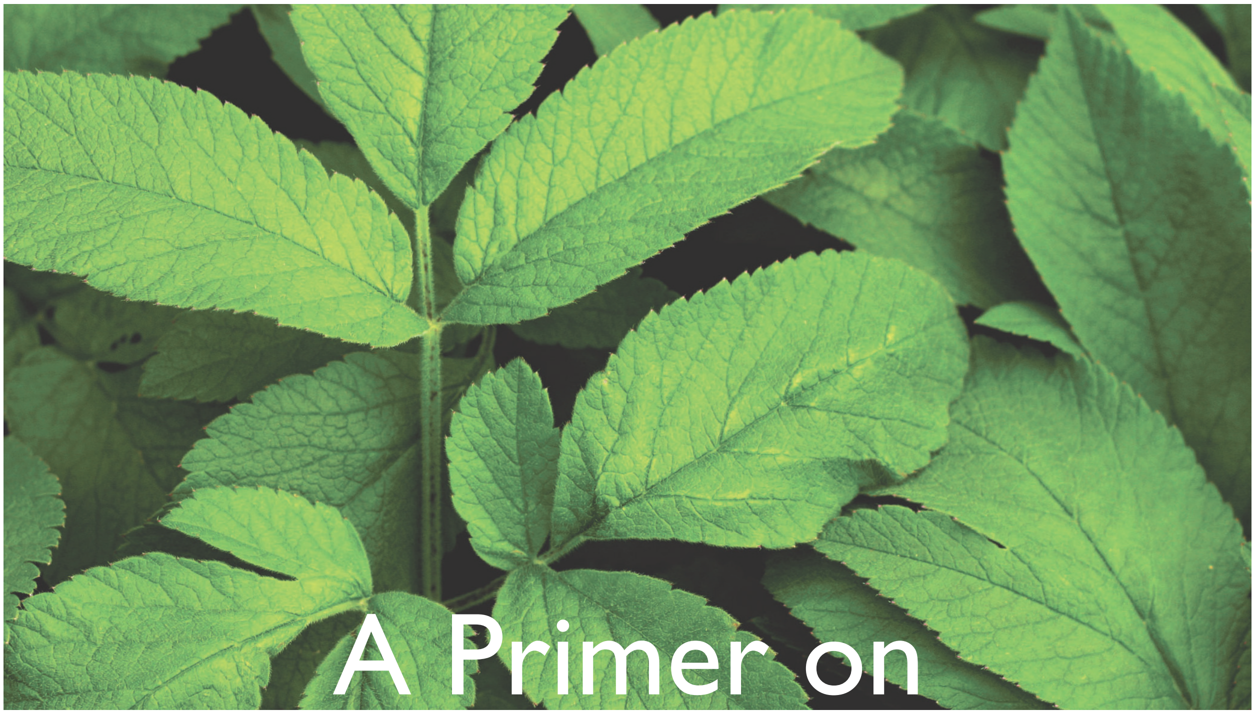
A Primer on Carbon Dioxide and Climate

CO2 COALITION



A Primer on Carbon Dioxide and Climate

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Introduction

The public requires an informed, dispassionate discussion of how our planet will be affected by CO_2 released from the combustion of fossil fuel and other sources. In a white paper, entitled *Carbon Dioxide Benefits the World; See for Yourself* the CO_2 Coalition, a new and independent non-profit organization summarized the scientific case that additional CO_2 will be a net benefit for the world. Following the words of the United States Declaration of Independence, the Coalition believes that "a decent respect to the opinions of mankind" requires that they should declare the causes which impel them to this politically incorrect view—and in more detail than is appropriate for a White Paper. That is the purpose of the present paper, a *A Primer on Carbon Dioxide and Climate*.

Atmospheric water, H_2O, as vapor and clouds, is by far the most important source of greenhouse warming of the Earth's surface. Atmospheric CO_2 also contributes to greenhouse warming but much less than H_2O. More CO_2 will cause some additional warming, both directly and with amplification (or possibly attenuation) by feedbacks, which are still very poorly understood. In addition to modest warming from more CO_2, the earth's temperature is affected by many other factors. Among these are solar activity, the distribution of atmospheric water vapor and clouds, atmospheric and ocean circulation patterns, volcanic activity, slow changes in the earth's orbital parameters. Whether more CO_2 will be good or bad for life on earth does not depend on the mere existence of greenhouse warming and related effects from more CO_2, like changes in the pH of the oceans, and benefits to plant growth. The issue is the magnitudes of the effects. As detailed below, we are persuaded that the net effects of increasing CO_2 will be very good for the world, and especially for its human population.

1. Global Warming: A Brief History and Future Prospects

Over the past 30 years, scientists have failed to significantly advance our understanding of the critical parameter: the sensitivity of atmosphere temperature to changes in CO_2 *concentrations.*

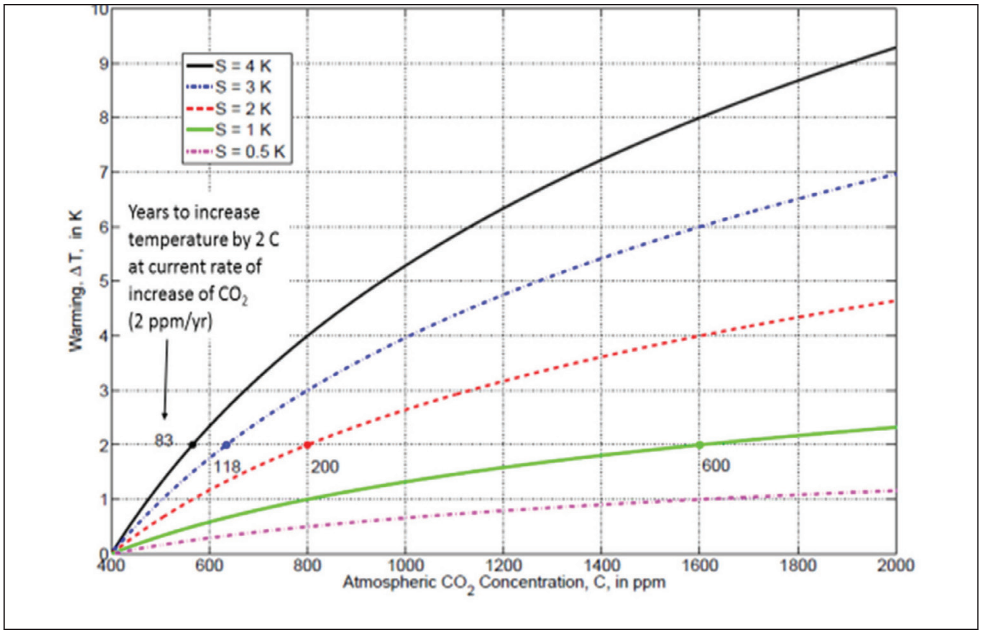
Svante Arrhenius, the great Swedish chemist, may have been the first to make a quantitative estimate of warming from CO_2. In his pioneering paper, *On the Influence of Carbonic Acid in the Air Upon the Temperature of the Ground* (1896), Arrhenius claimed that decreasing CO_2 to 2/3 of its then current value would cause the surface temperature to fall by 3.5 C, while increasing CO_2 by a factor of 3/2 would cause the temperature to increase by 3.4 C.

Summarizing his estimates, Arrhenius writes[3] "Thus, if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase very nearly in arithmetic progression." This remarkable conjecture implies a logarithmic dependence of the temperature increase on the CO_2 concentration, C, as represented by **Equation (1)**. T_1 and T_2 represent the Earth's equilibrium temperatures at CO_2 concentrations, C_1 and C_2, respectively (both assumed to be more than a few ppm), and $\log_2(x)$ denotes the base-2 logarithm of x (i.e., $\log_2(2) = 1$).

$$\Delta T = S \log_2(C_2/C_1) \quad \text{where } \Delta T = T_2 - T_1 . \qquad (1)$$

The parameter, S, is the doubling sensitivity, or equilibrium climate sensitivity, and it is normally given in degrees Celsius. The Earth's average surface temperature will eventually increase by an amount S of the atmospheric concentration if CO_2 were to double. The warmings from Equation (1) are plotted in **Figure 1** for a starting CO_2 concentration, C_1 = 400 parts per million by volume (ppm), for a range of possible doubling sensitivities, and assuming atmospheric levels of CO_2 continue to increase indefinitely at the current rate of 2 ppm/year.

