Climate change and the impact on the future of agriculture

David I Gustafson
Monsanto Company, 800 N. Lindbergh Boulevard, St. Louis, MO, 63167
Email: david.i.gustafson@monsanto.com

Monsanto, a company wholly dedicated to agriculture and a leading global provider of agricultural technology, recently called upon its Fellows to report on the science behind climate change and its likely impact on agriculture. The Monsanto Fellows Climate Change Panel found that although the exact magnitude of current and likely future human influences on climate is uncertain, several key facts about climate and the future of agriculture are known. Convincing data show that temperatures are increasing, and that changing precipitation patterns are already affecting agriculture. Impacts on crop production are likely to intensify, but not in a uniform manner, either spatially or temporally. Some regions, such as Africa, Australia, and certain portions of Europe, are projected to be quite negatively impacted, while other important agricultural production areas, such as Argentina and temperate portions of North America, may actually benefit from the expected changes, at least initially (over the next few decades). However, most models suggest that all regions are projected to suffer productivity declines by the end of the 21st century, unless successful mitigation measures are implemented soon. Exacerbating the climate change challenge, demographic and economic trends suggest that a doubling of overall crop productivity will be required by mid-century, in order to meet the food, feed, fuel, and fibre demands of an estimated world population of 9 billion by the year 2050. Clearly, new technologies are needed for agriculture to supply this escalating demand, while at the same time adapting to a changing climate and hopefully even contributing to climate mitigation, by reducing greenhouse gas emissions associated with crop production. Fortunately, good progress is already being made. For most crops of global importance, there is considerable buffering and redundancy in breeding, seed manufacturing, and research sites, which should enable us to keep pace with the expected rate of changes. Crop chemical manufacturing is managing its "carbon footprint," and there are new biotechnology-based crop traits in the research pipeline, such as drought tolerance and nitrogen-use efficiency, that will help in both mitigating and adapting to climate change.

Additional keywords: global warming, drought, climate change mitigation, carbon footprint

Introduction

Agriculture is the world's oldest industry, and climate change is its newest challenge. Despite the antiquity and existential necessity of agriculture, it nevertheless now finds itself embroiled in several contemporary controversies over its widespread use of technology to meet accelerating demands for food, feed, fibre, and fuel. The Green Revolution, powered by the widespread adoption of inorganic nitrogen fertilizers, is claimed by some to be causing undesirable environmental effects as it enables rapid population growth and even more demand (Hazell 2002). This technology-driven cycle of accelerating crop production is feared by some to be unsustainable, as the consumption of finite resources and the negative impacts of intensified crop production conspire to squeeze the ability of farmers to meet demand, in a kind of neo-Malthusian vortex (Dyson 2001). For example, the widespread use of inorganic nitrogen fertilizers results in significant greenhouse gas (GHG) emissions, thereby potentially contributing to the very heat and moisture stresses that may already be limiting the productivity of cropping systems (Stein and Yung 2003). Such concerns have caused some to express serious doubts about the long-term sustainability of modern agricultural techniques (Stewart et al. 2002).

But agriculture has never been easy. Weed control, in particular, has plagued agriculture from its onset. Indeed, the first few pages of the Bible describe this problem as a direct consequence of mankind's disobedience: "cursed is the ground because of you … both thorns and thistles it shall grow for you." In addition to unwanted weedy plants, there are numerous insect and fungal pests that plague farmers. But now, according to many environmental scientists, an even larger threat of Biblical or even Apocalyptic proportions looms over agriculture – global climate change (Gore 2006; Hansen et al. 2008; Weart 2003).

The question of whether mankind's increasing combustion of fossil fuels is inducing climate change has become a contentious and seemingly intractable geopolitical issue. Though it seems to have been accepted by much of the climate modeling community (Anderegg et al. 2010), a vocal minority of scientists hold to a firmly contrary view, for instance, Richard Lindzen (MIT) and Roy Spencer (ret. NASA). These actually lop-sided scientific debates have been selectively amplified in the popular media, in a manner that has created what seems to many to be an evenly divided body of squabbling scientists. This has largely confused both the lay public and policymakers, helping to stifle all attempts at a concerted global political approach to limiting GHG emissions (Gore 2006).

It was amidst this backdrop in late 2006 that the Board of Directors for Monsanto, a company wholly dedicated to agriculture, called upon its leading scientists to report on the science behind climate change and the extent of the threat to agriculture. Monsanto's Technology organization (led by Dr. Robert Fraley) accomplished this task by calling for volunteers from among its Fellows, who formed the Monsanto Fellows Climate Change Panel, which prepared the report. This paper summarizes that report and the conclusions that were presented to the Monsanto Board in June 2007. As this current summary is actually being prepared in July 2010, some of the data have been updated to include more recent information.

Methodology

The Monsanto Fellows Climate Change Panel was staffed largely by volunteers from among Monsanto's Fellows. Monsanto established its Fellow Program in 1948 in order to recognize, utilize, and develop its scientists and their scientific leadership skills. It includes a rigorous nomination process, oral reviews every three years, and claims one Nobel Prize winner (Chemistry, 2001) from among its ranks: Dr. William S. Knowles, who was recognized for his seminal work on chiral synthesis. There are now about 100 Fellows, representing less than 5% of the company's scientists. Twenty-one of them answered the call for volunteers issued in December 2006. The Panel was facilitated by Monsanto's Dr. David Butruille and was overseen by a three-person Steering Team: Dr. Fraley, Dr. Robert Reiter, and Dr. David Fischhoff. The Panel itself was organized around six theme areas, each led by one of the Monsanto Fellow volunteers:

Dr. Gregg Bogosian	Global and regional change and seasonal forecasting
Dr. Gerry Dill	Biological changes
Dr. Mike Edgerton	Reduction of carbon emission
Dr. David Gustafson	Evolution of risk
Dr. Mike Hall	Carbon sequestration
Dr. Ty Vaughn	Brainstorming

The six theme teams operated largely autonomously, but each of the Fellow volunteers served on two of the theme teams, which, in addition to regular contact with the Steering Team, fostered good communication exchange. Because this area of science was largely new to Monsanto, the work of the Panel necessitated interaction with a number of Consultants, who visited St. Louis for a one-day internal Climate Change Symposium on March 3, 2007. The Consultants were:

- Dr. Barry Goodwin, North Carolina State University
- Dr. Steve Long, University of Illinois
- Dr. Donald Ort, University of Illinois
- Dr. Nicholas Piggott, North Carolina State University
- Dr. Cynthia Rosenzweig, Columbia University
- Dr. Steve Schneider, Stanford University
- Dr. Mark Taylor, Sandia National Labs
- Thomas Zacharias, National Crop Insurance Services

On May 2, 2007, an internal meeting was held among all Panel members and two additional consultants: Dr. Andrew Leakey (University of Illinois) and Dr. Ralph Quatrano (Washington University). This internal meeting was used to share findings from among the six theme teams and develop a consensus on the final report to the Board.

Findings

The Panel collected extensive information on the development of modern climate science, and the origins of the theory of man-made global warming. While it was not asked – nor did it take – an explicit position on the accuracy of that theory, the Panel found unequivocal and convincing data that temperatures are now increasing, in a manner largely consistent with the theory, and that changing precipitation patterns are already affecting agriculture. However, the Panel found that the impacts of climate change would be highly regional in nature, as detailed further below. Crop yields in certain areas are likely to benefit from the predicted changes through mid 21st century, but productivity is expected to be hampered in all regions by the end of the century, unless mitigation occurs. The Panel found that modern agriculture is well positioned to deal with the expected pace of climate change, and has significant untapped potential to contribute to reduction of GHG emissions. Further details on each of these findings are presented below.

Development of modern climate science

This brief history of the development of modern climate science is drawn primarily on material presented in an excellent book by Stephen Weart, The Discovery of Global Warming (2003). According to Weart's studies, the possibility that climate might be affected by man-made GHG emissions, particularly those related to the combustion of coal and other fossil fuels, appears to have first been proposed in 1896 by Svante Arrhenius, a Swedish scientist, whose name should be recognizable to both biologists and chemists for the chemical reaction rate plotting method that bears his name (natural logarithm of the rate constant vs. the inverse of the absolute temperature). Another Swede, Arvid Högboom, refined Arrehnius' calculations. The numbers Högboom derived for the impact of doubling atmospheric CO2 on global temperatures were in the range of 10^0F, a bit higher than most of the values accepted today. However, given the rather low amounts of fossil fuel burning at that time, neither Arrhenius nor Högboom was particularly alarmed by the results, and a little warming sounded nice in Sweden anyhow. But the main reason for their lack of concern was that they incorrectly assumed it would take many millennia for human activities to double the amount of carbon dioxide in the air. This now appears to be a level that will be reached by about the year 2060, without some form of global regulatory intervention.

Subsequent scientific scrutiny of Arrhenius's and Högboom's calculations brought a large degree of scepticism in the early twentieth century. This sceptical attitude continued until 1938 when another scientist, Guy Stewart Callendar, announced a more detailed restatement of the basic theory. As with Arrhenius, a fellow northern European, Callendar believed that a little warming would be a good thing, perhaps even helping agriculture. And, just like Arrhenius, he incorrectly prognosticated a very gradual increase due to his assumption of a very slight rise in atmospheric carbon dioxide, and too weak of a dependence of global mean temperature on this parameter. But his calculations were largely ignored or dismissed, just as the previous work of Arrhenius and Högboom had been.

It was also during the 1930s that a Serbian engineer, Milutin Milankovitch, carried out excessively difficult and tedious calculations involving slight variations in the Earth's orbit, which he proposed as an explanation for a key feature of the Ice Age: the cyclical periods of glaciation in the "recent" (<1 million year) history of the Earth's climate. The changes he calculated in the tilt of the Earth's axis and the shape of its orbit were incredibly small. Such slight perturbations would only be capable of causing dramatic shifts in the Earth's climate if the planetary weather system was intrinsically "metastable"—capable of slipping into either a much colder or a much warmer condition. Increasingly, climate scientists came to believe this was possible. As a physical mechanism for how this might happen, they proposed the existence of so-called "positive feedback" which could cause warming to accelerate. For example, as snow and ice melt, they allow the underlying soil or open water to absorb much more incoming sunlight, further accelerating the rate of melting. Indeed, many such feedback processes have found their way into the modern climate simulation tools that are used today. Scientists began to accept the idea that rapid changes in the Earth's climate had taken place in the past and were possible in the future.

The next major advance came through a number of scientists (Keeling and Whorf 2004), who collaborated on the collection of the first accurate data on atmospheric carbon dioxide levels in Antarctica and at Mauna Loa, Hawaii (both far enough removed from local carbon dioxide sources to collect globally-representative information). The Mauna Loa data (see Figure 1) tell a compelling story about the rate at which the atmospheric carbon dioxide level continues to climb. The annual fluctuations are caused by vegetation in the Northern Hemisphere, which consumes carbon dioxide during summer months and then releases it during the winter months of decay.

