# GLOBAL CLIMATE CHANGE TRIGGERED BY GLOBAL WARMING

## A POSITION PAPER FROM THE CENTER FOR INQUIRY OFFICE OF PUBLIC POLICY

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## EXECUTIVE SUMMARY

This paper will offer compelling evidence from a large body of research that global climate change caused by global warming is already underway and requires our immediate attention. The research in question appears in refereed scientific literature, and most of it reflects a broad consensus of the worldwide climatology community. The principal points of this position paper are summarized below and are considered in detail, with supporting references, in the text that follows.

**Convincing evidence that the Earth's climate is undergoing significant, and in some cases alarming, changes has accumulated rapidly in recent years, especially during the past three decades.**

**The conclusion that there is significant warming of the Earth's surface is not based primarily on theoretical models, although these models do succeed in replicating the existing database with growing success. Instead, global warming is a fact confirmed by an enormous body of observations from many different sources. Indeed, the focus of research has now shifted from attempts to establish the existence of global warming to efforts to determine its causes.**

**Although the exact extent of harm from global warming may be difficult to predict now, it can be said with confidence that the harmful effects of global warming on climate will significantly outweigh the possible benefits.**

**The probability is extremely high that human generated greenhouse gases, with carbon dioxide the major offender, are the primary cause of well documented global warming and climate change today.**

**Much can be done <u>now</u> to mitigate the effects of global warming and the associated climate change. Difficulties in addressing the problem are not caused primarily by unavailable technology, but by the lack of sufficient incentives to implement the new technologies more aggressively.**

After consideration of these points, the paper will end with a brief analysis of the role of the political process in addressing these issues. No detailed recommendations will be made, but some general suggestions will be offered. This final section will argue that any solution to this major global problem will require contributions from all major elements of our society, from the academic research community to American industry. Getting the science right is the critical first step, but implementation of solutions will need more broadly based cooperation that takes economic realities, *and opportunities*, into account. We will end this paper on that note, expressing the view that without a determined political effort, a successful attack on climate change is unlikely soon.

## I  Introduction

**Convincing evidence that the Earth's climate is undergoing significant, and in some cases, alarming changes has accumulated rapidly in recent years, especially during the past three decades.**

Most climatologists regard the final decade of the twentieth century as the warmest in the past millennium (Albritton et al. 2001).  Recently, there have been observations suggesting that 2005 may have been the warmest year on record.  Rapid temperature increases in the Arctic have already produced a significant reduction in Arctic sea ice (Fisher et al. 2006).  Reduced sea ice decreases the reflection and increases the absorption of sunlight in the Arctic, an almost "runaway" process that further amplifies global warming.  Recent research has demonstrated that the Earth's energy budget is out of balance, with more energy captured from the Sun than is currently radiated back to space (Hansen et al. 2005).  This makes global warming inevitable.  This is *not due* to any measurable increase in the incoming solar energy, but to an increase in the amount of that energy captured and retained by the Earth.

Glaciers are melting rapidly in most parts of the globe (Albritton et al. 2001) and the net loss of ice to seawater from Greenland (Chen, Wilson, and Tapley, 2006; Dowdeswell 2006) and, more recently, from Antarctica (Alley et al. 2005; Hodgson et al. 2006; Overpeck et al. 2006) is alarming.  Measured increases in sub-ice-sheet meltwater are lubricating and accelerating the flow of this ice into the oceans.  Not only does this promote mean (average) sea level rise, which has already begun, it could eventually modify current patterns of global ocean circulation, an important regulator of climate. The oceans are also a major sink for removing carbon dioxide from the atmosphere (Sarmiento and Wofsy 1999). Because the atmospheric concentration of carbon dioxide continues to increase, a long-established equilibrium seems to have been compromised, and there is evidence that this absorption process is starting to saturate (McAvaney. et al. 2001).

The effects of these major changes in the oceans, which we know have occurred in previous paleoclimates, would be catastrophic if a significant fraction of the Greenland ice sheet or, far worse, the Antarctic ice sheet were to melt. A simple calculation shows that the frozen water in the Greenland ice sheet alone would, if melted, raise the global sea level by about seven meters (about 22 feet). This rise would be independent of the effect of higher temperatures on warming the ocean surface waters, which by decreasing their density would raise the sea level still higher, as has already begun.

While major changes in the oceans could well be the most alarming consequence of global warming for our civilization, many other known harmful effects are well documented. Some of these will be reviewed briefly below in our evaluation of the costs and possible benefits of global warming.

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There remains a small number of scientists who claim that the current warming trend may not reflect primarily human activity. We consider their arguments in this paper. In addition, some errors in analysis may have been made by colleagues whose position favors anthropogenic (human-caused) driving of the changes. The work of these critics is useful, and reflects the way science proceeds and should proceed. However, even these critics of the picture presented by a large majority of the climate community no longer deny the reality of global warming and the currently accelerating climate change.

Given many serious consequences certain to follow from increased climate change, we are naturally led to ask three questions relevant to any policy initiatives formulated to address global warming.

1) What are the tradeoffs between possible benefits claimed for global warming, when compared to the known harmful effects?
2) What are the most likely causes of the current rapid rise in the mean global surface temperature?

3) What can be done to mitigate global warming and the climate change that results?

These questions will be addressed in the following three sections of this paper.

## II What are the tradeoffs between possible benefits claimed for global warming, when compared to the known harmful effects?

Some of those reluctant to initiate programs to address the harmful effects of climate change frequently point out that there may also be benefits from global warming. Since some dislocation of current activities would be inevitable under any major program for change, these possible benefits should be examined and compared to the harmful effects of failing to initiate effective palliative measures. In effect, a rough benefit-to-cost assessment becomes important whenever investment of resources is involved, as is certainly the case here.

