
CLIMATE SCIENTISTS RESPOND

RESPONSE TO THE WRITTEN TESTIMONY
OF CHRISTOPHER MONCKTON
IN CONNECTION WITH THE MAY 6, 2010 HEARING
BEFORE THE SELECT COMMITTEE ON
ENERGY INDEPENDENCE AND GLOBAL WARMING



SEPTEMBER 2010

On May 6, 2010, Mr. Christopher Monckton testified by invitation to the Select Committee on Energy Independence and Global Warming of the U.S. House of Representatives.

Mr. Monckton, who is not a scientist, gave testimony that was in stark contrast to that of the scientists who were present at the hearing as well as the many official statements produced by the world's premiere scientific organizations, about the growing dangers of climate change.

Here, a number of top climate scientists have thoroughly refuted all of Mr. Monckton's major assertions, clearly demonstrating a number of obvious and elementary errors.

We encourage the U.S. Congress to give careful consideration to the implications this document has for the care that should be exercised in choosing expert witnesses to inform the legislative process.

EXECUTIVE SUMMARY

Despite ever-increasing scientific evidence that human activities are having a profound and harmful effect on the Earth's climate, there are ongoing claims to the contrary, often by those with no expertise in climate science or any scientific training whatsoever. A recent example of this is the testimony by Mr. Christopher Monckton before Congressman Edward Markey's Select Committee on Energy Independence and Global Warming held May 6, 2010.

While some responses from climate scientists to portions of Monckton's testimony were obtained from the other witnesses, not all of his assertions have been directly responded to. For those without some familiarity with climate science, his testimony may appear to have scientific validity. We have therefore undertaken the task of soliciting responses from highly qualified climate scientists in each of the areas touched upon in Monckton's testimony and have collected them in this single document.

Briefly, Mr. Monckton makes a number of scientific assertions about (1) the efficacy of warming from CO₂, (2) the benefits of elevated CO₂, (3) the relationship between CO₂ and ocean acidification, (4) recent global temperature trends, (5) and the sensitivity of the climate to CO₂. He has also claimed that (6) there is no need to take quick action to address the changing climate. In all cases, Mr. Monckton's assertions are shown to be without merit – they are based on a thorough misunderstanding of the science of climate change.

We believe the responses contained here strongly refute the statements made by Mr. Monckton. It is our hope that this document will be of use to members of Congress and their staffs as further hearings and debates on climate change and energy policy take place. We would be pleased to respond to any inquiries and offer necessary clarifications.

Dr. Ray Weymann, Director Emeritus and Staff Member Emeritus, Carnegie Observatories, Pasadena, California; Member, National Academy of Sciences.

Dr. Barry Bickmore, Associate Professor of Geological Sciences, Brigham Young University, Provo, Utah.

Dr. John Abraham, Associate Professor of Engineering, University of St. Thomas, St. Paul, Minnesota.

Dr. Michael Mann, Professor of Meteorology with a Joint Appointment with the Department of Geosciences and Director, Earth System Science Center, Penn State University, University Park, Pennsylvania.

Dr. Winslow Briggs, Director Emeritus and Staff Member Emeritus, Department of Plant Biology, Carnegie Institution for Science, Palo Alto, California; Member, National Academy of Sciences.

The opinions expressed in the Report reflect the participants' professional scientific judgment, and not necessarily the positions of their sponsoring institutions.

TABLE OF CONTENTS

Organization of Material	3
Assertion 1 and Responses <i>High CO₂ levels co-existed with equatorial glaciers, disproving the efficacy of warming from high CO₂ levels.</i>	4
Assertion 2 and Responses <i>Corals came into being during eras of high CO₂, therefore high CO₂ is not damaging.</i>	5
Assertion 3 and Responses <i>A high CO₂ concentration is beneficial.</i>	7
Assertion 4 and Responses <i>If increasing ocean acidification is occurring, it is not due to increasing CO₂.</i>	9
Assertion 5 and Responses <i>Global temperatures have varied due to natural causes in the past and there is nothing unusual about the recent rise.</i>	12
Assertion 6 and Responses <i>The Earth is now cooling and the previous decades of warming have stopped.</i>	14
Assertion 7 and Responses <i>Recent decades of warming were due to global brightening, not CO₂.</i>	16
Assertion 8 and Responses <i>The temperature response to radiative forcing (i.e. climate sensitivity) is very small and was over-estimated by a factor of 4 by the IPCC.</i>	19
Assertion 9 and Responses <i>Climate change is a non-problem. Even if the higher estimates of climate sensitivity were correct, there is no hurry to take any action.</i>	22
References Cited in Responses	27
Appendix A: Qualifications and Affiliations of the Respondents	29
Appendix B: Full Text of Responses	33
Appendix C: Additional Authoritative Material	44
Appendix D: Full Text of Written Testimony of Christopher Monckton	45

ORGANIZATION OF MATERIAL

We have divided key assertions of Mr. Monckton's written testimony into nine parts. For a coherent discussion of these assertions, we have rearranged portions of his testimony. *The assertions are paraphrases, not direct quotations*, but we believe they accurately represent the claims he made in his testimony. The complete unedited text of Mr. Monckton's written testimony appears in **Appendix D**.

For each assertion we have:

- a) reproduced the relevant section of his testimony in blue with his key assertions highlighted in red, and
- b) presented responses from climate scientists with special expertise in the relevant topic. These scientists were asked to review specific portions of his testimony and provide commentary. Following this we have given the full references to the literature cited in the responses, listed in alphabetical order of the first author of the material cited.

In several cases we have edited the responses in the main body of this document for brevity. In those cases we have also provided the full responses, which are given in **Appendix B** in alphabetical order of the names of the respondents. In a few instances we have added very brief explanatory comments of our own which are shown *in italics*.

In **Appendix A**, we list, in alphabetical order, all the respondents, together with their titles, affiliations, and qualifications.

As noted above, **Appendix B** contains the full responses from those contributors whose responses were edited for brevity in the main body of this document.

In **Appendix C**, we provide sources for recent additional authoritative material.

As noted above, **Appendix D** contains the full text of Mr. Monckton's testimony.

ASSERTION 1

High CO₂ levels co-existed with equatorial glaciers, disproving the efficacy of warming from high CO₂ levels.

Carbon dioxide concentration: In the Neoproterozoic Era, ~750 million years ago, dolomitic rocks, containing ~40% CO₂ bonded not only with calcium ions but also with magnesium, were precipitated from the oceans worldwide by a reaction that could not have occurred unless the atmospheric concentration of CO₂ had been ~300,000 parts per million by volume. Yet in that era equatorial glaciers came and went twice at sea level.

Today, the concentration is ~773 times less, at ~388 ppmv: yet there are no equatorial glaciers at sea level. If the warming effect of CO₂ were anything like as great as the vested-interest groups now seek to maintain, then, even after allowing for greater surface albedo and 5% less solar radiation, those glaciers could not possibly have existed (personal communication from Professor Ian Plimer, confirmed by on-site inspection of dolomitic and tillite deposits at Arkaroola Northern Flinders Ranges, South Australia).

Response from Dr. David Archer

Monckton seems to be referring to the Snowball Earth glaciations. The way those are thought to have worked is that in the snowball, the hydrologic cycle stopped, blocking the uptake of CO₂ from chemical weathering reactions. CO₂ continued to degas from the Earth in volcanic gases and in ocean hot springs, building up in the atmosphere until it got hot enough to overcome the high albedo of the ice, melting it catastrophically in a runaway ice albedo feedback. The climate flipped into a hothouse, leading to immense chemical weathering fluxes that pulled the CO₂ out of the air, resulting in CaCO₃ deposits overlying the glacial deposits called the cap carbonates. So in fact, the idea is that when the CO₂ got high enough, the glaciers couldn't exist any more, so they melted. Monckton is mixing the two different intervals in time, using a theory that relies on CO₂ as a greenhouse gas to argue that it proves the opposite.

Response from Dr. Jeffrey Kiehl

The statements concerning deep-time climates, CO₂ levels, and life are misleading... For example, the very high levels of CO₂ proposed for the Neoproterozoic occurred after the Snowball Earth conditions and were the result of very low weathering during snowball conditions. It was this large buildup of CO₂ that got Earth out of snowball conditions. So, the tropical glaciers melted once CO₂ started to increase. The geological record shows that evidence for glaciers preceded, but is not coincident in time with high CO₂.

Response from Dr. Lee Kump

One cannot characterize the Neoproterozoic Era with a single atmospheric CO₂ level. This was a time period of tremendous climate swings, from "Snowball Earth" episodes with glaciation extending into the tropics to extreme "super-greenhouse" ice-free climate states. Our understanding of the driver for these climate shifts is large variations in atmospheric CO₂ level...the climate fluctuations are entirely consistent with the CO₂ levels inferred.

By the way, the CO₂ content of dolomite is irrelevant to considerations of atmospheric CO₂ level. This mineral has formed throughout Earth history, at times when CO₂ levels are thought to have been very high (i.e., following the Snowball Earth) and also today.

ASSERTION 2

**Corals came into being during eras of high CO₂,
therefore high CO₂ is not damaging.**

In the Cambrian Era, ~550 million years ago, limestones, containing some 44% CO₂ bonded with calcium ions, were precipitated from the oceans. At that time, atmospheric CO₂ concentration was ~7000 ppmv, or ~18 times today's (IPCC, 2001): yet it was at that time that the calcite corals first achieved algal symbiosis. In the Jurassic era, ~175 million years ago, atmospheric CO₂ concentration was ~6000 ppmv, or ~15 times today's (IPCC, 2001): yet it was then that the delicate aragonite corals came into being.

Therefore, today's CO₂ concentration, though perhaps the highest in 20 million years, is by no means exceptional or damaging.

Response from Dr. Jeffrey Kiehl

It is ironic that Monckton will accept that the geologic record clearly indicates that high CO₂ leads to warm climates (thus CO₂ is a driver for climate), but then uses the existence of life at these times to conclude that we need not worry. The point is that past warm periods developed over millions of years of time and lasted for millions of years. Thus, species could adapt to these changes. However, we also know that some species did not adapt. The concern about the future is that the rate of warming that is occurring and will continue to occur over the next century is unprecedented in the deep past. It took over 30 million years for CO₂ levels to drop from 900 ppmv to their present levels, we are returning Earth back to this level in a mere 90 years. The accompanying rate of warming will also be unprecedented, certainly over the lifetime of our species. The issue is that our species and others will experience a rapid and large change that will have significant impacts on survivability. So both of Monckton's arguments are flawed.

Response from Dr. John Veron

It is not possible for me to make any sense of Mr. Monckton's assertions as they are not based on any scientific data or views that have ever been published. The levels quoted are higher than any spikes known to have existed. The time intervals quoted bear no relevance to the history of life.

Specifically:

Cambrian Era: Calcium carbonate (limestone) of the Cambrian, which abounds, has nothing to do with atmospheric carbon dioxide. Estimates of carbon dioxide levels at this time are not known with great certainty. There were no corals in the Cambrian, symbiotic or otherwise: they had not evolved then.

The Jurassic: There were high levels of carbon dioxide possibly reaching 2000 ppm for unknown time intervals with unknown effects on marine life. The spike immediately before the Jurassic caused the third great mass extinction. This extinction, which defines the Triassic/Jurassic boundary, was so drastic that it has been known since the early 18th century.

Response from Dr. Nancy Knowlton

This paragraph completely ignores the fact that the seawater chemistry and the buffering capacity of seawater were very different during the times described from what they are today... The problem with CO₂ emissions today is that the effects of burning fossil fuels on ocean pH first operate on the scales of decades to centuries, thus causing

the acidification that has been observed. Eventually the pH of the ocean will be buffered again, but for hundreds of years ocean organisms will be affected by abnormally high acidity (low pH), and it is the damages associated with acidification over the “short” term (the next hundreds of years) that concern biologists. (*see also Assertion 4*)

Response from Dr. Lee Kump

One must carefully distinguish between conditions that were acquired and sustained over millions of years such as these, and abrupt events such as fossil-fuel burning that disturb these longer-term equilibria. Over long time scales the carbon cycle is balanced, and the oceans (and the life in them) can form limestone at essentially any atmospheric CO₂ level. On these long time scales, rivers bring the building blocks for the calcium carbonate skeleton to the ocean; when CO₂ levels are high, these compounds must accumulate to higher concentrations to overcome the increased acidity generated by the CO₂, but this adjustment takes only millennia.

ASSERTION 3

A high CO₂ concentration is beneficial.

...today's CO₂ concentration, though perhaps the highest in 20 million years, is by no means exceptional or damaging. Indeed, it has been argued that trees and plants have been part-starved of CO₂ throughout that period. (Senate testimony of Professor Will Happer, Princeton University, 2009). It is also known that a doubling of today's CO₂ concentration, projected to occur later this century (IPCC, 2007), would increase the yield of some staple crops by up to 40%....

Response from Dr. Ken Caldeira

To Monckton's point about high CO₂ levels in the past, anyone with... an elementary understanding of geochemical cycles should understand that rates of CO₂ change are more important than amounts of CO₂ change. The processes that buffer changes in ocean chemistry take thousands of years, so ocean chemistry is well buffered against slow changes in atmospheric CO₂ content... CO₂ can only directly affect carbonate mineral saturation states on the time scale of millennia or less.

Response from Dr. Lee Kump

What the geologic record tells us is that rates of change are what matter most. Earth is a dynamic system, replete with dynamic balances that can be disrupted. Life flourished when rates of change were slow and the Earth system had time to adjust. But when rates of change were fast, life (and the rest of the Earth system) was unable to adjust in time; climates shifted quickly, the physical and chemical environment for life changed abruptly, and life suffered.

Response from Dr. Peter Reich

The best evidence from state-of-the-art free-air carbon dioxide enrichment experiments is inconsistent with the notion of major sustained increases in crop yield in a world of doubled atmospheric CO₂. Quantitative analyses and syntheses of those experiments indicate that the direct effects of elevated CO₂ will increase crop yields by 13% (on average for those with the C3 photosynthetic pathway, such as wheat, soybeans, rice) or 0% (on average for those with the C4 photosynthetic pathway, such as corn, sugar cane, and sorghum); not the 40% Lord Monckton suggests. Moreover, these estimates ignore (1) indirect effects of CO₂ as a greenhouse gas on future temperatures, precipitation, and their variability, and hence on future crop yields and (2) other consequences of fossil fuel-burning such as rising ozone pollution that will reduce crop yields. The bottom line for crop yields: combined effects of fossil-fuel burning (rising CO₂, rising O₃, climate change) are uncertain but at least as likely to be negative as positive, and shifting increasingly towards the negative the higher that CO₂ concentrations rise.

