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Scepticism and doubt in science and science education: the complexity of global warming as a socio-scientific issue

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Abstract This article looks critically at the complexity of the debate among climate scientists; the controversies in the science of global temperature measurement; and at the role played by *consensus*. It highlights the conflicting perspectives figuring in the mass media concerned with climate change, arguing that science teachers should be familiar with them, particularly given the sharply contested views likely to be brought into classroom discussion and the importance of developing intellectual scepticism and robust scientific literacy in students. We distinguish between rational scepticism and the pejorative meaning of the expression associated with attitudinal opposition to global warming—similar to the way in which Bauer (2006) contrasts *micro-scepticism* and *macro-scepticism* in reasoning generally. And we look closely and critically at the approaches which teachers might adopt in practice to teach about global warming at this difficult time.

Keywords Global warming · Climate change · Scepticism · Socio-scientific issues · Discussion · Scientific literacy

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Nullius in verba
The Royal Society's motto which translates as "Take nobody's word for it" dates back to 1663, and is an expression of the determination of the Fellows to withstand the domination of authority and to verify all statements by an appeal to facts determined by experiment.

Richard Feynman, Nobel Laureate in Physics 1965
"Learn from science that you must *doubt* the experts.... Science is the belief in the ignorance of experts" (1966).

Truth, doubt and global warming

Scientific methodologies require researchers to collect data through observation and experimentation and to advance our thinking about the world through the formulation and testing of hypotheses. Inherent in them is a measured amount of doubt about the truth of current understanding: scientific knowledge is provisional and contestable by its very character. According to Nigel Calder in the *Magic Universe: The Oxford Guide to Modern Science,* "the provisional nature of scientific knowledge seems to some critics to be a great weakness, but in fact it is its greatest strength" (Calder 2003, p. 199). Formal science teaching has somehow to convey that strength while at the same time convincing students of the powerfulness of the particular ideas which constitute the curriculum. That has always been the challenge in teaching science yet the prevailing emphasis forever seems to emphasise examinable content (*the* content, *the* truths of science) over methodology and investigation. Teaching students about the *provisional* nature of scientific knowledge—that proper scepticism is the foundation of intellectual progress—does not often figure as the *top* priority for school science education. But, as the inspirational physicist and Nobel Laureate, Richard Feynman said in 1966 to the (US) National Science Teachers' Association, endeavouring to counter the tendency to present science as incontrovertible knowledge, teachers should "… teach their students to think like a scientist and how to view the world with curiosity, open-mindedness, and above all, doubt" (Feynman 2000, p. 187).

With respect to climate change, this has now become a very serious challenge, for scientists *and* teachers have entered a new phase of complexities, not least because fundamental disagreement among scientists has become the norm, virtually flaunted in the media. Attempting to convey the provisional character of scientific knowledge to, say, secondary school students, is now compounded by doubt of a quite different order. Ordinary members of the public, while much persuaded of the importance of science and technology (see Sim 2006, below), now regularly report that they don't know who to trust (at worst whether to trust anyone at all) in debates about whether anthropogenic global warming is real and whether it is, substantially or not, a consequence of carbon emissions. Reactions seem very much worse than a decade ago when Kolstø reported that students put perceived disagreements amongst scientists down to their "interests, personal opinions, and incompetence" (Kolstø 2001a, p. 294). American public opinions give an indication of recent trends. In a poll conducted by the Pew Research Center in conjunction with the American Association for the Advancement of Science (AAAS), 62 % of the public thought there was *a lot* of disagreement among scientists. Views on whether there was *a lot* of solid evidence for global warming had reduced from 77 % in 2006 to 57 % in 2009 (with figures for the contrary—that there wasn't solid evidence—rising from 17 to 33 %). For 2010 government priorities, the public ranked global warming as the *lowest* of 21 priorities, the economy, jobs and terrorism ranking highest. See presentation by Leah Christian at the AAAS

Conference on Promoting Climate Literacy, February 2010 and http://www.people-press.org/2009/07/09/public-praises-science-scientists-faultpublic-media/

Handling classroom discussion on any socio-scientific issue, but particularly in respect of climate change, is very much harder for teachers now that disputation of ‘the basic facts’ is publicly portrayed as scientists being somehow *unable* to reach agreement on very fundamental things, worse still sometimes misleading each other as they pursue science. And, where students bring ill-informed or biased views from their parents and their peers into classroom debate, coloured by uncertainty and “the futility of it all” driven by the popular press, important learning is difficult to achieve. Furthermore, and unsurprisingly, students participate in discussions about global warming in other subjects in the curriculum, often without the awareness far less participation of science teachers, with unknown consequences for the accuracy of any science that may be cited in support of developed opinion (Day and Bryce 2011). Serious commentators and exponents of science do endeavour to educate the general public with care, of course, but sadly there are rather many others who effectively debunk the very character of science. The contemporary context for education, formally in schools and informally through the media, is significantly messier than it used to be. The traditional integrity and credibility of science teachers, based explicitly on being seen to be objective, open-minded enough to include multiple perspectives, and able to fairly discuss conflicting lines of evidence, is somewhat undermined. At worst in some quarters, science is acquiring a bad name. In this article, we therefore look closely at scepticism, both rational ‘scientific’ scepticism and public scepticism, in the context of current debate on global warming. We endeavour to theorise the substance of socio-scientific dispute and the context in which it is taking place. We develop a critique which we hope will be useful to science educators at the present time.

The substance of the critique is based on the premise that, at present, much classroom discussion focusing on climate change and global warming seems to exhibit a distinct lack of *critical* reflection and *appropriate* scepticism on the part of science teachers. We challenge the balance of the science which is commonly presented and whether students are exposed to the multiple perspectives that impinge on the debate. We shall present our argument from a critical theory perspective, exploring both the informed and public discussion of some of the issues surrounding ‘the science’ of climate change and the pedagogy required to enact open-minded and balanced democratic classroom discussion. To facilitate this process we pose three questions that we argue are vital for science teachers to address during their preparation for such discussions. In addition, we offer some suggestions as to how these questions might be answered. These questions for science teachers are:

1. Which concerns should they address and what scientific knowledge should they take into account in preparation for teaching school students about climate change?
2. In selecting content, what attention should be paid to the perspectives evident in the public debates between those who are now being termed ‘alarmists’ and those now referred to as ‘sceptics’ concerning global warming? We will come to the so-called ‘deniers’ later.
3. In preparations for classroom discussion, and anticipating sharply contested views, which approaches are likely to be successful, bearing in mind the ‘truth and doubt’ character of scientific thinking which we desire to impart?

To tackle these questions we must set them within the current context of science education reform and recognise that, while answers will be complex, contributions to the core pedagogical debates (particularly concerning the handling of contentious issues) have figured in much of the research about *scientific literacy* and the pressures to change the main rationale for what is taught in the name of science. The meaning of scientific literacy, as well as the challenges associated with its achievement in practice, continue to be subject to close scrutiny and debate and even scorn, with, for example, Morris Shamos (1995) originally regarding it as an ill-defined concept with little practical utility. Certainly the various definitions of scientific literacy involve different emphases (Jenkins 1990). Some definitions dwell upon the knowledge and ideas which need be acquired from school science. Others emphasise "scientific habits of mind" (Zeidler and Keefer 2003) and the attitudinal dispositions which should be gained through engaging in certain kinds of learning activities (not least discussion and cooperative learning about the more controversial aspects of science). Yet others focus on students' grasp of the nature of science itself where they should learn about the evidential basis of scientific thinking, as well as the impact of scientific technologies upon society and the planet. F. James Rutherford and Andrew Ahlgren (1990) set out the views of the American Association for the Advancement of Science some two decades ago and Rodger Bybee (2009) explains how the idea of scientific literacy was defined for the PISA surveys of 2006 (see below). It is worth remembering that in case studies analyzed with a view to determining the science understanding required for *functional* scientific literacy, Ryder concluded that many show that:

> science knowledge featuring in everyday contexts is characterised *by uncertainty and dispute amongst scientists*. Furthermore, far from being passive, individuals [students] may work actively with science knowledge, by examining the empirical basis of scientists' findings, questioning the disinterestedness of scientific/government institutions, and drawing on additional knowledge specific to the local context. This 'interactive' model reflects the ways in which science knowledge becomes 'knowledge in action' in public contexts. (Ryder 2001, p. 37, emphasis added)

In a recent article Ralph Levinson (2012) takes a different line, reasoning that, *if* the consensus view of global warming is accepted (a position which he seems to adopt), then the more important priority is for science teaching to:

> focus on developing the understanding of social processes through which facts are made public, and how trust and scepticism of these relations support the role of science as conditional knowledge, but avoids the relativism which gives credence to climate sceptics. (p. 3)

Our own judgement is that scepticism plays a vital role in education by providing students with the conceptual tools to come to *their own* opinions based on the balance of evidence. Thus we shall not assume here that the consensus view is true. With regard to developing scientific literacy, there are concerns about what is possible with non-specialist students (often flagged as the school science required for public understanding) and what is desirable for students likely to subsequently specialize in science or engineering (the 'pipeline' category, c.f. Aikenhead 2006). An unhelpfully narrow view of science is held by those who defend the traditional science disciplines, one which sustains the resistance to more humanistic forms of science education (Bryce 2010).

An important and helpful distinction is contained in Douglas Roberts' (2007a, b) detailed analysis of 'scientific literacy/science literacy' (SL) where he tracks the evolution of thinking about curricular intentions for science over recent decades. He notes the contrasts between literacy *within science* (what he labels as Vision I in science education) and literacy *about science-related situations* (what he labels as Vision II in science education). Vision I, looking inward at science itself, its products and processes, certainly narrows the student's experience with the breadth of science as a human endeavour, essentially leading students to understand issues the way a scientist would. Vision II, looking outward at situations in which science has a role and therefore requiring students to be well informed as to what science is *about*, has influenced more recent curricular innovations and, arguably, opens up debate with students to alternative perspectives. As Roberts notes: “an increasing number of voices have stressed the importance of starting with Vision II, that is with situations, then reaching into science to find what is relevant” (p. 3). He concedes that the more traditional Vision I emphasis risks only *token* exposure to situation-oriented material; but more innovative Vision II science teaching programmes “run the risk of paying insufficient attention to science” (p. 77). Importantly, as Aikenhead has emphasised in this debate:

> … the meaning of ‘science’ and the *content* of school science necessarily change when we embrace these new perspectives on learning and non-learning… When conventional, academic, decontextualized science (a Vision I view of SL) changes to contextualized science (a Vision II view of SL), the context *and content* are mostly dictated by students’ everyday worlds, rather than by scientists’, teachers’, or curriculum developers’ ideas of appropriate contexts and content for school science. (Aikenhead 2007, p. 65)

We would certainly concur with this point. And, with global warming figuring in most people’s daily lives, in some way or other, teachers necessarily have to contend with students’ requests for clarification (with their different viewpoints, idiosyncrasies and possible misconceptions) on matters which have important scientific dimensions. As we shall indicate, the very notion of *consensus* among scientists contrasts with the *truths* which normally figure in how science is handled in schools.

