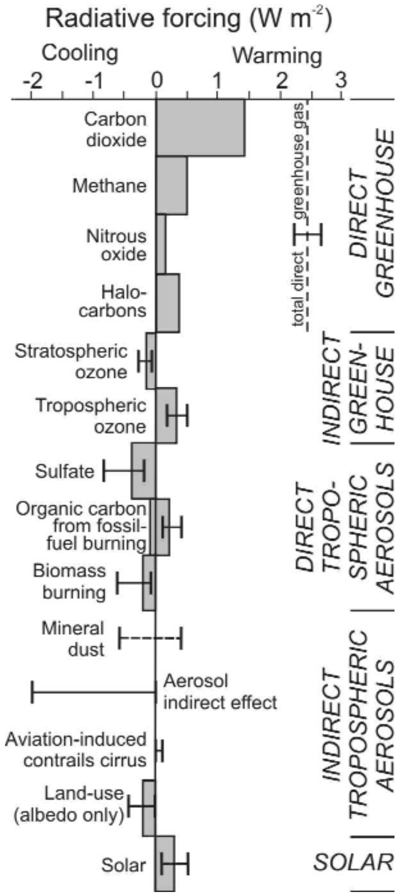

Figure 4. Causes of the lack of radiative balance on the Earth since 1700 (modified from IPCC 2001).

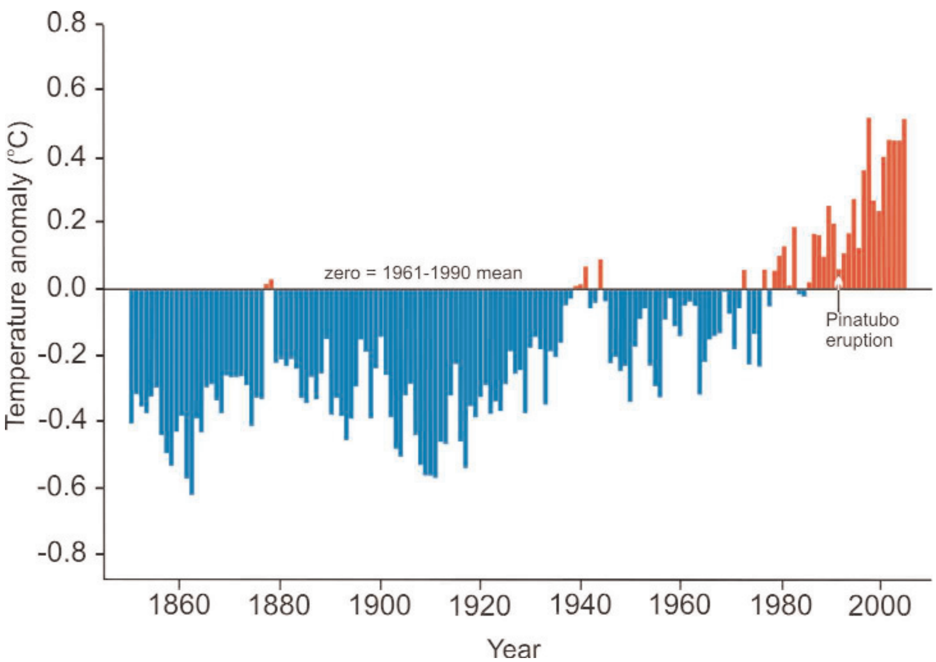

Figure 5. Changes in global surface air temperature since 1855 (graph from University of East Anglia [http://www.cru.uea.ac.uk/cru/info/warming/]; see Jones and Moberg 2003).

driver of climate (Caillon et al. 2003). At the millenial timescale of glacial fluctuations, however, radiative equilibrium is likely established for all types of radiative forcing and feedback mechanisms. As a result, the process driving variation in carbon dioxide, whether it be ventilation of the ocean or iron fertilization by windblown dust, causes changes in concentration of atmospheric carbon dioxide that then becomes an important control on global temperature through the greenhouse effect. Atmospheric carbon dioxide, methane and water vapour, together with changes in ocean circulation and productivity, all produce positive feedbacks to small changes in climate induced by Milankovitch changes in radiative forcing.

(3) What are predictions of future levels of atmospheric pollutants and what will be the consequences in terms of extreme climate events and global warming?