Rising CO₂ fertilization of productivity (and of carbon sequestration) of forests, grasslands, savannas of the world is also likely to be less than previously anticipated from overly simplistic models. This is because other limiting factors (such as soil fertility and soil water) and other vegetation changes (reduced vegetation diversity and complexity) will increasingly constrain positive impacts of CO₂ on productivity of non-agricultural systems. Moreover, as with crops, but likely more so (given that we can adaptively modify agriculture much more rapidly), the cascade of indirect effects of fossil-fuel burning are in aggregate likely to lead to loss of vitality, health, stability, diversity, and provisioning of ecosystem services from the world's forests, savannas, and grasslands. The cascade of indirect effects includes increases in ozone pollution, droughts, floods, windstorms, wildfires, and native and invasive insect and disease outbreaks, that will accompany rising CO₂ levels and associated climate change; and that will all have negative consequences for forests, savannas, and grasslands.

Response from Dr. Michael MacCracken

Monckton's discussion of the impacts of a continued rise in the level of CO₂, which he limits to the possible increase in the yield of some crops, is extremely superficial. Just the rise in the CO₂ concentration alone, independent of the impacts of climate change on the environment, is tending to acidify the oceans, and already leading to a shallowing of the depths at which the calcium carbonate making up fish skeletons, shells, and coral reefs dissolve. This is already starting to have impacts on Arctic marine systems (because the chemistry affects colder waters first) and a growing number of coastal aquaculture projects (including, for example, in the Pacific Northwest). *[See also responses to Assertion 4 below]*

While climate change leads to a very wide range of environmental and societal impacts, those that will lead to costs likely becoming far greater than the costs of switching off of fossil fuels include the following: (a) a rise in sea level of perhaps 1 ± 0.5 meters by roughly 2100, which will require substantial construction of costly barriers and likely significant population relocation from many low-lying areas; (b) poleward shifts in storm track and upward shifts in the snowline that will alter the amount and timing of river waters in ways that, combined with intensified evaporation and increasing societal needs, greatly limit available water resources; (c) create stresses on forests and other ecosystems that weaken them, making them much more susceptible to fires and pests; (d) human health and well-being are more greatly stressed by the rising heat index, the more frequent and intense occurrence of what have been relatively rare severe storm conditions, and a greater and spreading threat of pest and vector-borne infectious diseases—all requiring much more significant public health efforts; and (e) especially for those in currently marginal agricultural regions, more difficult conditions for farmers to deal with, including more frequent and faster onset of drought, rain coming in more intense events that overwhelms soil moisture capacity (causing loss of needed water to flooding runoff), intensified pressure from pests and weeds, and altered timing of plant flowering and growth that is expected to be generally disruptive and require greater efforts and training of farmers.

ASSERTION 4

If ocean acidification is occurring, it is not due to increasing CO₂.

Ocean “acidification”: It has been suggested that the oceans have “acidified” – or, more correctly, become less alkaline – by 0.1 acid-base units in recent decades. However, the fact of a movement towards neutrality in ocean chemistry, if such a movement has occurred, tells us nothing of the cause, which cannot be attributed to increases in CO₂ concentration. There is 70 times as much CO₂ dissolved in the oceans as there is in the atmosphere, and some 30% of any CO₂ we add to the atmosphere will eventually dissolve into the oceans. Accordingly, a doubling of CO₂ concentration, expected later this century, would raise the oceanic partial pressure of CO₂ by 30% of one-seventieth of what is already there. And that is an increase of 0.4% at most. Even this minuscule and chemically-irrelevant perturbation is probably overstated, since any “global warming” that resulted from the doubling of CO₂ concentration would warm the oceans and cause them to outgas CO₂, reducing the oceanic partial pressure.

Seawater is a highly buffered solution – it can take up a huge amount of dissolved inorganic carbon without significant effect on pH. There is not the slightest possibility that the oceans could approach the neutral pH of pure water (pH 7.0), even if all the fossil fuel reserves in the world were burned. A change in pH of 0.2 units this century, from its present 8.2 to 8.0, even if it were possible, would leave the sea containing no more than 10% of the “acidic” positively-charged hydrogen ions that occur in pure water. **If ocean “acidification” is happening, then CO₂ is not and will not be the culprit.**

Response from Dr. Ken Caldeira

To Monckton’s point about the added CO₂ being a small part of total carbon...Because of the reaction $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{HCO}_3^-$, to a first approximation, the hydrogen ion concentration of the ocean scales with atmospheric CO₂ content on the time scale of seconds to centuries. Because of the reaction $\text{CO}_3^{2-} + \text{H}^+ \rightleftharpoons \text{HCO}_3^-$ the carbonate-ion concentration [CO₃²⁻] scales inversely with [H⁺] and thus inversely with atmospheric CO₂ content. Since organisms need CO₃²⁻ to build their shells, the fact that there is a relatively small change in [HCO₃⁻] is largely irrelevant.

Response from Dr. Pieter Tans

Mr. Monckton’s assertions on acidification are remarkable...the basics of this subject have been understood for a long time. My comments have two parts. The first part answers Mr. Monckton’s assertions in plain English without math, while the second part, (*given only in the Full Response*), is more technical, and underpins the first part.

(Part 1)

“some 30% of any CO₂ we add to the atmosphere will eventually dissolve in the oceans”.

Actually, some 80% will eventually dissolve in the oceans if we wait long enough, about a thousand years.

“doubling of CO₂ ... raise the oceanic partial pressure of CO₂ by 30% of one-seventieth of what’s already there”.

Actually, it would double the partial pressure of dissolved CO₂. However, atmospheric CO₂ can equilibrate only with the dissolved CO₂ component which comprises less than 1% of total dissolved inorganic carbon.

“take up a huge amount without significant effect on pH”.

Actually, without a change in pH there can be no uptake of CO₂ by the oceans in the next decades and centuries. A change of pH is central to the uptake of CO₂.

“no more than 10% of the “acidic” positively-charged hydrogen ions”

The concentration of hydrogen ions itself is not relevant in this case – it is just a measure of acid-base equilibria, just like a thermometer gives a measure of temperature, but thermometers do not drive the climate. What matters is that the carbonate ion concentration drops substantially, which brings solid carbonates in the oceans closer to the point at which they dissolve. Hence the threat to organisms/ecosystems that depend on the formation of crystalline calcium carbonate (such as coral reefs), many of which are at the base of the ocean food chain.

“If ocean “acidification” is happening, then CO₂ is not and will not be the culprit”

Everything in this statement is demonstrably wrong. CO₂ is an acid, acidification has been measured in the surface oceans, and agrees with expectations based on well understood chemistry. CO₂ is the only possible culprit. There are not enough emissions of anything else that could cause the observed acidification.

Response from Dr. Nancy Knowlton

There is no question of “if”. Changes in pH have already been observed in many different parts of the ocean, and the chemistry driving short-term acidification is elementary and unavoidable.

This [Monckton’s] reasoning and calculation is incorrect. Yes, the whole ocean holds about 60 times as much carbon in the form of total dissolved inorganic carbon compared to the CO₂ in the atmosphere, but the change in partial pressure of CO₂ in the surface ocean will follow relatively close to that of the atmosphere.

Although warmer water does hold less CO₂, Monckton’s statement is incorrect, as shown in detail in my Full Response. So yes, seawater holds less total CO₂ with warming but as the calculations illustrate this is marginal and the pH remains significantly lower compared to present day conditions.

At present the average pH has already dropped to ~8.1 from preindustrial conditions of ~8.2. Because of the pH scale is logarithmic this means that there has already been a 30% increase in the concentration of hydrogen ions.

The remainder of the statement is simply chemical nonsense.

Response from Dr. Ove Hoegh-Guldberg

The submission from Monckton concerning the interaction between atmospheric carbon dioxide and the carbonate chemistry of seawater is profoundly wrong.

The claim that ocean acidification cannot be due to increasing atmospheric carbon dioxide concentration is at odds with experimental results, field observations, and our fundamental understanding of physical chemistry going back over 100 years.

The assertion that seawater is buffered to the point where it can take up a huge amount of dissolved carbon dioxide without significant effect on pH is also misleading. The current decline in ocean pH of 0.02 per decade has been confirmed by NOAA and other highly credible scientific organizations (e.g. Doney et al. 2009).

There is also a growing peer-reviewed literature which shows that changes of this magnitude are having and will have, significant and major impacts on the biology of the ocean (e.g. Raven et al. 2005, Kleypas and Langdon 2006, Hoegh-Guldberg et al. 2007).

Lastly, the issue of ocean acidification has never been about the pH of the ocean dropping below 7. This is simply a red herring. The fact of the matter is that we are acidifying the ocean (the correct term for decreasing pH irrespective

of whether or not the solution starts off alkaline) to a point that is [*having*] and will have, demonstrable impacts on important biological systems from phytoplankton to coral reefs. Of great concern, is the growing evidence that the level of ocean acidification is rapidly approaching conditions not seen for millions of years (Pelejero et al. 2010).

ASSERTION 5

Global temperatures have varied due to natural causes in the past and there is nothing unusual about the recent rise.

Global mean surface temperature: Throughout most of the past 550 million years, global temperatures were ~ 7 K (13 F°) warmer than the present. In each of the past four interglacial warm periods over the past 650,000 years, temperatures were warmer than the present by several degrees (A.A. Gore, *An Inconvenient Truth*, 2006).

In the current or Holocene warm period, which began 11,400 years ago at the abrupt termination of the Younger Dryas cooling event, some 7500 years were warmer than the present (Cuffey & Clow, 1997), and, in particular, the medieval, Roman, Minoan, and Holocene Climate Optima were warmer than the present (Cuffey & Clow, 1997).

The “global warming” that ceased late in 2001 (since when there has been a global cooling trend for eight full years) had begun in 1695, towards the end of the Maunder Minimum, a period of 70 years from 1645-1715 when the Sun was less active than at any time in the past 11,400 years (Hathaway, 2004). Solar activity increased with a rapidity unprecedented in the Holocene, reaching a Grand Solar Maximum during a period of 70 years from 1925-1995 when the Sun was very nearly as active as it had been at any time in the past 11,400 years (Hathaway, 2004; Usoskin, 2003; Solanki, 2005).

The first instrumental record of global temperatures was kept in Central England from 1659. From 1695-1735, a period of 40 years preceding the onset of the Industrial Revolution in 1750, temperatures in central England, which are a respectable proxy for global temperatures, rose by 2.2 K (4 F°). Yet global temperatures have risen by only 0.65 K (1.2 F°) since 1950, and 0.7 K (1.3 F°) in the whole of the 20th century. Throughout the 21st century, global temperatures have followed a declining trend. Accordingly, **neither global mean surface temperature nor its rates of change in recent decades have been exceptional, unusual, inexplicable, or unprecedented.**

Response from Dr. Gavin Schmidt

Monckton’s premise that current concern rests on the supposedly unprecedented current temperatures is simply false. It is well known that past climates have had much warmer temperatures than today and much colder temperatures as well. The difference between the Cretaceous hothouse and Snowball Earth is vastly bigger than possible changes projected for the 21st Century. But the point is not the absolute temperature today, or in 2100, but in the rapidity of the change and the fact that society – in a multitude of respects – is adapted to the relatively stable conditions that have existed over the last few centuries.

The differences in climate associated with those previous warm states were accompanied by sea level changes measured in meters that would be devastating if they happened today, and by other changes in climate the record only hints at. However, Monckton’s use of single locations as if they showed the global temperature is fallacious. Cuffey and Clow (1997) is a single record from Greenland, and the Central England Temperature is from one location in the UK. Neither are representative of the global mean, and other records and syntheses of multiple records show very different stories for the last few centuries. Indeed, every reasonable compilation of temperatures for this period do actually show that the late 20th Century is exceptionally warm and with a rate of warming that is indeed exceptional.

More importantly, the key issue is why global mean temperatures change. There are good reasons to be found in orbital configurations for why previous interglacials existed and why they are sometimes warmer than today and with greatly higher sea level (some 4 to 6 meters 125,000 ago). Similarly, the early Holocene was a period when the Earth was closer to the sun during Northern Hemisphere summertime giving rise to a relatively warm Greenland - but the same orbital factors were making the tropics cooler. These factors cannot explain any of the recent warming trends. Neither can solar changes since the output from the sun has been flat since around 1950, something inconsistent with the accelerating warming since then, and the fact of stratospheric cooling - a predicted outcome as a function of CO₂ increases, but opposite to the expected result of solar forcing.

Recent temperatures and their rates of change are exceptional over many centuries and the reasons are all too explicable—they are very likely rising because of the increase in greenhouse gases over the industrial period.

Response from Dr. James Hurrell

(this is an excerpt taken from “Questions for the Record”: Dr. Hurrell’s response to questions from the Committee concerning the May 6th hearing. We are grateful to Dr. Hurrell for providing us with a copy of this material.)

Paleoclimate research is important in order to determine how recent changes in climate fit into the longer-term perspective of changes driven by natural variability, and how the climate system has responded to past, naturally-driven changes in radiative forcing (e.g., from changes in solar radiation). Decades of field and laboratory research developing paleoclimate records has resulted in global networks of well-replicated data. A few key findings include:

- Average Northern Hemisphere temperatures during the second half of the 20th century were very likely higher than during any other 50-year period in the last 500 years, and likely the past 1,300 years.
- The last time polar regions were significantly warmer than present was about 125,000 years ago. At that time, average polar temperatures were up to 9 °F warmer than present, because of differences in the Earth’s orbit. Global average sea level was also likely 13-19 feet higher than during the 20th century, mainly due to the retreat of polar ice.
- It is very likely the glacial-interglacial carbon dioxide variations strongly amplified climate change, but it is unlikely they triggered the end of glacial periods. Polar temperatures, for instance, started to rise several centuries before atmospheric carbon dioxide concentrations rose.

It is very likely current atmospheric concentrations of greenhouse gases exceed by far the natural range over the last 650,000 years, and that the rates of increase have been five times faster over the past 40 years than over any other comparable period the past 2,000 years.

ASSERTION 6

The Earth is now cooling and the previous decades of warming have stopped.

This assertion is contained in the text of Assertion 4, above; specifically: The “global warming” that ceased late in 2001 (since when there has been a global cooling trend for eight full years.)

Response from Dr. James Hansen and Dr. Reto Ruedy

*Drs. Hansen and Ruedy called our attention to a recent paper [J. Hansen, R. Ruedy, M. Sato, and K. Lo, Global Surface Temperature Change, **Rev. Geophys.**, 2010 (in press)] which discusses global surface temperature changes in detail. Here are some relevant quotations:*

“Global warming on decadal time scales is continuing without letup..”

“The 12-month running mean global temperature in the GISS analysis (1880-present) has reached a new record in 2010. The new record temperature in 2010 is particularly meaningful because it occurs when the recent minimum of solar irradiance is having its maximum cooling effect.” (*Frohlich, 2006*); data at <http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant>

“At the time of this writing (July 2010) the tropical Pacific Ocean is changing from El Nino to La Nina conditions in the tropical Pacific Ocean. It is likely that global temperature for calendar year 2010 will reach a record level for the period of instrumental data, but that is not certain if La Nina conditions deepen rapidly. ...Figure 21 (*see below*) shows the 60-month (5-year) and 132-month (11-year) running means of global temperature. The 5-year mean is sufficient to remove a large part of the [*natural internal*] variability, while the 11-year mean also minimizes the effects of solar variability and volcanic eruptions.