**Possible benefits to agriculture at higher latitudes:** The most commonly cited benefit of global warming is the longer growing season that higher-latitude regions of North America and Asia would enjoy. That warmer temperatures are moving north in the Northern Hemisphere has been well documented. However, only if rainfall and other conditions conducive to successful agriculture also march north in tandem with temperature is this scenario likely to be realized. This is currently unknown. While several current general circulation models (GCMs) of global climate all agree that global warming will induce different changes in different geographical regions, further work is needed before they can predict with confidence the details of regional changes. We already have two historically recent examples that demonstrate the fragility of allegedly rich lands awaiting development. One is the American Rocky Mountain West, constantly threatened with water shortages and clearly incapable of supporting a large population in spite of much nineteenth-century hype to the contrary. The other is former Soviet Premier Nikita Khrushchev's "virgin lands" program for transforming central Asia into a vast breadbasket. The effort was largely a failure. In addition, a major dislocation of ecosystems can be expected as new plants and animals move into new regions and out of others. While we cannot say the end result of this process will always be harmful on balance, we can say that the ecosystems involved will all be stressed during these changes, especially if the changes are rapid. From the point of view of ecosystem health, rapid change is extremely unlikely to be beneficial.

**Possible benefits from increases in the rate of plant growth:** The other benefit that is often claimed for global warming is that plants will grow more rapidly. It is further noted that a more rapid rate of plant growth, combined with a higher carbon dioxide concentration in the atmosphere, will partially offset these higher concentrations by removing more of this gas through accelerated photosynthesis. However, these possible benefits must be weighed against other possible effects of accelerated plant growth in currently fallow regions, assuming that local soil and moisture conditions already noted might allow it. This would surely lead to ever larger human populations in potentially fragile areas, an impact hard to predict but not likely to be beneficial. There is even recent evidence that, while increasing the carbon dioxide concentration of the atmosphere appears to accelerate initial plant growth, the increased growth rate will taper off rather quickly. From these considerations, it is not obvious that there would be any net benefit at all.

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**Destructive effects of sea level rise:** Against these possible but still questionable benefits, we need to examine the harmful effects of the climate change that results from global warming. No one denies there will be problems, of which the most dramatic may be the rise in the mean sea level already discussed. For those living in the Washington, DC area, it is sobering to visit the museum of the National Academy of Sciences (NAS) on 6th and E Streets, NW. A hands-on exhibit reveals how much of coastal Maryland will be flooded by the Chesapeake Bay if the mean sea level rises by 0.5 meters, by 1.0 meter, and by 1.5 meters. A rise of 0.5 meters is approximately 1.6 feet. For reference, the measured rise in the mean global sea level that has already occurred in the twentieth century is of the order of one-half foot (Church et al. 2001). Since surface ocean water at current temperatures expands when the water temperature rises, global warming makes some coastal flooding inevitable, with potentially dire consequences for many highly populated areas located near sea level. Melting of glaciers and icecaps further accelerates the process.

Beyond these effects that are already taking place lies the risk of catastrophic sea level rise that substantial melting of the Greenland and Antarctic ice sheets would inevitably produce. To a complete melting of the Greenland ice sheets, leading to a sea level rise of approximately 22 feet, a complete melting of Antarctic ice would add an additional rise of almost 200 feet (Church et al. 2001). No one predicts that human-driven global warming will produce a complete loss of the Antarctic sea ice in the foreseeable future. Nevertheless, it is sobering to recall that, to the already noted accelerating melt of the Greenland ice sheet, recent evidence shows that snowfall in the interior of Antarctica, formerly cited to balance ice-sheet loss from coastal regions there, is *not* increasing (Monaghan et al. 2006). The significant losses from coastal Antarctic ice sheets means there is a net transfer of ice into sea water at high southern latitudes as well (Cook et al. 2005). Even a partial loss of Antarctic ice will result in a significant rise in sea level, with resulting inundation of coastal regions.

**The specter of catastrophic climate change:** There is another potentially catastrophic problem that could result from the impact of global warming on the world's oceans. This is a possible change in the global oceanic conveyor belt, which governs the many surface currents and coupled deep-water flows that are known to have important impacts on major regional climates. The best known and best studied of these is the Gulf Stream, which is known to play an important role in maintaining temperate conditions in northern Europe. Not all climate scientists agree on how much, if any, reduction in Gulf Stream flow has already begun, or on how important this warm current is to maintaining temperate conditions in northern Europe (Hátán et al. 2005; Kerr 2005; Seager 2006).

However, some reduction of this flow – called the thermohaline circulation from the driving force – is inevitable if enough less-salty, lower-density, meltwater is introduced into the North Atlantic. This is exactly what would result from rapid melting of the Greenland ice sheet, supplemented by further melting of the Arctic sea ice. It is also universally accepted that *some* cooling in northern Europe would then become inevitable (Stoker et al. 2001).

**One example of catastrophic climate change – the Younger Dryas:** What makes the well-studied period known as the "Younger Dryas" so disturbing is what it tells us about a sudden, devastating cold period that occurred *after* the Earth began to emerge from the last Ice Age. The Younger Dryas is a period of approximately one thousand years duration, centered around 12,000 B.C.E. During the inception of the Younger Dryas, the mean *global* surface temperature – known from sea-core sediments taken from many ocean basins around the globe – dropped over ten degrees Centigrade in a few decades. Furthermore, while the geological evidence is still under investigation, a large-scale picture of the Younger Dryas is emerging. As the Laurentian Ice Sheet that formerly covered much of North America was receding, a huge freshwater lake, Lake Agassiz, formed west of what is today Lake Superior. As long as the frigid waters of this lake drained through the current Mississippi Valley into the Gulf of Mexico, the situation was stable. Then, rather abruptly, geological processes in southern Canada appear to have blocked this southern outlet, releasing an enormous flow of cold water through the St. Lawrence Valley into the North Atlantic (Broecker 2006). The effect on suppressing the thermohaline-driven circulation of the global oceanic conveyor belt was sufficiently strong to plunge much of the Earth into a new period of drastically colder temperatures for about one millennium. A detailed account of the Younger Dryas, and of how ice-core data and other data can be used to confirm this picture, as well as other climate changes that have occurred since Earth emerged from the last major Ice Age, is presented with reference to many original sources in the National Academy of Sciences book *Climate Crash* (Cox 2005).