With respect to contemporary changes to science curricula, however, *multifaceted* definitions of scientific literacy seem to be converging (whether or not Roberts would agree is open to question). In Europe, the Organisation for Economic Cooperation and Development (OECD) in their Programme for International Student Assessment (PISA) in 2006 defines scientific literacy in terms of an individual’s:

- *Scientific knowledge and use of that knowledge to identify questions, to acquire new knowledge, to explain scientific phenomena, and to draw evidence-based conclusions about science-related issues*. For example, if individuals read about the melting of the polar icecap and, say, consequences for the population of polar bears, can they separate scientific from non-scientific aspects of the text? Can they apply their knowledge and justify personal stances?
- *Understanding of the characteristic features of science as a form of human knowledge and enquiry*. For example, do individuals know the difference between evidence-based explanations and personal opinions about the extent of global temperature variations and their effects on food crops, say as expressed on internet websites?
- *Awareness of how science and technology shape our material, intellectual and cultural environments*. For example, can young people explain the need for flood barriers and how they influence a community’s economic and social stability?
- *Willingness to engage with science-related issues, and with the ideas of science, as a reflective citizen*. For example, do they actually re-cycle waste material at home (like newspapers, glass, cans,…) and openly defend and encourage that practice in school discussions and debates? OECD (2006, examples added)

And, some time ago, the American *National Science Education Standards* defined a scientifically literate person as someone who is able to:

> … use appropriate scientific processes and principles in making personal decisions [and] engage intelligently in public discourse and debate about matters of scientific and technological concern. (National Research Council 1996)

As Troy Sadler (2004) points out, these documents characterise scientific literacy as an active objective; they provide benchmarks for *using* scientific knowledge and processes. If one asks, *towards what end,* the answer has to be about public participation, citizenship and appreciating government actions thought necessary in response to complex problems like global warming. Consistent with this, Mary Ratcliffe and Marcus Grace (2003, p. 38) state, in their advice to teachers: "An overarching aim may be that students will act as informed, responsible citizens when confronted with future scientific advancements." Thus the discussion of controversial issues in science in *science* classrooms has risen in priority as students learn about the actual conduct of science in the contemporary world in which scepticism has a vital role to play. Taking this further, researchers like Wolff-Michael Roth and Jacques Désautels (2002) stress the point that educational goals for science need to extend beyond passive forms of independent enquiry and be, in the words of Derek Hodson (2003), "oriented towards socio-political action". He explicitly seeks a form of school science education that will contribute towards education *for* citizenship, not simply be a dimension of education *about* citizenship. The point is supported by others like Lynn Carter (2008) who argues for the empowerment of teachers to tackle the "challenges of contemporaneity". More recently, Ajay Sharma (2012) writes:

> Science education needs to play an important role in making this happen. It should prepare students to play an active role as citizens in making the state as well as the society responsive to the issue in ways that are sustainable and evidence-based. (p. 48)

But regrets that:

> the sad truth is that socio-ecological concerns have yet to fundamentally impact the nature of educational experiences students have in science classrooms in American schools. (p. 49)

While agreeing with Sharma (2012) that climate change and global warming merit discussion in secondary school science, these discussions should, in our view, be balanced, i.e. inclusive of multiple perspectives, objective, open-minded and evidence-based. It would not be appropriate to present either an alarmist or a sceptical view uncritically. Distorted discussion, in either direction, is unwarranted and risks bias, subjective interpretation and, at the extremes, dogmatism.

Framing discussion of climate change and global warming from a critical perspective

Critical theories claim to provide a guide to human action, at least in general (as opposed to strictly personal) areas—such as the definition and achievement of social justice and the correct regulation of human interactions (Payne 2010 p. 153–154). As such, an analysis of the controversial disagreements among scientists and the even more complex tangles apparent in the dissemination of findings and their public interpretation ought to figure in the education of science teachers. However, this means that teachers must necessarily face up to a social context which stretches their traditional stance on evidence and its interpretations; reasoning and discussion goes beyond 'applied science', involving values, decision-making and community imperatives. Raymond Geuss notes that such thinking differs epistemologically from the theories in the natural sciences with which science teachers are familiar: such theories are objectifying whereas critical theories, of any sort, are reflective (Geuss 1981, p. 1–2). People involved in the latter take a questioning stance towards their own practices and can evolve a framework through which they may critique the social/political/scientific consensus of the day. However, to be useful to practitioners in schools, such a critique in the area of climate change must take account of prevailing orientations to what science instruction has tended to be for many, and what leading educators now consider to be both possible and desirable in respect of worthwhile teaching. Necessarily it takes science teachers into uncomfortable territory for they are *encultured* by their education in science, with firm consequences, not least the evident resistance to more humanistic approaches as stated in the previous section (and as one of us has argued before: see Bryce 2010).

In the wider context, the critical theorist Stuart Sim has suggested that, in recent times and from a cultural perspective, science and technology have taken on the dimensions of a belief system (Sim 2006, p. 74) since they have increasingly set the agenda by which our culture has developed. He argues that the general public have bought more and more into the mystique of science and technology, to the point where people find it difficult to conceive of a society in which science does not play a leading role. As key figures in public education, the role of science teachers is therefore particularly crucial. If, as Sim argues, there is such an increased acceptance of science and technology, then unquestioning belief is pervading global culture. The most effective way of countering it is by an engaged scepticism, which he loosely defines as an "open-minded and continually questioning and probing sense of doubt". He goes further and contends that modern democracy is under severe threat from narrow-minded purveyors of dogma. The general public is confronted by an array of "*empires of belief*", these empires being dominant organisations or groups led by the powerful that exercise dominion over ordinary people and that these empires currently invest an immense amount of time and effort (and presumably money) in trying to dictate how the general public should think, consume and behave.

Science is certainly *the* dominant intellectual paradigm of our time and as such, has increasingly acquired immense authority within modern society where it is able to mobilise vast resource, both public and private, for its operations. Notable examples of such scientific, political and financial authority are the US National Aeronautics and Space Administration (NASA), the UK Met office and the United Nations Intergovernmental Panel on Climate Change (IPCC), some aspects of whose work figure later in this article. However it can be argued that these bureaucratic, scientific institutions have become less accountable to the people who ultimately fund their work i.e. the taxpayers. More worrying is the emergence of the movement (in some scientific quarters) toward positioning the public within a compliance culture where "we *should* take their word for it". This is in marked contrast to their espoused democratic ideals.

For example, in the context of global climate change, the general public is increasingly told by the scientific establishment that the IPCC's view of climate science is that the evidence for anthropogenic climate change is unequivocal (IPCC 2007) and that the science is settled. This has led to calls by climate scientists/activists such as NASA's Jim Hansen for Governments across the world to commit trillions of dollars/pounds of taxpayers' money into mitigating the effects of climate change—during an age of austerity—based on the premise that the IPCC's perspective on the science is correct *since the IPCC only uses peer-reviewed articles in its assessments*. However, upon closer scrutiny of the fourth assessment document references, 30 % of the articles cited were not from peer-reviewed science journals at all, but came from a mixture of press releases, NGO pamphlets and opinion pieces from newspapers (Laframboise 2011). This hardly inspires confidence in the objectivity of such a 'scientific' publication focused on what has been described as one of today's most important scientific and social challenges. (We shall say more later about the detail of the consensus view as well as peer and non-peer reviewed material in respect of climate change research.)

In policy making, especially in the political arena, consensus building is a key democratic ingredient. In an attempt to make the 'science' relevant and useful, the politics of democracy tends to promote, and in some cases demand, 'scientific consensus' (Winstanley 2000). However, as a community of *belief* develops around a scientific theory, scepticism is no longer seen as a virtue. It is this negative political view of scepticism that we wish to challenge. In order to appreciate our concern, it is necessary to discuss the central role played by scepticism within science, how scepticism is reflected within science education and portrayed in the media, and how science teachers might handle controversial socio-scientific discussion within the classroom.

Scepticism and scientific method

Scientific scepticism doubts the veracity of assertions that are not supported by empirical evidence that is reproducible and therefore seeks to exclude other influences from the scientific search for truth. It can be described as a systematic form of continual informed questioning that requires the scientist: to *critically appraise* existing theories, actively looking for alternative plausible mechanisms of cause and effect that are consistent with their rigorous assessment of the empirical evidence; to undertake experiments that are *repeatable and transparent*, to look for evidence that contradicts rather than supports the validity of any given theory; and to *suspend judgment* about the validity of any given theory (i.e. to defer making an active decision to believe or disbelieve it) until it has both survived destructive testing and has been subjected to critical experiments, the evidence from which, makes it is possible to conclude that one theory is superior to all other current plausible theories.

Henry Bauer (2006) suggests that scientific scepticism is a double-edged sword. He argues that scepticism views the probability of a proposition as always less than 1, whereas belief or disbelief are absolute and assert that the probability equals 1 or 0 respectively; that the proper spirit of scepticism is constructive where it seeks to improve knowledge by stimulating better estimates of probability which he terms micro-scepticism, questioning the soundness of every detail of fact, method, logic; it is empirical. By contrast, macro-scepticism is deductive; it relies on current scientific knowledge, which makes it backward-looking and destructively critical rather than constructively critical. It appeals commonly to Occam's Razor: it is always "simplest" to explain things in the way we are used to doing. But knowledge advances through change; so the Razor becomes a Lobotomy as people forget Einstein's insistence that theories should be as simple as possible, but no simpler. As Bauer says:

> Micro-skepticism is agnostic as to whether any given claimed anomaly is the harbinger of a monster of a catch. So it is forward-looking, or at least it is not backward-looking. Constructive micro-skepticism is skeptical not because a claim contradicts some theoretical presumption but because it is aware of the difficulties in acquiring knowledge and looks for loopholes in the offered evidence; so it safeguards science

> against Type I errors, against accepting something that isn't so. Theory-based macro-skepticism does that too, of course, but it goes too far, leaving itself prone to Type II errors, namely, missing something important. Macro-skeptics never bring about scientific revolutions, and they resist them to the bitter end. (2006, p 423)

In contemplating what content should be considered by teachers and taught to students concerning the alarmist and sceptical perspectives, which relates to the first (of the three) questions posed, we must look at the controversies within the science itself and acknowledge where they 'fit' with, or strain, customary approaches to classroom science.

Debate on climate change: the tip of a (melting) iceberg

The complexity of how science combines both truth and doubt, and the public interpretation of it, is apparent in an article in the serious press. In a talk at the Royal Society in London in 2010, James Lovelock (who in our view is an exemplary micro-sceptic) underlined the importance of *scepticism* amongst scientists in their deliberations over the causes of global warming. Acknowledging the twists in the "climategate emails and the sloppy science revealed in the Intergovernmental Panel on Climate Change [IPCC]" (Glover 2010), the *Sunday Times* reporter was surprised to find that Lovelock actually admired the climate change sceptics. Given the significance of his contributions over many decades to our understanding of climate change and his more recent judgements that the *negative* feedback of the Earth system has now switched to *positive* feedback (Lovelock 2007), we should perhaps not be startled by the reporter's reaction. It does however reveal something about people's views of how scientists think and the expectations that scientists ought to be consistently sure of their own understandings and normally, if not always, consensually in agreement. Lovelock's statement about the climate change sceptics was:

> They have been a breath of fresh air. They have kept us from regarding the science of climate change as a religion. It had gone too far that way. There is a role for sceptics in science. They shouldn't be brushed aside. It is clear that *the angel side wasn't without sin*. (Lovelock, quoted in the *Sunday Times*, 14 March 2010, emphasis added)

Lovelock has always been described as original in his thinking, not least because of his unwillingness to accept pre-existing consensus amongst scientists when he devised his own experimentation. The thrust of his argument here was that being of a doubting attitude is far more useful, scientifically, than being firmly attached to either side of a debate, in this case about the contributory factors in the rise of atmospheric air temperatures, and consequently sea levels, in recent decades. The crucial thing is proof and Lovelock is currently concerned about the IPCC's continuing reliance on projections from computer models based primarily on atmospheric physics. He considers the rise in sea levels to be more dependable as a direct measure. [Global mean sea level has been rising at an average rate of 1.7 mm/year (plus or minus 0.5 mm) over the past 100 years, which is significantly larger than the rate averaged over the last several thousand years, according to the National Climatic Data Center (NCDC)—see at http://www.ncdc.noaa.gov/faqs/climfaq09.html].

With respect to the contributions from CO_2 emissions, Lovelock remains alarmed about their effects, comparing the estimate of mankind's output since the beginning of the industrial revolution to about 2030 to be comparable to the geological events of 55 million years ago (which raised the atmospheric temperature by more than 5 °C). The melting of the polar icecaps will lead to the planet being less reflective of sunlight, thereby exacerbating the effect dramatically. Lovelock's predictions for the middle of the present century are in line with those generally accepted by international scientists at the United Nations Climate Change Conference, COP15, in Denmark in December 2009 (i.e. between some 1 and 2 °C—see at http://en.cop15.dk), but there remains the prospect of a much greater increase. His concluding message was that:

> … we should have much more respect for uncertainties and learn to live with possibilities rather than striving for the 95 % probabilities that climate change scientists have been trying to provide. (Lovelock, quoted in the *Sunday Times*, 14 March 2010)

The 'possibilities' were alarmingly evident in the information made available for COP16 in Cancun in December 2010—see at http://www.cc2010.mx/en/ and further discussed at COP17 in Durban in November 2011—not least those changes already detected, agreed and accepted by a wide consensus of scientists, and the worsening pace of the changes quantified, including:

- more extreme weather such as longer dry periods in parts of the world;
- heavier precipitation elsewhere (warmer temperatures mean greater evaporation and a warmer atmosphere holds more moisture);
- more intense heat waves and more powerful tropical cyclones;
- glacier retreats and reduced snow cover near the poles;
- climate-induced changes in physical processes detrimentally affecting so many plant and animal communities, on a wide scale; and
- the damaging effects on human populations, most significantly to the greater harm to poorer communities.