Figure 1. Warming from Atmospheric CO_2,
for Assumed Doubling Sensitivities from Equation (1)*



*The IPCC's range of uncertainty in the value of S extends from 1.5 C to 4.5 C, with a central value of 3.0 C. However, various empirical observations indicate that the doubling sensitivity is close to its "feedback-free" value of S = 1 C. While Figure 1 indicates the number of years needed to increase global temperature by 2 C, these are underestimates, especially for the high sensitivities, because they do not include the substantial delays (decades to centuries) needed for the oceans to equilibrate with the atmosphere.

Source: (R.S. Lindzen (1995) *Constraining possibilities versus signal detection,* in Natural Climate Variability on Decade-to-Century Time Scales, Ed. D.G. Martinson, pp 182-186 National Academy Press, (Washington, DC, 1995)

The change of temperature, ΔT, in Equation (1) is the value averaged over the Earth's entire surface. It is a very small number compared with the temperature differences between day and night, or between winter and summer, or over the various solar and oceanic cycles at most locations on Earth. More CO_2 hinders atmospheric radiative heat transport but has no direct effect on convective heat transport. Since radiative heat transport is most important at night and near the poles, the surface warming from more CO_2 is be expected to be greater at night than during the day, and greater near the poles than near the equator,

If a 50% increase of CO_2 were to increase the temperature by 3.4 C—as in Arrhenius's aforementioned example—the doubling sensitivity would be S = 5.8 C. However, in his subsequent book, *Worlds in the Making; the Evolution of the Universe* (1906), Arrhenius again states the logarithmic law of warming, but with a somewhat smaller climate sensitivity, S = 4 C: "If the quantity of carbon dioxide in the air should sink to one half its present percentage, the temperature would fall by 4 K [i.e., degrees Kelvin, the same change as in degrees Celsius]; a diminution to one-quarter would reduce the temperature by 8 K. On the other hand any doubling of the percentage of carbon dioxide in the air would raise the temperature of the Earth's surface by 4 K and if the carbon dioxide were increased by four fold, the temperature would rise by 8 K."

Many subsequent studies of the physics of greenhouse gases have confirmed Arrhenius's conjecture that the temperature varies with the logarithm of the concentration of atmospheric CO_2, as in Equation (1). The logarithmic dependence arises from a peculiar detail of how CO_2 absorbs infrared radiation of various frequencies[5]—a peculiarity not shared with other greenhouse gases, particularly the most important, water vapor (H_2O), or the far less important greenhouse gas, methane (CH_4).

The logarithmic dependence is an important result in its own right: it reveals that adding more CO_2 to the atmosphere is a process of diminishing returns. For example, raising the value of C by 250 ppm from a starting value of 250 ppm will warm the Earth by an amount, S; but raising C by another 250 ppm, from 500 ppm to 750 ppm, will cause additional warming of only 0.58 S.

The numerical value of S—the sensitivity of the atmosphere to changes in C—is influenced by complex, poorly understood interactions between the atmosphere, the surface, the oceans, water vapor and clouds, and perhaps by extraterrestrial influences like solar activity or the cosmic ray background, that may influence cloud nucleation. Arrhenius's limited understanding of the absorption of radiation by CO_2, as well as the structure and dynamics of the atmosphere and its interactions with land and ocean, allowed him to make only an educated guess of the doubling sensitivity.

More than a century later—and after tens of billions of dollars spent on climate science—the value of S remains largely an educated guess. The IPCC's most recent report (2013) states: "equilibrium climate sensitivity (the doubling sensitivity) is likely in the range 1.5 K–4.5 K (high confidence)."[6] Remarkably this range is unchanged from the IPCC's first report (1990), which was based on research results available at that time, much of which was performed in the 1980s.

2. How Much Warming?

Because the associated science remains poorly understood, the computer models used to predict future warming do not incorporate known natural phenomena that significantly influence temperatures. To compensate, the models use a variety of special parametrizations, or "fudge factors."

Correctly estimating the magnitude of future atmospheric warming depends, critically, on the value of S. It also depends on future economic growth, technology, and energy-demand scenarios as well as the many natural factors that influence CO_2 emissions and absorption from the atmosphere. Such variables have large lead times and may imply large future investments.

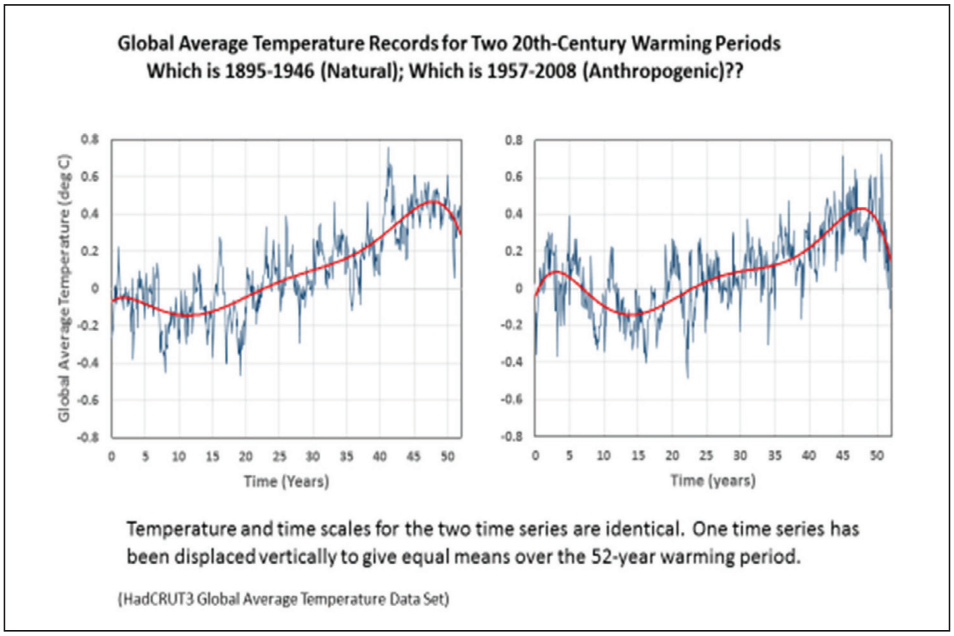
This discussion focuses on observational evidence related to the magnitude of S, the doubling sensitivity. Given knowledge of S, one can then estimate scientifically plausible future warming for various assumptions regarding future emissions.

High estimates of S derive primarily from computer climate models, not from empirical data. These models attempt to simulate the Earth's climate system in as much detail as possible. However, even with the most powerful supercomputers, science is not close to incorporating key climate processes and phenomena in a way that mirrors reality. For example, energy-exchange processes associated with evaporation, precipitation, and cloud formation—on a variety of dimensional and time scales—are extremely complex, poorly understood, and unreliably simulated.

Such models do not include significant natural internal variability associated with processes operating on time scales of less than a decade, several decades, or even centuries.[7] Therefore models do not include natural variability that could offset, and at times exceed, the effects of human activities. The IPCC's widely publicized finding that the recent increases of CO_2 and other greenhouse gases are the cause of most of the Earth's warming in the last half of the 20th century requires that one assume that natural causes of past climate change have mysteriously ceased. But poorly understood natural factors caused large climate changes in the fairly recent past: for example, the Medieval Warm Period, when Vikings settled Greenland or the Little Ice Age when the settlements were frozen out, and severe weather conditions prevailed over much of the globe. The most natural explanation for the warming from 1980 to 2000, and the lack of significant warming since around 1995 is that modest warming from steadily increasing atmospheric CO_2 was amplified for a few decades by natural warming, like the interval 1980 to 2000, and then nearly cancelled for a few more decades, as in the interval from 1995 to the present.