Figure 21 gives the lie to the frequent assertion that ‘global warming stopped in 1998’. Of course it is possible to find almost any trend for a limited period via judicious choice of start and end dates of a data set that has high temporal resolution, but that is not a meaningful exercise. Even a more moderate assessment, ‘the trend in global surface temperature has been nearly flat since the late 1990s despite continuing increases in the forcing due to the sum of the well-mixed greenhouse gases’ [*Solomon & Rosenlof et al., 2010*], is not supported by our data. On the contrary, we conclude that there has been no reduction in the global warming trend of 0.15-0.20 °C/decade that began in the late 1970s.”

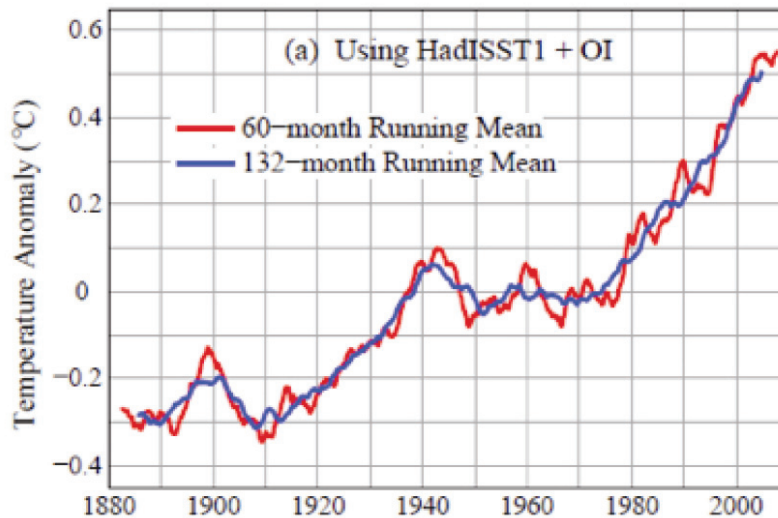


Figure 21 – From Hansen et al. manuscript

Response from Dr. David Easterling

(this response taken from a Dr. Easterling's answers to questions posed by Congressman Barton's office, following previous congressional testimony in 2009. We are grateful to Dr. Easterling for providing this material.)

The fact that the globally averaged surface air temperature has shown no trend or even slight cooling over the last 7 years is meaningless in regards to climate change due to increasing CO₂. In addition to CO₂ forced warming, the climate system also has natural variability, which is why one year's temperature is different from the next. This natural variability also can result in the climate having short periods of cooling or no trend even with strong overall warming due to increasing CO₂.

Response from Dr. James Hurrell

(this is an excerpt taken from "Questions for the Record": Dr. Hurrell's response to questions from the Committee concerning the May 6th hearing. We are grateful to Dr. Hurrell for providing this material.)

Lord Monckton spoke of the lack of warming since 1998, but failed to mention the role of natural variability. For instance, a historically large El Niño event made 1998 one of, if not the warmest year on record, while strong La Niña conditions contributed to relatively cooler worldwide conditions in 2008. Simply connecting these two points in time was done by Lord Monckton to misleadingly argue global warming has ceased, ignoring the fact that the longer-term temperature trend is clearly upward and most years since 2000 have remained very close to the record or near-record 1998 global warmth. Because of such natural variations in the climate system, climate scientists expect occasional, but temporary, slowdowns in the rate of warming even while greenhouse gas concentrations continue to increase.

ASSERTION 7

Recent decades of warming were due to global brightening, not CO₂.

In the global instrumental record, which commenced in 1850, the three supradecadal periods of most rapid warming were 1860-1880, 1910-1940, and 1975-2001. Warming rates in all three periods were identical at ~0.16 K (0.3 F°) per decade.

During the first two of these three periods, observations were insufficient to establish the causes of the warming: however, the principal cause cannot have been atmospheric CO₂ enrichment, because, on any view, mankind's emissions of CO₂ had not increased enough to cause any measurable warming on a global scale during those short periods.

In fact, the third period of rapid global warming, 1975-2001, was the only period of warming since 1950. From 1950-1975, and again from 2001-2010, global temperatures fell slightly (HadCRUTv3, cited in IPCC, 2007).

What, then, caused the third period of warming? Most of that third and most recent period of rapid warming fell within the satellite era, and the satellites confirmed measurements from ground stations showing a considerable, **and naturally-occurring, global brightening from 1983-2001** (Pinker et al., 2005).

Allowing for the fact that Dr. Pinker's result depended in part on the datasets of outgoing radiative flux from the ERBE satellite that had not been corrected at that time for orbital decay, it is possible to infer a net increase in surface radiative flux amounting to 0.106 W m⁻² year⁻¹ over the period, compared with the 0.16 W m⁻² year⁻¹ found by Dr. Pinker.

Elementary radiative-transfer calculations demonstrate that a natural surface global brightening amounting to ~1.9 W m⁻² over the 18-year period of study would be expected – using the IPCC's own methodology – to have caused a transient warming of 1 K (1.8 F°). To put this naturally-occurring global brightening into perspective, the IPCC's estimated total of all the anthropogenic influences on climate combined in the 256 years 1750-2005 is only 1.6 W m⁻².

Response from Dr. Benjamin Santer

(This response is extracted from Dr. Santer's May 20, 2010 testimony for the House Select Committee on Energy Independence and Global Warming. We are grateful to Dr. Santer for providing this material.)

“Over the past century, we have observed large and coherent changes in many different aspects of the Earth's climate. The oceans and land surface have warmed. Atmospheric moisture has increased. Glaciers have retreated over most of the globe. Sea level has risen. Snow and sea-ice extent have decreased in the Northern Hemisphere. The stratosphere has cooled, there are now reliable indications that the troposphere has warmed. The height of the tropopause has increased. Individually, all of these changes are consistent with our scientific understanding of how the climate system should be responding to anthropogenic forcing. Collectively, this behavior is inconsistent with the changes that we would expect to occur due to natural variability alone.”

Response from Dr. Bruce Wielicki

Lord Monckton is quoting an older paper by Pinker et al. (2005) that attempts to use geostationary weather satellite data to estimate these trends. Unfortunately, these satellite data were never designed with the accuracy of climate change in mind: the solar sensors that Dr. Pinker's work uses are known to degrade by several percent per year while in orbit, and have no on-board calibration systems. Yet the trends he puts faith in are 1% per decade, well below the accuracy of these instruments. As a result, the confidence in any of the geostationary data sets is based primarily on comparing their trends with highly calibrated radiation budget instruments (e.g., ERBE, CERES in Wong et al., 2006), and with ensembles of many surface radiation sites (e.g. Hinkelman et al., 2009). These comparisons show that the trends in Pinker for solar radiation are greatly exaggerated (Hinkelman et al., 2009).

The final check on how well we understand the Earth's radiative energy balance is the global net radiation (including both solar and thermal infrared components) of the Earth and how it changes over time. There is good agreement for the more accurate ERBE and CERES data for comparisons to ocean heat storage in-situ data from 1992 to 2004 (Wong et al., 2006). There is some inconsistency in more recent data for 2005 to 2009, (Trenberth, 2010), but this is not the time period considered in Lord Monckton's comments.

We conclude that Lord Monckton's conclusions cannot be supported by climate physics, nor is it supported by more accurate versions of the data he used.

Response from Dr. Norman Loeb

With regard to Mr. Monckton's use of the work of Pinker et al., (2005) he is totally misinterpreting the physics. In addition to ignoring the long-wavelength (*infrared; LW*) radiation, he also ignores the non-radiative terms involved in the surface energy budget: sensible and latent heat fluxes (*SH, LH*) and heat storage.

While a change in solar insolation at the surface alters how much solar heating of the surface occurs, changes in LW, LH and SH fluxes modify how much surface cooling occurs. There is no observational evidence or plausible physical justification to assume these cooling mechanisms remained constant during the period of apparent "global" brightening (which is questionable in its own right at the global scale).

By Monckton's logic, surface temperature variability is a simple linear function of variability in surface insolation. While this logic would make climate prediction much simpler than it is, life on Earth would be quite miserable. Not a place I'd want to live...

Response from Dr. Kevin Trenberth

Monckton has not given an appropriate description of the temperature record. One can take a sine curve and fit a series of straight lines to each cycle where all are upwards, and for each cycle has a correlation of 0.71. But this ignores the fact that the lines are not connected and there is no overall trend. One can just as readily fit a series of negative slopes. This highlights the meaningless nature of that kind of activity. One only has to look at the entire record to see that warming is obviously present, it is well outside the bounds of the variability from year to year, and it is strong after 1970 to the present. It does not cease in 2001. The last 10 years are not inconsistent with an upward trend.

Regarding 'global brightening', there is a side bar commentary on global dimming and brightening in Chapter 3 of IPCC. The station network showing these changes is confined to land and near urban areas. There is no evidence that such changes occurred over the oceans (70% of the Earth), indeed the evidence is otherwise. Again there is a

tendency to cherry pick low and high points in some record that are not representative of the bigger picture. Any brightening ignores the dimming beforehand, for instance.

There is no basis for Monckton's Pinker claims at all. The ERBS satellite shows no change in net radiation except for a non-physical jump about 1992 during a three-month gap when the battery on the spacecraft was changed. There is no evidence that this jump is real. (*The ERBS was the first of three Earth Radiation Budget Experiment (ERBE) satellites*).

As we have pointed out, (Trenberth & Fasullo, 2010) there is a mismatch between the top-of-the-atmosphere (TOA) radiation and the sum of the energy in the Earth system...We are analyzing climate model runs, and we find periods of a decade or a bit longer, with no increase in surface temperature in spite of the net imbalance in TOA radiation in the model being order 1 W m^{-2} ...This highlights that on decadal time scales, there is no good reason why there should be a one-to-one relationship between TOA radiation and surface temperatures. The best example is El Nino.

ASSERTION 8

The temperature response to radiative forcing (i.e. climate sensitivity) is very small and was over-estimated by a factor of 4 by the IPCC.

...Taking into account a further projected warming, using IPCC methods, of ~0.5 K (0.9 F°) from CO₂ and other anthropogenic sources, projected warming of 1.5 K (2.7 F°) should have occurred.

However, only a quarter of this projected warming was observed, suggesting the possibility that the IPCC may have overestimated the warming effect of greenhouse gases fourfold. This result is in line with similar result obtained by other methods: for instance, Lindzen & Choi (2009, 2010 submitted) find that the warming rate to be expected as a result of anthropogenic activities is one-quarter to one-fifth of the IPCC's central estimate.

There is no consensus on how much warming a given increase in CO₂ will cause.

Response from Dr. Kevin Trenberth

(A portion of these comments are taken from correspondence from Dr. Trenberth to Dr. James Hurrell)

1) The LC09 results are not robust.

The goal of the Lindzen & Choi 2009 paper, (hereafter LC09), was to quantify the cloud feedback by examining variability in top-of-atmosphere (TOA) radiative fluxes in the tropics as it relates to variability in mean sea surface temperature (SST). To do this they examine only tropical data...they select intervals of warming and cooling ...and compare fluxes at their endpoints.... The result one obtains in estimating the feedback by this method turns out to be heavily dependent on the endpoints chosen. In Trenberth, Fasullo, O'Dell & Wong (2010; *hereafter TFW*) we show that the apparent relationship is reduced to zero if one chooses to displace the endpoints selected in LC09 by a month or less.

2) LC09 misinterpret air-sea interactions in the tropics.

The main changes in tropical SST and radiative fluxes at TOA are associated with El Niño-Southern Oscillation (ENSO) and are not necessarily indicative of forced variability in a closed system. ENSO events cause strong and robust exchanges of energy between the ocean and atmosphere, and tropics and subtropics. Yet LC09 treat the tropical atmosphere as a closed and deterministic system in which variations in clouds are driven solely by SST... It is ... not possible to quantify the cloud feedback with a purely local analysis.

3) More robust methods show no discrepancies between models and observations.

In TFW, we compute correlations and regressions between tropical SSTs and top-of-atmosphere (TOA) longwave, shortwave and net radiation using a variety of methods. ...in our analysis comparing these relationships with models, we are unable to find any systematic model bias. More importantly, the nature of these relationships in models bears no relationship to simulated sensitivity...the metric developed by LC09 is entirely ineffective as a proxy for simulated sensitivity.

4) LC09 have compared observations to models prescribed with incomplete forcings.

...the model simulations used by LC09 have incomplete forcings. The AMIP protocol [*used by LC09*] started off as a test only of how an atmospheric model reacts to changes in ocean temperatures, and so models often only use the ocean temperature change when doing these kinds of experiments. However, over the period of this comparison,

many elements – greenhouse gases, aerosols, the sun and specifically, volcanoes, changed the radiative fluxes, and this needs to be taken into account...

...It is obviously inappropriate to expect such model simulations to replicate observed variability in TOA fluxes.

In connection with the use of models by LC09, we note that in IPCC Chapter 3, we showed linear trends for the last 150, 100, 50 and 25 years. We had empirically assessed that any shorter period trends were not meaningful. So the LC09 work and Monckton's use of it has no basis for saying anything about climate sensitivity. On the contrary, the IPCC assessed climate sensitivity and those arguments stand.

5) LC09 incorrectly compute the climate sensitivity.

By not allowing for the black body radiation...in their feedback parameter, LC09 underestimate climate sensitivity... In contrast, TFOW results yield a positive feedback parameter and greater sensitivity estimate, though we also caution that this approach is not a valid technique for estimating sensitivity, as a closed and therefore global domain is essential...

Response from Dr. James Annan

Occasional errors in the peer-reviewed literature such as Lindzen and Choi (GRL 2009) are easily and rapidly refuted, (e.g. Trenberth et al, GRL 2010.) The best estimate for the sensitivity of the climate is widely acknowledged to be about 3 °C for a doubling of CO₂, although there is uncertainty around this value and it could be somewhat higher or lower with the IPCC summarizing the consensus as a likely range of 2-4.5 °C (IPCC 2007 SPM p12). There are no credible scientific arguments to support Monckton's claim of a substantially lower value, and indeed there are no major inconsistencies between the numerous lines of analysis and modeling that support our understanding of the climate system.

In addition to exposing the errors in the Lindzen-Choi work on climate sensitivity by Trenberth et al (2010) and Murphy (2010), noted by others, it is possible to obtain empirical estimates of climate sensitivity based on observed responses to various forcings. An analysis combining several of these estimates (Annan & Hargreaves 2006) shows that climate sensitivity is constrained with high probability between 2 and 4.5 °C, with the most likely value around 3 °C, in agreement with previous estimates. A value as low as that claimed by Monckton (~ 0.75 °C) has a vanishingly small probability of being correct.