If the fundamental reality that global warming is a result of anthropogenic greenhouse gases is accepted, then the magnitude of that change becomes an important issue. Again, this paper is not the place for a full review of the issues, which are covered by IPCC (2001) and Weaver (2003) and updated in the 2005 conference on Avoiding Dangerous Climate Change (Tirpak et al. 2005). Quaternary geologists know well that changes in ocean circulation in the Younger Dryas resulted in a brutal cooling in Europe (and Atlantic Canada!) and that in the Sangamonian interglacial, sea level was about 6 m higher than during our present interglacial. The IPCC (2001) consensus was that melting of West Antarctica or Greenland to cause a massive rise in sea level was highly unlikely, but more recent work has questioned this assumption (e.g. Gregory et al. 2004). The likelihood of a Younger Dryas shutdown of the thermohaline circulation has also been argued to be unlikely by our 2006 Logan medallist (Hillaire-Marcel and Weaver 2005). As geologists, however, we have an obligation to urge the precautionary principle on society.

(4) If water vapour is a more effective greenhouse gas than carbon dioxide, then why isn't global warming a consequence of more water vapour?

The water vapour content of the atmosphere cannot be increased artificially because condensation and precipitation occur when the relative humidity reaches 100%. More water vapour can be held in the atmosphere at higher temperatures, so that if temperature increases as a result of other processes, there is a positive feedback as a result of water vapour.

IS SCIENTIFIC EDUCATION IMPORTANT?

I now want to turn to the question of why there is so much resistance to global warming among Canadian geoscientists. As outlined above, the fundamental scientific question is not what many would think of as a geological issue. It is an atmospheric science issue, and involves principally an understanding of atmospheric physics. Only the secondary questions involve what we normally recognize as geology.

Geologists have an important contribution to make to the climate change debate. We understand how climate has changed through geological time. We understand the complexity of natural systems. Above all, perhaps, we understand the meaning of extreme events. I return to these points below.

In a similar manner, geologists have an important contribution to make to understanding the genetic basis of evolution, but ours is not the central science in that debate.

Because atmospheric science and oceanography are more central to the climate change debate than is geoscience, perhaps this encourages a sceptical approach by geoscientists. Many of us are insecure with science outside our own experience as geologists. I became a geologist because at high school I loved the outdoors but did not like dissecting frogs. My pre-University background was not a strong foundation for understanding the physics of the atmosphere or the strengths and limitations of modelling. I learned early on in my university career that geophysicists who modelled, rarely seemed to have much connection with reality and the most distinguished emeritus geophysics professor at my alma mater showed by modelling that continental drift was impossible. The world has changed. Modelling is still the simplification of scientific problems in order to analyze fundamental processes, but the reality and complexity of models has completely changed. At the risk of being challenged for my choice of example, if weather forecasting is now done by models, we should at least be prepared to accept that modelling is a valid scientific approach to understanding climate change.

We are also all too busy. Most of us have too much to read without branching outside the demands of our jobs, families and volunteer activities. The climate change debate is complex and involves many issues that as geologists we may not deal with on a day-to-day basis. So much of what we learn is by word of mouth and by interaction with colleagues. It is for these reasons that I suspect Quaternary and marine geologists are more accepting of climate change driven by anthropogenic greenhouse gases, in contrast to those who work with older rocks. There is a challenge here for those involved in outreach: outreach must reach our colleagues as well as the general public.

This is not to categorize all dissent to global warming as lazy, ill-informed, or lacking an understanding of fundamental scientific principles. Science advances through intellectual disagreement and criticism. The peer-reviewed literature is an essential component of that debate. The scientific understanding of bandwagons in the past, such as plate tectonics and sequence stratigraphy, has been greatly enhanced by critical assessment. We must take care that political correctness does not prevent us from taking the scientific opponents of climate change seriously. Broadly based scientific meetings and the peer-reviewed scientific literature are the places for the scientific debate to take place.

WHAT CAN GEOLOGISTS CONTRIBUTE?