**The climate system is a nonlinear semichaotic system susceptible to significant shifts in its equilibrium state:** We cannot assert that the Younger Dryas scenario would necessarily be repeated if global warming causes much of the Greenland ice sheet to melt. There are too many other factors that would need to be considered. One such factor is the rate of melting, since the release of cold water from Lake Agassiz was apparently quite precipitous. However, the Younger Dryas does tell us that dramatic climate change can occur very quickly if some large-scale process triggers a dramatic shift in a parameter the climate depends upon, pushing the climate system beyond a critical point for stability. That this can occur results from our now knowing that the climate system is a highly nonlinear, semichaotic system. These systems can respond in hard-to-predict ways to a number of triggering processes that, under critical conditions, dramatically shift them from one equilibrium state to another, a property that mathematicians have already demonstrated in complex nonlinear systems. While this is a highly technical point, it is an extremely important one to grasp for understanding large-scale climate processes. A good description for an intelligent layperson can be found in the aforementioned book *Climate Crash* (Cox 2005).

The trigger for the Younger Dryas was the eruption of a massive cold water flow into the North Atlantic. A climate crash sharing many common features with the Younger Dryas has occurred even more recently during the allegedly stable Holocene, around 8200 B.C.E. (Ellison, Chapman and Hall 2006). The evidence for this more recent event was obtained from sea bottom sediments that, thanks to new techniques, now offer promise of providing further confirmation of their *global* character back through the last Ice Age (Nicholson, et al. 2006). The next triggering event could be different. It is difficult to predict if persistent increases in carbon dioxide and other greenhouse gases might induce a sudden major climate shift in the foreseeable future. While the probability would seem to be small today, no one can rule out such a future change with certainty. On timescales relevant to shifts in global equilibria, the rate of change of the mean global surface temperature over the past three decades is sobering.

**One example among many of a less obvious harmful effect of climate change:** If we assume that the climate system is sufficiently stable so that no Younger Dryas catastrophe awaits us before corrective measures can be taken, there are still many less harmful effects we can expect that are already underway as a result of global warming. Consider the effect of a modest sea level rise on migrating insectivorous songbirds returning to the United States from tropical America in the spring. Having lost roughly half of their body weight flying over water, these birds are critically dependent on food sources in low-lying coastal regions along the northern Gulf of Mexico. If the swampy areas of southern Louisiana alone were flooded by sea water, the reduction in the population of these birds could be drastic. Agricultural experts estimate that the insects eaten by these birds save American agriculture billions of dollars annually. Addressing bird migration raises an even subtler issue. Advocates of wind power to address global warming are often criticized because large windmills kill birds and bats. However, windmills can be defended to bird lovers by considering the net effect on birds and bats of rising sea levels. The number of migrating birds who perish from this new energy technology may be small compared to the number who will perish from starvation in migration, if these southern coastal areas are flooded by sea-level rise. Of course there are many other often-overlooked examples of economic hardships associated with sea level rise. Recently, managers of several American insurance companies announced that they may no longer insure low-lying coastal properties, emphasizing not Hurricane Katrina, but sea level rise.

Many of the deleterious effects of global warming on climate are not immediately obvious. To those already noted we can add many others. They include: the increase in pathogens in densely populated mid-latitude regions; documented evidence that storms are likely to become more violent (Emanuel 2006; Mann and Emanuel 2006); increasing severity of forest fires (Westerling et al. 2006); the further amplification of global warming from a decrease in the Earth's reflection of sunlight resulting from lesser ice and snow cover, especially in the Arctic; and many more subtle effects, of which the impact on the ecosystem illustrated by the example of migratory birds is only one.

**Section II Summary** Global warming is inducing instabilities in the Earth's climate that we already know have many harmful effects. What we do not know yet is *how* serious the situation might become. The possibilities range from bad and costly to fix – such as saving many valuable coastal areas from flooding and fighting new and more pervasive diseases – to the much less probable but potentially catastrophic effects of a sudden, significant climate shift that could be difficult to reverse.

**Although the exact extent of harm from global warming may be difficult to predict now, it can be said with confidence that the harmful effects of global warming on climate will significantly outweigh the possible benefits.**

However, we have yet to address the critical question of what is primarily responsible for the current warming trend. Is it our own anthropogenic activity? Or is it instead, as some have claimed, natural fluctuations that we are helpless to influence and so must simply stoically accept and ride out?

## III What are the most likely causes of the current rapid rise in the mean global surface temperature?

Showing that the effects of global warming and climate change are likely to be far more harmful than beneficial is only the first step we must take toward a solution. The question of the causes must now be addressed. Only if the causes can be addressed by determined action on our part is there any hope of mitigating or eliminating the harmful effects. Consequently, we need to examine climate fluctuations due to natural processes over which we may have no control. These have been proposed as the primary drivers of the current rapid global temperature rise. This section examines the arguments for these natural processes, and also for the human (anthropogenic) activities that many scientists believe are the primary causes.

**Two important definitions:** It is now useful to introduce more precise definitions of two terms that appear throughout this paper. *The mean global surface temperature* is defined as the average of the air temperature measured at the land surface, and of the surface water temperature measured over large bodies of water, statistically weighted by the fact that more measurements are available in some equal-area grid 'points' than in others. Since the advent of the space age, these temperatures can now be measured from satellite instruments in a uniform manner over the entire globe. By comparing the results of the more recent space observations with current measurements made in a more traditional way from the ground, or from ships and anchored sensors on the oceans, it has been possible to determine the accuracy of earlier ground-based and sea-based observations, which proved to be surprisingly good in most cases.