Excerpt from a paper by Dr. Daniel Murphy

*Dr. Murphy leads the Cloud and Aerosol Processes group in the Chemical Sciences Division within the Earth System Research Laboratory, a branch of NOAA, in Boulder, Colorado. Dr. Murphy's schedule has precluded him from providing a direct response, but we draw attention to the following excerpts from his recent paper: D. Murphy, Constraining Climate Sensitivity with Linear Fits to Outgoing Radiation. **Geophys. Res. Lett.**, 37, 2010. L09704, doi:10.1029/2010GL042911.*

There are important limitations to derivations of climate sensitivity from correlations between radiation and temperature data. In particular, because of heat transport between regions, obtaining the equilibrium temperature change by multiplying the forcing by a climate sensitivity is valid only for a global domain. The analysis of Lindzen & Choi (2009)...[hereafter...LC09]... erroneously applies global concepts to a limited region...

Derivation of a climate sensitivity with a regression for a limited region such as the tropics, as in the work of LC09, is ill-posed because of the large horizontal flows of energy and because cloudiness depends on temperature gradients as well as the local temperature...

Heat transport...allows climate feedbacks and responses in various geographical [*regions*] to be much larger or smaller than the global average...

The Earth as a whole can only gain and lose significant amounts of heat from sunlight and thermal emission. When considering a limited region, such as the tropics, heat transport to other regions must be considered, LC09 did not consider such heat transport even though small changes in the horizontal heat transport could swamp their signals.

...the LC09 method of correlating differences obtained from various time intervals results in...misleadingly high correlation coefficients. Within their method, choosing intervals in order to obtain the highest correlation coefficient will bias the result to a low climate sensitivity.

Response from Dr. Michael MacCracken

Global average temperature has risen about 0.8 °C since preindustrial times while the CO₂ concentration has risen less than 40%, so for Monckton's value of the climate sensitivity to be correct, the further 60% rise in CO₂ concentration to reach a doubling would have to have no warming effect on the climate. In addition, the 0.8 °C rise to date is not the full response to the change in atmospheric concentration because the ocean's heat capacity spreads the response to the warming over several decades—accounting for this would increase the warming to about 1.3 °C for the 40% rise in the CO₂ concentration were CO₂ the only factor acting—but it is not: see my discussion in Assertion 9).

The IPCC's estimate of the climate sensitivity is also in good accord with Earth's climatic history, which gives examples of how various types of forcings (e.g., changes in the Earth's orbit, periods of volcanic eruptions, changes in atmospheric composition, etc.) lead to warming and cooling, whereas Monckton's much lower value would not explain how the Earth's climate has changed over time, much less why Venus is so warm and Mars so cold. Quite simply, there is nothing but Monckton's unsupported assertion to suggest that the climate sensitivity is only one quarter of the value of the IPCC.

ASSERTION 9

Climate change is a non-problem. Even if the higher estimates of climate sensitivity were correct, there is no hurry to take any action.

“Global warming” is a non-problem, and the correct policy response to a non-problem is to have the courage to do nothing.

However, ad argumentum, let us assume that the IPCC is correct in finding that a warming of 3.26 ± 0.69 K (5.9 ± 1.2 °F: IPCC, 2007, ch.10, box 10.2) might occur at CO₂ doubling. We generalize this central prediction, deriving a simple equation to tell us how much warming the IPCC would predict for any given change in CO₂ concentration –

$$\Delta TS \approx (8.5 \pm 1.8) \ln(C/Co) \text{ °F}$$

Thus, the change in surface temperature in Fahrenheit degrees, as predicted by the IPCC, would be 6.7 to 10.3 (with a central estimate of 8.5) times the logarithm of the proportionate increase in CO₂ concentration. We check the equation by using it to work out the warming the IPCC would predict at CO₂ doubling: $8.5 \ln 2 \approx 5.9$ °F.

Using this equation, we can determine just how much “global warming” would be forestalled if the entire world were to shut down its economies and emit no carbon dioxide at all for an entire year. The atmospheric concentration of CO₂ is 388 parts per million by volume. Our emissions of 30 billion tons of CO₂ a year are causing this concentration to rise at 2 ppmv/year, and this ratio of 15 billion tons of emissions to each additional ppmv of CO₂ concentration has remained constant for 30 years.

Then the “global warming” that we might forestall if we shut down the entire global carbon economy for a full year would be $8.5 \ln[(388+2)/388] = 0.044$ °F. At that rate, almost a quarter of a century of global zero-carbon activity would be needed in order to forestall just one Fahrenheit degree of “global warming”.

Two conclusions ineluctably follow. First, **it would be orders of magnitude more cost- effective to adapt to any “global warming” that might occur than to try to prevent it from occurring by trying to tax or regulate emissions of carbon dioxide in any way.**

Secondly, **there is no hurry.** Even after 23 years doing nothing to address the imagined problem, and even if the IPCC has not exaggerated CO₂'s warming effect fourfold, the world will be just 1 F° warmer than it is today. If the IPCC has exaggerated fourfold, the world can do nothing for almost a century before global temperature rises by 1 °F.

There are many urgent priorities that need the attention of Congress, and it is not for me as an invited guest in your country to say what they are. Yet I can say this much: on any view, “global warming” is not one of them.

Response from Dr. Gavin Schmidt

First, the citation of IPCC is incorrect. The range of 3.26 ± 0.69 °C for a doubling of CO₂ is simply the mean and standard deviation of sensitivity given by 18 models, it is not a probabilistic statement. A much more credible

range comes from considering the observational constraints which imply that equilibrium climate sensitivity is likely to be in the range 2 to 4.5 °C, with a most likely value of around 3 °C. However, this is a minor error.

Human-emitted carbon dioxide accumulates in the atmosphere and has been doing for centuries. It is therefore extremely unlikely to be reversible in a year, and indeed, no-one has ever suggested it could be.

Monckton is correct in stating that the impact of a single 2 ppmv rise in CO₂ is small in terms of equilibrium temperature, but neglects to comprehend how the addition of 2 ppmv per year, every year, quickly multiplies the effects. Forestalling multiple degrees of warming under any business as usual scenario is indeed a formidable task. Stabilization of CO₂ concentrations will require cuts in emissions of 70% globally, and further cuts subsequently. These cuts would need to be sustained, not just applied for a year.

However, the conclusions Monckton draws from his thought experiment do not logically follow. Deciding on whether something that is difficult to achieve is worthwhile does not simply depend on the difficulty or costs of the task, but on combining the costs with the benefits. The benefits of forestalling much greater climate change than we have thus far seen are indeed difficult to quantify, and are subject to much uncertainty, but that does not justify assuming they are zero. Indeed, they are likely to be very large, particularly if sea level rise continues to accelerate.

Monckton's penultimate paragraph makes a number of illogical leaps. To start with, the IPCC have not 'exaggerated the effect fourfold' and Monckton has presented no valid evidence to support such a claim. Most importantly, the potential temperature rise with no action on emissions is far greater than 1 °F. Upper estimates for 2100 are over 10 times as much. Therefore the potential reduction in anticipated warming is also far greater than 1 °F, though some further warming is inevitable due to past emissions and economic inertia (Meinshausen et al, 2009).

Response from Dr. James Hurrell

(this is an excerpt taken from "Questions for the Record": Dr. Hurrell's response to questions from the Committee concerning the May 6th hearing. We are grateful to Dr. Hurrell for providing this material.)

The urgent need to act cannot be overstated. Anthropogenic climate change is already affecting our lives and livelihoods through extreme storms, unusual floods and droughts, intense heat waves, rising seas, and many changes in biological systems. Uncertainties do remain, but they concern things like the rate of melting of major ice sheets or the specific impacts of climate change on particular regions, not the broader issue of whether the climate is changing. The biggest questions are what choices we and our children will make about energy use. Economists have analyzed the costs of various policy responses and they tell us that the most cost-effective emission trajectories involve starting now to control emissions. Further delay will be costly.

In terms of the rate of change, most climate models produce warming trends in global surface temperature over the next two decades similar to that observed since 1990 (about 0.36°F per decade), regardless of the greenhouse gas emission scenario. By the middle of the 21st century, however, the choice of scenario becomes more important for the magnitude of surface warming, and by the end of the 21st century there are clear consequences for which scenario is followed. The best estimate of the global surface temperature change from today to the end of the century is +3.2 °F for a low emission scenario (e.g., corresponding to a carbon dioxide (CO₂) equivalent concentration of 600 parts per million (ppm) by 2100) and +7.2 °F for the higher emission scenarios (e.g., corresponding to 1,550 ppm).

Excerpt from a paper by Dr. Susan Solomon et al.

Dr. Solomon is a Senior Scientist in the Chemical Sciences Division of the NOAA Earth System Research Laboratory, Boulder, Colorado. Dr. Solomon's schedule has precluded her from providing a direct response, but we draw attention to the following excerpt from a recent paper published in the Proceedings of the National Academy of Sciences (S. Solomon, et al., Irreversible Climate Change due to Carbon Dioxide Emissions, Proc. National Acad. Sciences, Vol. 106 (6), pp. 1704-1709, 2009.

“It is sometimes imagined that slow processes such as climate changes pose small risks on the basis of the assumption that a choice can always be made to quickly reduce emissions and thereby reverse any harm within a few years or decades. We have shown that this assumption is incorrect for carbon dioxide because of [its] longevity...future carbon dioxide emissions would imply further irreversible effects on the planet.”

Response from Dr. Michael MacCracken

For those having little or no acquaintance with climate science, Monckton's assertions sound scientifically credible. After all, he even “derives” an equation! In fact, his argument is not only seriously in error, it is profoundly misleading and irresponsible.

First, as noted in my and others' responses to his Assertion 8, the IPCC climate sensitivity estimate, rather than being a remote possibility, worthy of being considered only *'ad argumentum'*, is much more in keeping with recent climate change, with our understanding of Earth's geological history, and with all we have learned about conditions on our neighboring planets, than the low value asserted by Monckton.

Second, the equation that Monckton derives applies to the change in the warming influence that is or would be induced by a change in the CO₂ concentration alone. His analysis totally ignores the warming influence of other human activities, including the increases being induced in the concentrations of methane, nitrous oxide, chlorine-containing and other halocarbons, and gases that lead to increased concentrations of tropospheric ozone, all of which are greenhouse gases that exert warming influences like CO₂. Monckton also ignores the emissions of black soot and changes in land cover that are contributing to warming and also the warming influence of the decreases in sulfur dioxide emissions that are being made to improve human health and visibility and to reduce the destructive consequences of acid rain. While the net effect of all of these factors has not so far been large, the role of non-CO₂ emissions in 21st century warming will be about comparable to the warming this century due to CO₂ emissions this century.

Third, Monckton's focus on the ultimate change in global average temperature is very misleading. Both observations and theoretical studies (both using models and simpler analyses) all make clear that there will be a pattern in the warming response which is not uniform across the globe. The changes will be larger over land than over the ocean and larger in mid and high latitudes than for the world as a whole. We all live on land, and many live in mid to high latitudes, so will suffer greater than average warming—very detrimentally affecting natural ecosystems, agriculture, and society. In high latitudes warming has been about twice as much as for the global average and this is leading to the accelerating retreat of sea ice and loss of ice mass from mountain glaciers and the Greenland and Antarctic ice sheets.

As commented on in detail in my response to Assertion 3, Monckton's analysis of impacts is far too superficial. I also comment there in detail on the impacts of climate change whose costs will likely be far greater than the costs of vastly reducing CO₂ emissions from fossil fuel use. These include: sea-level rise, impacts on water resources, damage to forests and associated fire losses, impacts on human health, droughts, and increased frequency of severe storms and flooding.

In summary, Monckton's recommendation to do nothing over the next 23 years makes no sense at all. His calculation of the actual amount of additional warming that would be expected is a significant underestimate for reasons stated above. Ramanathan and Feng (PNAS, 2008) show that the most likely value of 2.4 °C (with a range 1.4 °C to 4.3 °C) is

“the equilibrium warming above preindustrial temperatures that the world will observe **even if greenhouse gass concentrations are held fixed at their 2005 concentration levels** but without any other anthropogenic forcing such as the cooling effect of aerosols. The range of 1.4°C to 4.3°C in the committed warming overlaps and surpasses the currently perceived threshold range of 1°C to 3°C for dangerous anthropogenic interference with many climate-tipping elements...”

Obviously the committed warming will be worse still if we ‘do nothing’ for the next 23 years. Most egregiously, it is disingenuous in the extreme to ignore the obvious fact that if we ‘do nothing’ in the next 23 years, we can not then instantaneously drop CO₂ emissions to zero. During this time, and subsequently, the per capita emissions around the world would continue to increase, making reducing emissions significantly more difficult.

His dismissal of the potential consequences of the warming ignores the likely acceleration of various types of impacts as thresholds are neared and passed—a prime example being further acceleration of the loss of mass from the Greenland and Antarctic ice sheets and consequent accelerating rise in sea level.

What is needed is an initial effort that increases in intensity over time, the degree of which can be adjusted over time as information is refined. Given that the cutback in emissions required to stabilize the climate is so large (and growing as emissions continue to rise), not getting started on reducing emissions now will make both the climate change greater and the political actions that will be needed much more difficult. Monckton's statement that “there is no hurry” is not only wrong, it is totally irresponsible...

Response from Dr. David Karoly

I wish to make the following five brief points:

- 1.) The warming commitment due to anthropogenic increases in greenhouse gas concentrations in the atmosphere in 2005 was already 2.4 °C above pre-industrial temperatures, masked by the cooling influence of aerosols, as described by Ramanathan and Feng (2008). Hence, there is a commitment to substantial further global warming due to greenhouse gases already in the atmosphere. This commitment is likely to lead to an increase in global mean temperature greater than the level agreed by the governments of many countries in the Copenhagen Accord in December 2009, which sought emission reductions that would limit future increases in global temperature to less than 2°C above pre-industrial values. Any delay in global greenhouse gas emission reductions will lead to greater exceedence of that temperature level.
- 2.) Current levels of observed global warming are already causing adverse impacts on many human and natural systems, including increased frequency of heat waves and associated increased deaths, and sea-level rise and coastal inundation (IPCC WGII AR4).
- 3.) The long lifetime for increases in carbon dioxide concentrations in the atmosphere due to the long timescales in the carbon cycle mean that any further emissions of CO₂ into the atmosphere commit the world to nearly irreversible increases in temperature and sea level for more than a thousand years (Solomon et al, 2009).
- 4.) Human industrial and energy-production systems have long timescales for the introduction of low- and zero-carbon systems. Delay in introducing such systems commits the world to continued emissions at ever increasing levels.

5.) A decision to delay action to reduce greenhouse gas emissions is not a decision “to do nothing”. It is a decision to continue emissions of CO₂ and other greenhouse gases into the atmosphere by increasing amounts, committing the world to higher levels of global warming and more sea-level rise, with associated adverse impacts.