Many rock-hammering geologists and their laboratory-based colleagues want to feel that their discipline can contribute to the important societal issue of climate change. There are at least four important ways in which we do already contribute. I will not dwell on these because they are well known to many geologists and experts more informed and experienced than I have made these points cogently in the past:

1) The record and origins of climate change through geological time. Our perspective shows the great importance of astronomic forcing over geologic time and the complexity of feedback mechanisms in the climate system. Veizer (2005) provides a useful perspective on these issues.
2) Case studies of the physical behaviour of natural systems during past experiences of climate change. The Late Paleocene Thermal Maximum and the K/T boundary climates are classic examples of abrupt climate change in the past that are areas of active research on how the entire Earth System responded at those times.
3) An increase in extreme weather events with global warming is one of the key predictions of the IPCC. Sedimentologists have an important perspective on extreme weather because many of the rocks that we see, particularly clastic rocks, are the deposits of floods or storms. Many types of fluvial deposits or hyperpycnal turbidites are probably the result of the 100 year flood, rather than "normal" sedimentation. Our geological record, whether in the Quaternary or older geologic time, is a product of the abnormal.
4) The impact of past climate change on biota and society. The paleontologic record provides a geologic analogue of the relationship between overpopulation, societal specialization, environmental change, and extinction, as convincingly argued by Bill Fyfe and the late Digby MacLaren.

Furthermore, within our Canadian geography, we have some of the most critical environments for the future of global warming. The Labrador Sea is a vital component of the deep thermohaline circulation of the ocean (Hillaire-Marcel and Weaver 2005). It is the Arctic, rather than the Antarctic, that is currently warming rapidly (ACIA 2004) and it is in northern high latitudes that catastrophic release of methane pools resulting from dissociation of gas hydrates is most likely (Nisbet 2002).

As a Canadian Earth Science community, we have so much more to contribute to society than some of the NSERC reallocation successes like chemistry and astronomy. As Tom Pedersen and the NSERC Environmental Earth Science grant selection committee have recently argued: "Consider these keywords: Kyoto, water and air quality, acid rain, earthquakes and tsunamis, biodiversity, carbon, drought, radioactive waste disposal, land use change ... the list goes on"[1]. The Solid Earth Sciences grant selection committee could equally well point to the booming demand for conventional energy and minerals and the natural hazards of earthquakes and volcanoes, all of which demand the underpinnings of fundamental science.

WHAT'S IN A NAME?

Are we Earth Scientists, geoscientists, or geologists? GAC is still the Geological Association of Canada, and IGC is still the International Geological Congress. Geologists study rocks. The Geological Association of Canada provides a forum for scientists who work with rocks, rather than those working with the atmosphere or oceans. Yet the atmos-

[1] Quoted, with permission, from a February 2005 letter to the President of NSERC.

phere and oceans are intrinsically linked to our understanding of the Earth. To understand them, we need an understanding of Earth System Science (Barnes et al. 1995). Are our students in Earth Science departments today learning about Earth systems? From my limited knowledge, the adoption of Earth System Science appears quite patchy. Particularly in smaller universities with fewer faculty members, Earth Systems Science is not a major part of the curriculum and deficiencies in background understanding are commonly not remedied in graduate schools. The emphasis on a core curriculum strongly influenced by the needs of professional registration has probably slowed this needed reform.

Many members of the Geological Association of Canada regard themselves as geologists. I certainly do. Yet we are also part of a larger Earth Science community, that has a wider intellectual scope. Many have identified our recent failures to have an impact in NSERC reallocation or more broadly on the national agenda as a result of our fragmentation and inability to project the broader Earth Science perspective. We can learn from the engineers and chemists. They too work in an environment of professional registration or accreditation, yet seem capable of ensuring that their students have a fundamental underpinning of the basics in their field. All our graduating students seeking professional registration should be able to clearly explain the Earth's carbon cycle and the basic principles of the greenhouse effect.

SCIENTIFIC CONTROVERSIES: SCIENCE AND SOCIETY

Our scientific mythology admires iconoclasts, those who were ahead of their times in bucking the trends, and brought about paradigm shifts. Our heroes of one or two centuries ago are Hutton, Lyell, and Wegener. We forget those who thought that the moon came from the Pacific Ocean, or that continental drift was driven by the asymmetry of polar ice caps, or that sea-floor spreading was driven by an expanding earth.

The development of plate tectonics in the 1960s holds both analogies to and differences from the current climate change debate (Oreskes 2001). Plate tectonics was a classic example of a paradigm shift, on the same scale as the change from natural theology to evolution or from Newtonian to quantum mechanics. But it was also essentially an academic concept: there was no particular societal or political interest in the evolving concepts. As a paradigm shift, it provided for many geologists an opportunity to simplify their science and to relate issues that had previously seemed disparate. Plate tectonics was an exercise in synthesis. Like the climate change debate, it had its critics and detractors, and some dead ends were explored. Like the climate change debate, the scientific underpinning of the debate was in the peer-reviewed literature.

