Climatic Change (2010) 100:15–21
DOI 10.1007/s10584-010-9840-7

An overview of climate change science in 1977 marking the publication of Volume 100 of Climatic Change

L. D. Danny Harvey

Received: 8 March 2010 / Accepted: 11 March 2010 / Published online: 19 May 2010

In order to mark the 100th volume of *Climatic Change*, I will go back to the time of the first issue of *Climatic Change*, in 1977, and outline the state of knowledge concerning the climate science of global warming and of potential impacts such as existed at that time. I will argue that the science then concerning the climatic consequences of anthropogenic CO_2 emissions was sufficient to have justified what could, at the time, have been regarded as "precautionary" action. In the 33 years since the first issue of *Climatic Change*, the climate science has become substantially stronger, we have began to see happening what were mere predictions when the first issue of *Climatic Change* was published, and we have come to realize that the ecological and social consequences of the projected future warming will be worse than thought even 10 years ago. Action now to restrain and then reduce emissions of CO_2 and other greenhouse gas can therefore no longer be regarded as "precautionary". An appropriate term for what are still, unfortunately, only hypothetical emission reductions would be "reactive", as action at this late date will merely serve to reduce the magnitude of harm that we now clearly face.

Arrhenius (1896) argued, on the basis of earlier measurements of the absorptive properties of CO_2 and water vapor in the atmosphere, that variations in the amount of CO_2 in the atmosphere were the main factor in explaining past large variations in climate, and he noted that combustion of coal was adding to the amount of CO_2 in the atmosphere. He recognized that increasing temperature due to increasing CO_2 would be accompanied by an increase in the amount of water vapor in the atmosphere, and that this increase in water vapor would exert what we now call a "positive feedback" that would amplify the effects of increasing CO_2. He also recognized that retreat of ice and snow as the climate warmed would amplify the temperature changes in polar regions. Thus, many key features of our present understanding of how the climate reacts to increasing atmospheric CO_2 were identified over 100 years ago.

L. D. D. Harvey (✉)
Department of Geography, University of Toronto, 100 St George Street,
Toronto M5S 3G3, Canada
e-mail: harvey@geog.utoronto.ca

The buildup in the concentration of a gas in the atmosphere in response to a given steady or growing emission depends on the time scales with which the gas is removed from the atmosphere, which were unknown in the late nineteenth century. However, by the late 1950s, the basic times scales for the absorption of CO_2 by the oceans had been worked out by Roger Revelle, Hans Suess, Bert Bolin and others based on observations of the distribution of natural ^{14}C in the oceans and based on observations of the variation in the amount of tritium and ^{14}C in the atmospheric produced by atmospheric testing of nuclear weapons. This work showed that any CO_2 increase due to human emissions would be irreversible on human time scales, and implied that the atmospheric CO_2 concentration should be increasing year by year due to the emissions at the time. This prediction was confirmed soon after when Charles Keeling began systematic measurements in 1958 at Mauna Loa observatory, Hawaii, of the atmospheric CO_2 concentration at an elevation of 3397 m, far removed from local sources of CO_2. By 1960 it was clear that the atmospheric CO_2 concentration was increasing. By 1977, the atmospheric CO_2 concentration had been observed to have increased by 20 ppmv—from 315 ppmv in 1958 to 335 ppmv by 1977. Various analyses based on the changing ratio of the isotopes ^{13}C and ^{12}C in the atmosphere, and numerous other lines of evidence, established beyond any doubt that the observed CO_2 increase was due to human emissions. The results of a major symposium on the response of the carbon cycle to human emissions were published in 1973 (Woodwell and Pecan 1973).

Given an increase in atmospheric CO_2 concentration, the next major question that had to be settled was the magnitude of the resulting radiative perturbation. Tyndall had discovered that CO_2 absorbs infrared radiation in 1859. Additional measurements were made by Langley and others through to the 1890s and used by Arrhenius (1896) in his calculations. Calendar (1938, 1941) surveyed a wide array of spectroscopic measurements of the emission and absorption of CO_2, and thereby convincingly showed that changes in atmospheric CO_2 concentration would have important effects on the radiative energy budget of the Earth (see also Fleming 2007). By the early to mid 1970s, fairly detailed and accurate narrow-band models of the absorption spectrum of CO_2 were available, as well as that of other gases that absorb at the same wavelengths as CO_2, and algorithms for computing the changes in radiative fluxes when CO_2 increases were well established and closely validated, as reviewed by Ramanathan and Coakley (1978).