The inability to include key elements of natural internal variability also affects the capacity of computer climate models to hindcast, that is, to replicate climate history, especially the warming that occurred in the first half of the 20th century. During roughly 1910–40, atmospheric CO_2 levels were too small to have caused much warming. **Figure 2**—which shows global average temperatures during 1895–1946 and 1957–2008—demonstrates the problem faced by computer climate models. Figure 2 shows nearly identical temperature rises over identical 52-year periods: the later warming episode has been ascribed by climate modelers primarily to human greenhouse gas emissions, especially CO_2; yet the earlier episode had an uncannily similar temperature rise, in magnitude and trajectory, despite the absence of significant CO_2 increases at the time. The earlier warming episode, began near the end of the Little Ice Age, a period that began about the year 1400 and ended around 1900, and coincided with several centuries of greatly diminished solar activity.[8] Models have difficulty reproducing this earlier episode and must resort to a number of special adjustments to compensate.[9]

Figure 2. Average Global Temperature During the 20th Century's Two Warming Periods*



*The warming from 1957–2008 is on the left. The irregular blue lines are monthly data. The smooth red lines are polynomial fits to the monthly data. The earlier warming, from 1895 to 1946, occurred before significant CO_2 increases and must come from other, natural influences.

Source: HadCRUT3 data set, Climatic Research Unit of the University of East Anglia

To reproduce the later 20th century warming using a high value of S (3 C or larger), as well as little in the way of natural internal variability, climate models must assume that cooling anthropogenic aerosols canceled much of the warming from more CO_2 Without aerosol cooling, models would predict substantially more warming than has been observed.

Volcanic aerosols, such as those that arose from the Pinatubo eruption of 1991, are observed to be a temporary cooling source.[10] Climate models assume longer-term cooling effects from anthropogenic aerosols, mainly a byproduct of combustion. The behavior of aerosols, especially their interaction with clouds and precipitation, is poorly understood. The IPCC consistently identifies aerosols as the largest source of uncertainty in the calculation of radiative forcing—the quantity that drives climate change in climate models.[11]

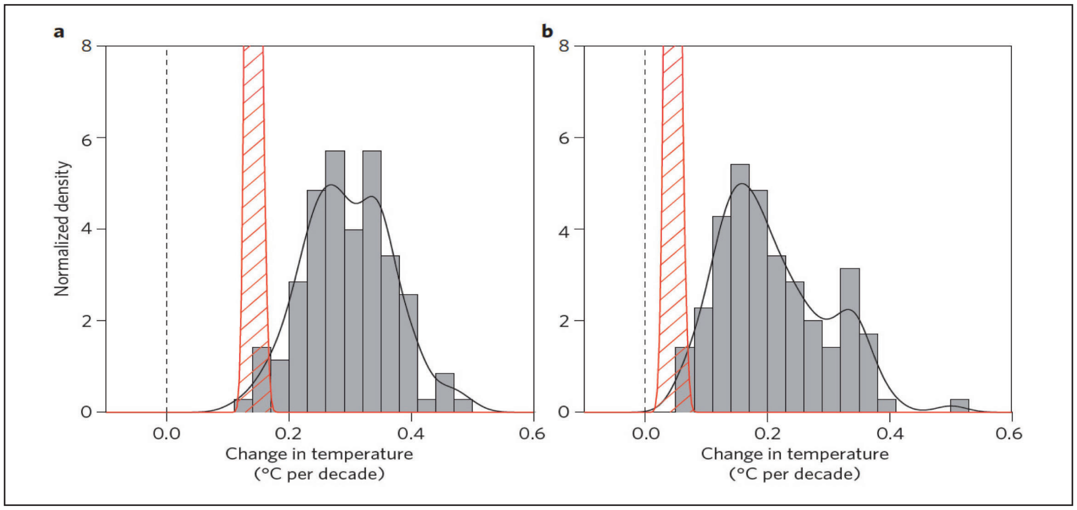
Different models use different values[12] of aerosol cooling, so aerosols are essentially a fudge factor to enable models to reproduce the late 20th century warming while retaining a high value of S. The IPCC has further obscured the fudge-factor nature of aerosol cooling by defining it as part of the calculated anthropogenic forcing. Without a solid understanding of the aerosol cooling factor—and without consistency in its magnitude among different models—the IPCC's claim that climate models confirm that the late 20th century warming arose mainly from human greenhouse gas emissions has little scientific merit. Given the incompleteness and uncertainties of current climate models, analysis and evaluation of their performance must fall back on the fundamental feature of the scientific method: comparing prediction to subsequent observation.

Contrary to the predictions of most climate models, there has been little, if any, recent warming of the Earth's surface: satellite measurements, as well as published statistical analyses,[13] show that the lower atmosphere and the Earth's surface have experienced virtually no warming for 20 years or more.[14] This absence of warming—a flat-lining of global temperature—has occurred despite a simultaneous 13% increase in atmospheric CO_2.

On page 13 of the Summary for Policy Maker of the Fifth Assessment Report of the IPCC we read "The total anthropogenic radiative forcing best estimate for 2011 is 43% higher than that reported in [the 4th Assessment Report of 2007] for the year 2005. This is caused by a combination of continued growth in most greenhouse gas concentrations and improved estimates of RF [radiative forcing] by aerosols indicating a weaker net cooling effect (smaller negative RF)." Thus, the radiative forcing from greenhouse gases was actually 43% higher than the IPCC estimated six years earlier (partly because the aerosol cooling component was realized to be smaller than previously thought). Yet this large computed increase in radiative forcing produced little, if any, increase in global temperature.

The discrepancy between models and observations is summarized by Fyfe et al (**Figure 3**)[15]; the actual warming during 1993–2012 was about one-half of the predicted value; the warming during 1998–2012 was about one-fifth of that predicted. The actual discrepancy is likely worse than indicated by Fyfe et al, who used surface temperature records plagued with systematic errors, such as urban heat island effects arising from poor station siting[16] and inhomogeneities[17] that give a false additional warming trend to the Earth's land surface temperature.[17] Satellite data[18] offer more accurate, unbiased measurements of atmospheric temperature and display generally smaller longer-term temperature trends than surface data sets.

Figure 3. Trends in Global Mean Temperature, 1993–2012 (a) and 1998–2012 (b)*



*Histograms of observed trends (red hatching) from the HadCRUT4 data set. Histograms of model trends (gray bars) are based on 117 simulations by climate models; black curves are smoothed versions of the histograms. The ranges of observed trends represent observational uncertainty and errors; ranges for the models' trends reflect forcing uncertainties, as well as differences in model responses to external forcing (the doubling sensitivity, S).

Source: (J.C Fyfe et al, *Overestimated Global Warming over the Past 20 Years,* Nature Climate Change 3, 767 (2013)

The number and diversity of explanations for the discrepancies between predicted and observed temperature changes shown in Fig. 3, shows that the science is far from "settled," as enthusiasts frequently claim. In fact, the simplest and most likely explanation for the predictive failure of climate models is that the IPCC's central value for doubling sensitivity, (S = 3.0 C), is far too large.

With a smaller value of S, normal, natural processes become more likely to offset the effect of increasing CO_2.—this is what we have probably observed for the last 20 years. Further, as discussed below, various empirical studies utilizing differing approaches and assumptions, find values of S of around 1 C—below the lower limit of the IPCC's uncertainty range.

What is the actual value of S? If one assumes negligible overall feedback, that is negligible amplification or attenuation of the warming from CO_2 alone, the doubling sensitivity can be calculated to be about S = 1 C, well below the central value of 3 C and far below the upper end of 4.5 C. Empirical approaches using entirely different methods find a value of S of around 1 C—the value associated with vanishing net feedbacks. For example several investigations of the relationship between satellite measurements of changes in terrestrial outgoing radiation and short-term natural fluctuations in surface or atmospheric temperature show that the Earth cools itself off far more efficiently when warmed than is predicted by climate models.