REFERENCES CITED IN RESPONSES

- Annan, J.D. and Hargreaves, J.C., Using Multiple Observationally-Based Constraints to Estimate Climate Sensitivity, *Geophysical Research Letters*, **33**, L06704, 2006.
- Cuffey, K.M. and Clow, G.D., Temperature, Accumulation, and Ice Sheet Elevation in Central Greenland Through the Last Deglacial Transition, *J. Geophysical Research*, **102**, 26, 383-26,396, 1997.
- Doney, S., Fabry, V., Feely, R., and Kleypas, J., Ocean Acidification: The Other CO₂ Problem, *Annual Review of Marine Science*, **1**, 169-192, 2009.
- Hansen, J., Ruedy, R., Sato, M., and Lo, K., Global Surface Temperature Change, *Rev. Geophys.*, 2010 (in press).
- Hinkelman, L., Stackhouse, P.W., Wielicki, B.W., Zhang, T., and Wilson, S.R., Surface Insolation Trends from Satellite and Ground Measurements: Comparisons and Challenges, *J. Geophysical Research*, **114**, D00D20, 2009.
- Hoegh-Guldberg, O., et al., Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, **318**, 1737-1742, 2007.
- Kleypas, J. A. and Langdon, C., Coral Reefs and Changing Seawater Chemistry, Chapter 5 In: *Coral Reefs and Climate Change: Science and Management*. AGU Monograph Series, Coastal and Estuarine Studies, edited by J. Phinney, O. Hoegh Guldberg, J. Kleypas, W. Skirving and A. E. Strong. Washington DC: Geophys. Union, 2006.
- Lindzen, R. S. and Choi, Y.-S., On the Determination of Climate Feedbacks from ERBE Data, *Geophysical Research Letters*, **36**, L16705, doi:10.1029/2009GL039628, 2009.
- Meinshausen, M., et al., Greenhouse-Gas Emission Targets for Limiting Global Warming to 2 °C, *Nature*, **458**, 1158-1162, 2009.
- Murphy, D., Constraining Climate Sensitivity with Linear Fits to Outgoing Radiation, *Geophys. Res. Lett.*, **37**, L09704, 2010.
- Pelejero, C., Calvo, E., and Hoegh-Guldberg, O., Paleo-Perspectives on Ocean Acidification, *Trends in Ecology & Evolution*, **25**, 332-344, 2010.
- Pinker, R., Zhang, B., and Dutton, E.G., Do Satellites Detect Trends in Surface Solar Radiation?, *Science*, **308**, 850-854, 2005.
- Ramanathan, V. and Feng, Y., On Avoiding Dangerous Anthropogenic Interference with the Climate System: Formidable Challenges Ahead, *PNAS*, **105**, 14245–14250, 2008.
- Raven, J., et al., Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, In: Policy document 12/05, London Royal Society, 2005.
- Solomon, S., Rosenlof, K.H., Portmann, R.W., Daniel, J.S., Davis, S.M., Sanford, T.J., and Plattner, G.-K., Contributions of Stratospheric Water Vapor to Decadal Changes in the Rate of Global Warming, *Science*, **327**, 1219-1222, 2010.

Solomon, S., Plattner, G.-K., Knutti, R., and Friedlingstein, P., Irreversible Climate Change Due to Carbon Dioxide Emissions, PNAS, **106**, 1704-1709, 2009.

Takahashi, T., Broecker, W.S., and Bainbridge, A.E., The Alkalinity and Total Carbon Concentrations in the World Oceans, in Carbon Cycle Modeling, SCOPE, **16**, ed. B. Bolin, Wiley & Sons, New York, pp. 271-286, 1981.

Trenberth, K.E., Global Change: The Ocean is Warming, Isn't It?, Nature, **465**, 304, 2010.

Trenberth, K.E. and Fasullo, J.T., Tracking Earth's Energy, Science, **328**, 316-317, 2010.

Trenberth, K.E., Fasullo, J.T. O'Dell, C., and Wong, T., Relationship Between Tropical Sea Surface Temperature and Top-of-Atmosphere Radiation, Geo. Res. Lett., **37**, L03702, 2010.

Wong, T., Wielicki, B.A., and Lee, R.B., Re-Examination of the Observed Decadal Variability of Earth Radiation Budget Using Altitude-Corrected ERBE/ERBS Nonscanner WFOV Data, J. Climate, **19**, 4028-4040, 2006.

APPENDIX A

Qualifications and Affiliations of the Respondents

The following is an alphabetical list of the respondents for this document including the name, title, organizational affiliation, and the respondent's area(s) of expertise and current research interests. Without exception, all the respondents have published dozens (and in several instances well over a hundred) publications in the professional peer-reviewed climate-science literature.

Dr. James Annan: is a member of the Global Change Projection Research Program within the Research Institute for Global Change, which is affiliated with the Japan Agency for Marine-Earth Science and Technology. Dr. Annan's research interest currently centers on probabilistic climate prediction. He has published numerous papers on various aspects of climate science, especially computer models and their validation.

<http://www.jamstec.go.jp/frsgc/research/d5/jdannan/ - research>

Dr. David Archer: Professor, Department of Geophysical Sciences, University of Chicago. Dr. Archer has published on a wide range of topics pertaining to the global carbon cycle and its relation to global climate, with special focus on ocean sedimentary processes such as CaCO₃ dissolution and methane hydrate formation and their impact on the evolution of atmospheric CO₂. He is also the author of three books on climate change. He teaches classes on global warming, environmental chemistry, and global geochemical cycles.

<http://geosci.uchicago.edu/people/archer.shtml>

Dr. Ken Caldeira: Senior Scientist, Department of Global Ecology, Carnegie Institution, California and Professor by Courtesy, Department of Environmental Earth System Sciences, Stanford University, California. Dr. Caldeira's research and publications have covered numerous aspects of climate science including the global carbon cycle, ocean acidification, and biophysical effects of land-cover change and climate intervention ("geo-engineering").

<http://dge.stanford.edu/labs/caldeiralab/>

Dr. David Easterling: Chief, Scientific Services Division, NCDC, National Oceanic and Atmosphere Administration (NOAA). He is an authority on global surface temperature records and the author of numerous papers dealing with the production and analysis of global surface temperature records.

Dr. James Hansen: Director, NASA Goddard Institute for Space Studies. Dr. Hansen also holds the position of adjunct professor in the Department of Earth and Environmental Sciences, Columbia University, New York. He is a member of the National Academy of Sciences. He is a pioneer in the development of techniques for producing global surface temperature records and the GISS records are recognized as a gold standard for such records.

<http://www.giss.nasa.gov/staff/jhansen.html>

Dr. Ove Hoegh-Guldberg: Director, Global Change Institute, and Professor of Marine Studies, University of Queensland, Australia. Dr. Hoegh-Guldberg is one of the world's leading authorities on coral reefs and their response to a high CO₂ environment and a changing climate. In addition to his numerous publications in this area, he is a member of several associations dealing with this topic including the

Royal Society working group on Ocean Acidification and the Australian Research Council Center of Excellence for Coral Reef Studies.

<http://www.coralreefecosystems.org/>

Dr. James Hurrell: Senior Scientist in the Climate Analysis Section and Chief Scientist for Community Climate Projects at the National Center for Atmospheric Research, Boulder, Colorado. His research interests include climate variability and anthropogenic climate change. He has contributed to the Intergovernmental Panel on Climate Change (IPCC) assessments, and is actively involved in the international research program on Climate Variability and Predictability.

<http://www.cgd.ucar.edu/cas/jhurrell/>

Dr. David Karoly: Professor, School of Earth Sciences, University of Melbourne, Australia and an Australian Research Council Federation Fellow. He was Chair of the Premier of Victoria's Climate Change Reference Group during 2008-09, and a member of the Australian Academy of Science's National Committee on Earth System Science. He is actively involved in research in climate change and climate variability, especially greenhouse climate change, stratospheric ozone depletion, and interannual climate variations due to El Niño-Southern Oscillation.

Dr. Jeffrey Kiehl: Senior Scientist, Climate Change Research Section, National Center for Atmospheric Research, Boulder, Colorado. His areas of interest include greenhouse Climates of the Deep past, periods ranging between 300 to 50 million years ago. His current focus is on the Latest Permian and Early Triassic (~251 million years ago), which is a time in Earth's past where the largest extinction of marine and terrestrial life occurred. He is also currently interested in climate feedback processes, especially cloud climate feedbacks.

<http://www.cgd.ucar.edu/ccr/aboutus/staff/kiehl/kiehl.html>

Dr. Nancy Knowlton: Holds the Sant Chair in Marine Science at the Smithsonian's National Museum of Natural History. She was previously Director, Scripps Center for Marine Biodiversity and Conservation and Adjunct Professor of Marine Biology, Scripps Institution of Oceanography, University of California at San Diego. Her research interests include the ecology, evolution, behavior, and systematics of coral reef organisms and more broadly speciation, marine biodiversity and conservation.

Dr. Lee Kump: Professor of Geosciences, Pennsylvania State University. His current research interests include biogeochemical cycles, low-temperature sedimentary geochemistry, and atmosphere/ocean evolution. He is a coauthor of a college-level Earth science textbook as well as a coauthor of a book for the general public on climate science.

<http://www.geosc.psu.edu/~kump/>

Dr. Norman Loeb: is a scientist at the NASA Langley Research Center. He is an expert on the Earth's energy budget with special interest in the role of clouds and aerosols. He a principal investigator for the Clouds and the Earth's Radiant Energy System (CERES) mission, as well as a Co-Investigator for the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) project.

<http://earthsky.org/scientists/norman-loeb>

http://www.nasa.gov/centers/langley/news/researchernews/snapshot_nloeb.html

<http://earthsky.org/earth/norman-loeb-studies-clouds-effect-on-earths-climate-low-b>

Dr. Michael MacCracken: Chief Scientist, Climate Change Programs with the Climate Institute in Washington DC, a non-partisan, non-governmental organization established in 1986 to heighten national and international awareness of climate change. Dr. MacCracken recently completed a four-year term as president of the International Association of Meteorology and Atmospheric Sciences. For 25 years he was an atmospheric physicist at the Physics Department of the University of California's Lawrence Livermore National Laboratory (LLNL). His research included numerical modeling of various causes of climate change including study of the potential climatic effects of greenhouse gases, volcanic aerosols, and land-cover change.

Dr. Peter Reich: Regents Professor and Distinguished McKnight University Professor, University of Minnesota's Department of Forest Resources. His teaching and research focus on ecology, global change, and the sustainability of managed and unmanaged terrestrial ecosystems. Regionally, his interests lie in the forests and grasslands of mid-North America and globally on terrestrial ecosystems in aggregate.
http://environment.umn.edu/about/ione_bios/peter_reich.html

Dr. Reto Ruedy: is a scientist at the NASA Goddard Institute for Space Studies and Adjunct Professor, Columbia University. Dr. Ruedy's research interests center on the global surface temperature record, analysis of the most important contributors to the overall greenhouse effect, and the role of aerosols in both the current climate as well as the climate of the past century.
<http://www.giss.nasa.gov/staff/rruedy.html>

Dr. Benjamin Santer: Research Scientist, Program for Climate Model Diagnosis and Intercomparison (PCMDI), Lawrence Livermore National Laboratory. The PCMDI develops improved methods and tools for the diagnosis and comparison of general circulation models that simulate the global climate. Its current scientific projects focus on supporting model intercomparison, on developing a model parameterization testbed, and on devising robust statistical methods for climate-change detection and attribution.
<http://www-pcmdi.llnl.gov/about/staff/Santer/index.php>

Dr. Gavin Schmidt: Climate Scientist, NASA Goddard Institute for Space Studies, New York. Dr. Schmidt's research activities include coupled ocean-atmospheric modeling, use of climate proxy data, and modeling both recent and past climates.
<http://www.giss.nasa.gov/staff/gschmidt/>

Dr. Pieter Tans: Senior Scientist, NOAA Earth System Research Laboratory, Boulder, Colorado. His areas of interest include biogeochemical cycles, atmospheric chemistry, climate and global change, stable isotopes, and paleoclimate. His current research focuses on global atmospheric measurements of CO₂, CH₄, CO, and other atmospheric constituents along with the isotopic ratios in several of those species. His is also involved in research on numerical models of atmospheric transport and field measurements of air-sea gas exchange.
<http://cires.colorado.edu/people/tans/>

Dr. Kevin Trenberth: Senior Scientist and Head, Climate Analysis Section at the National Center for Atmospheric Research, Boulder, Colorado. He was a lead author of the 1995, 2001 and 2007 Scientific Assessments of Climate Change reports from the Intergovernmental Panel on Climate Change. He has been prominent in all aspects of climate variability and climate change research. His recent research has

focused on the global energy and water cycles and how they are changing. His work mainly involves empirical studies and quantitative diagnostic calculations.

<http://www.cgd.ucar.edu/cas/trenbert.html>

Dr. John Veron: Professor, University Center for Marine Studies, University of Queensland. He is the former Chief Scientist of the Australian Institute of Marine Science. He is widely known for his work on coral reefs and is the author of over 14 books and monographs, including the 3-volume work on corals of the world. He has been the recipient of the Darwin Medal, the Silver Jubilee Pin of the Australian Marine Sciences Association, the Australasian Science Prize, and the Whitley Medal. He concentrates on conservation and the effects of climate change on coral reefs.

<http://profiles.bacs.uq.edu.au/John.Veron.html>

<http://www.coralreefresearch.org/>

Dr. Bruce Wielicki: Senior Scientist Radiation Sciences, NASA Langley Research Center. He is the science team lead for the NASA Climate Absolute Radiance and Refractivity Observatory (CLARREO) project at NASA Langley. His research interests include remote sensing of single- and multiple-cloud layer properties from multispectral imagery, validation of remotely-sensed cloud properties, effects of clouds on the Earth's radiation budget, and cloud radiative transfer modeling.

http://asd-www.larc.nasa.gov/people_html/wielicki.html

APPENDIX B

Full Text of Responses

Full response from Dr. David Archer

Paleoclimate reconstructions from deep time are potentially useful as tests of our understanding and models of modern climate, because the climate changes are more dramatic as we look far back in time, relative to the much more modest climate changes in more recent times. However, the difficulty is that the data become more uncertain as you go back in time. CO₂ concentrations are nailed by ice-core measurements, dovetailing beautifully with the directly measured CO₂ concentrations from the atmospheric sampling sites, beginning with Moana Loa in the middle 1950's. Before this time it is much more difficult to reconstruct atmospheric CO₂ concentrations. There are a variety of proxy methods, based on the microscopic structures of plant leaves that respond to CO₂ (stomata vent cells), carbon isotopic measurements (most reliably in my opinion from CaCO₃ formed in arid soils, but measurements are also made of biomarker molecular fossils in ocean sediments).