Another key technology advance came at about the same time from Cesare Emiliani, a geology student from Italy working at the University of Chicago, who worked out many of the experimental details in a new isotopic method for inferring prehistoric temperatures, based on the presence of a rare nuclear isotope of oxygen, ^{18}O. In 1947, the nuclear chemist Harold Urey had discovered that the ratio of ^{18}O in the shells of a class of marine organisms (*foraminifera*) was directly related to the temperature of the water at the time that the organism had lived. Since these shells can be found at the bottom of the ocean in discrete layers that may be simply counted and dated, the past temperature of the Earth's oceans could be directly determined. Once the technical details were worked out, climate scientists had a much better record of historical temperatures with which to test various models of the ice ages and of the climate's true sensitivity to the small variations in sunlight

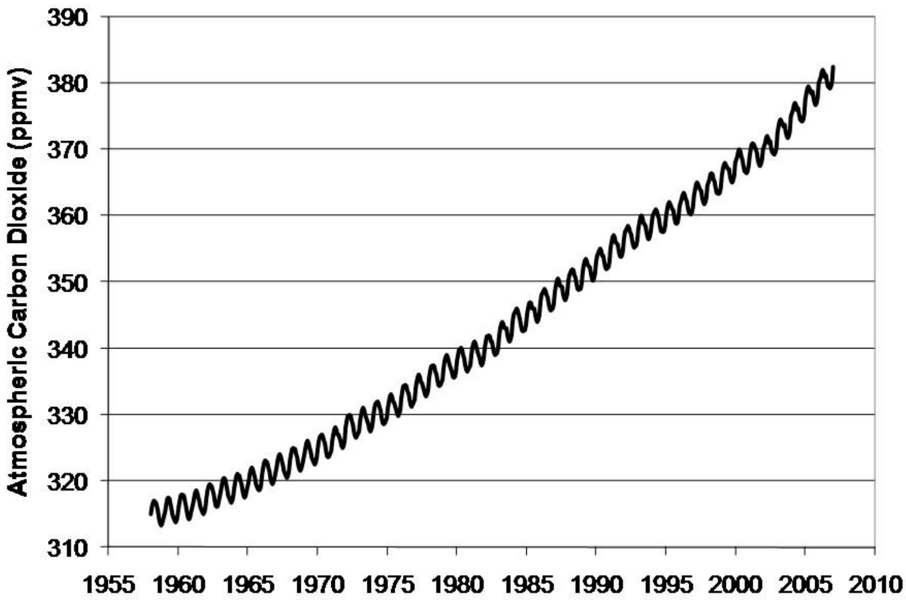

Figure 1. Carbon dioxide levels in the atmosphere, as measured at Mauna Loa (source: Keeling and Whorf 2004).

suggested by Milankovitch's calculations. A series of debates then ensued within the climate science community on whether the Earth's climate was really as sensitive to small perturbations as the increasing body of evidence was suggesting. This concept is still being debated, and is partly responsible for the scepticism about the global warming theory in the scientific community today.

The next big advance in climate science was the computer, first analog, then digital, then the supercomputers of today. But scientists have been continually stymied when they try to model the weather, no matter how powerful their computers have become. We continue to be aware of this limitation in our personal lives today. Forecasts for anything more than about 48 hours out are notoriously inaccurate. It turns out that the inability to predict the weather is not because our computers are not fast enough, or that we have the math all wrong. It has to do with the coupled systems of nonlinear differential equations that govern the system. It turns out that such systems defy reliable prediction, as first explained in detail in 1961 by Edward Lorenz (the so-called "Butterfly Effect"). Tiny changes in the initial values for such systems unavoidably cause chaotic results within just a few time steps of the computer simulation. But the Butterfly Effect is not just a technical flaw in the computer programs – it is essential aspect of the weather. Lorenz mathematically proved that such nonlinear systems have this intrinsically chaotic behaviour (Gleick 1988). So there is a built-in limitation to the ability of any computer model, no matter how powerful or sophisticated, to accurately predict the weather.

Acceptance of Lorenz's proof of the existence of such "chaotic systems" helped shape the thinking of modern climate scientists that relatively rapid changes in the earth's climate were possible. But it also presents an apparent discrepancy for those who also claim that modern global climate models can accurately forecast future climate. It turns out that no discrepancy, in fact, exists. Climate represents the long-term trend in weather, rather than the daily fluctuations that we call "weather." These long-term trends represent a different class of differential equations, so-called Boundary Value problems, rather than the Initial Value problems that are subject to Lorenz's Butterfly Effect. Thus it turns out that reasonably accurate climate forecasts should be possible, once we have good models and good input data.

From the mid-1960s into the early 1970s, climate science became engrossed in unravelling a new puzzle that has ended up hurting its credibility in the eyes of the public and has also made it easier for sceptics to poke apparent holes in the current chorus of global warming warnings. The key question was this: was there a danger that man-made pollution could cause drastic cooling due to the continued release of aerosols, particulate matter, and even contrails produced by jet travel? The question received additional attention when researchers found compelling evidence that the Earth was somewhat "overdue" for its next period of heavy glaciation, at least according to the time series of temperature records that were emerging from ice core records (see Figure 2). In 1972, these data helped prompt