Research probing the empirical relationship between the sun's influence on cosmic ray flux and terrestrial paleoclimate[21] has found strong correlations consistent with values of S of around 1.3 C, while an analysis of 20th century instrumental data found a best estimate of 0.9 C.[22] A recent study, covering the period 1750–2011 and using the IPCC's computed figures for radiative forcing, finds S = 1.6 C,[22] with recent findings of smaller aerosol cooling reducing the best estimate to S= 1.45 C.[24] All of these findings, though differing in methodology and approach, were anchored in the analysis and interpretation of empirical data.

The much larger doubling sensitivities claimed by the IPCC arise from the climate models' assumption of large positive feedbacks that amplify the basic radiative warming mechanism. To achieve the IPCC's central estimate of S = 3 C, the sum of all feedbacks must raise S from its feedback-free value of about 1 C by a factor of 3—and even more to reach its upper limit of 4.5 C.

The most popular proposed feedback mechanism arises from a computed increase of water vapor at higher altitudes of the atmosphere. Changes in cloudiness can provide significant positive feedback that increases S; or negative feedback that decreases S, depending on the details of the response of high and low clouds to the basic radiative warming mechanism. The complexity and difficulty in modeling changes in clouds is responsible for much of the variation between models, and is likely largely responsible for much of the average model's greatly exaggerated values of S.[25] It is therefore not surprising that different assumptions and different theoretical approaches to physical processes in models yield greatly different results for S. For example, a recent climate model formulation by Harde yields the value S = 0.6 C, even lower than the aforementioned studies.[26]

A further methodological problem with the climate models that contributes to the lack of progress in reducing the uncertainty in S is the practice of treating variation between models as random noise, rather than as a source of information about the physics of climate. Treating variations as random noise leads to the idea of a model "ensemble average," wherein the broad envelope of the models' predictions represents only statistical uncertainty, not clues as to why some models do better than others. While an individual model's results are uncertain due to chaotic variations between runs, the practice of treating intramodel variation as statistical noise slows progress in understanding the physics of climate.

Net Assessment

The weight of empirical evidence, based on decades of data gathering and analysis, points to a doubling sensitivity, S, significantly smaller than the IPCC's central estimate of 3 C. As discussed, S may well be below even the lower end of the IPCC's range of 1.5 C. These differences have an enormous impact on the magnitude of future warming scenarios. A value of S = 1 C, the current rate of increase of atmospheric CO_2 (about 2 ppm per year) predicts only about 0.6 C global warming over the next century.

Put in perspective, this prospective future warming is less than the 20th century warming already recorded by surface temperature data sets. Since most projections call for CO_2 emissions to peak sometime this century, ultimately slowing the rate of increase of atmospheric CO_2, even this small warming may be an overestimate. In this paper, we take a CO_2-induced future warming of about 1 C as a notional expected value, with the realization that this number may well be overestimated.

This modest warming is well below that considered by economists analyzing possible economic costs from future warming. More typically, a 2.5 C–3 C rise, or more, is assumed as scripture. At values of 1 C, Tol's review [27] finds generally small net beneficial effects on global GDP, but with large attendant uncertainties. None of the studies include the positive effects of CO_2 fertilization and water-use efficiency on crop productivity, to be discussed later.

Though there is much less methane (CH_4) in the atmosphere than CO_2 (about 1.9 ppm vs. 400 ppm), on a per-molecule basis CH_4 should be a far stronger greenhouse gas than CO_2: whereas CO_2 is well into its saturation, or diminishing returns, regime—where the forcing is proportional only to the log of concentration (Equation (1))—the forcing from the much less abundant CH_4 is less "saturated." According to the IPCC, the current atmospheric radiative forcing from additional methane, relative to that in 1750, is fully half that of additional CO_2.[28]

The calculation of radiative forcing by methane in the atmosphere is complicated by two factors that create large uncertainty. First, in the actual atmosphere the infrared wavelengths corresponding to the key methane absorption band are dominated by a coincident strong water vapor absorption band, thereby limiting additional radiative forcing from methane. Second, unlike CO_2, methane is chemically active in the atmosphere: its decay products—ozone O_3, stratospheric water vapor, and a small amount of CO_2—are themselves greenhouse gases and contribute to radiative forcing.

To compute methane's radiative forcing, the reaction pathways must be known accurately for the conditions found in the atmosphere where the chemistry takes place. The radiative forcing of each end product in the atmosphere must then be computed accurately. Presumably these key uncertainties will be reduced with future research.

According to the IPCC, the total radiative forcing from all anthropogenic greenhouse gases is already nearly equivalent to the doubling of CO_2 relative to the pre-industrial era.[28] Yet we have not experienced global warming remotely near the level implied by the high doubling sensitivities proposed by the IPCC—another sign that global warming prospects have been exaggerated.

The temperature impact of trace greenhouse gases such as methane (CH4), nitrous oxide (N2O), and halocarbons (CFCs), must be reduced by the same approximate factor of three as for CO2, as discussed above. This is because the model-computed radiative forcings from these trace gases have been subjected to the same positive feedbacks used to exaggerate the climatic effects of CO_2 forcing.

3. Harmful Effects of CO_2

Widely available weather data fail to show evidence of the extreme effects extensively repeated in the popular media.

Hundreds of harmful effects have been ascribed to “climate change.” Virtually every unusual event or alleged trend has been “traced” to humanity’s impact on the climate, with the burning of fossil fuels typically singled out as the root cause. But much of the alleged effect is usually strongly influenced by factors other than climate change.

Consider asthma as an example. Its prevalence in the United States, especially in children, increased by nearly a factor of two in the late decades of the 20th century. This increase has since slowed, but asthma remains a major health problem. High levels of traditional air pollution, including indoor pollution, are implicated in rapidly developing countries, such as China.[29] Recent research has also implicated viruses in asthma attacks, as well as in the actual development of asthma.[30]

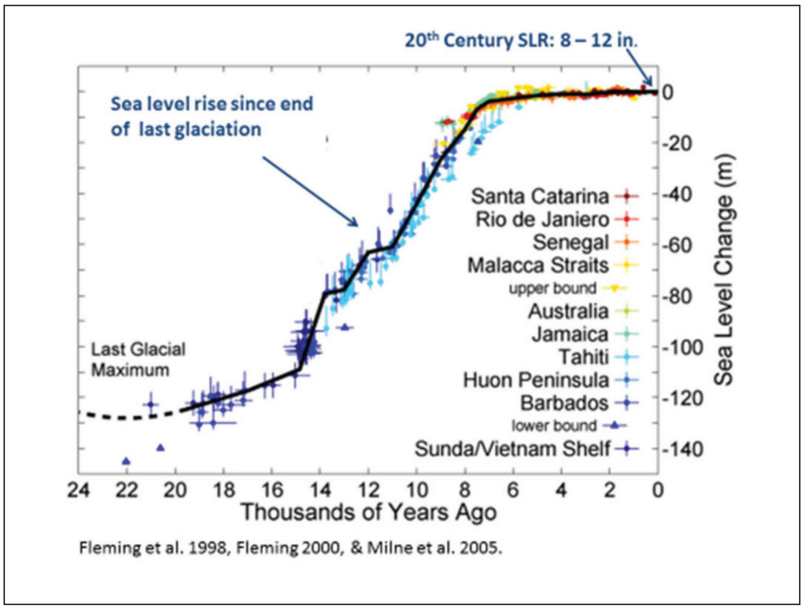
In 2011, the National Institutes of Health stated: “…we don’t know why asthma rates are rising….”[31] Nevertheless, an alleged link between asthma and “climate change” is now promoted by the current U.S. administration—the Centers for Disease Control and Prevention website links asthma prevalence to climate change, invoking an alleged correlation with global warming (e.g., more frost free days, longer pollen seasons) as a cause of increased allergens and rising asthma prevalence.[32] Yet there has been no global warming since around 1995. Further, because CO_2 partial pressures in human blood are around 40 Torr[33] in comparison to about 0.3 Torr for the current atmosphere with 400 ppm CO_2, doubling or quadrupling atmosphere concentrations of CO_2 cannot affect body chemistry.