There are still mysteries lurking in our understanding of deep climate. There was a glaciation at the end of the Ordovician, a quicky in the midst of a long interval of hothouse conditions, when CO₂ seems like it should have been high. There is also the Paleocene Eocene Thermal Maximum event, which seems to suggest strongly that the climate sensitivity of the Earth was higher than it is now, even though this was an ice-free world that would seem to us like it ought to have lower climate sensitivity. In general, notwithstanding the small mysteries (there will always be mysteries in a progressing scientific field), the paleo data support a climate sensitivity which is at least as high as projected for the future, if not higher (as ice sheets take time to respond fully, for example).

Monckton seems to be referring to the snowball Earth glaciations. The way those are thought to have worked is that in the snowball, the hydrologic cycle stopped, blocking the uptake of CO₂ from chemical weathering reactions. CO₂ continued to degas from the Earth in volcanic gases and in ocean hot springs, building up in the atmosphere until it got hot enough to overcome the high albedo of the ice, melting it catastrophically in a runaway ice albedo feedback. The climate flipped into a hothouse, leading to immense chemical weathering fluxes that pulled the CO₂ out of the air, resulting in CaCO₃ deposits overlying the glacial deposits called the cap carbonates. So in fact, the idea is that when the CO₂ got high enough, the glaciers couldn't exist any more, so they melted. Monckton is mixing the two different intervals in time, using a theory that relies on CO₂ as a greenhouse gas to argue that it proves the opposite. In short, Monckton's statement is ridiculous.

Full Response from Dr. Ken Caldeira

Some of your questions are touched on here: <http://www.whoi.edu/OCB-OA/FAQs/>

To Monckton's point about high CO₂ levels in the past, anyone with even an elementary understanding of geochemical cycles would understand that rates of CO₂ change are more important than amounts of CO₂ change. The processes that buffer changes in ocean chemistry take thousands of years (carbonate dissolution and silicate rock weathering), so ocean chemistry is well buffered against slow changes in atmospheric CO₂ content. On long time scales, the carbonate mineral saturation state of the ocean is controlled by the need for sedimentation to balance river inputs. CO₂ can only directly affect carbonate mineral saturation states on the time scale of millennia or less.

To Monckton's point about the added CO₂ being a small part of total carbon, this exhibits ignorance

about the role of CO_2 in ocean chemistry. Because of the reaction $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{HCO}_3^-$, to a first approximation, the hydrogen ion concentration of the ocean scales with atmospheric CO_2 content on the time scale of seconds to centuries. Because of the reaction $\text{CO}_3^{2-} + \text{H}^+ \rightleftharpoons \text{HCO}_3^-$, the carbonate-ion concentration $[\text{CO}_3^{2-}]$ scales inversely with $[\text{H}^+]$ and thus inversely with atmospheric CO_2 content. Since organisms need CO_3^{2-} to build their shells, the fact that there is a relatively small change in $[\text{HCO}_3^-]$ is largely irrelevant. A doubling of atmospheric CO_2 content approximately halves the carbonate ion content. This is enough to produce undersaturated conditions in some parts of the surface ocean. (Currently, the entire ocean surface is saturated with respect to these minerals, but precipitation is kinetically impeded.)

Monckton could read this kind of stuff in many places if he wished to become better educated in the science.

Full Response from Dr. Ove Hough-Guldberg

The submission from Monckton (trained in classics and journalism, and not chemistry) concerning the interaction between atmospheric carbon dioxide and the carbonate chemistry of seawater is profoundly wrong.

For example, the claim that ocean acidification cannot be due to increasing atmospheric carbon dioxide concentration is at odds with experimental results, field observations and our fundamental understanding of physical chemistry going back over 100 years.

The assertion that seawater is buffered to the point where it can take up a huge amount of dissolved carbon dioxide without significant effect on pH is also misleading. The current decline in ocean pH of 0.02 per decade has been confirmed by NOAA and other highly credible scientific organizations (e.g. Doney et al. 2009).

There is also a growing peer-reviewed literature which shows that changes of this magnitude are having and will have, significant and major impacts on the biology of the ocean (e.g. Raven et al. 2005, Kleypas and Langdon 2006, Hoegh-Guldberg et al., 2007).

Lastly, the issue of ocean acidification has never been about the pH of the ocean dropping below 7. This is simply a red herring. The fact of the matter is that we are acidifying the ocean (the correct term for decreasing pH irrespective of whether or not the solution starts off alkaline) to a point that is [having] and will have demonstrable impacts on important biological systems from phytoplankton to coral reefs. Of great concern, is the growing evidence that the level of ocean acidification is rapidly approaching conditions not been seen for millions of years (Pelejero et al. 2010).

Full Response from Dr. Jeffrey Kiehl

The statements concerning deep time climates, CO_2 levels, and life are misleading. For example, the very high levels of CO_2 proposed for the Neoproterozoic occurred after the Snowball Earth conditions and were the result of very low weathering during snowball conditions. It was this large buildup of CO_2 that got Earth out of snowball conditions. So, the tropical glaciers melted once CO_2 started to increase. The geological record shows that evidence for glaciers preceded, but is not coincident in time with high CO_2 . The other argument that is made is that life existed during warm, high CO_2 time periods in the past. My response, yes and so what? It is ironic that Monckton will accept that the geologic record clearly indicates that high CO_2 leads to warm climates (thus CO_2 is a driver for climate), but then uses the existence of life at these times to conclude that we need not worry. The point is that past warm periods developed over millions of years of time and lasted for millions of years. Thus, species could adapt to these changes.

However, we also know that some species did not adapt. The concern about the future is that the rate of warming that is occurring and will continue to occur over the next century is unprecedented in the deep past. It took over 30 million years for CO₂ levels to drop from 900 ppmv to their present levels, we are returning Earth back to this level in a mere 90 years. The accompanying rate of warming will also be unprecedented, certainly over the lifetime of our species. The issue is that our species and others will experience a rapid and large change that will have significant impacts on survivability. So, both of Monckton's arguments are flawed.

Having said all of this, I feel that any attempt to correct Monckton will have little success. It is a sad commentary on the state of the world, when people no longer trust scientific investigation, but much rather prefer to listen to things that reinforce their belief systems.

Full Response from Dr. Nancy Knowlton

This paragraph completely ignores the fact that the seawater chemistry/chemical composition, and the buffering capacity of seawater were very different during the times described from what they are today. The relationship between CO₂ concentration in the atmosphere, and ocean pH (acidity), and the seawater carbonate saturation state (this is essentially an index of how easy it is to form calcium carbonate) depends on the buffer capacity of the ocean. The buffer capacity is a direct function of the composition of seawater in terms of major ions such as sodium, magnesium, calcium, chloride, sulfate and so on. Thus, the relationship between atmospheric CO₂ and ocean pH (acidity) is also dependent on the rate of CO₂ additions to the atmosphere and the amount of time required to increase the buffer capacity of the ocean by natural processes such as calcium carbonate dissolution and continental weathering.

The ocean has to buffer itself after increases in CO₂. Even though CO₂ concentration was high at times in the past, the ocean was not generally acidified and the saturation state of carbonate minerals was typically high, which is why corals could build their skeletons.

With respect to the current situation, it is true that on the time scale of thousands of years, the dissolving of existing calcium carbonate (CaCO₃) in the ocean (chalky sediments on the seafloor, reefs, etc.) will start to neutralize and buffer the anthropogenic CO₂ that is entering the ocean from the atmosphere, and on even longer timescales of hundreds of thousands to millions of years, material from weathering of rocks and erosion on land will be carried to the ocean and complete the buffering process.

The problem with CO₂ emissions today is that the effects of burning fossil fuels on ocean pH first operate on the scales of decades to centuries, thus causing the acidification that has been observed. Eventually the pH of the ocean will be buffered again, but for hundreds of years ocean organisms will be affected by abnormally high acidity (low pH), and it is the damages associated with acidification over the "short" term (the next hundreds of years) that concern biologists.

To draw an everyday comparison, imagine a glass of water with a piece of chalk sitting in it. If you add vinegar, the water will immediately become more acidic, although eventually the chalk will dissolve and bring the pH back to normal.

"If ocean "acidification" is happening, then CO₂ is not and will not be the culprit."

1) There is no question of "if". Changes in pH have already been observed in many different parts of the ocean, and the chemistry driving short-term acidification is elementary and unavoidable. High

concentrations of CO_2 in the atmosphere cause CO_2 to dissolve into surface waters of the ocean because it is impossible for differences in concentration to be maintained – the concentrations equilibrate via interchange at the air/water interface. Based on changes in isotopic ratios of carbon in the atmosphere, there is no doubt that the majority of the observed increase in CO_2 in atmosphere and ocean originates from human burning of fossil fuels.

- 2) This reasoning and calculation is incorrect. Yes, the whole ocean holds about 60 times as much carbon in the form of total dissolved inorganic carbon ($\text{CO}_2 + \text{HCO}_3^- + \text{CO}_3^{2-}$) compared to the CO_2 in the atmosphere, but the change in partial pressure of CO_2 in the surface ocean will follow relatively close to that of the atmosphere.

Here is an example: If you assume typical present day conditions with a temperature of 20°C , salinity of 35, partial pressure of CO_2 ; ($p\text{CO}_2$) of $=390\ \mu\text{atm}$, and total alkalinity; (TAA_T) $=2350\ \mu\text{mol/kg}$ this gives a total dissolved inorganic carbon (C_T) of $2079\ \mu\text{mol/kg}$; $\text{pH}=8.06$; $\text{CO}_2(\text{aq})=12\ \mu\text{mol/kg}$. If we keep the same assumptions, but double the partial pressure of CO_2 to $780\ \mu\text{atm}$ this gives $C_T=2203\ \mu\text{mol/kg}$; $\text{pH}=7.80$; $\text{CO}_2=25\ \mu\text{mol/kg}$. This corresponds to a 82% increase in acidity (i.e., hydrogen ion concentration). This calculation is elementary chemistry.

- 3) Although warmer water does hold less CO_2 , this calculation is also incorrect. Using the same assumptions as above but assuming a temperature of 22°C (2 degrees warming) and a $p\text{CO}_2$ of $780\ \mu\text{atm}$, then $C_T=2191\ \mu\text{mol/kg}$; $\text{pH}=7.80$; $\text{CO}_2=24\ \mu\text{mol/kg}$. So yes, seawater holds less total CO_2 with warming but as the two calculations illustrate this is marginal and the pH remains significantly lower compared to present day conditions.

$T=35$; $p\text{CO}_2=750\ \mu\text{atm}$; $\text{TA}=2350\ \mu\text{mol/kg}$ gives dissolved inorganic carbon in seawater of $=2184\ \mu\text{mol/kg}$ which results in a $\text{pH}=7.82$ (versus 8.06 at 20°C , see above); $\text{CO}_2(\text{aq})=23\ \mu\text{mol/kg}$.

- 4) It is true that burning all fossil fuels will not make the ocean acidic ($\text{pH}<7$) – the resulting pH would be about 7.5, or still slightly basic. However this is irrelevant because ocean animals and ecosystems suffer will be significantly affected long before the pH falls below 7.0.
- 5) At present the average pH has already dropped to ~ 8.1 from preindustrial conditions of ~ 8.2 . Because of the pH scale is logarithmic this means that there has already been a 30% increase in the concentration of hydrogen ions (H^+ , what is measured on the pH scale). Moreover, pH at the end of the century under business as usual scenarios is predicted to decrease to an average of 7.9-7.8 (not 8.0); this future change represents an additional increase of 60-100% in the concentration of hydrogen ions (H^+). The remainder of the statement is simply chemical nonsense.

Full Response from Dr. Lee Kump

One cannot characterize the Neoproterozoic Era with a single atmospheric CO_2 level. This was a time period of tremendous climate swings, from “Snowball Earth” episodes with glaciation extending into the tropics to extreme “super-greenhouse” ice-free climate states. Our understanding of the driver for these climate shifts is large variations in atmospheric CO_2 level. Beginning about 725 million year ago, CO_2 levels began falling from levels considerably higher than today (in accordance with the warm climate state and to compensate for a less-luminous sun) to values approaching today’s ($\sim 300\ \text{ppm}$). As they fell, the climate cooled, eventually crossing a threshold beyond which the cooling effects of ice sheets and sea ice

advancing equatorward overcame the strong solar heating of the tropics, and the ice extended quickly to the tropics. In this cold, dry climate, the process that normally balances the release of CO₂ from volcanoes, the “weathering” of rocks that converts rocks to soils (and removes CO₂ from the atmosphere, sequestering it into limestone after rivers transfer the neutralized carbon to the ocean), essentially shut down. Volcanoes still emitted CO₂, so the atmospheric level rose slowly. Over millions of years, levels approached the 300,000 parts per million cited by Stockton. At that level, the strong greenhouse effect was capable of overcoming the cooling effect of the ice, and the ice melted catastrophically. Earth was left with a strong greenhouse effect that created an extremely warm, ice-free climate. Under these conditions, weathering proceeded at high rates, creating the dolomites of the “cap carbonates” and slowly drawing down the atmospheric CO₂ level. Eventually, CO₂ levels fell again below the threshold, so that by 650 million years ago, the second Snowball Earth was triggered, and the cycle repeated itself.

Thus, the climate fluctuations are entirely consistent with the CO₂ levels inferred.

By the way, the CO₂ content of dolomite is irrelevant to considerations of atmospheric CO₂ level. This mineral has formed throughout Earth history, at times when CO₂ levels are thought to have been very high (i.e., following the Snowball Earth's) and also today.

In contrast to the personal communication cited, all climate models that have been used to study the Neoproterozoic create equatorial ice when subjected to today's CO₂ level, precisely because of the reduced solar luminosity of the time.

One must carefully distinguish between conditions that were acquired and sustained over millions of years such as these, and abrupt events such as fossil-fuel burning that disturb these longer-term equilibria. Over long time scales, the carbon cycle is balanced, and the oceans (and the life in them) can form limestone at essentially any atmospheric CO₂ level. On these long time scales, rivers bring the building blocks for the calcium carbonate skeleton to the ocean; when CO₂ levels are high, these compounds must accumulate to higher concentrations to overcome the increased acidity generated by the CO₂, but this adjustment takes only millennia. Here's an analogy: Take a pot of cold water and add salt to it until no more will dissolve and a small amount sits on the bottom. The solution is now “saturated” with salt. If you warm the pot on the stove rapidly the solution will become undersaturated, and the salt on the bottom of the pot will dissolve. You can add more salt to the solution, and eventually it too will become saturated, and salt will accumulate on the bottom, just as it did in the cold pot. Only now there's more salt dissolved in the water. The pot is the ocean, temperature is like the CO₂ level, and you are the river. Given a bit of time to add some extra salt to the pot, you created a situation in the warm pot where salt wouldn't dissolve (and in fact, might even grow), just as in the cold pot.

What the geologic record tells us is that rates of change are what matter most. Earth is a dynamic system, replete with dynamic balances that can be disrupted. Life flourished when rates of change were slow and the Earth system had time to adjust. But when rates of change were fast, life (and the rest of the Earth system) was unable to adjust in time; climates shifted quickly, the physical and chemical environment for life changed abruptly, and life suffered.