The next step in the evolution of our understanding concerned determining *which* changes in radiative fluxes resulting from increasing CO_2 are the drivers of surface temperature change. Manabe and Wetherald (1967) showed, through analysis of the results of vertically resolved radiative–convective models, that the surface temperature response does not directly depend on the increase in downward infrared radiation at the surface, but rather, is more closely related to the reduction in outgoing infrared radiation at the top of the atmosphere when CO_2 increases. This perturbation is substantially larger than the increase in downward radiation at the surface, but still underestimates the relevant driving factor. By 1975 it was realized that the relevant perturbation is the net reduction in upward radiation at the tropopause level (Schneider 1975). This consists of the reduction in upward emission at the tropopause as well as the increase in downward emission from the stratosphere, and is about 40% larger than the reduction in outgoing radiation at the top of the atmosphere. The corresponding expected increase in surface temperature

is also 40% larger. This concept was further refined with the idea of the "adjusted" radiative forcing, which takes into account the rapid (within months) cooling of the stratosphere that occurs in response to increasing CO_2 and largely independently of the surface-troposphere response (Schneider 1975). Thus, by 1977 the accurate calculation of the perturbation in infrared radiative fluxes was possible and the relevant radiative forcing when CO_2 concentration increases was well understood. The radiative forcing for a hypothetical doubling of the CO_2 concentration was found to be about 4 W/m^2. Projections based on rapidly growing emissions indicated that the CO_2 concentration could reach twice that observed when Charles Keeling began his measurements by mid 21st century and six to eight times that in the next century (Hoffert 1974; Keeling and Bacastow 1977).

The next major question concerned the climatic response to increasing CO_2. Arrhenius (1896) had calculated an increase of about 5°C. There are a number of key benchmarks in establishing the global mean warming in response to a given CO_2 increase. The first is the response to be expected in the absence of any temperature feedbacks other than the increase in the emission of infrared radiation through the Planck function (which had been measured experimentally in the nineteenth century and derived theoretically in the early twentieth century). This is a warming of about 1.2°C for a CO_2 doubling. The second benchmark concerns the feedback due to increasing amounts of water vapor in the atmosphere as the climate warms. Work in the 1960s with one-dimensional (vertically resolved but globally averaged) radiative–convective models indicated that, subject to the assumption that relative humidity remains constant at all levels in the troposphere as the climate warms, the water vapor feedback would roughly double the expected climate response, to about 2.3°C global mean warming (Manabe and Wetherald 1967). As noted earlier, it had been realized since at least Arrhenius' time that the retreat of snow and ice at high latitudes would amplify the temperature response in polar regions (due to a regional positive feedback involving surface albedo). The big unknown in the 1960s and 1970s (and still now) was the role of cloud feedbacks, which could either amplify or diminish the final warming for a fixed CO_2 increase. Great progress had been made during the 1960s and 1970s in simulating the major features of the Earth's climate and weather patterns using three-dimensional general circulation models (GCMs) of the atmosphere (as reviewed in Appendix B of NRC 1975), but these models had barely been applied to the question of the change in climate resulting from increasing CO_2 by 1977. The first such study was that of Manabe and Wetherald (1975) at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, using an atmospheric GCM with idealized land–ocean geography. This model gave a global mean warming of 2.9°C in response to a CO_2 doubling and indicated an intensification of the hydrological cycle. No indication of changes in soil moisture was given then, although it was noted that the increase in evaporation from soils would exceed the increase in rainfall in some regions. The potential of a significant (5 m) increase in sea level over a period of several hundred years was recognized soon thereafter (Geophysics Study Committee et al. 1977).

Calculations by Augustsson and Ramanthan (1977) that took into account both the major (15-μm) and minor (7.6- and 10-μm) absorption bands of CO_2 indicated that the radiative forcing for CO_2 does not saturate at very high CO_2 concentrations, but rather, that the additional forcing for each doubling in concentration is roughly constant. Thus, the radiative forcing and hence the potential temperature response

for a factor of 8 increase in the atmospheric CO_2 concentration (calculated by Keeling and Bacastow (1977) as an upper limit to the potential CO_2 increase due to human emissions) would be three times that of a doubling. As Augustsson and Ramanthan (1977) had calculated a warming for a CO_2 doubling of 2.0–3.2°C, this implied a future warming potential of about 6–10°C in the global mean. At about the same time, GCM simulations of conditions during the peak of the last ice age (about 18,000 years ago), driven by reconstructions of sea surface temperature from the CLIMAP project and of the extent and height of glacial ice sheets, indicated that the difference in global mean temperature between the present and a full glacial climate was only about 5°C (Gates 1976). The seminal work by Hays et al. (1976) provided strong evidence that glacial–interglacial temperature changes in turn had been driven by rather subtle variations in the Earth's orbit. The prospect of significant changes in climate due to human emissions of greenhouse gases was very real.

Thus, at the time of the first issue of *Climatic Change*, the basic outline of the "CO_2 problem" was well established: humans were unquestionably increasing the CO_2 concentration in the atmosphere, the concentration would double within a century under reasonable business-as-usual scenarios of increasing emissions, this increase would be irreversible on human time scales and would trap infrared radiation based on well-establishment and non-controversial radiation physics, and this heat trapping would exert a warming effect on the climate. The magnitude of the warming effect at the time was uncertain but it was realized then that it was likely to be non-trivial and possibly catastrophic, with the only available estimates at that time based on admittedly simple and crude calculations using computer models. However, the potential consequences of a CO_2 doubling were grave, particularly with regard to drying of soils and sea level rise.