All claims of harm from more CO_2 appear to lack scientific merit, but four require special attention because of their persistent coverage in the popular media and by government sources: sea level rise; Arctic sea ice melt; extreme weather; and ocean acidification. In the following we will summarize and assess the science for each of these.

Sea Levels

Historical data show that sea levels have been rising since the end of the last Ice Age (approximately 20,000 years ago). **Figure 4** illustrates the cumulative sea level rise—more than 400 feet—during this period. Early humans were able to walk to many places that are now islands, including Great Britain, Tasmania, and Sicily. It was also possible to walk from Siberia to Alaska. With the disappearance of the great land glaciers, the rate of sea level rise slowed substantially, averaging only 2–3 mm/year in the 20th century.

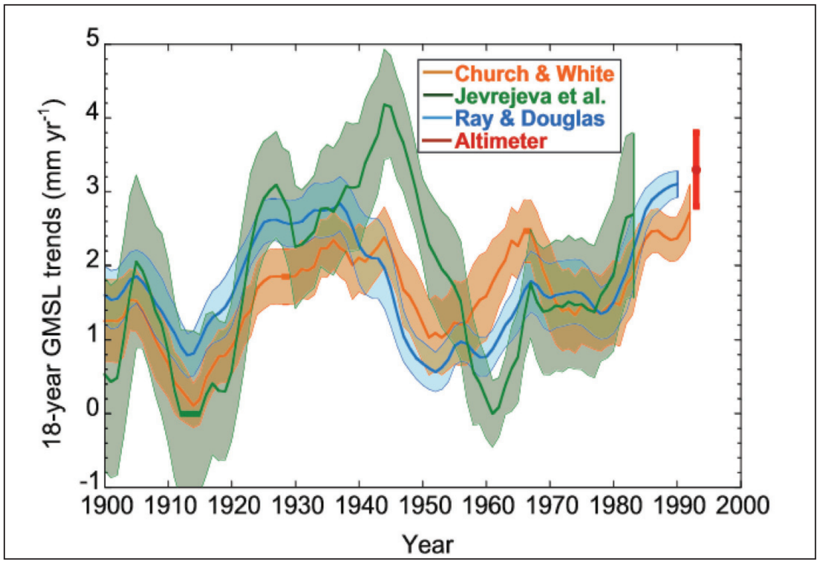
Figure 4. Sea level Rise Since the Last Glaciation



Source: K. Fleming et al., Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites, Earth and Planetary Science Letters Vol. 163, Issues 1-4 pp. 327-342 (1998).

Figure 5 shows detailed records, taken from the IPCC's Fifth Assessment Report, of the rate of global mean sea level (GMSL) rise in the 20th century and 21th century: the rate of sea level rise is clearly not uniform in recent times, varying substantially over decades. The rise in sea level also varies widely from place to place, with some locations actually experiencing a drop in sea level.[34]

Figure 5. Trends in Global Mean Sea Level*



*18-year tends estimated at one-year intervals. The shading represents the 90% confidence level. The vertical red bar represents the observed trend since 1993, per satellite altimetry, along with its 90% confidence level.

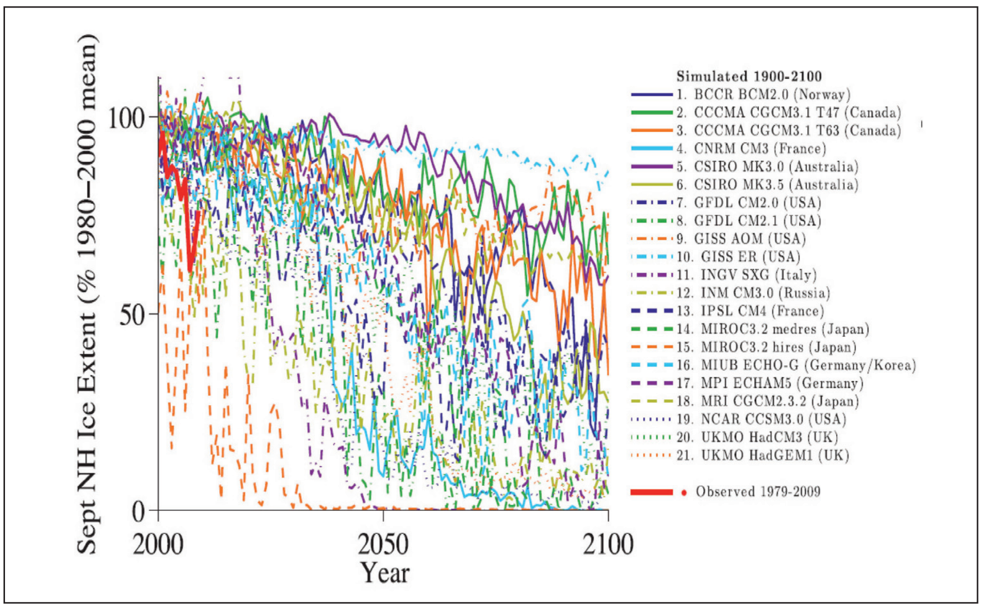
Data source: IPCC's Fifth Annual Report (2013), Working Group I, Figure 3.14

Figure 5 shows the pre-satellite era data joining smoothly with satellite altimetry measurements (beginning in 1993), and have since shown a steady increase of about 3.3 mm/year (or about 13 inches/century). There is no evidence of acceleration in the rate of sea level rise. In fact, the GMSL rise appears to have been as fast, or faster, in the mid-20th century as it is today—despite about 30% higher CO_2 now than in the mid-20th century and the subsequent warming of the last half of the 20th century. There is no evidence to support extreme claims of imminent coastline flooding, inundation of cities, or the disappearance of significant land areas. The empirical data on GMSL, as well as the outlook for only small future CO_2-induced warming suggest that fears of extreme and rapid GMSL rise are unfounded.

Arctic Sea Ice

The extent of Arctic sea ice, a popular "thermometer" for global warming, is made more vivid in the popular media by its possible connection to polar bear populations. As in the case of global temperature, climate models exhibit very high intra-model variability. **Figure 6** shows the projections of 21 models for the state of Arctic sea ice through the year 2100.[35] With such high variability, the utility of climate models as predictors of the future state of the Arctic appears very limited—and the value of empirical data, great.

Figure 6. Model Projections of the Rate of Arctic Sea-Level Loss*

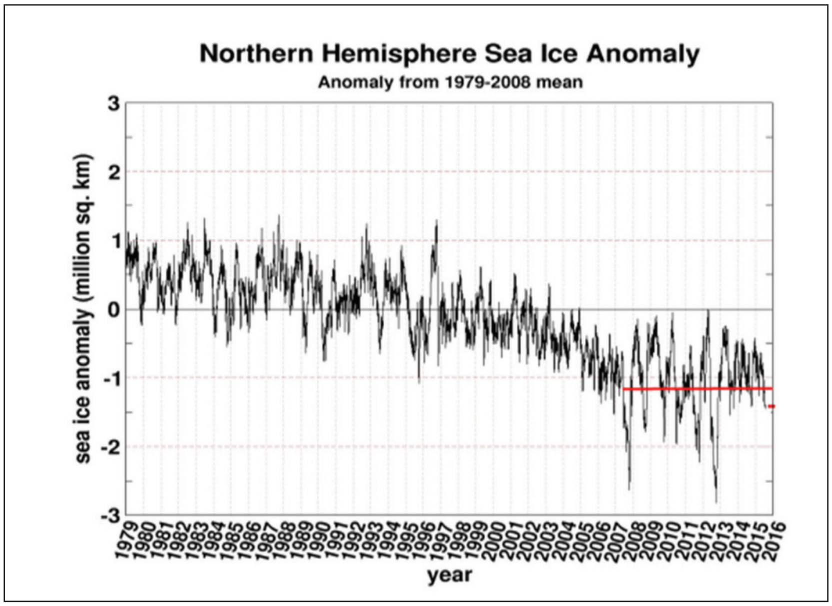


*September sea ice extent to the year 2100, relative to the 1980–2000 mean. Projections for the year 2100 vary from 85% (one model) ice cover to less than 1% ice cover (four models).