Full Response from Dr. Peter Reich

The best evidence from state-of-the-art free-air carbon dioxide enrichment experiments is inconsistent with the notion of major sustained increases in crop yield in a world of doubled atmospheric CO₂.

Quantitative analyses and syntheses of those experiments indicate that the direct effects of elevated CO₂ will increase crop yields by 13% (on average for those with the C3 photosynthetic pathway, such as wheat, soybeans, rice) or 0% (on average for those with the C4 photosynthetic pathway, such as corn, sugar cane, and sorghum); not the 40% Lord Monckton suggests. Moreover, these estimates ignore (1) indirect effects of CO₂ as a greenhouse gas on future temperatures and precipitation, and their variability, and hence on future crop yields and (2) other consequences of fossil fuel-burning such as rising ozone pollution that will reduce crop yields. The bottom line for crop yields: combined effects of fossil-fuel burning (rising CO₂, rising O₃, climate change) are uncertain but at least as likely to be negative as positive, and shifting increasingly towards the negative the higher that CO₂ concentrations rise.

Rising CO₂ fertilization of productivity (and of carbon sequestration) of forests, grasslands, savannas of the world is also likely to be less than previously anticipated from overly simplistic models. This is because other limiting factors (such as soil fertility and soil water) and other vegetation changes (reduced vegetation diversity and complexity) will increasingly constrain positive impacts of CO₂ on productivity of non-agricultural systems. Moreover, as with crops, but likely more so (given that we can adaptively modify agriculture much more rapidly), the cascade of indirect effects of fossil-fuel burning are in aggregate likely to lead to loss of vitality, health, stability, diversity, and provisioning of ecosystem services from the world's forests, savannas, and grasslands. The cascade of indirect effects includes increases in ozone pollution, droughts, floods, windstorms, wildfires, and native and invasive insect and disease outbreaks, that will accompany rising CO₂ levels and associated climate change; and that will all have negative consequences for forests, savannas, and grasslands.

Full Response from Dr. Pieter Tans

Mr. Monckton's assertions on acidification are remarkable. They demonstrate that his lack of understanding of ocean carbonate chemistry is nearly complete. It is remarkable because the basics of this subject have been understood for a long time.

My comments have two parts. The first part answers Mr. Monckton's assertions in plain English without math, while the second part, is more technical and underpins the first part.

Part 1

“some 30% of any CO₂ we add to the atmosphere will eventually dissolve in the oceans”.

Actually, some 80% will eventually dissolve in the oceans if we wait long enough, about a thousand years.

“doubling of CO₂ raise the oceanic partial pressure of CO₂ by 30% of one-seventieth of what's already there”.

Actually, it would double the partial pressure of dissolved CO₂. However, atmospheric CO₂ can equilibrate only with the dissolved CO₂ component which comprises less than 1% of total dissolved inorganic carbon.

“take up a huge amount without significant effect on pH”.

Actually, without a change in pH there can be no uptake of CO₂ by the oceans in the next decades and centuries. A change of pH is central to the uptake of CO₂.

“no more than 10% of the “acidic” positively-charged hydrogen ions”

The concentration of hydrogen ions itself is not relevant in this case – it is just a measure of acid-base equilibria, just like a thermometer gives a measure of temperature, but thermometers do not drive the

climate. What matters is that the carbonate ion concentration drops substantially, which brings solid carbonates in the oceans closer to the point at which they dissolve. Hence the threat to organisms/ ecosystems that depend on the formation of crystalline calcium carbonate (such as coral reefs), many of which are at the base of the ocean food chain.

“If ocean “acidification” is happening, then CO₂ is not and will not be the culprit”

Everything in this statement is demonstrably wrong. CO₂ is an acid, acidification has been measured in the surface oceans and agrees with expectations based on well understood chemistry. CO₂ is the only possible culprit. There are not enough emissions of anything else that could cause the observed acidification.

Part 2

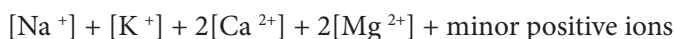
Dissolved CO₂ in the average surface ocean waters comprised in pre-industrial times only about 0.5% of what is called dissolved inorganic carbon (DIC), the sum of three species that are in constant chemical equilibrium everywhere in the oceans, namely dissolved CO₂ (CO₂(aq)), bicarbonate ions (HCO₃⁻), and carbonate ions (CO₃²⁻). Average total DIC of surface waters of the tropical and temperate oceans has been estimated from the measurements of the GEOSECS Expeditions in 1972-1977 as 2000±20 μmol/kg seawater (Takahashi, 1981). Here I choose DIC = 2000 μmol/kg because that would be, at an average temperature of 19.2 °C, in equilibrium with atmospheric CO₂ of 330 ppm, the observed value of the deseasonalized CO₂ trend in early 1975. CO₂(aq) in most ocean surface waters has been observed to be nearly in equilibrium with atmospheric CO₂. The components adding up to 2000 μmol/kg are 10.71 μmol/kg of CO₂(aq), 1770.6 μmol/kg of HCO₃⁻, and 218.6 μmol/kg of CO₃²⁻. The equilibria are listed in Table 1.

CO ₂ (atm) ⇌ CO ₂ (aq)	[CO ₂ (aq)] = K ₀ *CO ₂ (atm)	(A)
CO ₂ (aq) + H ₂ O ⇌ H ⁺ + HCO ₃ ⁻	[H ⁺] * [HCO ₃ ⁻] = K ₁ * [CO ₂ (aq)]	(B)
HCO ₃ ⁻ ⇌ H ⁺ + CO ₃ ²⁻	[H ⁺] * [CO ₃ ²⁻] = K ₂ * [HCO ₃ ⁻]	(C)

Table 1. The equilibrium reactions are in the left column, and they each obey their corresponding equation in the middle column, with K₀, K₁, K₂ denoting Henry’s Law solubility constant, and the first and second carbonic acid dissociation constants respectively. The constants depend on temperature, salinity, and the dissociation constants also depend on pressure. The square brackets [] indicate the dissolved concentrations of the chemical species. A, B, C are just labels to refer to their corresponding equations.

If one does not know about the existence of the (bi-)carbonate ions, one would estimate, based on the solubility of CO₂, that the total amount of CO₂(aq) in the oceans would be less than half as much as the amount in the atmosphere, in equilibrium. Due to bicarbonate and carbonate the total amount of oceanic DIC in the 19th century was about 60 times the amount in the atmosphere.

What is the ocean’s chemical uptake capacity for additional CO₂? It is set by the condition that the oceans do not have a net electrical charge, which implies that the sum of positive ions must balance the sum of negative ions. With square brackets indicating the concentration of a chemical species (ions in this case) in seawater, the condition can be written as



is equal to



Since all the major species (basically sea salt) can vary appreciably only on geologic time scales except for the carbon species, the overall electric charge neutrality dictates that on time scales of up to a few thousand years the sum $[\text{HCO}_3^-] + 2[\text{CO}_3^{2-}]$ must remain constant. A substantial amount of additional CO_2 can be accommodated only because most of the extra $\text{CO}_2(\text{aq})$ will react with carbonate ions in the net reaction



spreading the available negative charge of CO_3^{2-} over two carbons instead of one. The reaction can happen as long as there is still a sufficient amount of CO_3^{2-} available. As CO_3^{2-} is gradually depleted, a progressively larger fraction of the added CO_2 will have to remain as $\text{CO}_2(\text{aq})$. We can make this more quantitative by combining the equations (B) and (C) above, giving a condition that must always be met,

$$[\text{HCO}_3^-]^2 = K_1/K_2 * [\text{CO}_2(\text{aq})] [\text{CO}_3^{2-}]. \quad (\text{D2})$$

In equilibrium with the observed increase in $\text{CO}_2(\text{atm})$ of 17.6% from 330 ppm in 1975 to 388 ppm today, $[\text{CO}_2(\text{aq})]$ in most of the surface oceans must also increase by 17.6%. How much does $[\text{CO}_3^{2-}]$ have to decrease and $[\text{HCO}_3^-]$ increase to satisfy (D2)? As shown by the reaction D1, when we decrease $[\text{CO}_3^{2-}]$ by an amount “x”, we have to increase $[\text{HCO}_3^-]$ by an amount “2x”. A bit of trial and error shows that $[\text{CO}_3^{2-}]$ decreases to 195.7 $\mu\text{mol/kg}$ and $[\text{HCO}_3^-]$ increases to 1816.4 $\mu\text{mol/kg}$. Total DIC, the sum of all three dissolved species, has increased by 24.7 $\mu\text{mol/kg}$ or 1.24%. A more complete treatment of the chemistry, especially the inclusion of boric acid and borate ions, leads to somewhat more carbon uptake, namely 1.65%. Note that the relative increase of $[\text{CO}_2(\text{aq})]$ is 17.6%, approximately 10 times larger. Although the pre-industrial oceans contained 60 times more total dissolved carbon than the atmosphere the ocean uptake of additional carbon does not follow a partitioning of 60:1, but is much smaller. The ocean’s uptake capacity is primarily limited by its carbonate ion reservoir, which is “only” about 6 times the size of the atmosphere. Thus the oceans are expected to take up eventually ~80% of the fossil fuel emissions. That will take a very long time, about a thousand years, because most of the deep oceans are not accessible on a time scale of a few decades. Therefore, observations show that the current actual uptake by the oceans is more in the vicinity of 30%.

$\text{CO}_2(\text{aq})$ has been observed to rise in lockstep with atmospheric CO_2 in most of the surface oceans, and so has the acidity. Acidity is expressed as pH, defined as the negative logarithm (base 10) of the hydrogen ion concentration. We can use equilibrium (C) above to express $[\text{H}^+]$ as

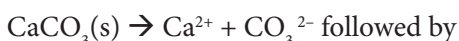
$$[\text{H}^+] = K_2 * [\text{HCO}_3^-] / [\text{CO}_3^{2-}], \text{ and thus}$$

$\text{pH} = -^{10}\log[\text{H}^+] = -^{10}\log(K_2) + ^{10}\log[\text{CO}_3^{2-}] - ^{10}\log[\text{HCO}_3^-]$, and the change in pH from pre-industrial values as

$$\text{pH} - \text{pH}_o = ^{10}\log([\text{CO}_3^{2-}] / [\text{CO}_3^{2-}]_o) - ^{10}\log([\text{HCO}_3^-] / [\text{HCO}_3^-]_o),$$

in which the subscripts “o” indicate pre-industrial values. In a similar way as outlined above one can estimate that in pre-industrial times, when atmospheric CO_2 was 280 ppm, the three dissolved carbon species in equilibrium with the atmosphere were $[\text{CO}_2(\text{aq})]_o = 9.09 \mu\text{mol/kg}$, $[\text{HCO}_3^-]_o = 1714.2 \mu\text{mol/kg}$, and $[\text{CO}_3^{2-}]_o = 241.5 \mu\text{mol/kg}$, and total DIC = 1964.9 $\mu\text{mol/kg}$. The pH has changed by $^{10}\log(195.7/241.5) - ^{10}\log(1816.4/1714.2) = -0.12$ since pre-industrial times. Importantly, $[\text{CO}_3^{2-}]$ has decreased substantially, to 81% of its value in the mid-19th century, while the stability of calcium carbonate minerals depends on the product of $[\text{Ca}^{2+}] * [\text{CO}_3^{2-}]$. Changes in the solubility product are primarily controlled by the large relative changes of $[\text{CO}_3^{2-}]$, and when it drops below a certain level calcium carbonates will start

dissolving. $[Ca^{2+}]$ does not change appreciably until the carbonate minerals start dissolving or their formation rate slows down because of the lower availability of CO_3^{2-} . When that happens atmospheric CO_2 would be lowered by the net reactions



The $CO_2(aq)$ molecule in the above reaction has ultimately come from the atmosphere. The addition of Ca^{2+} allows the sum of $[HCO_3^-] + 2[CO_3^{2-}]$ to grow, enabling the oceans to take in more carbon. However, dissolution of $CaCO_3(s)$ is precisely what could spell mass extinction for the oceans.

There is enough coal, oil, and natural gas in the Earth's crust that we have the technology to mine to make that a plausible potential future. "Skeptics" take heart, there is evidence in the geologic record that this has happened many millions of years ago; mankind is merely repeating such events!

Full Response from Dr. John Veron

Most atmospheric carbon dioxide in geological time originates from basaltic lava flows (traps) and volcanoes. These are geological events which occur (a) over long time intervals (10's of millions of years) initiated by continental movements and (b) in very short spikes (centuries) initiated by asteroid impacts (as with the last mass extinction). A third source is the periodic release of methane and associated gases of organic origin which rapidly oxidizes to carbon dioxide (as with the two most important marine extinctions of our era). These have had drastic effects on life, including mass extinctions where the majority of marine species have gone extinct.

Four of the Earth's five mass extinction events are known to have occurred at times of high or sudden increases in carbon dioxide which has caused chemical changes in the ocean surface leading to anoxia (lethally low oxygen) and the presence of poisonous gases especially hydrogen sulfide (rotten-egg gas). The fifth had the same outcome from a different source but also involving carbon dioxide.

It is not possible for me to make any sense of Mr Monckton's assertions as they are not based on any scientific data or views that have ever been published. The levels quoted are higher than any spikes known to have existed. The time intervals quoted bear no relevance to the history of life.

Specifically:

Cambrian Era: Calcium carbonate (limestone) of the Cambrian, which abounds, has nothing to do with atmospheric carbon dioxide. Estimates of carbon dioxide levels at this time are not known with great certainty. There were no corals in the Cambrian, symbiotic or otherwise: they had not evolved then.

The Jurassic: There were high levels of carbon dioxide possibly reaching 2000ppm for unknown time intervals with unknown effects on marine life. The spike immediately before the Jurassic caused the third great mass extinction. This extinction, which defines the Triassic/Jurassic boundary, was so drastic that it has been known since the early 18th century.