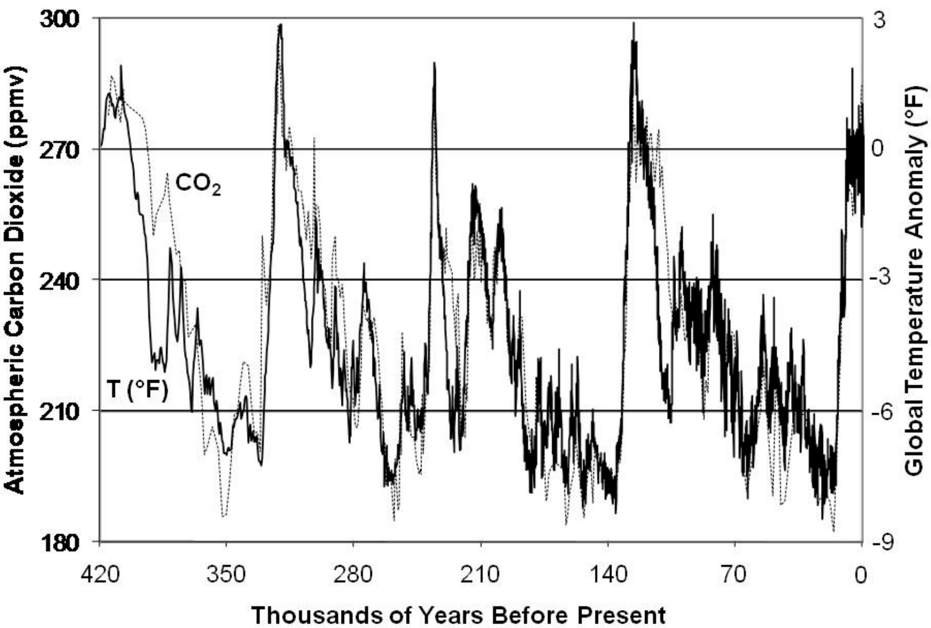

Figure 2. Global mean temperatures and carbon dioxide levels for the past 420 thousand years, based on the analysis of air bubbles trapped in ice cores collected on Antarctica (source: Vostok ice cores).

the leading glacial-epoch experts to meet at Brown University and to conclude, "the natural end of the warm epoch is undoubtedly near." There were several naysayers at the conference, but the majority succeeded in issuing a statement saying that serious cooling "must be expected with the next few millennia or even centuries." This press release and the hullabaloo that followed managed to make it to the front page of *Time Magazine* that year and even prompted a letter of warning to Richard Nixon.

At the time of these cooling warnings, some scientists were instead already concerned with the possibility of global warming from man-made carbon dioxide in the atmosphere, but the majority view at that time was that global cooling was the greater danger, due to the man-made addition of aerosols and particulate matter into the atmosphere (sometimes known as "global dimming"). Looking back at the temperature record for that period now, it seems hard to fault the consensus view. The current spate of warming began in around 1970, and the data for the previous thirty years had showed steady cooling.

During the 1970s, the question of rising carbon dioxide levels in the Earth's own current atmosphere would occasionally still come up, based largely on the vocal advocacy of Schneider and others. But it received little traction in either the larger scientific community or the public, since there was still no convincing evidence of a global warming trend at that time. Schneider and a colleague published an apparently prophetic paper during this period, suggesting that warming due to higher carbon dioxide levels would soon begin to dominate the Earth's climate after 1980. A 1977 National Academy of Sciences panel issued a report also suggesting that catastrophic warming, not cooling, was the greatest threat to the Earth's climate. But this all came too soon after the 1972 Brown University group's warnings of an imminent ice age to win very many converts. At the end of the decade a World Climate Conference was held in Geneva in 1979, convening 300 experts from 50 countries. They issued a consensus statement recognizing the "clear possibility" that an increase in carbon dioxide "may result in significant and possibly major long-term changes of the global-scale climate."

The 1980s saw the development of the first true Global Climate Models (GCMs) by independent teams of researchers from around the world. Among the key advances in the development of these models were the addition of a true oceanic circulation model, representation of land topography, and several feedback processes, such as the melting of snow or ice mentioned previously. Positive feedback processes have the potential to greatly accelerate the rate of warming. On the other hand, negative feedback would tend to retard warming and act more like a thermostat to keep temperatures where they are. A simple example of this is cloud formation. As the ocean warms, more water evaporates, but this increased atmospheric water content could increase cloud cover, which would tend to reflect more sunlight back out to space, thereby slowing the rate of warming.

James Hansen, a scientist with NASA, has argued for strong positive feedback, based on his analysis of climate over the past 65 million years (Hansen et al. 2008). A re-plotting of both Hansen's paleoclimatic data and more recent data as a "phase-space" diagram is shown in Figure 3, with global mean temperatures as a function of the direct radiative forcing caused by atmospheric carbon dioxide. These results are consistent with strong positive feedback, and also show that temperatures far higher than those observed at present are possible in the earth's climate system. The fact that the recent temperature trajectory has still not "caught up" with the warmer temperatures of the past is a function of the slowness with which air temperatures have been able to responded to the relatively rapid (in geologic terms) shock to the earth's energy balance caused by the rapid increase in CO_2. But the graph clearly implies that much warmer temperatures are inevitable. On the basis of analyses such as these, Hansen has asserted that 350 ppm should be the highest tolerable concentration for atmospheric carbon dioxide. As shown previously in Figure 1, the current concentration is nearly 390 ppm, with no sign of a decrease in sight.