Source: I. Eisenman et al, Consistent Changes in the Sea Ice Seasonal Cycle in response to Global Warming, J. Climate 24, 20 5325-5335 (October 2011) doi: http://dx.doi.org/10.1175/2011JCLI4051.1

Figure 7 shows the extent of Arctic sea ice as monitored via satellite—the most accurate empirical data—since 1979. Since 2006, the trendline for Arctic sea ice has been constant, though punctuated by the large volatility that is characteristic of Arctic climate.

Figure 7. Arctic Sea Ice*



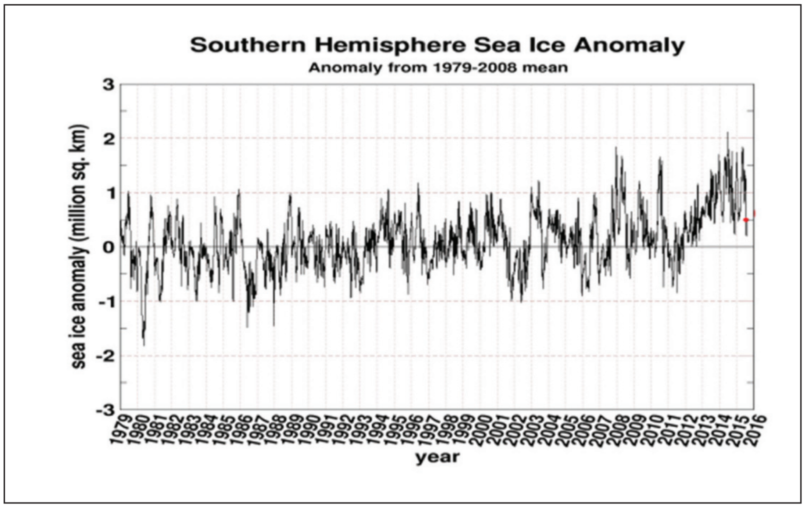
*The vertical axis represents the monthly departure of sea ice area, from its 1979–2008 mean. The post-1979 decline—followed by stabilization since the mid-2000s (horizontal red line)—is clearly visible.

Source: Cryosphere Today of the University of Illinois Polar Research Group

While the satellite data reveal declining sea ice corresponding to the late 20th century warming, there is controversy over the state of Arctic ice in the *early* 20th century. A study of Arctic temperatures, utilizing floating buoy temperature measurements in the pre-satellite era, found that the Arctic was warmer in the 1930s than at the end of the 20th century.[36] Between the 1930s temperature peak and the late 1960s, the Arctic displayed a rapid cooling of almost 2 C in only 30 years. The IPCC is aware of this issue and its Fifth Assessment Report states: “Arctic temperature anomalies in the 1930s were apparently as large as those in the 1990s and 2000s. There is still considerable discussion of the ultimate causes of the warm temperature anomalies that occurred in the Arctic in the 1920s and 1930s.”[37]

Thus, as with global average temperature, there is the unresolved problem of reconciling a significant early 20th century natural warming of the Arctic with a later (presumed) mostly anthropogenic warming. While the decline and subsequent stabilization of Arctic sea ice are generally consistent with climate model forecasts and the temperature history of the Arctic, Antarctic sea ice behavior has confounded the predictions of climate models. As shown in **Figure 8**, Antarctic sea ice actually *increased* substantially during the same period that Arctic ice declined.

Figure 8. Antarctic Sea Ice*



*The vertical axis represents the departure of sea ice area, from its 1979–2008 mean. Note the increase in sea ice area during the late 20th century warming and into the 21st century warming hiatus.

Source: Cryosphere Today of the University of Illinois Polar Research Group

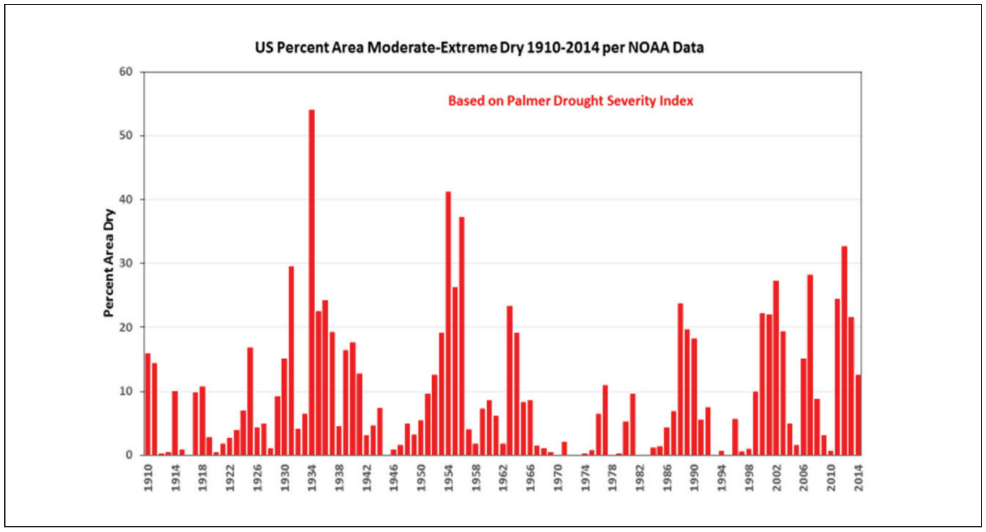
With the post 1979 Arctic sea-ice decrease and contemporaneous Antarctic sea-ice increase, the total global sea-ice area has remained constant, to within a few percent, throughout the late 20th century's warming period. Indeed, global sea ice has been essentially unchanged since 1979. The reasons for this unexpected result are the subject of ongoing research. Nevertheless, the empirical data give no indication of an impending disappearance of either Arctic or Antarctic sea ice. And with the outlook for only modest future warming from CO_2, the prospect of the ultimate disappearance of global sea ice due to CO_2 appears remote.

Extreme Weather

U.S. government agencies maintain detailed weather records. As with other aspects related to global warming, the empirical data on extreme weather events tell a story very different from that typically recounted in popular media. For example, the National Oceanic and Atmospheric Agency (NOAA) monitors drought and wet conditions across the United States. **Figure 9** and **Figure 10** show the data, since 1910, on the share of U.S. land area classified as under conditions of moderate-to-severe drought and moderate-to-severe excessive moisture, respectively.