See *Feeling the Heat: Climate Science and the Basis of the Convention* at http://unfccc.int/essential_background/the_science/items/6064.php.

Just how significant these are is exemplified by a recent article by Radic and Hock (2011) concerning glacier melt. They judge that total (world) glacier volume will be reduced by 21 ± 6 % by 2100 with some regions, like New Zealand and Europe's Alps, projected to lose up to 75 % of their present ice volume. Such losses would have a very substantial impact on regional hydrology and water availability.

Laws, scientific models and the truths we teach

One aspect worth recognising is concerned with the *kind* of explanatory models we use in science, for ourselves, and with the students we teach. Essentially, scientists and philosophers of science have always preferred simple over complex models. Physical and chemical laws are couched in terms of relatively few variables and only a limited set of factors is normally implicated in explanations which are developed in science. Even in biology, which tends to deal with more complex systems, scientists strive to reduce the effect of possible confounding variables through experimental comparisons with controls. In genetics, the laws of segregation and independent assortment are prime examples of how a complex system can be described through careful observation and the isolation of extraneous variables. *Parsimony* is the order of the day when it comes to theorising and the *laws* are prominent in what we teach students (Newton's laws; the Gas laws; periodicity in Mendeleev's table of the elements; the relation between mass and energy; Mendel's laws of heredity; etc…). This relates to the differences between ‘textbook science’ (the accepted canons of science which make up the typical curriculum) and ‘frontier science’, or ‘science-in-the-making’; and, in practice, to Roberts’ Visions I and II respectively. The former emphasise simple models and these are what we get students used to; the latter often now involve complex modelling, certainly in relation to multivariate situations such as those figuring in climate research. This means that an implicit feature of taught science doesn’t help with an understanding of how many environmental scientists now typically, scientifically, reason. The interface between scientists and the public (including students) is the more difficult in consequence, for discussion and exchange run into difficulties where the parties *think* rather differently. And this even spills into the thinking among physical scientists themselves.

A pointed example is contained in the paper by Simon Shackley, Peter Young, Stuart Parkinson and Bryann Wynne (1998), where the authors were concerned with the dominance of computer modeling in the formulation of government policy on climate change and environmental ‘management’. In this kind of research, ‘Global Circulation Models’ (GCMs) of the Earth’s atmosphere have predominated. The writers note the disconnection between such models and the principle of parsimony in scientific theorizing (or Occam’s Razor), citing Popper:

> The method of science depends on our attempts to describe the world with simple theories. Theories that are complex may become untestable, even if they happen to be true. Science may be described as the art of systematic oversimplification: the art of discerning what we may with advantage omit. (Popper 1982, p. 185)

This accords with the idea that the *falsification* of knowledge claims is the safe way to increase our understanding. Simpler models are easier to falsify, hence they are preferable. As Shackley et al. point out, there is an argument that defends the use of complex models on the grounds that ‘the traditional physical approach, and its demonstrated use of parsimony in scientific explanation, is not applicable to open systems’ (p. 173). Nevertheless, these authors are concerned that specialists who use complex models may be blind to alternatives, including simpler ideas, and fail to recognize that how they reason about the consequences of their science may be compromised. They conclude that:

> … the emergence of consensus around particular concepts of ‘good science’ are neither predetermined by nature, nor are they without larger political significance. This is because they inadvertently assist the development of political consensus as to the appropriate policy response. We have argued that it is partly these political implications of the global scientific culture which place GCMs at the top of a ‘natural’ hierarchy of ‘good science’ and valid knowledge for international policy actors. (Shackley, Young, Parkinson and Wynne 1998, p. 193)

So, even at the heart of climate change modeling, there are researchers who fear for a complex kind of biasing in preferred ways of working. In this regard, Shackley et al.’s paper was somewhat prescient, given the storm of debates about global warming which arose nearly a decade later. Thus, there are some fundamental difficulties for students and their teachers when they endeavour to discuss the ideas which environmental scientists put about when they forecast climate change and global warming.

The challenge of temperature measurements

Not only are the ways of thinking different in kind and complexity between school science and real science, the basic measurements involved in climate change research turn out to be complicated. When the scientific method is emphasized during school practical experiments, teachers typically train students to "change one variable and keep all the other variables constant' or 'change one thing and keep everything else the same". Along with this, the reproducibility of measurements (i.e. the notion of reliability) and whether the variables measured in experiments actually relate to the phenomena being investigated (i.e. the notion of validity) have to be considered rather carefully. These ideas are recognisable to most senior school students, along with related affairs such as accuracy and the prospects for experimental and instrumental errors. All of these are at the heart of the scientific literacy we seek to inculcate and which sets science apart from other forms of human enquiry such as history, theology and political science. As we said at the outset, scientific knowledge is robust yet tentative; and it is emergent since it is constantly revised over time as new experimental results become available. While this seems patently crucial to the education of young people, applying the scientific method to a complex adaptive system such as global climate change turns out to be far from straightforward. This is because the main issues which plague real-world science are substantially concerned with the reliability and validity of fundamental measurements used to track temperature change. Describing how some scientists have actually made these measurements will certainly raise scepticism in students but they may also lead to dismay, given the details we spell out below.

Starting from the goals of scientific literacy cited earlier, science teachers might focus classroom discussion about climate change on how scientists have come to know that temperatures are rising. What reliable methods have they used and how much hotter is Earth getting each year? How do we know it is to do with greenhouse gases (GHG), factory emissions, engine exhausts, fossil fuel burning and/or deforestation and so forth? Strictly speaking, the term climate change is a misnomer in that the climate is always changing. The Earth's climate has been through repeated cycles of warming and cooling, as well as glacial and interglacial periods over geological time with none of these cyclical changes being attributable to man (Carter 2010). We must qualify what we mean by climate change. According to the United Nation's Framework Convention on Climate Change (UNFCCC), climate change refers to human-caused alterations in temperature. Article 21 refers to a 'change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods' (See at http://unfccc.int/2860.php.). The Intergovernmental Panel on Climate Change, working under the aegis of the UNFCCC, concluded its Fourth Assessment Report of 2007 (IPCC 2007) quite emphatically, that:

> climate change is unequivocal, and that most of the observed increase in global average temperature since the mid-20th century it (sic) *is very likely* due to the observed increase in anthropogenic GHG concentrations' (in the words of the May 2011 statement in the IPCC Chairman's Progress Report to the Sixteenth World Meteorological Congress in Geneva, emphasis added—The Fifth Assessment Report is not due until 2014). See at http://www.ipcc.ch/news_and_events/press_information.shtml.

Thus the real issue is whether the ~0.7 °C increase in the average global temperature observed over the last 160 years (approximately the late industrial age during which recorded measurements have been kept) can be attributed to human activity, referred to as *anthropogenic global warming* (AGW), or to natural climate variability. It is pertinent to note that the IPCC's chapter specifically directs it to assess peer-review research 'relevant to the understanding of the risk of human-induced climate change'. In that sense, a scientifically literate member of the public might not look to it with neutrality, though it would appear that many do. The IPCC does present a consensus view among international scientists concerned about AGW, though it would be wrong to label them all as 'alarmists' *per se*. With respect to earlier periods of time, scientists must resort to palaeontology and, in combining inferred measurements with recorded recent-past measurements, estimates of global temperature change become difficult. While more details will figure in a later section, we should note that studies of the geological record of climate reveal many instances of natural changes of a speed and magnitude that would be hazardous to the human population and to the economic wellbeing of society as a whole if they were to occur today. That such natural change will occur again in the future, including episodic step events, longer term cooling and warming trends, is certain. The important point is, however, that in order to grasp something of the details about AGW, a scientifically literate citizen would need to understand some straightforward science and some rather more complex ideas which do not appear in standard textbooks, but which figure prominently in websites and have become central to the whole debate, including basic paleoclimatology, tree-ring data, and the now famous (or infamous, depending on your perspective) 'Hockey stick graph'. The latter has attained such prominence that teachers might well expect students to bring it into classroom discussions concerning scientific controversies.

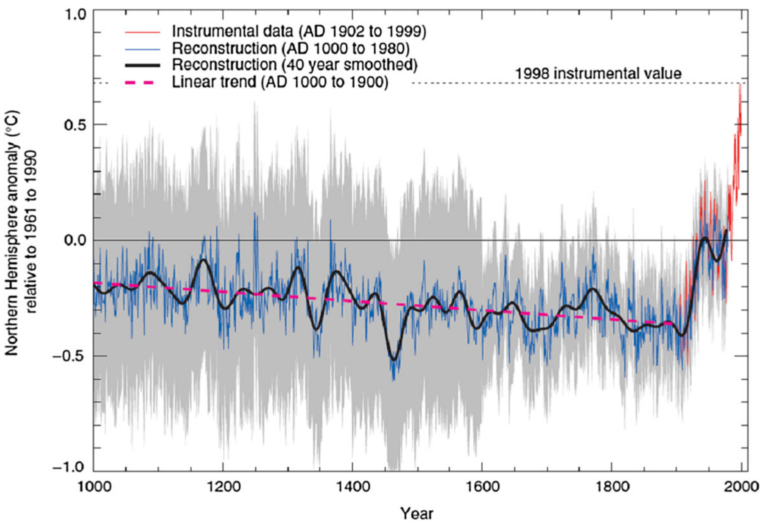

Fig. 1 The 'Hockey stick' graph from the IPCC's Third report (2001): Variations of the Earth's surface temperature over the last 1000 years. Taken from Figure 2.20: Millennial Northern Hemisphere (NH) temperature reconstruction (*blue*) and instrumental data (*red*) from AD 1000 to 1999, adapted from Mann, Bradley and Hughes (1999). Smoother version of NH series (*black*), linear trend from AD 1000 to 1850 (*purple-dashed*) and two standard error limits (*grey shaded*) are shown. (IPCC AR3 Working Group I: The Scientific Basis p. 134)

Doubts about the reliability of global temperature measurements

The Hockey stick graph (Fig. 1), first presented by Michel Mann, Raymond Bradley and Malcolm Hughes (1999), shows the average global temperature over the past 1,000 years, usually shown as the year-by-year departures from an average. For the first 900 years there is little variation, a fairly straight plot, hence the shaft of an ice-hockey stick. Then, in the 20th century, comes a sharp rise like the hockey stick's blade. The IPCC brought this graph to prominence in its summary report in 2001. However, although originally intended as an icon of global warming, "… the hockey stick has become something else—a symbol of the conflict between mainstream climate scientists and their critics. The contrarians have made it the focus of their attacks for a decade, hoping that by demolishing the hockey stick graph they can destroy the credibility of climate scientists" (Pearce 2010).

The recent warming by ~0.7 °C (the blade of the hockey stick) is of course a statistically derived figure, not an actual measurement on some global thermometer. There are temperature-sensing stations sited all around the world (the familiar-to-many white, wood-slatted boxes known as *Stevenson screens*) which take readings of the local temperature. These data sets are maintained by communities of scientists working in different regions, examples being the UK Met office and the US National Oceanic and Atmospheric Administration (NOAA). Each of these gathers data from temperature sensing stations sited all around the region or country in question and this data set is averaged over weeks and months. Thus, an annual average temperature is an average of the average monthly temperatures summated across the entire network covering the whole of the country. The collated data from different countries are computed to give a global average. This raises several questions: How reliable is that figure? Is this a valid method for assessing changes in temperature across the globe over time? How is quality control maintained in the temperature record and who is responsible for that quality control?

Clearly, the average global temperature is only as reliable as the individual instruments will allow and where these temperature-sensing stations are located, together with the frequency at which the readings are taken and how well trained the instrument reader is since not all of the stations in the network can be read remotely. The US climate sensing network is widely regarded as one of the best. Since it was commissioned in 1890, the US Weather Bureau—now the National Oceanic and Atmospheric Administration's National Weather Service (NOAA/NWS)—has used *Stevenson screen instrument shelters*. It is now known that the NWS made a specification change to the Stevenson box some time ago requiring the original whitewash coating to be switched to a latex based coating. The US meteorologist Anthony Watts (see SPPI 2010, below) found that this type of coating does make a difference to the temperature readings, due mainly to the significantly different infrared properties of the Titanium oxide pigmented latex based paints as against whitewash coatings. The latex-based painted screens were, in effect, slightly insulated since there was a difference of 0.17 °C in maximum temperatures and 0.44 °C in minimum temperatures between different surfaces. This may not seem like much but, to put this change in context, the whole of the twentieth Century increase in average temperature increase is ~0.67 °C so if this was the case then Watts' results could potentially explain some two thirds of that observed change.