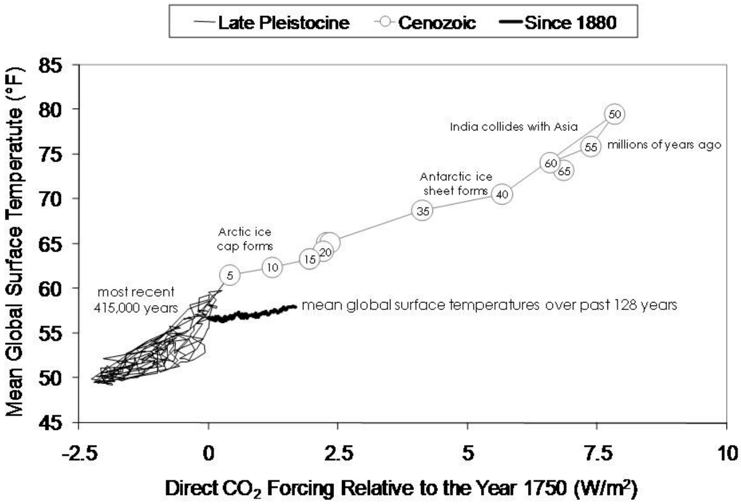

Figure 3. Phase-space diagram of global mean temperatures as a function of the direct forcing of carbon dioxide (sources: replot of data from NCDC, Vostok ice cores, and Hansen et al. 2008)

By the mid-1980s political pressure began to grow, first in Europe and eventually in the United States, for "something to be done" about the global warming issue. Although he failed to win the nomination, Al Gore was a leading presidential candidate on the Democratic side, and he made concerns over global warming one of his key issues during his 1988 campaign. The first "tipping point" came during that hot summer of 1988, when much of the Midwestern United States was suffering a prolonged drought and an unusually hot summer. Responding to all of these pressures, the United States finally relinquished its veto power and the United Nations created the Intergovernmental Panel on Climate Change (IPCC), which now continues to lead the world efforts in this area, with a considerable amount of funding and political clout. Many of today's leading climate scientists chose to join the IPCC, which has since issued a series of four detailed assessment reports: most recently in 2007 (IPCC 2007a, 2007b).

The most recent IPCC report reflects considerable progress based on large amounts of new and much more comprehensive data, improvements in the understanding of the underlying processes, and more sophisticated analyses of the model results. All of these factors enable better characterization of the uncertainties in climate predictions. The report quantifies the relative impacts of man-made and natural factors in terms of "net radiative forcing" in units of energy per unit area (watts per square meter). According to the IPCC, the most important factors include changes in the abundance of greenhouse gases, particularly carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). They conclude that the changes brought on by the increasing concentrations of these gases have a significantly greater effect than the other factors, such as man-made ozone, albedo (surface reflectivity) effects, aerosols (direct and indirect via cloud formation), and variations in solar activity. Of all the other factors affecting climate, the IPCC scientists currently believe that the largest cooling factor is the presence of man-made aerosols in the atmosphere, which are just enough to offset all of the warming factors except for carbon dioxide, which ends up driving the overall global system in the direction of warming.

The 2007 IPCC report is the first from the panel to discuss a very troubling and recently discovered man-made impact on the sea: ocean acidification (Caldeira and Wickett 2003). New data show that at least half the carbon dioxide produced by man has been absorbed by the oceans, and this has already dropped its pH by 0.1 units, which corresponds to a 30% increase in the concentration of hydrogen ions. As the pH drops and acidification continues, the solubility of calcium carbonate, the chemical that forms the shells of many marine organisms, will increase. The species at risk include coral, molluscs, and a number of microscopic organisms.

Warming is now accelerating

The Panel found convincing evidence that global temperatures are increasing, consistent with the basic tenets behind the theory of man-made global warming (IPCC 2007a). All temperature records, whether based on ground or satellite observations, agree that warming has been steadily accelerating since the late 1960's (NCDC 2010; Smith and Reynolds 2004; Smith et al. 2005; United States Climate Change Science Program 2008), especially on the land surfaces of the Northern Hemisphere, where most of the world's crop production takes place (Figure 4).

A seven-year moving average (centered) has been added to Figure 4, in order to see the overall trend a little more easily. The striking thing is that the temperature trend has been accelerating in a continuous manner for the past forty years. Why has this very strong warming signal suddenly appeared in the record? A variety of possible explanations could be offered, but it seems likely to be a result of the carbon dioxide warming effect finally becoming dominant over the mix of other man-made activities that have a net cooling effect, especially conventional air pollution due to particulate matter. The upward curvature is also consistent with positive feedback being induced by increased evaporation of water into the atmosphere with that warming itself adding to the overall greenhouse effect.

Whatever the actual cause of the emergence of this accelerating warming curve, it is fit extremely well by the following equation, which was obtained by simple least squares regression to the seven-year moving average of the observed data from January 1968 to January 2007, when the Panel was conducting its investigations. It is a quadratic in terms of time:

$$T = [a\,(Y - 1968)^2] + [b\,(Y - 1968)] \qquad [1]$$

where T is the Northern Hemisphere land surface warming relative to the year 1968 (°F),
Y is the year (conventional Gregorian calendar),
a is 0.0008338 °F/yr^2, and
b is 0.024337 °F/yr.