The other term we use frequently here is *climate*. Most people realize that climate and weather differ mainly in the timescales involved. The timescale for climate used by many contemporary climatologists is of the order of 30 years, while weather is a daily phenomenon that we know can change abruptly in 24 hours. The recent advent of paleoclimatology based on deep ice-core studies has somewhat shaken the idea of gradual climate change. As discussed above, we now know that the Earth's global climate can become rapidly unstable under certain conditions. Indeed, changes of over ten degrees Centigrade in one or two decades have occurred *many times* over the past 400,000 years (Folland et al. 2001). This has now been extended to 600,000 years, and will be discussed further in the soon-to-be-released IPCC-2006 Science Report. It is only somewhat reassuring that ice-core studies suggest that the global climate system has probably been more stable over the past 10,000 years (the Holocene) than at any time over the 600,000-year record. Yet even during this relatively stable Holocene epoch, there is evidence that regional climate change was an important factor in the rise and fall of several early historical civilizations (Cox 2005). Perhaps the best way to define global climate is the average of the global weather, averaged over a time interval appropriate to the rate at which the climate is changing. That is the viewpoint we have adopted in this paper, using a definition of an inherently dynamic phenomenon that emphasizes our primary concern, which is *climate change*.

With this background we now examine the question of what is likely to be mainly responsible for the current rapid rise in the mean global surface temperature. We begin by discussing what is almost certainly not causing it.

**Might the Sun be driving global warming?** We said in the introduction that the Sun is not responsible for the current rapid global temperature rise. (We emphasize here that these remarks refer to the last several decades. The role of the Sun over longer epochs remains an area of active research.) Three hypotheses have been advanced for solar driving of the current rapid temperature rise. One hypothesis speculates that there is a small but persistent rise in the solar flux at the minimum phase of solar sunspot activity, when the small periodic increase in flux due to this activity is absent. So far, measurements from space lack the accuracy to establish the precise value, but they do put an upper limit on any possible increase, which is far too small to explain the observed terrestrial temperature rise. In addition, there are other solar observers who infer from other sensitive data that there is no secular increase in this flux at all, over the last three decades of measurements (Hudson 2004).

A second solar hypothesis is that the tiny energy increase in the ultraviolet radiation at the peak of the sunspot cycle produces enough change in the upper layers of the Earth's atmosphere that, properly coupled through planetary waves with the weather-producing lower layers, it will exert a sufficient effect on the lower atmosphere (the troposphere) to produce cyclic and increasing global warming. This hypothesis demands that there be a significant and persistent increase in the level of solar activity, hence ultraviolet radiation, over recent solar cycles, and that a strong periodic signature of the solar cycle be seen in this process. Neither has been observed (North, Wu, and Stevens 2004), nor is there any evidence to date for a coupling mechanism nearly strong enough to support this view.

The final hypothesis for solar forcing of global warming involves the modulation of intergalactic cosmic rays by the solar-cycle-dependent interplanetary magnetic field. Reductions in this magnetic field during the minimum of solar activity increases comicray penetration into the Earth's atmosphere. It was postulated that during this period of increased cosmic ray penetration, cloud formation would be enhanced through the "cloud chamber" effect well known to physicists in the high-energy laboratory. An early, surprisingly high positive correlation of increased cloud formation with enhanced cosmic-ray flux stimulated interest in this possibility, but further work with a more extensive database has negated it. This was not surprising, given a large number of other problems with this hypothesis too technical to review here.

In summary, there is no evidence that the Sun is responsible for current global warming, and a great deal of evidence to suggest otherwise. Solar forcing of the current global warming is *extremely* unlikely (Ramaswamy et al. 2001).

**Might "internal modes of the climate system" be causing global warming?** Another possibility for nonanthropogenic forcing of climate change that has been tentatively proposed is that some long-term quasi-periodic process confined to the Earth itself is responsible. To date, no one has provided a plausible, testable mechanism for such Earth-bound forcing. While there is speculation that a very large scale phenomenon such as the El Niño Southern Oscillation (ENSO) might play a role in quasi-periodic global warming and climate change, there is no convincing evidence to support this. In the assessment of the IPCC-2001 Science Report, the likelihood that internal modes of the climate system are causing global warming and influencing the current climate change range from unlikely to extremely unlikely (Stocker et al. 2001).

If the Sun and natural processes confined to the Earth are not driving global warming, what are the other possibilities? Before we consider what human activity is contributing, it is necessary to lay to rest two other suggestions that have emerged, if only infrequently, and to offer a brief comment about the Earth's orbital dynamics that are now thought to be the primary drivers of the quasi-periodic long-duration Ice Ages.

**What about the "urban heat-island" effect?** It has been suggested that the urban heat-island effect may be responsible for global warming (Singer 2002). Because large urban areas are warmer by several degrees than their surroundings, this author suggests that when these effects are averaged into a computation of the global temperature, with proper allowance for the higher density of records in the urban areas, the increase in the global temperature can be explained. This is not correct. The work of a number of scientists that has appeared in the refereed literature and which takes into account the relative density of observing stations shows that, while the urban heat-island effect is indeed large in major urban centers, its effect on the mean global surface temperature is almost negligible (Folland et al. 2001).

**Are climate scientists biased toward anthropogenic forcing?** In contrast to the legitimate research that raised the possibility that either the Sun or internal modes of the climate system might be responsible for global warming and climate change, there is a final suggestion one occasionally hears that reflects a serious ignorance of how science proceeds. This is the speculation that the work of the great majority of climate scientists who support anthropogenic forcing of global warming and climate change is motivated primarily by a desire to get more support for their research. Thus, it is further suggested, they are introducing a strong bias into the way they report their results.