I would now like to make the argument that there was enough information, when the first issue of *Climatic Change* was published, to have justified measures to stabilize total global industrial (fossil fuel and cement-related) CO_2 emissions or at least slow down the rate of increase in global industrial CO_2 emissions (which stood at 5.0 GtC/year in 1977 and had risen to 8.0 GtC/year by 2005). The rationale is that the prospect of large, irreversible, and potentially disastrous environmental changes requires precautionary action. Uncertainty is a major reason for precautionary action, but instead has been (and continues to be) used as a pretext for taking no action. These principles were later enshrined in the United Nations Framework Convention on Climate Change, which was negotiated at the UN Conference on Environment and Development in Rio de Janeiro in 1992 (Articles 2 and 3 in particular). A prudent global society, concerned about risks to the well-being of future generations, surely would have taken precautionary action based on the evidence that was available by the late 1970s. There was, however, only the slightest beginnings of awareness at that time of the potential of slowing the growth in CO_2 emissions through more efficient use of energy, but by the mid 1980s, much had been written on the subject (as reviewed in Bach 1984) drawing, in part, on the initial successes in reducing energy use in response to the fourfold increase in the price of oil in the late 1970s.

It is interesting to examine some of the major developments that have occurred since the first issue of *Climatic Change*. First, the climate science is much stronger than it was in 1977. Key processes related to the critical water vapor feedback in atmospheric GCMs have been validated against a variety of observations, and several lines of evidence that are independent of GCMs have been developed that broadly

support the expectation, in 1977, of a global mean warming of 2–4°C in response to a CO_2 doubling. These additional independent lines of evidence include analyses of temperature changes during the past 150 years, analysis of times in the geological past when climates were quite different from today, and analysis of past natural variations in atmospheric CO_2 on time scales of millions of years. Second, we are now observing changes in the climate system that were mere predictions in 1977. First and foremost has been the observed warming. Coincidentally, volume 1 of *Climatic Change* was published after the coldest year (1976) in the culmination of a modest downward trend in global mean temperature that began in the early 1960s (see Fig. 1). From 1977 to the present there has been a global mean warming of about 0.5°C. The evidence that a real warming of the climate has been occurring for the past three decades is overwhelming. Third, we are now beginning to see some of the consequences of global warming, and it now appears that the consequences (especially for ecosystems and the survival of species) will be much worse than thought even 10 years ago (see, for example, Schneider et al. 2007, Parry et al. 2008 and Smith et al. 2009). Fourth, in the last 10 years in particular, the prospect of positive feedbacks between climate and the carbon cycle that could largely take global warming out of human control has grown more real (through, for example, massive release (2–3 GtC/yr) of CO_2 and CH_4 from carbon-rich yedoma soils in Siberia (Khvorostyanov et al. 2008) and large releases of CO_2 from massive dieback of the Amazon rainforest if a quasi-permanent El Niño-like state develops (Cox et al. 2004)).

On this basis, it is too late regard any actions that we might take now to significantly restrain greenhouse gas emissions as "precautionary" because now we can see clearly the consequences of our inaction over the past 30 years. The term "precautionary" implies acting *before* one can see an impending disaster. The appropriate term now is "damage control".

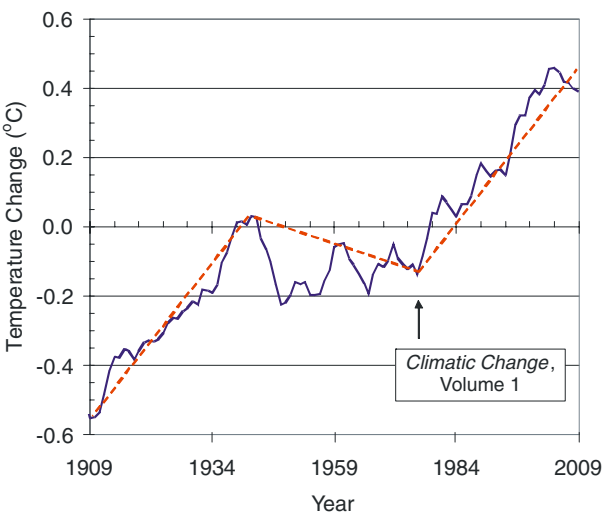

Fig. 1 Five-year running mean (*solid line*) from 1909 to 2009 of the annual deviations in global mean temperature from the 1961–1990 mean, trend lines (*dashed*) and publication of the first issue of *Climatic Change*

The launching of *Climatic Change* in 1977 was prescient. The climate science of the mid-to-late 1970s lead to the expectation that the issue of climatic change due to human emissions of CO_2 was going to become *the* environmental issue of the coming century, one that would impact every area of human activity. Unfortunately, that expectation has turned out to be correct. The global warming issue is here to stay. The first 33 years of *Climatic Change* witnessed relentless efforts at delay, denial, obfuscation, and deliberate efforts to confuse and mislead the public while the climate science and case for strong action to restrain emissions grew ever stronger (see, for example, Hoggan and Littlemore 2009 and Schneider 2010). One can only hope that the next 33 years of *Climatic Change* will witness a substantial part of the great transformation in the world's energy systems (Harvey 2010a, b) that is needed in order to limit greenhouse gas concentrations to levels that might still avert complete global ecological and social catastrophe.

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