Full Response from Dr. Bruce Wielicki

- a) Lord Monckton is only considering the changes in reflected solar radiation. This is only half of what drives the Earth's climate energy balance: the other being the thermal infrared emission to space. The variations he is speaking of are thought to be natural variability of clouds in the climate system (e.g. Wong et al, 2006, Hinkelman et al, 2009) and only the net effect of both solar and infrared effects will push the climate system to warmer or colder states. He uses only the solar contribution, and therefore cannot know the magnitude or even the sign of the warming/cooling effect with the paper he quotes.
- b) The original global dimming and brightening papers were based on a network of surface radiation measurements at a few sites, most of them in Europe. More recent studies have shown using global satellite data that the large regional variability in clouds in these regions is not representative of global average changes in radiation (Hinkelman et al, 2009). While these surface networks are slowly improving, they still contain few observations over the oceans, the southern hemisphere, Africa, or Asia. And the accuracy with which they can observe long term trends of a few Wm^{-2} (climate radiative forcing levels) remains uncertain.
- c) Lord Monckton is quoting an older paper by Pinker et al. 2005 that attempts to use geostationary weather satellite data to estimate these trends. Unfortunately, these satellite data were never designed with the accuracy of climate change in mind: the solar sensors that Dr. Pinker's work uses are known to degrade by several percent per year while in orbit, and have no on-board calibration systems. Yet the trends he puts faith in are 1% per decade, well below the accuracy of these instruments. As a result, the confidence in any of the geostationary data sets is based primarily on comparing their trends with highly calibrated radiation budget instruments (e.g. ERBE, CERES in Wong et al., 2006), and with ensembles of many surface radiation sites (e.g. Hinkelman et al, 2009). These comparisons show that the trends in Pinker for solar radiation are greatly exaggerated (Hinkelman et al., 2009). In fact, the "trend" from 1983 to 2004 is less than 0.25 Wm^{-2} per decade in SW reflected flux (Hinkelman et al 2009): a factor of 4 smaller than those quoted by Lord Monckton. And again: reflected solar radiation trends must be considered with thermal infrared trends if natural variability is the argument (i.e. changes in clouds) as it is for Lord Monckton. There is always some level of compensation in solar and infrared radiation balance trends for clouds: they act in different directions: as a reflective cooling effect at solar wavelengths (reflecting sunlight back to deep space) and as a greenhouse warming effect in the thermal infrared (blocking the emission of thermal infrared radiation from the surface and lower atmosphere that the Earth uses to cool itself).
- d) The final check on how well we understand the Earth's radiative energy balance is the global net radiation (including both solar and thermal infrared components) of the Earth and how it changes over time. There is good agreement for the more accurate ERBS and CERES data for comparisons to ocean heat storage in-situ data from 1992 to 2004 (Wong et al, 2006). There is some inconsistency in more recent data for 2005 to 2009, (Trenberth, 2010), but this is not the time period considered in Lord Monckton's comments. The more recent inconsistency is under research by both the ocean and radiation science communities. An earlier inconsistency was shown to be caused primarily by the shift in the ocean in-situ observing system from an older technology (XBTs) to a newer technology (ARGO). It is a cautionary note that achieving climate change accuracy in all climate observing systems is a major challenge in accuracy and rigor of analysis, and requires independent confirmation of

surprising results. It also requires extensive expertise in understanding the strengths and weaknesses of the data sets used.

- e) We conclude that Lord Monckton's conclusions cannot be supported by climate physics (it ignores the infrared radiation that could offset or even change the overall sign of the result), nor is it supported by more accurate versions of the data he used (Pinker et al. 2005).

APPENDIX C

Additional Authoritative Material

“Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia” Authors: Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations; National Research Council (Dr. Susan Solomon, Chair). Published by the National Academies Press.

“America’s Climate Choices: Advancing the Science of Climate Change” Authors: COMMITTEE ON AMERICA’S CLIMATE CHOICES: PANEL ON ADVANCING THE SCIENCE OF CLIMATE CHANGE ; National Research Council. (Dr. Pamela Matson, Chair). Published by the National Academies Press.

“America’s Climate Choices: Advancing the Science of Climate Change” Authors: COMMITTEE ON AMERICA’S CLIMATE CHOICES: PANEL ON LIMITING THE MAGNITUDE OF FUTURE CLIMATE CHANGE ; National Research Council. (Dr. Robert Fri, Chair). Published by the National Academies Press.

The Copenhagen Diagnosis: Updating the World on the Latest Climate Science : 2009 I. Allison, N.L. Bindoff, R.A. Bindshadler, P.M. Cox, N. de Noblet, M.H. England, J.E. Francis, N. Gruber, A.M. Haywood, D.J. Karoly, G. Kaser, C. Le Quéré, T.M. Lenton, M.E. Mann, B.I. McNeil, A.J. Pitman, S. Rahmstorf, E. Rignot, H.J. Schellnhuber, S.H. Schneider, S.C. Sherwood, R.C.J. Somerville, K. Steffen, E.J. Steig, M. Visbeck, A.J. Weaver. The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 60pp.

Arctic Climate Impact Assessment Scientific Report, Project Director, John E. Walsh, University of Alaska, Fairbanks, 2007.

State of the Climate in 2009, Published by the National Oceanic and Atmospheric Administration. Appeared in the Bulletin of the American Meteorological Society (BAMS), Vol. 91, 2010.

Global Climate Change Impacts in the United States, published by the United States Global Change Research Program, June 16, 2009.

APPENDIX D

Full Text of Written Testimony of Christopher Monckton

The following testimony was downloaded from the Website of the House Select Committee on Energy Independence and Global Warming

Testimony of The Viscount Monckton of Brenchley Before Congress, 6 May 2010

The Select Committee, in its letter inviting testimony for the present hearing, cites various scientific bodies as having concluded that –

1. The global climate has warmed;
2. Human activities account for most of the warming since the mid-20th century;
3. Climate change is already causing a broad range of impacts in the United States;
4. The impacts of climate change are expected to grow in the coming decades.

The first statement requires heavy qualification and, since the second is wrong, the third and fourth are without foundation and must fall.

The Select Committee has requested answers to the following questions:

1. What are the observed changes to the climate system?

Carbon dioxide concentration: In the Neoproterozoic Era, ~750 million years ago, dolomitic rocks, containing ~40% CO₂ bonded not only with calcium ions but also with magnesium, were precipitated from the oceans worldwide by a reaction that could not have occurred unless the atmospheric concentration of CO₂ had been ~300,000 parts per million by volume. Yet in that era equatorial glaciers came and went twice at sea level.

Today, the concentration is ~773 times less, at ~388 ppmv: yet there are no equatorial glaciers at sea level. If the warming effect of CO₂ were anything like as great as the vested-interest groups now seek to maintain, then, even after allowing for greater surface albedo and 5% less solar radiation, those glaciers could not possibly have existed (personal communication from Professor Ian Plimer, confirmed by on-site inspection of dolomitic and tillite deposits at Arkaroola Northern Flinders Ranges, South Australia).

In the Cambrian Era, ~550 million years ago, limestones, containing some 44% CO₂ bonded with calcium ions, were precipitated from the oceans. At that time, atmospheric CO₂ concentration was ~7000 ppmv, or ~18 times today's (IPCC, 2001): yet it was at that time that the calcite corals first achieved algal symbiosis. In the Jurassic era, ~175 million years ago, atmospheric CO₂ concentration was ~6000 ppmv, or ~15 times today's (IPCC, 2001): yet it was then that the delicate aragonite corals came into being.

Therefore, today's CO₂ concentration, though perhaps the highest in 20 million years, is by no means exceptional or damaging. Indeed, it has been argued that trees and plants have been part-starved of CO₂ throughout that period (Senate testimony of Professor Will Happer, Princeton University, 2009). It is also known that a doubling of today's CO₂ concentration, projected to occur later this century (IPCC, 2007), would increase the yield of some staple crops by up to 40% (lecture by Dr. Leighton Steward, Parliament Chamber, Copenhagen, December 2009).

Global mean surface temperature: Throughout most of the past 550 million years, global temperatures were ~7 K (13 F°) warmer than the present. In each of the past four interglacial warm periods over the past 650,000 years, temperatures were warmer than the present by several degrees (A. A. Gore, *An Inconvenient Truth*, 2006).

In the current or Holocene warm period, which began 11,400 years ago at the abrupt termination of the Younger Dryas cooling event, some 7500 years were warmer than the present (Cuffey & Clow, 1997), and, in particular, the medieval, Roman, Minoan, and Holocene Climate Optima were warmer than the present (Cuffey & Clow, 1997.) The “global warming” that ceased late in 2001 (since when there has been a global cooling trend for eight full years) had begun in 1695, towards the end of the Maunder Minimum, a period of 70 years from 1645-1715 when the Sun was less active than at any time in the past 11,400 years (Hathaway, 2004). Solar activity increased with a rapidity unprecedented in the Holocene, reaching a Grand Solar Maximum during a period of 70 years from 1925-1995 when the Sun was very nearly as active as it had been at any time in the past 11,400 years (Hathaway, 2004; Usoskin, 2003; Solanki, 2005).

The first instrumental record of global temperatures was kept in Central England from 1659. From 1695-1735, a period of 40 years preceding the onset of the Industrial Revolution in 1750, global temperatures, rose by 2.2 K (4 F°). Yet global temperatures have risen by only 0.65 K (1.2 F°) since 1950, and 0.7 K (1.3 F°) in the whole of the 20th century. Throughout the 21st century, global temperatures have followed a declining trend. Accordingly, neither global mean surface temperature nor its rates of change in recent decades have been exceptional, unusual, inexplicable, or unprecedented.

Ocean “acidification”: It has been suggested that the oceans have “acidified” – or, more correctly, become less alkaline – by 0.1 acid-base units in recent decades. However, the fact of a movement towards neutrality in ocean chemistry, if such a movement has occurred, tells us nothing of the cause, which cannot be attributed to increases in CO₂ concentration. There is 70 times as much CO₂ dissolved in the oceans as there is in the atmosphere, and some 30% of any CO₂ we add to the atmosphere will eventually dissolve into the oceans. Accordingly, a doubling of CO₂ concentration, expected later this century, would raise the oceanic partial pressure of CO₂ by 30% of one-seventieth of what is already there. And that is an increase of 0.4% at most. Even this minuscule and chemically-irrelevant perturbation is probably overstated, since any “global warming” that resulted from the doubling of CO₂ concentration would warm the oceans and cause them to outgas CO₂, reducing the oceanic partial pressure.

Seawater is a highly buffered solution – it can take up a huge amount of dissolved inorganic carbon without significant effect on pH. There is not the slightest possibility that the oceans could approach the neutral pH of pure water (pH 7.0), even if all the fossil fuel reserves in the world were burned. A change in pH of 0.2 units this century, from its present 8.2 to 8.0, even if it were possible, would leave the sea containing no more than 10% of the “acidic” positively-charged hydrogen ions that occur in pure water. If ocean “acidification” is happening, then CO₂ is not and will not be the culprit.

2. What evidence provides attribution of these changes to human activities?

In the global instrumental record, which commenced in 1850, the three supradecadal periods of most rapid warming were 1860-1880, 1910-1940, and 1975-2001. Warming rates in all three periods were identical at ~0.16 K (0.3 F°) per decade.

During the first two of these three periods, observations were insufficient to establish the causes of the warming: however, the principal cause cannot have been atmospheric CO₂ enrichment, because, on any view, mankind's emissions of CO₂ had not increased enough to cause any measurable warming on a global scale during those short periods.

In fact, the third period of rapid global warming, 1975-2001, was the only period of warming since 1950. From 1950-1975, and again from 2001-2010, global temperatures fell slightly (HadCRUTv3, cited in IPCC, 2007).

What, then, caused the third period of warming? Most of that third and most recent period of rapid warming fell within the satellite era, and the satellites confirmed measurements from ground stations showing a considerable, and naturally-occurring, global brightening from 1983-2001 (Pinker et al., 2005).

Allowing for the fact that Dr. Pinker's result depended in part on the datasets of outgoing radiative flux from the ERBE satellite that had not been corrected at that time for orbital decay, it is possible to infer a net increase in surface radiative flux amounting to 0.106 W m⁻² year⁻¹ over the period, compared with the 0.16 W m⁻² year⁻¹ found by Dr. Pinker.

Elementary radiative-transfer calculations demonstrate that a natural surface global brightening amounting to ~1.9 W m⁻² over the 18-year period of study would be expected – using the IPCC's own methodology – to have caused a transient warming of 1 K (1.8 F°). To put this naturally-occurring global brightening into perspective, the IPCC's estimated total of all the anthropogenic influences on climate combined in the 256 years 1750-2005 is only 1.6 W m⁻².

Taking into account a further projected warming, using IPCC methods, of ~0.5 K (0.9 F°) from CO₂ and other anthropogenic sources, projected warming of 1.5 K (2.7 F°) should have occurred.

However, only a quarter of this projected warming was observed, suggesting the possibility that the IPCC may have overestimated the warming effect of greenhouse gases fourfold. This result is in line with similar result obtained by other methods: for instance, Lindzen & Choi (2009, 2010 submitted) find that the warming rate to be expected as a result of anthropogenic activities is one-quarter to one-fifth of the IPCC's central estimate.

There is no consensus on how much warming a given increase in CO₂ will cause.

3. Assuming *ad argumentum* that the IPCC's projections of future warming are correct, what policy measures should be taken?

Warming at the very much reduced rate that measured (as opposed to merely modeled) results suggest would be 0.7-0.8 K (1.3-1.4 F°) at CO₂ doubling. That would be harmless and beneficial – a doubling of CO₂ concentration would increase yields of some staple crops by 40%. Therefore, one need not anticipate any significant adverse impact from CO₂-induced "global warming". "Global warming" is a non-problem, and the correct policy response to a non-problem is to have the courage to do nothing.

However, *ad argumentum*, let us assume that the IPCC is correct in finding that a warming of 3.26 ± 0.69 K (5.9 ± 1.2 F°: IPCC, 2007, ch.10, box 10.2) might occur at CO₂ doubling. We generalize this central prediction, deriving a simple equation to tell us how much warming the IPCC would predict for any given

change in CO₂ concentration –

$$\Delta T_s \approx (8.5 \pm 1.8) \ln(C/C_0) \text{ F}^\circ$$

Thus, the change in surface temperature in Fahrenheit degrees, as predicted by the IPCC, would be 6.7 to 10.3 (with a central estimate of 8.5) times the logarithm of the proportionate increase in CO₂ concentration. We check the equation by using it to work out the warming the IPCC would predict at CO₂ doubling: $8.5 \ln 2 \approx 5.9 \text{ F}^\circ$.

Using this equation, we can determine just how much “global warming” would be forestalled if the entire world were to shut down its economies and emit no carbon dioxide at all for an entire year. The atmospheric concentration of CO₂ is 388 parts per million by volume. Our emissions of 30 bn tons of CO₂ a year are causing this concentration to rise at 2 ppmv/year, and this ratio of 15 bn tons of emissions to each additional ppmv of CO₂ concentration has remained constant for 30 years.

Then the “global warming” that we might forestall if we shut down the entire global carbon economy for a full year would be $8.5 \ln[(388+2)/388] = 0.044 \text{ F}^\circ$. At that rate, almost a quarter of a century of global zero-carbon activity would be needed in order to forestall just one Fahrenheit degree of “global warming”.

Two conclusions ineluctably follow. First, it would be orders of magnitude more cost-effective to adapt to any “global warming” that might occur than to try to prevent it from occurring by trying to tax or regulate emissions of carbon dioxide in any way.

Secondly, there is no hurry. Even after 23 years doing nothing to address the imagined problem, and even if the IPCC has not exaggerated CO₂'s warming effect fourfold, the world will be just 1 F° warmer than it is today. If the IPCC has exaggerated fourfold, the world can do nothing for almost a century before global temperature rises by 1 F°.

There are many urgent priorities that need the attention of Congress, and it is not for me as an invited guest in your country to say what they are. Yet I can say this much: on any view, “global warming” is not one of them.