Intrigued by this, Watts set up a network of 650 volunteers to visually inspect and photograph a sample of 850 of the 1,221 (about 70 % of the network) climate monitoring stations overseen by NOAA/NWS in order to check how many of these climate monitoring stations had been painted with the Latex-based paint since 1979. What they found went well beyond surface coatings. They found that 89 % of the stations that were surveyed failed to meet the NWS's own siting standard which required the stations to be 30 m or more away from an artificial heating or radiating/reflecting heat source. In addition, they found that technology changes to weather stations over time also caused many of them to report false warming temperature trends. Sixty-eight stations were located next to wastewater treatment plants which are known to cause temperatures to be higher than in surrounding areas due to bacterial decomposition of the waste. They also found stations sited in asphalt parking lots (car parks); and near roads, hot rooftops and buildings that absorb and radiate heat. Furthermore, they subsequently established that adjustments to the data made by NOAA and the National Aeronautics and Space Administration (NASA) caused recent temperatures to look even higher when they looked into the historical temperature records for each site. Revelations like these have made some scientists and journalists sceptical of the arguments and evidence offered by those who have been otherwise persuaded of global warming, some thence tagged 'alarmists'. A scientifically literate school-leaver is likely to conclude that such records are unreliable due to changes in specification to station instrumentation, siting issues and poor record keeping, all of which cast doubt on the validity of conclusions based on this data and the reliability of the record itself. If this case was replicated across the world, then the surface temperature record, relied upon by the IPCC to reach its conclusions, is suspect. School students encountering information like this are certainly more likely to become sceptics, rather than alarmists, about global warming. Teachers should appreciate that advanced students', reading about the controversy in the science, might come across the Science and Public Policy Institute's (SPPI's) 2010 Paper: *Surface Temperature Records: Policy-driven Deception?* where the authors' (D'Aleo and Watts) first conclusion is:

> Instrumental temperature data for the pre-satellite era (1850-1980) have been so widely, systematically, and uni-directionally tampered with that it cannot be credibly asserted there has been any significant "global warming" in the 20th century. (p. 6)

A more recent update of the relevant research appears in the peer reviewed *Journal of Geophysical Science*—(see Fall, Watts, Neilson-Gammon, Jones, Niyogi, Christy and Pielke, Jr. 2011).

Even more basic doubts are raised when one looks at the errors of measurement typically found in this kind of research. Since the data is an average over a week, month or year, what does it show when error bars for standard deviation are plotted? Data can be downloaded from the internet which allows a scientifically literate citizen to check this out for themselves. Calculations using raw figures taken from the UK Met Office website to illustrate the findings are available from the authors on request. The data show that the 1.36 °C increase in UK temperature from 1910 to 2009 is *within* the error range of the mean.

Temperature anomaly plots

Climate scientists have taken to drawing *temperature anomaly* plots to relate the change in mean temperature over time (how much hotter or colder is a particular year?) to an averaged thirty-year long span called a *climate normal*. For example, the IPCC uses the thirty year baseline of 1961 to 1990. The USA tends to update theirs regularly; at present they are using the years 1971 to 2000. The temperature anomaly plot for the UK is shown in Fig. 2. Looking closely at its details, we can see that over the last one hundred years, there has been an increase in the temperature anomaly data. However, there were 42 years

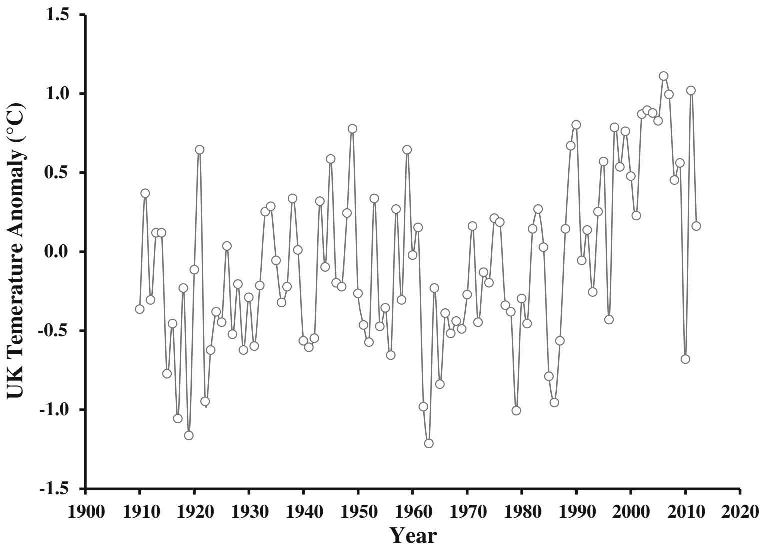

Fig. 2 United Kingdom Temperature anomaly data from 1910 to 2009. *Note* Climate normal used to plot the temperature anomaly was 1971 to 2000

above the 0 °C anomaly with 58 years being below the 0 °C line. In addition, the anomaly line is stochastic with the maximum deviation from the climate normal ranges from −1.2 °C to +1.2 °C. This data is hardly conclusive evidence of accelerated global warming. One should also note that the last 13 years have been continuously above the line, but how one calculates the climate normal affects the temperature anomaly produced for any given year. For example, if we choose the thirty years from 1971 to 2000, the average annual temperature is 8.58 °C; but, if we choose the thirty years from 1980 to 2010, the average annual temperature is 8.88 °C which represents a 0.3 °C elevation in the climate normal which changes the anomaly for the relatively cold years 1919 and 1962 from −1.08 and −1.13 to −1.16 and −1.21 respectively thereby making them seem colder. When we pick two particularly warm years, e.g. 1921 and 2006, the anomalies change from +0.73 to +0.65 and +1.19 to +1.11 respectively. This suggests that we can make the data yield cooler or warmer trends depending on one's choice of the 30 year period used for the climate normal.

With respect to the past, scientists cannot know with a high degree of certainty what global temperatures were in the absence of any direct measurements. However (and to yield the shaft of the hockey stick), a number of *proxy* data have been used, such as oxygen isotope analysis (Shackleton and Opdyke 1973); pollen and diatom evidence (Davis 2003); ice core samples (Dansgaard, Johnsen, Moller and Lanway, Jr. 1969); and tree-ring measurements where ring thickness is considered to be related to air/surface temperatures for the year in question (Briffa 1990). The latter's original research (Briffa 1983) assumed that in hot summers trees grow more, hence wider and denser growth rings; thin rings would follow years in which major volcanic eruptions occurred. We need to bear in mind that these proxies are approximations since, for example, tree ring thickness is affected by other factors which are unrelated to global temperature, such as the photosynthetic rate of the particular tree species over time, the state of health of the tree, as well as the precipitation rate of the habitat rather than the prevailing air temperature, and so forth. These issues require the scientifically literate to remember that there is a not-insignificant degree of error in such data when interpretations are made.

When science teachers begin to reflect upon what attention should be paid to perspectives evident in the *public* debate between those who are now termed ‘alarmist’ and those now referred to as ‘sceptics’ concerning climate change and global warming (the second question posed earlier in the article) it is clear that the public debate has become value-laden and thus more complex. The value-laden nature of civic discourse can make science teachers’ decisions about what to include within such classroom discussions all the more difficult. In the next section we highlight the complexity within public discourse and offer some critical reflections on this discourse.

Controversies and the public domain

In researching material for this article, we have been struck by the sheer amount of science that has featured in articles about climate change and global warming in the public domain—in the press, magazine articles, television debates, and of course the internet. Their prominence and impact on public discussion stands in marked contrast to what science textbooks have to say about the subject. While it might fairly be said that the scientific issues are too recent for there to be suitably digested material in school textbooks, the most problematic factor (signalled in our introduction) is the complexity and conflict apparent in the publicised arguments between scientists and among informed, serious scientific journalists. It is not at all easy to resolve the contradictions evident among informed, or apparently informed, individuals. Attentive students of science surfing the internet and viewing reports from serious bodies and organisations would, we are forced to conclude, become confused at best, bewildered at worst. (A short summary of published research, drawn from peer-reviewed publications, concerned with the geological record of global climate and with natural emissions of CO_2 and demonstrating that many scientific findings do not accord with the prevailing scientific consensus on global warming is available from the authors.) Understandably, it has to be recognised therefore that the boundaries between science and public policy debate have become blurred—to such an extent that a thought-provoking journalist like Fred Pearce (2010) writes: “Controversial science [has] morphed into a propaganda tool”. And K. Lloyd Billingsley (2010), a director of the Pacific Research Institute for Public Policy (an independent, non-profit think tank) to state:

> Global warming is a hoax inside a fraud wrapped in a myth. Its devious promoters deploy scare tactics to quash economic growth and expand government. http://www.pacificresearch.org/press/dump-doomsday-dogma.

From which it is evident that the controversies in the science of climate change are impacting upon the politics of national and world energy issues and contributing to the international tensions between the developed and developing nations.

Regarding the more consensual aspects of global warming debate and in particular intergovernmental accord, the international agreement finalized in 1997 and known as the *Kyoto protocol* emerged from the 1992 UNFCCC pledge to stabilize greenhouse gas concentrations “at a level that would prevent dangerous anthropogenic interference with the climate system”. After years of negotiation it went into force in 2005 with binding targets for greenhouse-gas reductions by 5.2 % (on average across the different gases) by 2012 for the developed countries, most of whom have now signed up to it (with the notable exception of the USA). Such a reduction would equate to a 29 % cut as compared to 1990, according to Robert Henson (2011). Developing countries, including India and China, were not mandated by the Kyoto treaty to reduce CO_2 emissions. 2012 is the year in which the treaty ended and, at COP17 in December 2011, nations struggled to find a successor agreement. In the final hours, compromises were struck and delegates agreed to start negotiations on a new accord that would put all countries under the same legal regime enforcing commitments to control greenhouse gases—to take effect by 2020 at the latest. Something of the feelings about the last minute, reluctant decision-taking are reflected in the statement made by Alden Meyer, director of strategy and policy for the Union of Concerned Scientists (UCS): "The good news is we avoided a train wreck. The bad news is that we did very little here to affect the emissions curve."

Prominent among the political proponents of global warming has been former US Vice President Al Gore, whose 2006 documentary *An Inconvenient Truth,* directed by Davis Guggenheim, has grossed in excess of $50 M through worldwide showings (Gore 2006). It is often used in schools and universities to graphically illustrate the extent of global warming and damage to the environment from CO_2 emissions. It has been claimed that it has done more to re-energise the environmental movement than most school science programmes dealing with the topic. Importantly, there has been significant support from many scientists for the accuracy of much of the evidence cited in the programme/film/book (largely data from Antarctic ice cores showing carbon dioxide concentrations higher now than at any time during the past 650,000 years). Similarly, the *Arctic Climate Impact Assessment* (ACIA) study analysing rising temperatures, the loss of sea ice, and the unprecedented melting of the Greenland ice sheet, as well as the impact on wildlife and people, has involved hundreds of scientists in its conduct and has received considerable support from many others for its published findings—see ACIA 2005 at http://amap.no/acia/.

In the other direction, an example of determined and skilful journalistic writing is the book by Christopher Booker (2009), *The Real Global Warming Disaster.* In it, the author identifies scientists whose studies offer evidence running counter to the global warming studies, thus challenging the IPCC's reports. Only a very well informed reader—one prepared to minutely cross-check the findings of numerous studies, their subsequent translations and simplifications for dissemination purposes, and to set aside the perceived status of particular sources and scientists—would be able to weigh up carefully whether scepticism about global warming was warranted. There is not scope in this article to do that justice though, at the risk of being journalistic ourselves, we might note that elsewhere Booker has espoused 'intelligent design' in preference to Darwinian evolution which would predispose science teachers to be doubtful about him (see Booker 2011).