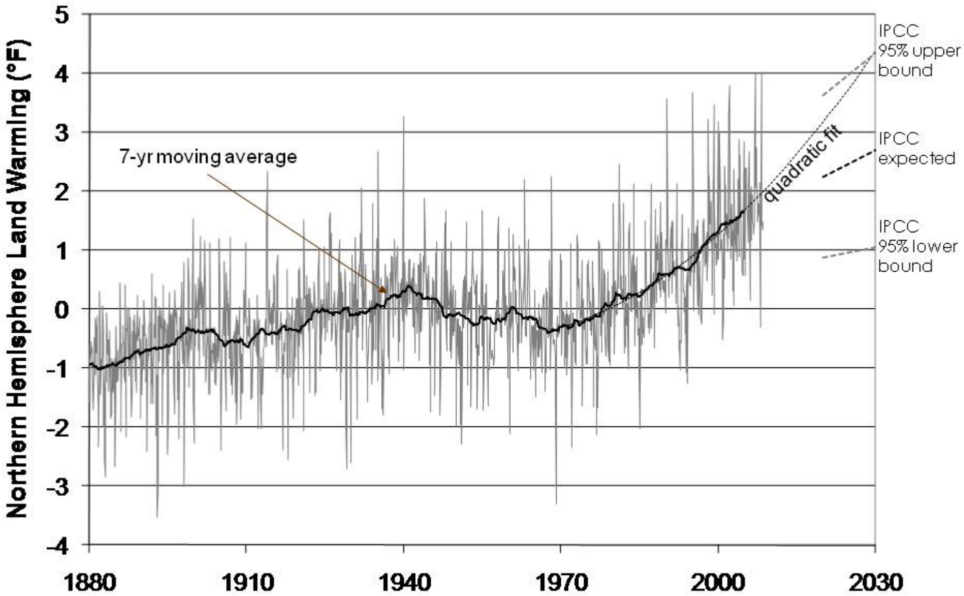

Figure 4. Observed monthly Northern Hemisphere land surface temperature anomalies (relative to the 20th century mean) are shown along with the seven-year moving average, a quadratic fit to this moving average from 1968 to the present time (Equation 1), and IPCC predictions for the warming trend in the Northern Hemisphere during the decade of the 2020s (source of observed temperatures: National Climatic Data Center http://www.ncdc.noaa.gov/cmb-faq/anomalies.html).

As is plainly visible in Figure 4, this quadratic fit predicts much faster warming than the IPCC model predictions for the decade of the 2020s. A closer look at how well Equation 1 fits the observed warming since 1968 is shown in

Figure 5. The degree of fit is surprisingly good, and the monthly temperature anomalies observed since it was first fit to the data (January 2007) continue to bounce around the simple quadratic fit in a satisfyingly accurate manner, as shown in the lower right of Figure 5. As shown in the upper left portion of Figure 5, if temperatures were to continue to follow this quadratic through the end of the twenty-first century, it would result in a degree of global warming that would clearly be noticeable and unacceptable (16°F by the year 2100). Of course, it is unknown whether this very intense rate of global warming will continue at such an alarming pace, but this possibility is deeply unsettling.

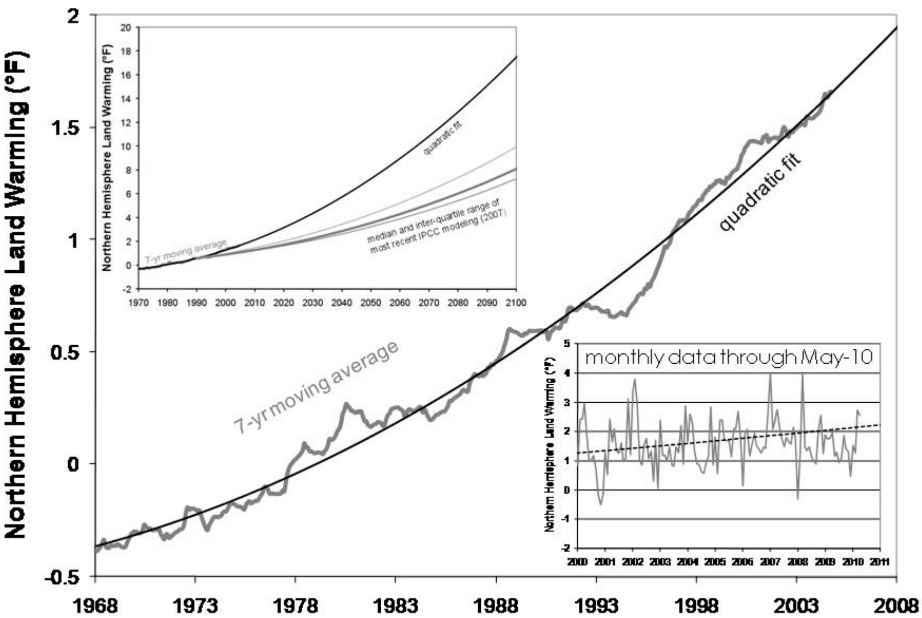

Figure 5. Seven-year moving average of observed Northern Hemisphere land surface temperature anomalies for the past forty years in comparison with the quadratic fit (Equation 1). The inset at lower right shows observed monthly anomalies through May 2010 (most current available as this went to press), in comparison to Equation 1. The inset at upper left shows the predictions for the 21st century for Equation 1 and the median of IPCC model predictions.

As for the hypothesis that man-made GHG emissions are largely responsible for the observed warming, there is considerable evidence that it is true. As shown in Figure 6, the rapidly rising concentrations of CO2, N2O, and CH4 are directly attributable to the recent increases in world population. Although CO2 is the most important of these three gases and is mainly a result of burning coal and other fossil fuels as fuel and a source of electricity, agriculture is responsible for the majority of the N2O and CH4 emissions. Combined with the impact of land use change (the carbon released when land is converted to crop land), agriculture is directly responsible for approximately 25% of all man-made GHGs (Burney et al. 2010).

As indicated in Figure 6, the maximum rate of world population growth occurred in the early 1960s, with a doubling period of only 32 years. Growth has slowed since that time. Various models have been proposed for world population by mid 21st century (IPPC 2001). However, it is expected to total over 9 billion, with a doubling of demand for food, due the combination of a larger population and rising global affluence (Field to Market, The Alliance for Sustainable Agriculture 2009).