In reply to this, it is worth noting that aside from proving a new hypothesis, there is nothing that will enhance a scientist's reputation more than disproving one that has gained some notoriety. Generally speaking, the better the scientist, the more likely personal pride will motivate him or her to proceed within the "rules". The idea that there is an unwritten self-serving understanding among climate scientists to falsely exaggerate the implications of their work for financial gain reflects widespread ignorance of how science proceeds.

**Might the Earth's orbital dynamics that cause the major Ice Ages play a role in global warming?** While the Milankovich effect, named after its proponent, is now regarded as the likely cause of the Ice Ages, these changes in the eccentricity of the Earth's orbit around the Sun and in the Earth's spin-axis orientation occur over far too long a duration to explain the relatively rapid global warming now occurring (Morell 2004). Also, since we know that the next major changes due to these processes will be to enter a new cold period, the present trends are of the wrong kind to be explained by the Earth's dynamics.

To date, no convincing case can be made that global warming is caused by natural processes over which we may have no control in the foreseeable future.

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Since the case for natural forcing of the current rapid global temperature rise is weak, we are compelled to ask what human activities are likely to be major causes. Here a near consensus has arisen among most climatologists that anthropogenically generated greenhouse gases are the main culprit. While the scientific arguments supporting this position are now known to most thinking people, it is useful to repeat them here in the interest of presenting a complete contemporary picture of global warming and climate change.

**The well-understood greenhouse effect:** To begin, there is complete agreement among research scientists whose work appears in the refereed literature that the "greenhouse effect" is a real physical process that it is making *some* contribution to global warming. The greenhouse effect occurs because the Sun's relatively short-wavelength radiation from the hot solar surface passes through the Earth's atmosphere and reaches ground level to be absorbed by the Earth, where the surface temperature is much lower than the Sun's. A large faction of the much longer-wavelength infrared radiation emitted by the cooler Earth is absorbed by the Earth's atmosphere. Thus a part of the Sun's radiant energy that impinges on the Earth's surface is trapped by our atmosphere. If the amount of incoming solar radiation that is absorbed and trapped exceeds the amount that is reflected and reradiated into space, there is an imbalance and the Earth's temperature will begin to rise. The excess amount will warm the atmosphere until a higher equilibrium temperature is reached, in which the total rate of energy loss from the Earth to space equals the amount that is retained by the Earth.

Indeed, thanks to the greenhouse effect, our atmosphere has had equilibrium temperatures (within a limited range, determined by many different processes) sufficient to sustain, ultimately, human life. If the Earth had no atmosphere, the mean global surface temperature would be approximately 50 degrees Centigrade colder!

The problem of the current global warming occurs because of the aforementioned net imbalance in the Earth's energy budget, with more solar energy being retained than is radiated back into space. This is due to the increase in greenhouse gases produced by human activity since the beginning of the Industrial Revolution, a process that continues today with an ever increasing atmospheric concentration of the offending gases (Prentice et al. 2001; Sarmiento andGruber 2002). Once more we note that this situation makes global warming and some associated climate changes *inevitable*.

**The dominant role of carbon dioxide today:** Greenhouse gases produce this imbalance when their concentration in the atmosphere is increased. The role of the most offending greenhouse gas, carbon dioxide, will illustrate the process. Because carbon dioxide gas is a major byproduct of burning the fossil fuels that power much of our industry and transportation, its production and release into the atmosphere continue to increase today. We have seen that carbon dioxide is an efficient absorber of the infrared radiation emitted by the Earth, and that increasing its concentration in our atmosphere increases the rate at which the Earth's infrared radiation is trapped. Moreover, by warming the atmosphere above the previous equilibrium temperature, more water vapor is produced, and water vapor is the most effective greenhouse gas of all (Soden et al. 2005). Matters become still worse when the warming associated with these processes is further amplified by the well-known effect of deforestation, which reduces the capacity of the land to absorb atmospheric carbon dioxide. Since the land is the only other major natural sink for this greenhouse gas, along with the oceans, deforestation must be added to the list of harmful practices contributing significantly to global warming (Sarmiento and Wofsy 1999).

Other warming processes are set in motion by those stimulated by an increased concentration of atmospheric carbon dioxide. Some of these could producing "runaway" phenomena until they go to completion. We have already cited the effect of reducing the bright reflecting ice cover in the Arctic, leading to greater absorption of solar radiation by the less reflecting water surface, thus inducing still more melting. In this case, the process could continue until the Arctic Ocean is entirely ice free. Methane is an even more efficient greenhouse gas than carbon dioxide. Melting of the permafrost at high latitudes could release large quantities of methane into the atmosphere, and Arctic regions are warming most rapidly of all. While the consequences of methane release are still being debated in the scientific literature, this and other processes triggered by continued global warming are now under investigation, as their cumulative effect could be extremely harmful (Prather et al. 2001).

If the above description of the dominant effect of carbon dioxide is still not convincing to the reader, he/she might be convinced by noting that once carbon dioxide gas is released into our atmosphere, it stays there for well over a century. Carbon dioxide, and methane and nitrous oxides too, are all well-mixed greenhouse gases produced in abundance by the human activities that have increased dramatically since the beginning of the Industrial Revolution and, in the absence of effective regulation, their concentration can be expected to increase at an accelerated pace today. This means that even if we could freeze the release of these greenhouse gases at the current rate of production, their concentration in our atmosphere will continue to increase for at least several decades. This fact, more than any other, may be the reason some climatologists are genuinely alarmed, especially in light of the rapid industrialization of China and India with their huge populations yearning for better material lives, coupled with the apparent reluctance of some influential circles in our own country to take global warming and climate change seriously.