Concerning the IPCC reports of global warming, the 'climategate' controversy was of course triggered by the leaks of emails from the Climatic Research Unit (CRU) at the University of East Anglia, headed by Phil Jones. He appears to have been involved in a deception to "hide the decline" in preparing a temperature chart, the decline referring to late-twentieth century tree-ring data which suggested a cooling in contrast to the temperature data which indicated warming, saying to colleagues that they should delete emails to keep sceptics from gaining access to particular information (see Adam 2010). Under the UK's Freedom of Information Act, critics demanded to see the data for themselves and to scrutinize the interchanges between key scientists involved over the years. A hacker subsequently stole some 1000 emails from the CRU computers, their publication opening up a torrent of criticism for Jones's behaviour, including his role as a referee in the peer-review process involved in the submission of articles on climate change mechanisms. This resulted in a UK Parliamentary enquiry into the conduct of the scientists concerned, in particular Phil Jones. The formal report into the conduct of the (CRU) by a Review Team, chaired by Sir Muir Russell and published in July 2010, subsequently concluded that the CRU scientists did not subvert the peer review process and that their "rigour and honesty as scientists are not in doubt" (Russell 2010, paragraph 13). Thus no evidence was found to undermine the conclusions of the IPCC assessments. However the report did conclude that there had been "a consistent pattern of failing to display the proper degree of openness" (paragraph 15); and "… there was unhelpfulness in responding to requests and evidence that e-mails might have been deleted in order to make them unavailable should a subsequent request be made for them" (paragraph 27). The net effect of the whole affair has been to inflame scepticism about global warming to a new level. Adam's interview with Jones, one year after the event, published in *Nature*, indicates the personal difficulties he has had in trying to recover from the affair (including the threats to himself and his family from those who might be described as rather more than 'sceptical'). Ironically, the whole scenario appears to have been counter-productive: "Now scientists say it's even harder to convince the world of the reality of climate change" (MacKie 2010).

The workings of consensus and the possibilities of confirmation bias

A fair statement about the current consensus position would be that most scientists agree that global warming is taking place, but they debate the causes and what could or should be done about it. They also dispute the magnitude and rate of global warming using credible peer-reviewed published research. Worryingly, however and from a scientific perspective, is the fact that the issue has become so highly politicised resulting in the term 'consensus' being used, at times, as a stick to beat any scientific opinion which runs in opposition to the collective wisdom of the environmental activists and those scientists who promote the view that humans are responsible for climate change. Consensus built upon (provisionally) established knowledge should be taught, of course, but opposing views which are argued on good scientific grounds should not be excluded from consideration. Untangling the science and the politics is very difficult, however (and we may note the title of the text by Carter (2010) referred to earlier—*Climate: the Counter Consensus*). We might remind ourselves of the life of Galileo, in another era and a quite different context, to say that scientific progress shouldn't be gauged by the extent of a consensus. Then, the consensus was hardly among scientists and the telling participants commanded the authority of early 17^{th} Century religion. It was, nevertheless, a matter of consensual thinking versus the reasoning of an individual subsequently described by both Einstein and Hawking as the "father of modern science".

Confirmation bias refers to the tendency for people to gather, select or search for evidence which favours their existing preconceptions. As human beings we so easily seek out whatever will substantiate our existing thoughts or hypotheses. Explanations for this bias are not at all confined to self-deception; both motivated and unintentional strategies are probably involved, the latter making use of whatever available heuristics are thought to be useful in handling a difficult idea or solving a problem—and so reasoning in a particular way can be unintentional. With regard to global warming, it is very apparent that amongst scientists themselves the debate about temperature increases and possible causes seems to be troubled by confirmation bias (biases on both sides). Prevailing consensus acts to selectively filter new efforts to investigate trends which have emerged from the analysis of past data; new findings which do not confirm old ones tend to be dismissed at best, deprecated at worst, and people can be vilified for thinking ‘wrongly’, as happened with Phil Jones.

An example of this confirmation bias is the apparent need for AGW proponents to reconcile the divergence between the observed temperature record and their predictions of increased warming based on climate models (Kaufmann, Kauppi, Mann and Stock 2011). We are not suggesting here that it is not important to research why warming appears to have not occurred as predicted but what this paper and others have tried to do is explain this through the “tweaking” of computer models rather than research using more direct measures.

> The finding that the recent hiatus in warming is driven largely by natural factors does not contradict the hypothesis: “most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.” (Kaufmann, Kauppi, Mann and Stock 2011, p. 11791, quoting Houghton, Jenkins and Ephraums 1990)

In a recent public lecture entitled *Scientific Heresy*, Matt Ridley—author of *Nature via Nurture* (2003) and the biography of *Francis Crick* (2006)—has put the issue very firmly, taking ‘scepticism’ to a new level:

> My argument is that like religion, science as an institution is and always has been plagued by the temptations of confirmation bias. With alarming ease it morphs into pseudoscience even – perhaps especially – in the hands of elite experts and especially when predicting the future and when there’s lavish funding at stake. It needs heretics. (Ridley 2011)

Combining religion and science like this arguably goes far beyond that which might be debatable by science teachers in schools, but it perhaps helps to put into context the current pressures for confirmation studies in frontier science. In respect of those in climate research, the *Berkeley Earth Project* team was recently set up by Californian Richard

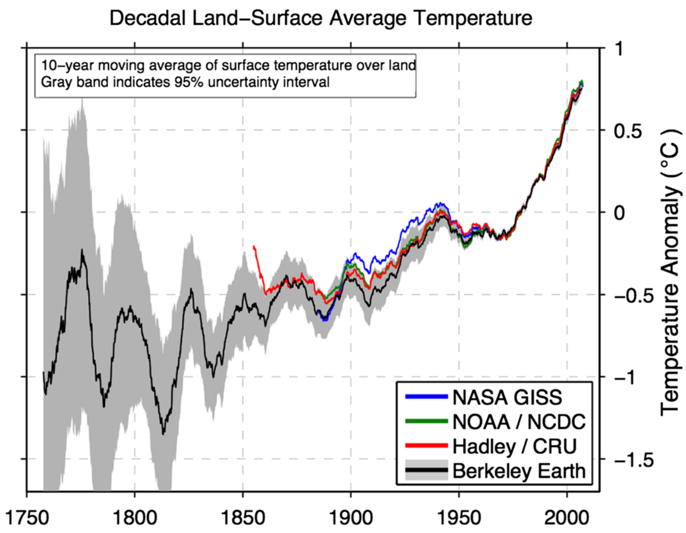

Fig. 3 Berkeley Earth Surface Temperature summary chart showing the Decadel Land-Surface Average Temperatures, downloaded from http://berkeleyearth.org/analysis.php

Muller in an attempt to assess the extent of global warming using *different* methods than those employed to date. Muller also, quite explicitly, sought to be completely open with data and its analysis, in contrast to what was thought to have happened at East Anglia. The ten-man team, including Nobel Laureate Saul Perlmutter, has been supported financially from sources that back organisations lobbying *against* action on climate change. To date, their findings are given in full on the website http://berkeleyearth.org/ with an indication that they have been submitted for peer review in the normal way. In October 2011, wide media coverage was given to the principal finding that the temperature anomaly graph obtained from their new methods was remarkably like those obtained previously by other researchers (see Fig. 3). In the words of the former BBC Environment Correspondent, Richard Black:

> What came out was a graph remarkably similar to those produced by the world's three most important and established groups, whose work had been decried as unreliable and shoddy in climate sceptic circles (Black 2011).
> http://www.bbc.co.uk/news/science-environment-15373071.

Yet, within weeks (and immediately preceding the commencement of COP17 in Durban in November 2011), 'climategate 2' began with a further set of emails being released from East Anglia. It is not appropriate to take this further here, suffice to say that efforts to achieve consensus appear more and more as a 'battle' rather than as controlled, rational and constructive debate. Young students being inducted into the ways in which climate scientists work in the modern world continue to see adversaries locked into heated argument.

In charged debate, a worse term than 'sceptic' is 'denier'. The pejorative use of this expression, with its linkage to the ideologically unrelated idea of *Holocaust denial*, is thoroughly unwarranted and socio-scientific discussion concerning climate change should scotch its use. If we return to the article by Henry Bauer (2006) and his distinction between micro-scepticism and macro-scepticism, it is worth noting that scepticism is a habit of mind exercised by individuals or groups of individuals and that it is one of the traditional norms of scientific activity. The need to convince peers, or at least satisfy them that what one suggests is at least plausible, has helped make what is published and accepted as 'science' more reliable than it would otherwise be. Bauer suggests that, "once a discovery has been accepted by the scientific community, collective skepticism about it is dropped" (p. 424). What Thomas Kuhn (1962) called "normal science" proceeds as though this discovery were true. If it happens to be a substantive fact, such as that the earth is approximately spherical, then there is no problem; but if it is a theory, then eventually it might require modification in the light of new data. In the meantime Bauer claims, it acts to suppress other views, including those that will supersede it in the future and that collective scepticism is now directed, toward challenges of the conventional viewpoint and not toward that viewpoint itself. Consequently such a stance enthrones macro-skepticism as the order of the day. This unfortunate state of affairs brings to mind the point made by Robert Merton that "most institutions demand unqualified faith; but the institution of science makes scepticism a virtue" (Merton 1962).

If we look at the issue of climate change and global warming through the prism of critical theory, we are confronted by an inherently complex issue which is beset by a struggle between the scientific 'establishment' who hold the theory of anthropogenic climate change to be true based on the scientific consensus as set out by the IPCC (the alarmists) and a growing group of scientists who are sceptical about the IPCC's claims. The position protagonists in the climate change debate hold, vis-à-vis the consensus, biases how they view their own scepticisim. Alarmists' scepticism, it could be argued, exhibits macro-scepticism since their scepticism has been shown to focus on being highly critical of articles, submitted for peer review, that are sceptical of the consensus. This is further evidenced by the editorial stance taken by the journal *Nature*, and the revelations revealed by the climategate scandal of 2009. Climate sceptics' scepticism, it could be argued, exhibits micro-scepticism since their scepticism is focused on critically probing the theory through an appeal to the empirical evidence and extending our understanding of the climate system by pointing out where further work is required, in essence behaving in a proper scientific manner. Regardless, both sides in this debate are quick to accuse each other of cherry-picking data that supports their perspective to the exclusion of other studies that support the alternative view. However, both sides would do well to heed the warning made by Lakatos that "blind commitment to a theory is not an intellectual virtue; it is an intellectual crime" (Lakatos 1978).

This brings us to the third question in our introduction: in handling classroom discussion on global warming, which approaches are likely to be successful, bearing in mind the 'truth and doubt' character of scientific thinking which we desire to impart? Does the contemporary literature in science education acknowledge the difficulties facing science teachers who, by virtue of their enculturation, may so easily be not micro-sceptical in territory which goes so far beyond that which they are used to? (And, of course, teachers are members of the public too.)

Teaching about global warming

In this section we draw from our own research and pertinent recent literature on argumentation and reasoning in science; on discussion and the handling of socio-scientific issues; on the approaches known as cooperative or collaborative learning.

Scientific reasoning

Science teachers naturally feel that they are encouraging students to work like scientists and we may note how that has been theorized. Anton Lawson's (2009) article on scientific reasoning, argues that an *If/then/Therefore* pattern of argumentation lies at the heart of how scientists reason. He developed it on the basis of how they generate possible explanations for puzzling observations, therefore arguing persuasively about how teachers might approach practical work and empirical investigations in science. He has defended its general applicability in science, demonstrating it in relation to prominent scientific breakthroughs, archival reports, thought experiments, engineering research and some geological research. Lawson—following Peirce—reckons that much hypothesizing begins with *abduction*, or *analogical reasoning*, the inferential process that "involves [the] reasoning used to mentally derive causal claims (i.e., hypotheses/theories) from premises" (Lawson 2009, p. 338). Thereafter deductive reasoning processes usually follow, deductions relating to the specifics of the situation in hand, on what we have knowledge of—not logical in the purely abstract sense, but in a pragmatic sense—so that we develop our potential understandings. Applying this to how we might rationalize the useful discussion of socio-scientific issues in classrooms we might reckon as follows. Importantly, we should recognize that socio-scientific topics can and will be raised by teachers, and by students where they are permitted or encouraged to do so (classroom conditions conducive to this will be discussed in the next section), and therefore many will *hear* about the controversies relating to climate change. For us, this is a crucial point regarding socio-scientific discussion: students *hear* about global warming in their wider lives and teachers have to react to what is brought into the classroom, and to *talk* about what is articulated by their charges. Students will attend to reported observations (described by their teacher, their peers, televised reports, and so forth) about global warming, adverse climate patterns, links to CO_2 emissions, etc. Together with viewing associated images, say of melting glaciers and icebergs, then they can or, with help, will make deductions and reason to a point of view.