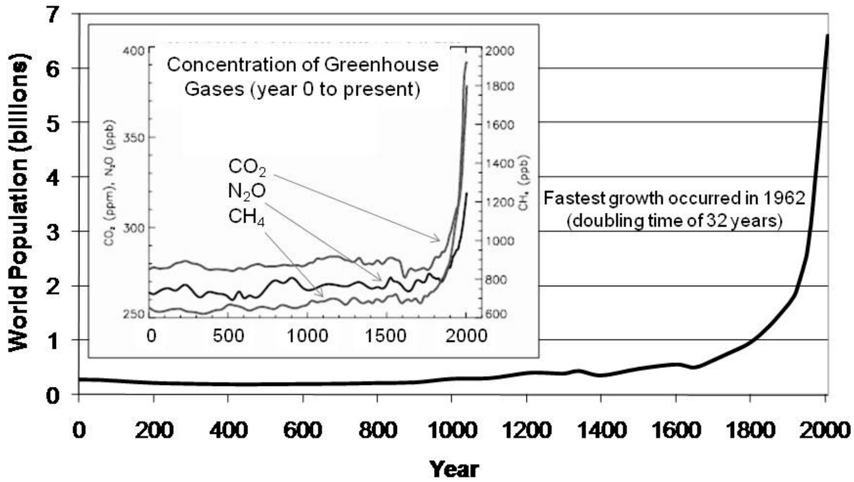

Figure 6. Median of world population estimates for the past two thousand years. The inset shows the growth of atmospheric greenhouse gases over the same period (source: United Nations for population estimates and IPCC for greenhouse gas concentrations).

The challenge to meet this increasing demand for food will be made doubly difficult by the increasing stress of man-made global warming. The three man-made GHGs highlighted in Figure 6 (CO2, N2O, and CH4) are already exerting a significant warming impact. As shown in Figure 7, the cumulative impact of these gases is steadily increasing and is now nearly 3 W/m2 (United States Climate Change Science Program 2008). This represents about 2% of the energy absorbed by incoming solar radiation. In other words, this is the additional warming that would be caused by moving the earth a million miles closer to the sun.

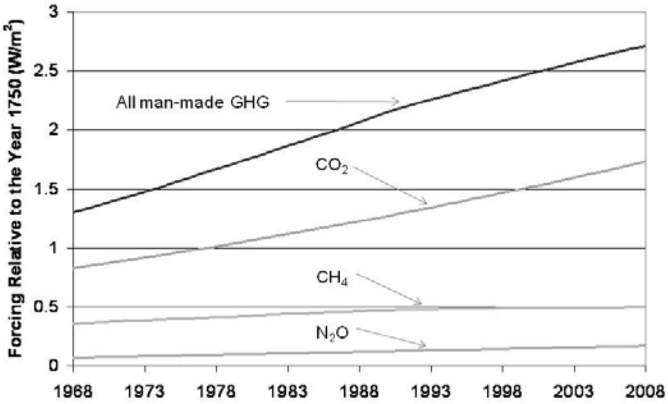

Figure 7. The steadily increasing warming impact of all man-made greenhouse gases (GHGs) and the individual contribution of the top three man-made GHGs: carbon dioxide, methane, and nitrous oxide (source: National Climatic Data Center).

Expected course of climate change

Projections of future warming are heavily dependent on the rate of continuing economic development and the degree to which subsequent generations will adopt new technologies to reduce greenhouse gas emissions (IPCC 2001). However, regardless of the particular development scenario, the pattern of global warming will be non-uniform, both in terms of temperature rise and changes in precipitation (Christiansen et al. 2007; Diffenbaugh et al. 2005; IPCC 2007a, 2007b; LeGrande et al. 2006; Seager et al. 2007). The following general statements characterize the expected pattern of future climate change.

Warming is predicted to occur mainly …

- over land areas rather than over the oceans
- near the poles rather than in the tropics
- at night rather than during mid-day
- in winters rather than in summers

Precipitation changes are less certain, but …

- an overall increase certain, especially near the poles
- decreases will occur in many sub-tropical areas
- current deserts are likely to expand
- more frequent extreme events are likely

Impact on agriculture

Considering all of these impacts from the perspective of agriculture, there is little doubt that water, either too much of it or too little, is the biggest threat. By the middle of the twenty-first century, average annual river runoff and water availability should increase by 10–40% in high latitudes and in typically wet tropical regions, but water will decrease by 10–30% over currently drier areas. Thus, drought-stricken areas will likely increase in spatial extent. Conversely, heavy precipitation events will increase in frequency, which are often a source of crop damage. Water availability will be severely impacted in those regions dependent on freshwater sourced by snow cover and glaciers, since both of these freshwater resources will become severely limited during the course of the 21^{st} century.

Crop productivity is projected to increase slightly due to climatic factors at mid to high latitudes until mid-century, when the excess heat will begin to harm yield. At lower latitudes, which are dominated by developing countries of lower adaptive ability, crop yields are probably already being negatively impacted by climate factors, and this trend will worsen as the warming proceeds. Crops in all world areas are expected to be negatively impacted by changes in rainfall patterns, not only in terms of drought, but also heavy precipitation events, and the possible increased frequency of severe storms. Aquaculture and fisheries will be adversely affected due to the combination of warming, acidification, and other stressors (such as hypoxia).

In addition to the obvious effects of higher temperature and increased moisture stresses (both too much and too little rainfall), pest pressure is expected to intensify. Weeds will experience changes in their range and some will become more productive and prolific, due to the natural fertilization of higher CO_2 levels and potentially lengthened growing seasons (United States Climate Change Science Program 2008). These changes in weed populations have implications for both pathogens and the insects that utilize such hosts.