Some areas are always subject to excessively dry or wet conditions; sometimes these conditions persist for extended periods. But there are no data to suggest an overall trend of any kind for drought conditions. A U.S. government report notes: "droughts have, for the most part, become shorter, less frequent, and cover a smaller portion of the U.S. over the last century."[38]

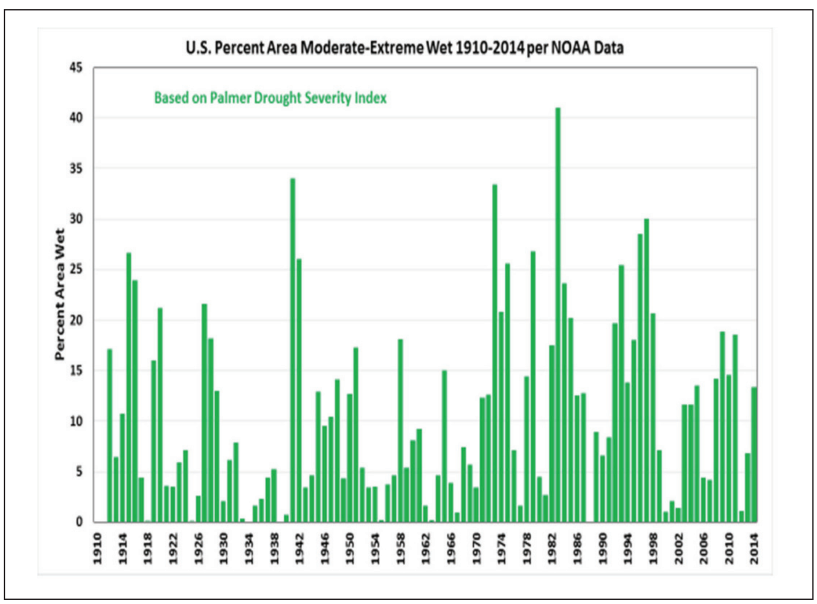
Figure 9. U.S. Land Area Facing Moderate-to-Extreme Drought Conditions*



*Though the Dust Bowl of the 1930s is visible, there is no discernible long term trend— there is a suggestion of possible cyclic effects.

Source: National Oceanic and Atmospheric Agency

Figure 10. U.S. Land Area Facing Moderate to Extreme Wet Conditions*

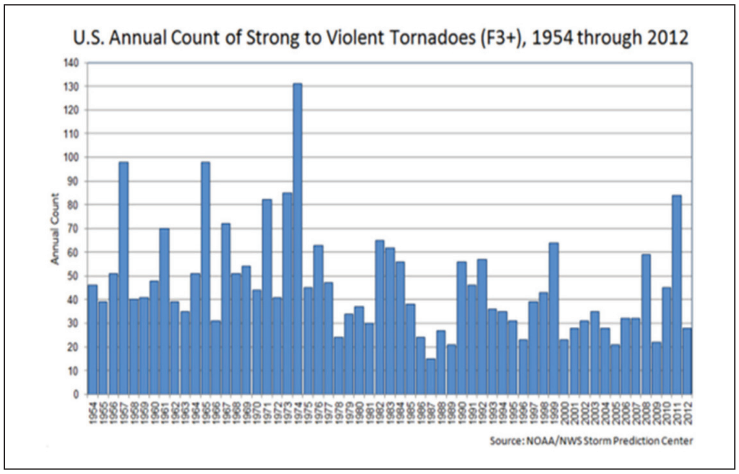


*Though there is significant year-to-year volatility, there may be a small upward trend in the percentage of wet lands. However, streamflow data from the USGS suggest that floods have not increased in the US in frequency or intensity since at least 1950.[38]

Source: National Oceanic and Atmospheric Agency

Deadly tornadoes strike the U.S. annually, primarily but not exclusively in the middle Mississippi valley. NOAA data on the number of strong tornadoes since 1954 are shown in **Figure 11**. Again, despite the late 20th century warming period, the data show no upward trend in strong tornadoes; in fact, there appears to be a slight downward trend in the frequency of strong tornadoes.

Figure 11. Strong Tornadoes in the U.S. Since 1954*

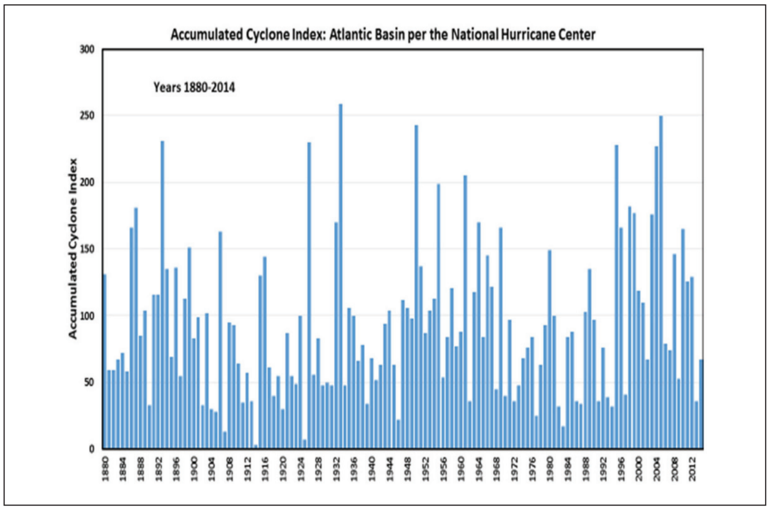


*Force F3 and greater on the Fujita scale. A slow decline in frequency appears to be visible. During this period, the total number of reported tornadoes—including weaker F1 and F2 tornadoes—rose because of the advent and deployment of radar-detection technology.

Source: National Oceanic and Atmospheric Agency

Hurricane landfalls in the U.S., such as Katrina in 2005, can inflict vast destruction. But U.S. government data show no trend in the number and intensity of Atlantic Basin tropical cyclones. **Figure 12** plots the accumulated cyclone energy (ACE) for Atlantic Basin tropical cyclones since 1880. The ACE index accounts for the number, intensity (sustained wind velocity), and lifetime of major storms: though there is substantial year-to-year volatility, these storms have not become more frequent, more intense, or more impactful in terms of damage to the U.S. economy.[39]

Figure 12. ACE Index for the Atlantic Basin, Since 1880*

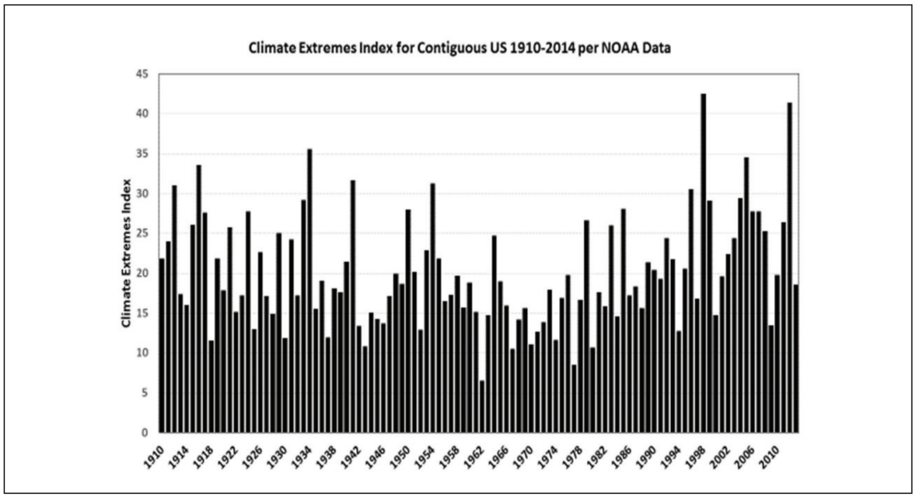


*The ACE index measures total tropical cyclone energy over a complete season: the number of storms, their intensity (wind velocity squared), and life. The data show the year-to-year volatility characteristic of tropical storm/hurricane activity, but there is no discernible trend.

Data source: U.S. National Hurricane Center

NOAA has developed, and tracks, a comprehensive composite index, the Climate Extremes Index (CEI), that takes into account a wide variety of weather extremes, including temperature (maximum and minimum temperatures much above or below normal), areas under severe drought or afflicted with excessive moisture, extremes in precipitation frequency and quantity in one-day events, and wind (tropical storms and hurricanes). While all areas of the U.S. occasionally experience weather extremes, **Figure 13** shows that, since 1910, the country has experienced no discernible trend in the overall frequency and extent of such effects. In fact the relatively small values of the CEI tell us that at any moment in time, only a small fraction of the US land area is experiencing weather extremes.