Finally, there is one more disturbing result that is emerging from research on carbon dioxide in the Earth's atmosphere. As its atmospheric concentration increases, so does its partial pressure over the oceans and the ability of the surface layers of the ocean to absorb it. Current research suggests that the oceans are already beginning to saturate in their ability to take up atmospheric carbon dioxide at the current rate (Sarmiento and Wofsy 1999). As noted above, these investigators have also shown that the oceans are one of the two most effective sinks for removing carbon dioxide from the atmosphere, along with bioprocesses on land.

Thus from almost every point of view, the increasing atmospheric concentration of carbon dioxide is viewed by most climatologists as the greatest problem we face in addressing global warming and global climate change today.

**How reliable are climate models, and how good are the predictions based upon them?**

All major computer models that calculate a mean global surface temperature in response to the input of many physical processes agree on the importance of greenhouse gases, and especially carbon dioxide, in driving global warming and climate change. However, since these models alone permit us to predict future climate change, we need to ask how reliable are their predictions. The best of these models, the GCMs, are still often criticized for many reasons, even with the advent of fast computers and a rapid growth of sophisticated modeling. Some of this criticism is undoubtedly justified, which is why this paper began by emphasizing that the current global warming is based primarily on an enormous amount of hard data – carefully made observations taken over the entire globe – and not primarily on models. In addition, there may be no climate modeler anywhere today who would claim that there exists a current model that has a sufficiently fine grid to predict detailed local climate patterns over the globe as the climate changes.

However, some relatively recent problems with climate models have been at least partially solved, removing some of the most frequently heard criticisms. Several of the

GCMs have now been refined to the point of replicating the *past* temperature history of the Earth remarkably well, when their output is compared to either direct temperature measurements or reasonable proxies for estimating past climate conditions. An excellent review of climate models, circa 2000 C.E., is given in McAvaney et al. (2001), and this will be updated in the forthcoming IPCC-2006 Science Report.

One of the problems that current research is beginning to address is the influence of aerosols on how much global warming occurs. The IPCC-2001 Science Report (Penner et al. 2001; Ramaswamy et al. 2001) discusses aerosols extensively, and notes that their role in global warming – outside of the tropospheric cooling effect of large volcanic eruptions – is much less well understood that that of greenhouse gases. This becomes significant when we consider that recent research suggests a larger role for aerosols in general, and that this role is likely to contribute to a net *cooling* (Bréon 2006). During the middle of the twentieth century, the mean global surface temperature failed to increase, contrary to what the effect of increasing greenhouse gas emission led many scientists to expect. However, industrial aerosols were also increasing at a rapid rate during the same period *until strongly regulated due to concerns about "acid rain*." Inclusion of strong aerosol cooling would clearly tend to counterbalance the normal temperature increase from greenhouse gases alone. Additional work showed that a decrease in the amount of solar radiation reaching the Earth's surface, coinciding approximately with the aforementioned flat temperature profile and called "global dimming," ended in the late 1980s, and that now we are experiencing "global brightening" along with a rapid global temperature rise (Wild et al. 2005). (It is important to note that this is *not* an increase in the solar flux impinging on the top of our atmosphere, but only on the amount that reaches the ground.) If we consider these two recent developments together, much of the apparent mystery of the flat temperature profile in the mid-twentieth century appears to go away. Current work on models is exploring this possibility, as our understanding of aerosols improves.

Another puzzle for GCM modelers until recently was a disagreement between their model predictions and what appeared to be reliable observations showing that temperatures in the troposphere did not increase during the current period of a rapid rise in the mean global surface temperature. The models predicted the two temperatures should march together. However, a serious error was found in the calibration of the satellite data used for the tropospheric temperature measurements. When this error was corrected, it brought the two temperatures much closer together (Mears and Wentz 2005). Confidence in the models was correspondingly increased.

While further work is required to improve climate models, it is clear that they are improving rapidly. Future climate predictions, while still only valid within a range, are also improving. A benchmark for the sensitivity of different models to the actual climate has been to compare their outputs by assuming a doubling of the atmospheric concentration of carbon dioxide since the beginning of the Industrial Revolution, a doubling that is now almost universally expected to occur. Between 1995 and the publication of the IPCC-2001 Science Report, there was little increase in the computed range of predicted global temperature increases under this assumption, and the range was from 1.5 to 4.5 degrees Centigrade (1.0 degree Centigrade equals 1.8 degrees Fahrenheit). However, when the results of the improved, and generally considered best three United States GCMs were compared in 2002, the range of predicted global temperature increases had been narrowed to 2.5 – 3.0 degrees Centigrade (Kerr, R.A., 2004). A rise of 2.5 degrees Centigrade may not seem like much, but when we consider the climate changes that have already occurred in response to the *measured* increase in the twentieth century of 0.6 degrees Centigrade (with an estimated uncertainty of 0.2 degrees Centigrade), it becomes disturbing.

**SECTION III SUMMARY** No scientist to date has made a strong case (defined here as one supported by a large number of his colleagues who publish in the refereed journals) for any observation(s) or mechanism(s) that can explain the current rapid global warming trend by invoking natural causes. Arguments for solar forcing, for forcing by internal modes of the climate system (natural processes that operate within the Earth system itself), and for the urban heat-island effect, have either failed to offer hard evidence or have been completely discredited. Nor do Earth's long-duration, quasi-periodic dynamical motions explain the current rapid temperature rise.

In contrast, global warming forced by a growing atmospheric concentration of greenhouse gases, especially carbon dioxide, is based on sound science that refers to a mechanism that is well understood and universally accepted by the scientific community. Models that incorporate this and many other known processes support this conclusion, and the models themselves, while still in need of improvement, are becoming increasingly reliable for making global predictions

**The probability is extremely high that human generated greenhouse gases, with carbon dioxide the major offender, are the primary cause of well documented global warming and climate change today.**

## IV What can be done to mitigate global warming and the climate change that results?

In view of the pervasive problem and the potentially serious – *and expensive* – consequences of global warming and the associated climate change, some comfort can be taken from the enormous body of evidence that the chief underlying causes of the current rapid changes are human activity and not uncontrollable natural processes. This does not tell us there are easy solutions – all considered, there are probably none known today – or that every potential problem can be solved completely. However, human ingenuity should not be underestimated, as the response of this country to past crises and challenges demonstrates. This section will review briefly a number of studies and initiatives that all promise to mitigate the current effects of excessive emission of anthropogenic greenhouse gases. No one initiative by itself can make a major contribution in the near term.  If all are pursued together, a real near-term impact becomes possible, and the longer-term results should be highly beneficial to future generations over the entire globe.