As with weeds, insect pests are expected to increase their ranges, especially toward the poles. Insects are also hosts to other organisms, including some that have both agricultural and human health implications. Plant diseases are nearly all made worse by warmer temperatures, so this represents yet another potential threat to crops. Finally, the phenomenon of resistance among all categories of pests is expected to become a greater concern, as the number of annual generations increases, especially for those regions which no longer experience wintertime temperatures cold enough to kill off potentially resistant survivors.

Drought is expected to become an increasing threat to agriculture, but it will be highly regionalized (Solomon et al. 2009). It is expected to be most intense in southern Africa, the Mediterranean, southwestern North America, eastern Brazil, western Australia, and southeast Asia. Given the importance of each of these areas to crop production, this highlights the importance of developing new crop varieties with drought tolerance, whether via biotechnology or advanced breeding techniques.

Fortunately, there is strong evidence that recent advances in agricultural technology are keeping pace with the rate of climate change, with strong potential for continued adaptation to warmer temperatures and even mitigation of GHG emissions (Burney et al. 2010; Pielke et al. 2007). The primary mitigating effect of modern agricultural technology is its potential to boost crop yield, which Burney and co-authors found has resulted in the avoidance of a vast sum of GHG emissions, somewhere in the range of 85-161 gigatons of carbon (GtC). The upper end of this range represents one-third of all human GHG emissions since 1850.

In addition to advances in yield, today's crops have become more efficient in terms of their conversion of inputs (nitrogen, water, energy) into harvestable material (Field to Market, The Alliance for Sustainable Agriculture 2009). The advent of new traits introduced through biotechnology has further accelerated these benefits and holds the potential for step changes in both yield and input efficiency. Crops engineered to produce their own insecticide (*Bt*) are using solar energy, rather than fossil fuels, to power crop protection, which results in a significant reduction in the carbon footprint of crop production systems. Conventional crop chemical production is associated with GHG emissions of approximately 20 kg CO_2e per kg of crop chemical produced (Wang et al. 2007). While this is a relatively modest amount of GHG emissions relative to the much larger amounts associated with tillage operations, it does represent the single most significant source of emissions for a company such as Monsanto. Monsanto has been self-reporting its emissions for more than 20 years and has been actively managing all chemical production processes in order to lower the amount released per unit of crop chemical produced.

Another widely used biotechnology trait is herbicide tolerant technology. The simplicity and agronomic advantages of herbicide tolerance crops have resulted in them now being widely grown in North America and several other world areas (Gianessi 2008). Such crops facilitate the use of conservation tillage, which provides further GHG reductions by incremental sequestration of carbon in the soil and the avoidance of fuel consumption during the tillage operation (Brookes and Barfoot 2008). In a reduced tillage system, the farmer also conserves soil, with the large decrease in CO_2 emissions sufficient to outweigh potential increases in N_2O emissions associated with higher soil moisture and less aeration (Holland 2004).

New traits in development offer the promise of further improvements in the GHG profile of crop production. These include both nitrogen use efficiency traits, which could reduce N_2O emissions; and drought tolerance traits, which could reduce the crop irrigation requirements, thereby resulting in lower use of diesel to pump ground water. Reducing the nutrient and water requirements of crops would also have clear sustainability advantages beyond only the GHG reductions, especially in areas where access to such inputs is limited (as in sub-Saharan Africa).

The Panel also found that today's advanced breeding techniques are continuously adapting the germplasm of crops to climate change by testing in a range of higher stress environments around the world. Assuming the rate of warming continues to be fairly gradual, this would suggest that advanced breeding techniques will continue to be able to keep pace. To be sure, current modeling suggests there conditions by mid-century will begin to become harmful to crop productivity, making it that much more critical to utilize all technology available to meet the world's growing food needs.

Conclusions

Unfortunately, for those of us in the scientific world, the issue of climate change has become a polarizing political issue, and is likely to remain so, given the existential threat that it represents, and the wide disparities in how it would impact the various nations of the world. For most developed countries, food security does not even register as a potential concern, and climate change is just another reason for expecting more gridlock among policymakers. However, for developing countries, agriculture and food security are daily concerns, and many are already dealing with increasing heat, moisture, and pest stress – the very same difficulties that that are predicted to worsen as climate change proceeds – hence the global dilemma.

Within this global context, Monsanto assembled the Monsanto Fellows Climate Change Panel, which found that climate change is already underway, and that rising global temperatures and changing precipitation patterns will increasingly impact agriculture. The changes will be non-uniform and are likely to increase the crop productivity advantages already enjoyed throughout much of the Americas and parts of Asia. Severe drought will become a major concern in many important regions, especially those with Mediterranean (already semi-arid) climates.

Despite these stresses and the enormity of the future challenge, the Panel found that today's agricultural production systems are secure and sufficient to meet the forecasted pace of climate change, at least through mid-century. Beyond that time, modeling suggests that crop productivity in all regions could begin to be harmed by the higher temperatures predicted for that period, unless successful GHG mitigation measures are implemented soon. By boosting yields and improving the overall sustainability profile of cropping systems, the use of modern agricultural technology has already made tremendous contributions to help reduce the overall carbon footprint of agriculture. However, there is enormous untapped potential to make further progress in this area, limited primarily by unfavourable policy toward some of those technologies, especially biotechnology. Thus, there is a pressing challenge for those engaged in production agriculture to educate all of society on how modern agricultural technology and new practices will be needed to adapt to future climate change, and even to mitigate its overall impact.

Acknowledgements

This paper would not have been possible without the support of many other scientists, including all of the climate change experts invited to assist the Monsanto Fellows Climate Change Panel, and especially the following Monsanto colleagues: David Butruille, Gregg Bogosian, Gerald Dill, Mike Edgerton, David Fischhoff, Mike Hall, Ty Vaughn, and Toni Voelker.

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