Climate change science does not involve a scientific paradigm shift. Rather, the debate around global warming is forcing us to recognize our ability to change Earth systems. Politicians and NGOs representing civil society are involved in the global warming debate and it has immediate consequences for society. Plate tectonics science could be carried out from an ivory tower and the debates would be debates among scientists. Our debates about global change, of necessity, go beyond the ivory tower and we have to adjust our scientific behaviour to this reality.

The science of global change involves *analyzing* how complex systems behave through time, rather than *synthesizing* disparate data as was the case for plate tectonics. As geologists, our notion of time is long but fuzzy: we are good at analyzing spatial relationships, but the relationship to time is imprecise. Climate change does not help us explain things that we are familiar with scientifically. We perhaps yearn for the funding or the societal recognition that success in climate change studies could bring, but for most of us it has no impact on our professional lives. Do we also fear that success of climate change scientists will somehow diminish our own importance? Surely, there is lots of geology beyond global change. It is not a long term threat to the oil industry or the mineral industry or to funding for pre-Holocene geology.

Another important difference between the plate tectonics debate and the global change debate is that the consequences of error are more severe today than they were in the 1960s. So what if sea-floor spreading was a wrong hypothesis? Who would care? The impact on society would be only indirect. But the consequences of getting global warming wrong could be catastrophic. A 7 m rise in sea level would ruin the US economy a lot more effectively than would energy conservation or emissions limits. We have a responsibility to apply the precautionary principle.

Rather than looking to the successful debates of the past, we should look at how other scientific groups with major societal impacts deal with scientific controversy and civil society. Given the recent turmoil within the Canadian Medical Association Journal, I hesitate to hold up the medical profession as a model, but I suggest we have much to learn from it. The analogy for the climate change debate is not with medical debates over hormone replacement therapy or drinking moderate amounts of red wine, where there are complex benefits and risks to be weighed. The better analogy is with the medical debates over obesity and smoking. The dangers to society of greenhouse gases are analogous to the dangers of obesity and smoking in two ways. First, the scientific uncertainty is around the edges (the role of sugar, the degree of the second-hand smoke risk), but the basic scientific issue is quite clear. Second, the potential impact on society is enormous, whether it be from smoking, obesity or climate change, and the precautionary principle requires that action be taken to protect society.

The need for rigorous scientific debate cannot be confused with the need to provide the public and policy makers with clear information. If I go to my family doctor and ask for an opinion on a blood test result, I expect a balanced answer and to be pointed to further information or a second opinion. I also expect the same degree of professionalism if I meet a doctor in a social situation. My experience is that I do not get the same degree of professionalism from geologists on the subject of climate change. I have commonly got a colourful opinion rather than a clear scientific assessment. Our move to professional registration over the last decade has resulted in an emphasis on life-long learning and has made us more aware of our professional responsibility to society. This life-long learning means that we should all be informed about important geoscience issues. I challenge you all to spend the time to inform yourselves. It is your professional responsibility. Depending on the medium you prefer, Weaver (2003), White (2006), or Bard (2006) *en français* are good starting points. I also challenge you to adopt the precautionary principle.

CONCLUSIONS: WHAT WE CAN DO AS AN EARTH SCIENCE COMMUNITY

No critique is complete without specific recommendations.

1) As individuals, we should be informed on issues that affect society. We would not expect a medical doctor to provide erroneous or unbalanced opinions in a social setting, let alone a professional setting. Neither should geologists. We can learn from the medical community that it is more important to convey the precautionary principle to the public and policy makers than to air the details of our healthy scientific scepticism.
2) As geologists, we should recognize that we are part of a broader Earth Science community. We must work harder to teach Earth Systems science at our universities. We should continue to welcome oceanographers and atmospheric scientists as part of our community. We should work with them to bring the importance of Earth Science to the attention of policy makers.
3) The Earth Science community must continue to debate scientific issues. The debate should take place at broadly based scientific conferences and in the peer-reviewed literature.
4) We should all be optimistic and positive about the future of Earth Sciences. Earth Scientists hold many of the answers for society. We should focus on the positive in our interactions with society.

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