It is also worth noting that with intelligent planning there is no reason why investing in the technologies discussed here should not help the American economy rather than harming it.  In short, there is money to be made if the political process, working with business interests, will support rational programs to address this process, rather than stall in order to maintain an increasingly dangerous industrial status quo.

The following discussion begins with technologies that are available *now* and ends with others that are promising, but still require further research and development until their feasibility and practicability can be established.

**Fuel-efficient automobiles:**  Practical, affordable automobiles that easily double the 20-some average gasoline mileage of the majority of American sedans are available today; and there are working designs for increasing this higher efficiency by as much as 50 percent.  By supporting reasonable incentives for manufacturers and other incentives such as tax breaks for buyers, it should be possible to reduce the gasoline consumption of most Americans drivers within five years.  The problem is not technical.  All it would take is political will.

**Better regulation of existing coal-burning power plants:**  Improved regulation is also possible with public education and political will, as demonstrated by the Clean Air Act passed in Maryland this year (2006). Sponsored by Democratic Senator Pinsky, it was signed by Republican Governor Ehrlich, thanks to a combination of public education and political will on the part of a large coalition of concerned citizens and dedicated legislators. This act will reduce many pollutants, including carbon dioxide, in a number of large coal-fired power plants that were the major polluters in the state. Similar legislation is under consideration or has already been passed in six other northeastern states. This action was possible because the citizens in these states were sufficiently well informed to insist upon action.

**More energy-efficient buildings and homes:** This is an excellent example of where the knowledge and techniques are already available. Building heating and air conditioning are major consumers of energy in urban areas. Clustering buildings to minimize heat loss by reducing surface areas has long been successfully employed in the Scandinavian countries. Better insulation of stand-alone buildings is also a well-developed technology. With proper incentives, more builders and homeowners would apply it. Many buildings can be efficiently heated in winter and air conditioned in summer by tapping the almost constant temperature of the Earth (about 55 degrees Fahrenheit) just a few meters below the surface, and some already are.

**Wind power:** This "new/old" technology has been revived recently as one of the feasible methods of reducing America's dependence on foreign oil. It is also very nonpolluting. Wind energy in the Great Plains area is sufficient to fill *all* the nonautomotive energy requirements of that part of the country, and this can be done there while largely avoiding the flyways of migrating birds mentioned earlier. Wind energy in other parts of the country is generally less efficient, and also raises more problems with migratory flyways and scenic vistas. Nevertheless, intelligent citing of the windmill farms and new methods for alerting birds and bats to the hazard could greatly reduce these problems and make wind energy part of the mix there as well. Most of the windfarm technology is well known, and ongoing research on large propellers and proper cycling techniques for peak loads makes wind energy an attractive partial substitute for burning more fossil fuels. As with all technically feasible sources of our future energy, the more wind power is developed, the more the relative price is likely to drop.

**Solar power** Solar power is already used extensively for home and water heating, and sometimes for electricity generation, in areas of frequent sunshine such as the Southwest. It could be used more for this purpose, and no doubt will be if the cost of solar cells is reduced, which current research suggests is impending. Reliance on solar power for a large fraction of a highly populated region's energy requirements may be some years away, as even where the Sun shines often urban areas with large daily energy demands will be reluctant to risk serious outages unless – as is sometimes possible – large-scale energy storage facilities are nearby to provide backup on cloudy days. Nevertheless, increased use of solar energy where these problems can be solved makes good sense from every point of view. Solar energy is remarkably nonpolluting and the Sun's output is far more steady and reliable than any other energy resource available to us. If the problem of developing relatively high-temperature cryogenic (extremely low temperature) conductors – not currently available – can be solved, solar power will undoubtedly become a major source of the mix, for then long-distance power transmission with minimum line loss from areas like the American Southwest becomes possible.

**Nuclear power:** Since the Chernobyl disaster in Russia and our own Three-Mile Island accident at a nuclear power plant in Pennsylvania, nuclear power has not been popular in the United States. Yet approximately 20 % of our electricity is generated in this way, and the dramatically increased efficiency and the accident-free record of American nuclear power plants since Three-Mile Island has been outstanding. Furthermore, no operating American nuclear power plant has ever been as lacking in safety features as Chernobyl, and there are now new designs that are both still safer and more efficient than the best ones that have been operating here so successfully, if quietly, for the past three decades (Clery 2005).

While problems remain, they are recognized and have been largely addressed. Nuclear waste disposal is one example. Contrary to alarmist concerns, current methods of storing low-radiation-level wastes, which have a long half-life, are safe, but the political problem has prevented a solution. (The high-radiation-level wastes have a much shorter half-life.) Clearly, unlike other methods of generating electricity on which the modern world increasingly depends, nuclear generation often suffers from opposition that goes beyond the realm of rational argument. It is easier to frighten people about the risks associated with anything nuclear than with any other technology, even when sober-minded cost-benefit assessments demonstrate otherwise. One example involves comparing nuclear to coal-fired power plants, which release more radioactive materials into the atmosphere, are built to less stringent safety standards, and are largely responsible for the acid rain that has already had a devastating effect on many lakes and forested areas that lie downwind. Yet people who will accept a nearby coal-fired power plant will often shudder at the prospect of a nuclear one that is located miles away. A major educational effort will be needed for nuclear power to make a comeback in America. Yet it is certainly one of the cleanest ways to generate electricity, and probably one of the safest. This conclusion is supported by noting that the long-term harmful effects of even the Chernobyl disaster may have been greatly exaggerated, and no less an environmentalist than the co-founder of Greenpeace has recently advocated the construction of new nuclear power plants (Chesser and Baker 2006; Moore 2006).