For example, in relation to the Hockey stick graph:

> *If* we measure the air temperature, year-on-year, and combine the measurements with what glacial ice core samples tell us were past temperatures,
> *then* we should be able to deduce whether there has been global warming in recent times.
> *Therefore,* if the reported data show that the extent of the rise is greater than that of normal fluctuations, we can conclude that accelerated global warming has taken place (the global warming hypothesis is supported).

Or, speculating about the future:

> *If* we make ourselves less dependent on fossil fuel consumption, resorting to renewable sources, like wind power turbines,
> *then* we should reduce CO_2 emissions.
> *Therefore,* we might stem the increase in Earth surface temperatures.

Conducting classroom discussion, with all that is required for the teacher in managing debate (see below), involves a variety of sources of information, often conflicting and perhaps partially understood ideas, which themselves require clarification. And reasoning scientifically about them requires emphasis: the modern science teacher has much to do “to draw the connections that a scientist would between facts, methods, and values” (Ford 2008, p. 420). Ford’s arguments for the correct kind of pedagogy for learning science emphasise the *problematisation* of scientific knowledge: “students should be asked to articulate interpretations of scientific ideas in light of data, entertain alternative possibilities, and try to achieve consensus” (Ford 2008, p. 420).

However, among Lawson’s (2009) conclusions concerning the reality of educational practice is that “… developing many such hypothesis-driven, inquiry-based lessons and properly matching the lessons’ intellectual demands with the students’ initial reasoning skills and their declarative knowledge remains an *unmet* educational challenge” (p. 362).

Discussion and the handling of socio-scientific issues

Admittedly, research suggests that science teachers’ use of discussion is presently limited. A number of studies have shown that while many teachers understand that within the context of science discussions can be of some use, teachers often fail to see their purpose and report that they are generally uncomfortable leading them (Bryce and Gray 2004). Donna Alvermann, David O’Brien and Deborah Dillon (1990) have also shown that, although social studies, art and English teachers could articulate abstract definitions of a good discussion, their enacted classroom discussions seldom resembled these definitions. Additionally, other research has suggested that, when observed, social studies teachers only use discussion in about 10 % of their lessons and that it is of poor quality, short in duration and teacher-dominated (Hess 2004). With respect to improving socio-scientific discussion, argumentation skills are essential to success as they require students to be able to break down an opposing argument into its component parts and to analyse each point critically. These in turn are dependent on the student's listening and communication skills, which in turn are dependent on social skills.

Importantly, discussion can be seen as an educational outcome as well as a teaching method (Larson 2000). Our own research has found that science teachers (endeavouring to improve their practice in the context of handling global warming with 14 year olds) hold equally complex conceptual understandings of discussion to those held by their social science colleagues (Day and Bryce 2011). However, they differ in terms of emphasis, with science teachers tending to stress discussion as an educational outcome to be practised and social science teachers tending to emphasize discussion as an instructional method to be used frequently. Discussion as teacher-mediated discourse is a useful starting point for the practice of discussion for democratic citizenship since the development of social, listening, communication, and argumentation skills must first be acquired (as a prerequisite to engagement in open-ended inquiry for the development of relevant reasoning skills and for the transfer of knowledge to real-life contexts). All forms of discussion within the classroom are, to varying degrees, teacher mediated since it is the teacher who sets the parameters and context for debate. It is generally the teacher who initiates the first exchanges within any kind of discussion. What makes this open-ended inquiry is when the willingness of the teacher allows students to take control of the dialogue which, in the case of global warming and (given what we have set out in the earlier sections of this article) requires skilful management and in ways which can be far from traditional. Ratcliffe and Grace (2003) give advice on how a teacher can commence the encouragement of debate, advocating strategies to progressively widen the number of students participating ('snowballing' the inclusion of individuals through ascribing different roles in structured role-play) or using structured cost-benefit analysis when weighing up the pros and cons of, say, energy-saving strategies that might be used to tackle environmental problems. In our own (action) research with a school department of science teachers, three cycles (three academic years) of teaching and reflection intended to increase the use of discussion have yielded positive dividends with the staff concerned (see Day and Bryce 2012 and detail below).

Argumentation, social skills and the teacher's stance

Socio-scientific discussion is limited by the participants' abilities to: (a) effectively communicate and defend their opinions, (b) listen to and respect those views which differ from their own, and (c) be open-minded enough to take on board others' views (Levinson 2006). The communicative virtues (to use the term employed by Nicholas Burbules and Suzanne Rice 1991) underpinning open discussion about climate change can only work when the students understand that their voice is heard, that no one view has a greater weight because of their position of authority in the school or social status in the classroom, and where patient attention to others' words (listening skills) are encouraged. This has implications for the role of the teacher. Questions as to whether the teacher should take a procedurally neutral, devil's advocate, or balanced role have been debated in general (Oulton, Dillon and Grace 2004) but in relation to climate change, scepticism—in its true sense—would seem to us to be appropriate and therefore a neutral stance, neither 'alarmist' nor 'denier', should be adopted. For many socio-scientific issues, however, viewpoints can become hotly contested. How the teacher deals with such arguments is crucial to the learning which occurs. Differences of opinion should not develop into a quarrel or dispute in the emotional sense of the term. Jonathan Osborne has described what constitutes an 'argument' and why it differs from a mere difference of opinion or quarrel. The former is an attempt to establish *truth* and commonly consists of a *claim* that may be supported by data, *warrants* (that relate the data to the claim), *backings* (the premises of the warrant), or *qualifiers* (the limits of the claim). Some or all of these elements may be the subject to *rebuttals* or counter-arguments (Jonathan Osborne 2010). High quality arguments contain rebuttals since they require the student to compare and contrast different lines of thought (Osborne, Erduran and Simon 2004). Whereas a difference of opinion requires nothing more than a statement of the opinions between two or more discussants without any further cognitive effort or willingness to explore the differences further through reference to either data, warrants, backing or qualifiers. Thus an argument requires the differing parties to mutually exchange a critique of each other's views in an attempt to convince the other of the merits of their view. In turn, this may lead to the adoption, accommodation, assimilation or rejection of opinions based on the shared critique offered by the participants.

Consequently, the learning that occurs during argumentation requires opportunities for students to advance their claims, to justify their ideas and to be challenged, thus learning to argue can be seen as a core process in learning to think and to construct new understanding. Osborne (2010) suggests that comprehending why ideas are wrong matters as much as understanding why others might be correct. In addition, he points out that effective learning in argumentative discourse is dependent on a number of factors, chief among them being the explicit teaching of the norms of social interaction (i.e. social skills) and to understand that the function of their discussion is to persuade others of the validity of their argument. Students do require materials to support them in asking appropriate questions; to help them differentiate between relevant and irrelevant evidence (Chin and Osborne 2010); and to negotiate arguments. However, argumentation requires context to be meaningful to students, therefore we suggest that it forms an *integral* part of socio-scientific discussion. We do not see argumentation as an instrumental skill required *for* discussion; rather we suggest that it is a skill required for students' cognitive development and critical engagement *within* the discussion itself. Thus students' development and practice of these skills in the context of socio-scientific discussion forms part of their development trajectory towards becoming more scientifically literate. There are a number of well-researched pedagogic approaches which can be used by science teachers to address these dispositions and social skills. Before we illustrate how a science teacher might apply them, it is important to recognise some other findings from research exploring the limitations (or constraints) in how students reason about scientific issues and the extent of prevailing scepticism.

Stein Kolstø (2006) found from interviews with secondary students that they did not view their textbook science as crucial knowledge and none of them in his study used such knowledge [recently taught, relevant material] in their arguments. Important scientific information was from frontier science, often as portrayed in the media, with all aspects of argument and consensus (or more often the lack of it) involved. Whereas Norris (1995) had considered the *believability* of reports of scientific findings required emphasis, Kolstø (2001b) found that 16-year-old students did have an eye to believability but that they tended to be shallow in their analysis. They need to check out believability and for that need help with the sources they should use. He concluded that it was 'knowledge of different kinds of *sources* of scientific information [that] needs to be more emphasized in science education for citizenship' (p. 877).

Troy Sadler, Sasha Barab and Brianna Scott (2007) suggest "the extent to which students demonstrate scepticism in the context of socio-scientific discussion remains an open question". In other work (such as Sadler, Zeidler, and Chambers 2004) it has been suggested that many students are not as sceptical of information as they ought to be. A significant proportion of high school students in Sadler et al.'s studies ascribed contradictory conclusions only to discrepancies in data and failed to recognise potential biases or unique analytical approaches, despite being assured that the scientist groups in question analysed identical data sets.

In terms of socio-scientific reasoning, Sadler, Barab and Scott (2007) claim that advanced practice should include the ability to demonstrate scepticism in the face of potentially biased information and strategies to make well-grounded decisions regarding the selection of information sources. Less sophisticated practice would entail a tendency to accept information at face value without recognising potential biases. Sadler, Barab and Scott posit the concept of socio-scientific reasoning as operationalized in terms four constitutive practices involving (1) recognising the inherent complexity of socio-scientific issues, (2) examining issues from multiple perspectives, (3) appreciating that SSI are subject to ongoing inquiry, and (4) exhibiting scepticism when presented with potentially biased information. When students demonstrate all of these practices then they are said to show advanced socio-scientific reasoning.

Cooperative learning as a strategy

Cooperative learning is widely recognised as a useful pedagogic approach for the promotion of socialisation and learning among students, through working together in small groups to achieve shared goals, across different subjects (Cohen 1994). In addition, its use has been shown to promote better understanding in high school science (Hanze and Berger 2007). The model of cooperative learning most referred to in the literature and, we contend, particularly useful in practice in encouraging science teachers to become favourably disposed to socio-scientific discussion in their lessons, is *Learning Together*, developed originally by David Johnson and Roger Johnson (1989). It involves students working together in small heterogeneous groups to produce a group product (Slavin 1983). Group members help each other in a cordial environment, based on a collaborative relationship amongst the participants (McCulloch 1985). As students work towards a common group goal, academic learning and achievement become valued by peers (Slavin 1987). This is due to the fact that the students know that they cannot reach their learning goals if the other students in the learning group do not complete their tasks. A typical group may contain between two and six members, with four being ideal. Since the group members produce a single product, or come to settled agreement, and receive rewards together, group building activities and regular discussion within groups about how well they are working together is a major focus of this method (Thousand, Villa and Nevin 1994). The 'Learning Together' approach has been used for both higher cognitive processes as well as mastery of basic facts and skills (Johnson and Johnson 1989). Essentially, assignments are constructed in such a way as to promote positive interdependence and individual accountability (Thousand Villa and Nevin 1994), because simply placing students in groups and expecting them to work together does not of itself produce cooperation (Johnson et al. 1998). Five key elements need to be included in effective group work: *positive interdependence* amongst group members; nevertheless *individual accountability*; *face-to-face interactions* in the classroom setting; *social skills* such as listening to what others are saying, taking turns to speak and trusting other group members; and thereafter *group processing* to contributing to the achievement of the educational goal.

In our own experience (Day and Bryce 2012), the most demanding of these elements for teachers new to working with cooperative learning has been ensuring positive interdependence and maintaining students' objectivity during group processing activities. Gains were made when teachers explained clearly the success criteria for assessing individual students' contribution to the group. Effective use of cooperative learning requires practice and repeated deployment by the teacher in order to become comfortable with the approach and proficient in handling its use with diverse class groups. In addition, cooperative learning lessons take longer to plan, prepare for and enact than other, more traditional approaches. Also for cooperative learning lessons to be successful, teachers need to focus on social as well as academic aims for these lessons. Regarding the latter, group discussions can be preoccupied with differences in conceptual understandings. Inevitably here, these include basic conceptions, like the distinction between *weather* and *climate* which is far from clear. And they include more complex understandings, like the distinction between the concepts of *correlation* and *cause and effect* when considering the relation between increasing atmospheric CO_2 concentration and the increase in average global temperature over time.

Our own research looked at students working cooperatively to analyse greenhouse gas data and testing the claim that increased CO_2 emissions over the last 150 years are responsible for increased global warming when plotted with temperature over the same period. We found that 50.4 % of these 14 year-old students could interpret the data provided objectively; i.e. argue that the data does *not* provide conclusive support for the claim. However, only 10.4 % of the students could then provide a reasoned argument as to why this was the case with reference to the data provided. This suggests that while working cooperatively, students struggle to objectively balance the overall trend in the data against the finer details within that data. In addition, on further analysis, most of the 49.6 % of students who suggested that the data *did* support the claim, reiterated an 'alarmist' view without reference to the data provided (Day and Bryce 2012). This finding supports those of Sadler, Barab and Scott (2007) and Kolstø (2001b) in so far as a significant number of students were not exhibiting a sufficient level of genuine scepticism when faced with data that conflicted with the consensus view. It does seem that in a variety of countries, very many secondary school students are currently so influenced by their upbringing and school lessons—particularly here, by their education in science—that they do not readily take to (micro-) scepticism. There is clearly more to be done to encourage science teachers to develop themselves professionally with greater determination in this regard.

In summary, while discussing the issues of climate change and global warming, students can learn science *content* and about the *concerns* surrounding the interpretation of data; as well as *conceptual matters* surrounding hypothesized mechanisms about the effect of variables such as cloud cover, solar activity, and climate forcing which are all high level cognitions. In addition, students can develop *reflection* since they must confront their own personal biases and must acknowledge how these affect the way in which they interpret the evidence that they find (essentially metacognition). Furthermore, as they engage in debate with classmates, they are practising the social, argumentation and listening skills required as part of the *communicative virtues* outline earlier, since the public at large (and the student body) will consist of individuals with strong but opposing views on the issue. The teacher's role is to challenge the students to clarify, refine and review their reasoning and to mediate between opposing views, possibly even to direct the students to do more research, to help focus their discussion around a key question, or even to force a conclusion to a debate in order to move the lesson along. Most importantly, cooperative learning has been shown to open up the classroom discourse within discussions that focus on climate change and global warming, moving the discussion away from a teacher-dominated discourse towards a more pupil-centred activity (Day and Bryce 2012). Nevertheless, it is clear from research in a variety of settings that, at present, the *enacted* curriculum in school science falls well short of ensuring healthy, useful forms of scepticism.

Re-focusing the pedagogy of science

In the introduction to this article, we tendered the observation that, at present, science teachers commonly fail to display an appropriate level of scepticism and doubt which might be expected of them when planning and preparing to engage in classroom discussions that focus on climate change and global warming. To advance this claim we have shown that research suggest that students are not as sceptical as they ought to be with regard to the believability of reports of scientific findings (Norris 1995), the trustworthiness of knowledge claims (Kolstø 2001b) and scepticism when presented with potentially biased claims (Sadler, Barab and Scott 2007). This suggests that students need to be explicitly taught how to be sceptical, how to identify bias in scientific claims and how to critically reflect on how science findings are actually reported. Science teachers need to be concerned that a significant proportion of the public presently do not use what they learn in and from science in caring about global warming and its causes. Thus our critique argues that, for many teachers, a paradigm shift is essentially required: to widen their conceptions of science and the societal context in which scientists actually operate; to refocus both what school science instruction can and should do (many would say *must* do); and to recognise that their election to engage in systematic, cooperative learning strategies, and to work up its efficacy for themselves personally, should make science in school worthwhile, valid and pertinent to the world we all now live in.

Whichever teaching approach is adopted by teachers to help students develop an informed view on climate change and global warming through a more open, student-centred discourse—whether it be some blurred combination of whole class discussion, cooperative learning and group problem solving, or any other—it should be clear from our critique that an important distinction should be drawn between science teachers:

- encouraging intellectual (rational) scepticism in the course of their teaching of science and in handling the discussion of socio-scientific issues,
  and
- promoting ‘scepticism’ about climate change and global warming, in the sense that that expression has come to signify an attitudinal opposition to the possibility of anthropogenic global warming; i.e. outright opposition to what the so-called ‘alarmists’ are said to stand for.

The former (rational scepticism) is not only desirable; it is a necessary and important aspect of being scientific in orientation and having a commitment to furthering one’s understanding of everything in the environment (broadly defined); in Osborne’s (2010) words, “knowing what is wrong matters as much as knowing what is right”. The latter, being ‘sceptical’ in the sense of the fashionable slogan, is both counter-alarmist in practice *and* actually anti-sceptical in the intellectual, scientific sense. In the spirit of our opening reference to the quotation from Richard Feynman, teachers should not shun true scepticism. Judging by some of the research findings we have referred to, however, perhaps many do. In the present ‘climate’, they may feel themselves pressed to do so, simply because of the weight and complexity of the science that they (and all members of the public) now face with respect to global warming. There has never been a more important time for science teachers to prioritise robust, scientific scepticism. The science teacher’s sceptical focus should be as a 'hypothesis tester" where s/he helps students to weigh-up competing/conflicting evidence. This also means that they need to come to a view about what constitutes worthwhile evidence.

Thinking more generally about what critical theory might have to say about science teachers' personal biases and beliefs when planning to enact discussions on climate change and global warming, we are reminded that critical theory (and by extension any critical pedagogy) ought to enable students to identify where personal interests lie (at the individual and corporate level), thereby freeing them from potential coercion (indoctrination?) and allowing them to adopt a more questioning (critical) stance towards the social/political/scientific consensus of the day. We would suggest that many science teachers need to adopt a more critical perspective when planning such discussions. If they are ill prepared to think in this manner, or cannot reflect on their own personal biases, then how can they expect to teach their students to be more sceptical?

Reflecting critically upon the future, have we confidence in current forms of science education to say that it will serve citizens well? For example, 50 years from now, should global temperatures have risen by as much as the gloomiest of present day forecasters have said, what will people say, reflecting on the science they learned in school? Can we be confident now that they will say that their school science really prepared them for what took place on the planet? Conversely, should global temperatures not have risen significantly, will citizens of the future be any less confident in science and scientists? And, will it still be said in teacher education courses and in research circles that students should be taught *how* to think, not *what* to think?

In truth, we don't know what is causing global warming. We have argued that we need good honest science—based on co-operation rather than competition—to provide the answers. But it is probably a combination of complex factors involving astrophysics (variations in solar energy associated with the Earth-Sun relationship); geophysics (plate tectonics, volcanism, glaciation, ocean and atmospheric currents, rising sea levels); and human activities (use of fossil fuel for heat and energy, deforestation, etc…). While the current article has focused on the latter two aspects, the former should not be overlooked. For example, an article in *Nature* interestingly, and very counter-intuitively, has recently revealed that scientists are being forced to re-think the contribution of solar radiation to Earth warming. The findings do not give comfort to climate sceptics. The solar cycle lasts 11 years and when the sun was last at its dimmest—in December 2009—it was, according to recent measurements (Haigh, Winning, Taumi and Harder 2010), *warming* the earth the most (and vice versa). The effects of radiative warming are out of phase with the cyclical causes. Thus the sun's role in warming the planet may have been overestimated, now that we have a clearer understanding of how the mixture of light emitted by the sun changes as its intensity shifts. According to Haigh et al., the findings also help explain some regional climate phenomena, such as how Europe can have very cold winters at a time when the world as a whole is experiencing global warming.

One theme which has not been explored in this article should at least be acknowledged, is the frequent assertion that some scientists associated with global warming are *deliberately* biased in their interpretations of climate change data—either in favour of the alarmist or in favour of the denier perspective. This is predicated on the view that vested financial interests are so great, and the geo-politics of the energy industry so complex, that impartiality is not maintained throughout the scientific profession providing evidence concerning global temperatures. Bluntly put, that prejudice exists among some researchers (on both sides of the debate, reflected in what Muir Russell (2010, paragraph 15) described as "failing to display the proper degree of openness" and that it is difficult to assert the independence of science or scientists. While such matters are well beyond the scope of this article, we certainly feel there is a clear need for more openness, greater accuracy in measurement and reporting, and greater courage on the part of researchers to say the truth (and this reflects our concern, raised early in the article, that many young people don't know 'whether to trust anyone at all' on the question of global warming). From the view of scientist as humanist we argue in harmony with the great scientist, Robert Oppenheimer that, regardless of who funds them, the true scientist should find a way to share what he/she knows. In another context, but one also involving world-threatening issues, he spoke about the responsibilities of scientists in ways which seem to us to be equally applicable to global warming at the present time. On 2 November 1945, in his speech on the atomic age and scientific responsibility, Oppenheimer said:

> …It is not possible to be a scientist unless you believe that it is good to learn. It is not good to be a scientist, and it is not possible, unless you think it is of the highest value to share your knowledge, to share it with anyone who is interested. It is not possible to be a scientist unless you believe that the knowledge of the world, and the power which this gives, is a thing which is of intrinsic value to humanity, and that you are using it to help in the spread of knowledge, and are willing to take the consequences. (See Cambridge Editorial Partnership 2010, p. 116)

From the perspective of the scientist as teacher we reiterate the passionate message of Richard Feynman that teachers should "teach their students to think like scientists and how to view the world with curiosity, open-mindedness and, above all, doubt" (Feynman 2000, p. 187). And from the perspective of teacher as wise educator we are reminded of the quotation that we began the article with and would hope that science teachers and their students could share socio-scientific discussion in the spirit of the Royal Society motto, "Take nobody's word for it".

References

ACIA (2005). *Arctic Climate Impact Assessment.* Scientific Report. Cambridge: Cambridge University Press. See at http://amap.no/acia/.

Adam, D. (2010). The hottest year. *Nature, 468*, 362–364.

Aikenhead, G. (2006). *Science education for everyday life: Evidence-based practice*. New York: Teachers College Press.

Aikenhead, G. (2007). Expanding the research agenda for Scientific Literacy. In C. Linder, L. Ostman & P-O Wickman, P-O. (Eds.), Promoting scientific literacy: Science education research in transaction. *Proceedings of the Linnaeus tercentenary symposium* held at Uppsala University, Uppsala Sweden, May 2007. http://nadidaktik.se/MSU/sem9/Linneproceedings.pdf.

Alvermann, D. E., O'Brien, D. G., & Dillon, D. R. (1990). What teachers do when they say they're having discussions of content area reading assignments: A qualitative analysis. *Reading Research Quarterly, 25*, 296–322.

Bauer, H. H. (2006). The two-edged sword of Skepticism: occam's razor and occam's lobotomy. *Journal of Scientific Exploration, 20*, 421–427. doi: 0892-3310/06.

Billingsley, K. L. (2010, April 22). Dump Doomsday Dogma. *FrontPage Magazine*. http://www.pacific-research.org/press/dump-doomsday-dogma.

Black, R. (2011). Global warming 'confirmed' by independent study. BBC front page, 21 October.

Booker, C. (2009). *The real global warming disaster*. London: Continuum.

Booker, C. (2011, 17 January). Charles Darwin zealots have made science a substitute religion. *The Telegraph.* http://www.telegraph.co.uk/comment/columnists/christopherbooker/4550448/Charles-Darwin-zealots-have-made-science-a-substitute-religion.html.

Briffa, K. R., Bartholin, T. S., Eckstein, D., Jones, P. D., Karlén, W., Schweingruber, F. H., & Zetterberg, P. (1990). A 1,400-year tree-ring record of summer temperatures in Fennoscandia. *Nature, 346*, 434–439. doi:10.1038/346434a0.

Briffa, K. R., Jones, P. D., Wigley, T. M. L., Pilcher, J. R., & Baillie, M. G. L. (1983). Climate reconstruction from tree rings: Part 1, basic methodology and preliminary results for England. *International Journal of Climatology, 3*, 233–242.

Bryce, T. G. K. (2010) Sardonic science? The resistance to more humanistic forms of science education. *Cultural Studies of Science Education. 5*, 591–612. Also published on-line March 2010. doi 10.1007/s11422-010-9266-6.

Bryce, T. G. K., & Gray, D. S. (2004). Tough acts to follow: The challenges to science teachers presented by biotechnological progress. *International Journal of Science Education, 26*, 717–733. doi:10.1080/0950069032000138833.

Burbules, N., & Rice, S. (1991). Dialogue across differences: Continuing the conversation. *Harvard Educational Review, 61*, 393–416.

Bybee, R. B. (2009). Program for international student assessment (PISA) 2006 and scientific literacy: A perspective for science education leaders. *Science Educator, 18*, 1–13.

Calder, N. (2003). *Magic Universe: The Oxford guide to modern science*. Oxford: Oxford University Press.

Cambridge Editorial Partnership. (2010). *Speeches that changed the world*. London: Quercus Publishing Plc.

Carter, L. (2008). Sociocultural influences on science education: Innovation for contemporary times. *Science Education, 92*, 165–181.

Carter, R. M. (2010). *Climate: The counter consensus*. London: Stacey International.

Chin, C., & Osborne, J. (2010). Students' questions and discursive interaction: Their impact on argumentation during collaborative group discussions in science. *Journal of Research in Science Teaching, 7*, 883–908. doi:10.1002/tea.20385.