**Imaginative new technologies for managing energy consumption:** This section is necessarily brief, because we cannot predict what new technologies might arise to address cleaner techniques for generating energy or better ways to conserve it, if doing so becomes a major national priority and more creative minds begin to tackle the problems in earnest. However, the general history of technology, and of innovation in America in particular, virtually guarantees that if the nation does make pursuit of a more energy efficient future a national priority, some good new ideas will surface and the financing will not be far behind. There is no nation in the world today that is as well suited to tackling this problem, and the benefits would be both national and global.

**Exploration of techniques for sequestering carbon dioxide:** To date no one has demonstrated a convincing scheme for removing sufficient carbon dioxide from the atmosphere to have any impact on the problems reviewed here. For completion we should note that two schemes have been proposed, and at least the first has been tested on a small scale. Seeding small ocean regions with appropriate nutrients to enhance the growth of phytoplankton that generate energy through photosynthesis – and thus remove carbon dioxide from the ambient water – has been attempted and gave some initially encouraging results. However, the process has since been severely criticized and largely discredited by many professional oceanographers. The other proposed scheme is to capture enormous quantities of carbon dioxide and pump it into the deep ocean, thus circumventing the problem that the rate for ocean mixing between different depths is far too slow for normal mixing to provide relief. We are aware of no practical proposal to do this, or even of any small-scale experiment to test the concept. The scale of the effort is staggering, especially considering that the sources of carbon dioxide emission are widely distributed over the globe. However, neither are we willing to underestimate human ingenuity, given the incentive.

**SECTION IV SUMMARY** While the problems of global warming and the associated climate change are likely to be with us for some time, the fact that evidence strongly indicates that human activity is the primary cause of the current rapid changes means that we are not helpless to mitigate the effects. Several promising technologies, some already well developed and available, exist to help us manage our energy resources better while maintaining a healthier environment. These include fuel-efficient automobiles, better regulation of existing coal-burning power plants, more energy-efficient buildings and homes, wind power, solar power, and nuclear power. Nor can imaginative new technologies be ruled out.

**Much can be done <u>now</u> to mitigate the effects of global warming and the associated climate change. Difficulties in addressing the problem are not caused primarily by unavailable technology, but by the lack of sufficient incentives to implement the new technologies more aggressively.**

## V FINAL SUMMARY: concerning the political dimension of organizing action to address the problem of climate change caused by global warming

The need for active government involvement in addressing this problem becomes clear if we consider what every educated American must know, or should know, about American industry. A good case can be made that, when opportunity presents itself, or a major world crisis develops, American business can and has on several past occasions adapted more rapidly and more effectively than any other organized economy in modern times. The rapid arming of the Allies during World War II, the Moon race of the 1960s, and the almost instantaneous adjustment to the collapse of the former U.S.S.R. are major examples. In regard to the first example, Winston Churchill once said, "American industry is like a giant boiler. Once the fire is lit under it, there is no limit to the power it can generate."

Yet it is also useful to consider one serious vulnerability of the American capitalistic system.  When there is no *perceived* crisis facing us, there is an equally demonstrable tendency to succumb to an “era of good feeling” and the inertia of established ways. Examples can be found in the 1920s that led to the Great Depression, the 1990s (when *both* political parties were debating what to do with the “trillion-dollar surplus”), and, on a smaller scale, the eventual bankruptcy of Bethlehem Steel, which boasted many of the highest paid executives in America following World War II, but failed to implement modern methods for making steel that were introduced into war-damaged industries abroad.  American CEOs and boards of directors are often forced by the wishes of their shareholders to concentrate on short-term profits, or they may be replaced by others who will.  This can make effective long-term planning difficult, even if the “captains of industry” are intelligent, well-educated people, as they often are.

This brings us to the reason why government involvement with the solution to the problem of climate change is essential, and also why a corresponding education of the electorate is the only way this is likely to be achieved.  Only major dedication by the American federal government to address the problem of climate change aggressively seems likely to stimulate business and industry to move significantly beyond the inertia of established ways today.  In addition, America is a democratic country, and the people will eventually get what they want.  If what they what is determined by an understanding of the underlying issues, this will produce one outcome.  If the electorate is dominated by scientifically ignorant people who are influenced primarily by equally ignorant public figures, or by well-funded advocates of the status quo, a far different outcome is virtually guaranteed.

We believe that the speed with which the problems of global warming and climate change can be addressed will be largely determined by what the American people want, and how our federal government responds to their wishes. Given the many opportunities for addressing this major global problem through profitable entrepreneurial activities on many levels, there is no reason why rational politicians of both liberal and conservative orientations cannot find solutions to these problems, if the people will have it. It would seem that we are confronted with a major challenge on two fronts, educational and political. One hopes future generations will say that ours made the right choices.

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**Comments on the references:** Most of the references are to summary articles found in major, and easily accessible, refereed sources. Those wishing to track the material to the original papers will find those papers referenced in the ones that appear here. The latter papers number literally in the thousands. An effort has also been made to refer to the most recent work, as climate science is a rapidly moving field. The main thrust of this paper is educational, ending with a few suggestions that have been advanced by many others. The need for a further understanding of the main issues among policy makers today is evident from some of the misleading, or even erroneous, ideas occasionally advanced by advocates of the status quo, which does *not* mean that scientific criticism of the ideas proposed by the advocates of action is a bad thing. Only by considering the results of all the work in the refereed literature will we arrive at the best policies, noting that the emphasis is on the work that has passed the muster of the scientific peer-review process. That is what we are trying to summarize in this paper.

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