Cohen, E. G. (1994). Restructuring the classroom: Conditions for productive small groups. *Review of Educational Research, 64*, 1–35.

COP15. (2009). United Nations climate change conference. Accessed on 5 November 2010 at http://en.cop15.dk.

COP16. (2010). United Nations climate change conference. Accessed on 15 December 2010 at http://www.cc2010.mx/en/.

COP17. (2011). United Nations climate change conference. Accessed on 12 December 2011 at http://www.cop17-cmp7durban.com/.

Dansgaard, W., Johnsen, S., Moller, J., & Langway, C. C, Jr. (1969). One thousand centuries of climate record from cAMP century on the Greenland ice sheet. *Science, 166*, 377–380. doi:10.1126/science.166.3903.377.

Davis, B., Brewer, S., Stevenson, A., & Guit, J. (2003). The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews, 17*, 1701–1716. doi:10.1016/S0277-3791(03)00173-2.

Day, S. P., & Bryce, T. G. K. (2011). Does the discussion of socio-scientific issues require a paradigm shift in science teachers' thinking? *International Journal of Science Education, 33*, 1675–1702. doi:10.1080/09500693.2010.519804.

Day, S. P., & Bryce, T. G. K. (2012). The benefits of cooperative learning to socio-scientific discussion in secondary school science. *International Journal of Science Education,*. doi:10.1080/09500693.2011.642324.

Fall, S., Watts, A., Nielson-Gammon, J., Jones, E., Niyogi, D., Christy, J. R., et al. (2011). Analysis of the impacts of station exposure on the U.S. historical climatology network temperatures and temperature trends. *Journal of Geophysical Research, 116*, D14120. doi:10.1029/2010JD015146.

Feynman, R. P. (2000). *The pleasure of finding things out*. London: Allen Lane, The Penguin Press.

Ford, M. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*, 404–423. doi:10.1002/sce.20263.

Geuss, R. (1981). *The idea of a critical theory: Habermas and the Frankfurt School*. Cambridge: Cambridge University Press.

Glover, C. (2010, Mar 14). The climate guru warming to non-believers. *Sunday Times*, p. 9.

Gore, A. (2006). *An inconvenient truth*. Los Angeles: Paramount Pictures.

Haigh, J. D., Winning, A. R., Toumi, R., & Harder, J. W. (2010). An influence of solar spectral variations on radiative forcing of climate. *Nature, 467*, 696–699. doi:10.1038/nature09426.

Hanze, M., & Berger, R. (2007). Cooperative learning, motivational effects, and student characteristics: An experimental study comparing cooperative learning and direct instruction in 12th grade physics classes. *Learning and Instruction, 17*, 29–41. doi:10.1016/j.learninstruc.2006.11.004.

Henson, B. (2011). *The rough guide to climate change* (3rd ed.). London: Rough Guides.

Hess, D. E. (2004). Discussion in social studies: Is it worth the trouble? *Social Education, 68*, 151–155.

Hodson, D. (2003). Time for action: Science education for an alternative future. *International Journal of Science Education, 25*, 645–670. doi:10.1080/09500690305021.
Houghton, J. T., Jenkins, G. J., & Ephraums, J. (Eds.). (1990). *Climate change: The IPCC scientific assessment, WG1*. Cambridge: Cambridge University Press.
UNFCCC. United Nations Framework Convention on Climate Change. See at: http://unfccc.int/2860.php.
IPCC. (2007). Climate change 2007: The physical science basis. Contributions from Working Group 1 to the Fourth Assessment Report of the IPCC. In S. Solomon, et al. (Eds.), *Intergovernmental panel on climate change*. Cambridge: Cambridge University Press.
Jenkins, E. (1990). Scientific literacy and school science education. *School Science Review, 71*(256), 43–51.
Johnson, D. W., & Johnson, R. T. (1989). *Cooperation and competition: Theory and research*. Edina, MN: Interaction Book Company.
Johnson, D. W., Johnson, R. T., & Holubec, E. (1998). *Cooperation in the classroom*. Boston: Allyn and Bacon.
Kaufmann, R. K., Kauppi, H., Mann, M. L., & Stock, J. H. (2011). Reconciling anthropogenic climate change with observed temperature 1998–2008. *Proceedings of the National Academy of Sciences USA* 108, 11790–11793. doi:10.1073/pnas.1102467108.
Kolstø, S. D. (2001a). Scientific literacy for citizenship: Tools for dealing with the science dimension of controversial socioscientific issues. *Science Education, 85*, 291–310. doi:10.1002/sce.1011.
Kolstø, S. D. (2001b). 'To trust or not to trust,'.- pupils' ways of judging information encountered in a socio-scientific issue. *International Journal of Science Education, 23*, 877–901. doi:10.1080/09500690010016102.
Kolstø, S. D. (2006). Patterns in students' argumentation confronted with a risk-focused socio-scientific issue. *International Journal of Science Education, 28*, 1689–1716. doi:10.1080/09500690600560878.
Kuhn, T. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.
Laframboise, D. (2011). *The delinquent teenager who was mistaken for the world's top climate expert: IPCC exposed*. Toronto: Amazon.
Lakatos, I. (1978). *Philosophical papers 1*. Cambridge: Cambridge University Press.
Larson, B. E. (2000). Classroom discussion: A method of instruction and a curriculum outcome. *Teaching and Teacher Education, 16*, 661–677. doi:10.1016/S0742-051X(00)00013-5.
Lawson, A. E. (2009). Basic inferences of scientific reasoning, argumentation and discovery. *Science Education, 94*, 336–364. doi:10.1002/sce.20357.
Levinson, R. (2006). Towards a theoretical framework for teaching controversial socio-scientific issues. *International Journal of Science Education, 28*, 1201–1224. doi:10.1080/09500690600560753.
Levinson, R. (2012). A perspective on knowing about global warming and a critical comment about schools and curriculum in relation to socio-scientific issues. *Cultural Studies of Science Education, 7*, 693–701. doi:10.1007/s11422-012-9407-1.
Lovelock, J. (2007). *Climate change on the living earth.* Lecture given to The Royal Society, 29 October. Accessed on March 12, 2010 at http://royalsociety.org/General_WF.aspx?pageid=4294968606&terms=lovelock.
MacKie, R. (2010, November 14) Climate change: Science's fresh fight to win over the skeptics. *The Guardian.* http://www.guardian.co.uk/environment/2010/nov/14/climate-change-science-email-scandal.
Mann, M. E., Bradley, R. S. & Hughes, M. K. (1999). Northern Hemisphere temperatures during the last millennium: Inferences, uncertainties and limitations. *Geophysical Research Letters*. 26. 6. doi: 10.1029/1999GL900070.
McCulloch, J. (1985). Lickona's curriculum for cooperation. *Ethics in Education, 4*, 12–15.
Merton, R. K. (1962). *Social theory and social structures*. New York: Free Press.
National Research Council. (1996). *National science education standards*. Washington: National Academy Press.
Norris, S. P. (1995). Learning to live with scientific expertise: Toward a theory of intellectual communalism for guiding science teaching. *Science Education, 79*, 201–217. doi:10.1002/sce.3730790206.
OECD. (2006). *Assessing scientific, reading and mathematical literacy: A framework for PISA 2006*. Paris: OECD.
Oppenheimer, R. (2010). Speech on the atomic age and scientific responsibility, 2 November 1945, cited in *Speeches that changed the world*, Cambridge Editorial Partnership, London: Quercus Publishing Plc.
Osborne, J. (2010). Arguing to learn in science: The role of collaborative, critical discourse. *Science, 328*, 463–466. doi:10.1126/science.1183944.
Osborne, J., Erduran, S., & Simon, S. (2004). Enhancing the quality of argumentation in school science. *Journal of Research in Science Teaching, 41*, 994–1020. doi:10.1002/tea.20035.
Oulton, C., Dillon, J., & Grace, M. M. (2004). Reconceptualizing the teaching of controversial issues. *International Journal of Science Education, 26*, 411–423. doi:10.1080/0950069032000072746.

Payne, M. (2010). Critical theory. In M. Payne & J. R. Barbera (Eds.), *A dictionary of cultural and critical theory* (2nd ed.). Oxford: Wiley-Blackwell Publishing.
Pearce, F. (2010, February 9). Hockey stick graph took pride of place in IPCC report despite doubts. *The Guardian*. See at http://www.guardian.co.uk/environment/2010/feb/09/hockey-stick-graph-ipcc-report.
Popper, K. (1982). *The open universe*. London: Hutchinson.
Radic, V., & Hock, R. (2011). Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. *Nature Geoscience,*. doi:10.1038/ngeo1052.
Ratcliffe, M., & Grace, M. (2003). *Science education for citizenship*. Maidenhead: Open University Press.
Ridley, M. (2011). Scientific Heresy. The Angus Millar Lecture of the Royal Society of the Arts, Edinburgh, 31 October.
Roberts, D. A. (2007a). Scientific Literacy/Science Literacy. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 729–780). A project of the National Association for Research in Science Teaching.
Roberts, D. A. (2007b). Linne scientific literacy symposium. Opening remarks. In C. Linder, L. Ostman & P-O Wickman. (Eds.), Promoting scientific literacy: Science education research in transaction. *Proceedings of the Linnaeus Tercentenary Symposium* held at Uppsala University, Uppsala Sweden, May 2007. http://uu.diva-portal.org/smash/record.jsf?pid=diva2:40649.
Roth, W.-M., & Désautels, J. (Eds.). (2002). *Science education as/for sociopolitical action*. New York: Peter Lang.
Russell, M. (2010). The independent climate change E-mails review. www.cce-review.org/pdf/FINAL%20REPORT.pdf.
Rutherford, J., & Ahlgren, A. (1990). *Science for all Americans*. New York: Oxford University Press.
Ryder, J. (2001). Identifying science understanding for functional scientific literacy. *Studies in Science Education, 36*, 1–44. doi:10.1080/03057260108560166.
Sadler, T. (2004). Moral and ethical dimensions of socio-scientific decision making as integral components of scientific literacy. *Science Educator, 13*, 39–48.
Sadler, T. D., Zeidler, D. L., & Chambers, F. W. (2004). Student conceptualisations of the nature of science in response to a socio-scientific issue. *International Journal of Science Education, 26*, 387–409. doi:10.1080/0950069032000119456.
Sadler, T., Barab S. A., & Scott, B. (2007). What do students gain by engaging in socio-scientific inquiry? *Research in Science Education, 37*, 371–391. doi:10.1007/s11165-006-9030-9.
Shackleton, N., & Opdyke, N. (1973). Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28–238: Oxygen isotope temperatures and ice volumes in a 105 and 106 year scale. *Quaternary Research, 3*(1), 39–55. doi:10.1016/0033-5894(73)90052-5.
Shackley, S., Young, P., Parkinson, S., & Wynne, B. (1998). Uncertainty, complexity and concepts of good science in climate change modeling: Are GCMs the best tools? *Climatic Change, 38*, 159–205. doi:10.1023/A:1005310109968.
Shamos, M. H. (1995). *The myth of scientific literacy*. New Brunswick, NJ: Rutgers University Press.
Sharma, A. (2012). Global climate change: What has science education got to do with it? *Science & Education, 21*, 33–53. doi:10.1007/s11191-011-9372-1.
Sim, S. (2006). *Empires of belief: why we need scepticism and doubt in the twenty-first century*. Edinburgh: Edinburgh University Press.
Slavin, R. E. (1983). *Cooperative learning*. New York: Longman.
Slavin, R. E. (1987). Cooperative learning and the cooperative school. *Educational Leadership, 47*, 52–54.
SPPI (2010). *Surface temperature records: Policy-driven deception?* J. D'Aleo and A. Watts. Science and Public Policy Institute. See at http://scienceandpublicpolicy.org/originals/policy_driven_deception.html?Itemid=0.
Thousand, J. S., Villa, R. A., & Nevin, A. I. (1994). *Creativity and collaborative learning: A practical guide to empowering, students and teacher*. Baltimore, MD: Paul H. Brookes.
Winstanley, D. (2000). In support of skepticism. *Environmental Science & Policy, 3*, 19–20.
Zeidler, D. L., & Keefer, M. (2003). The role of moral reasoning and the status of socioscientific issues in science education: Philosophical, psychological and pedagogical considerations. In D. L. Zeidler (Ed.), *The role of moral reasoning on socioscientific issues and discourse in science education*. The Netherlands: Kluwer Academic Press.

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