Figure 13. CEI Since 1910*

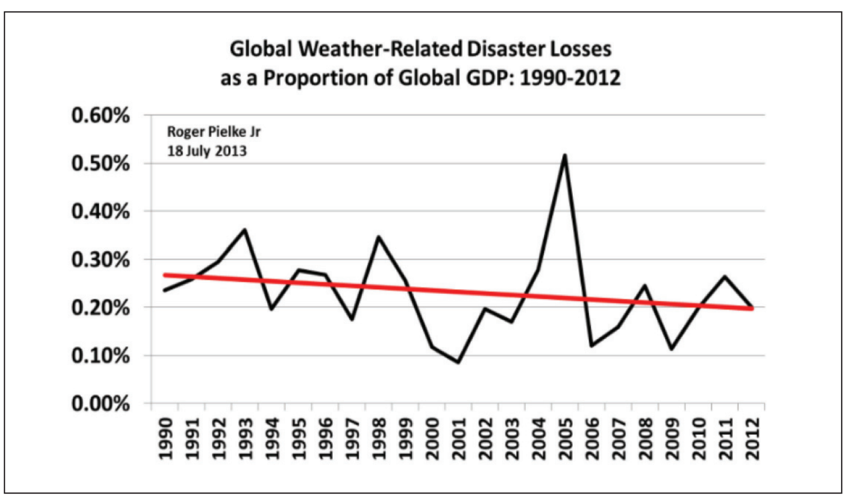


*In the CEI, a value of 100 means that the entire contiguous U.S. is experiencing one or more types of extreme weather. The index displays no discernible overall trend and indicates that only a relatively small fraction of the contiguous US experiences extreme weather events at any moment in time.

Data source: National Oceanic and Atmospheric Agency

In case after case, observational data tell the same story: there is no evidence, in the country's extensive empirical records (maintained largely by U.S. government agencies), of a rising incidence of extreme weather events. What about the rest of the world? **Figure 14** shows that global weather-related losses, as a percentage of global GDP, actually declined by about 25% during 1990–2012—a fact inconsistent with claims of rising global losses from climate change.[38]

Figure 14. Global Weather-related Losses as a Percentage of Global GDP, 1990–2012



Source R. A. Pielke Jr. Senate Testimony July 18, 2013[38]

Limitations on data quality, availability, and consistency complicate assessments of global patterns of extreme weather. In a notable change from the earlier, more aggressive views espoused in its 2007 report, the IPCC's 2013 report takes a cautious posture, including the intuitively expected conclusion: "Numerous regional studies indicate that changes in the observed frequencies of extremes can be explained by or inferred by shifts in the overall probability distribution of the climate variable."[40]

This means, for example, that an obvious expected consequence of 20th century warming is that there will be more days significantly warmer than previous normal highs and fewer days significantly cooler than previous normal lows. The implication of this statement—in view of studies finding improved mortality and human wellbeing at somewhat warmer temperatures—is that benefits to humanity from such warming are currently being realized.[41]

Ocean Acidification

It is widely asserted that CO_2 increases in the atmosphere threaten to make oceans acidic and harmful to marine life—despite the fact that current levels of CO_2 (about 400 ppm) are much less than the levels (several thousand ppm) that prevailed during most of the Phanerozoic eon, as life flourished in the oceans, as well as on land. As outlined below, the basic chemistry involved in the interaction between oceans and atmospheric CO_2, shows that fears of destructive ocean "acidification" are unfounded.

The random molecular motion in water causes a small fraction of molecules to break apart into a positive hydrogen ion (H^+) and a negative hydroxyl ion (OH^-), represented symbolically by

$$\mathbf{H_20 \leftrightarrow H^+ + OH^-} \qquad \mathbf{(2)}$$

It is customary to use a dimensionless number, pH, to specify the concentrations (or more precisely, the "activities") of these ions. The concentrations, in units of moles per liter, are:

$$\mathbf{[H^+]= 10^{-pH} \quad and \quad [OH^-] =10^{pH-14}.} \qquad \mathbf{(3)}$$

The product of the concentrations is the "dissociation constant" of water molecules:

$$\mathbf{[H^+][OH^-] = 10^{-14}.} \qquad \mathbf{(4)}$$

This value is for a temperature of 25 C. The dissociation constant increases with temperature and has some dependence on pressure. As seen from **Equation (3)**, the pH of a solution depends logarithmically on the hydrogen (or hydroxyl) ion concentration.

$$\mathbf{pH = - \log[H+].} \qquad \mathbf{(5)}$$

By convention and for convenience, the pH is defined as the base-10 logarithm of the hydrogen-ion concentration in moles per liter. For a neutral solution—neither acidic nor alkaline—the hydrogen-ion concentration is equal to the hydroxyl-ion concentration (pH = 7 at 25 C). If the hydrogen ion concentration exceeds the hydroxyl ion concentration, the solution is said to be acidic (pH < 7); if the hydroxyl ion concentration exceeds the hydrogen ion concentration, the solution is said to be alkaline, or basic (pH > 7).

Ocean water is famously salty. Typical salinities are about 35 grams of salt per kilogram of ocean water—this is often written as 35‰—though values can reach around 40‰ in the eastern Mediterranean and Red Sea and much smaller values elsewhere, for example about 32‰ off Alaska's southeast coast. Ordinary table salt (NaCl) dominates, but there are substantial amounts of other salts, such as KCl and MgSO4. These salts dissociate completely in the ocean into positive ions (cations), such as Na^+, K^+, and Mg^{2+} , and negative ions (anions), such as Cl^- and $SO_4^{-2.}$ These fully dissociated ions give salty ocean water a much higher electrical conductivity than fresh water. In practice, salinities are determined by measuring the electrical conductivity of ocean water, with appropriate corrections for temperature.

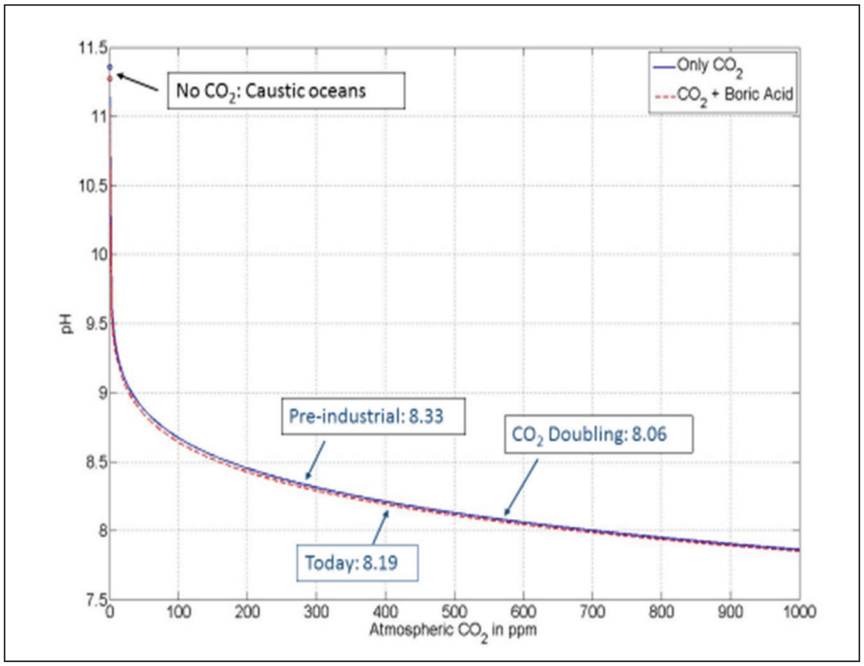
The positive charge of the fully dissociated cations slightly exceeds the negative charge of the fully dissociated anions. The Alkalinity, [A], is the excess of positive over negative charge (in moles of elementary charge per kg of ocean water) from the fully-dissociated ions. The value of the alkalinity is typically [A] ≈ 2.3 mM (millimoles per kg) and is proportional to the salinity. But the net charge of ocean water must be zero. Therefore, about 2.3 mM of negative ions are needed to compensate for the excess positive charge of the cations. Most of these compensating anions are provided by the conjugate bases of weak acids, mostly notably bicarbonate ions, HCO_3, and carbonate ions CO_3^- from carbonic acid, H_2CO_3. There are also much smaller contributions from boric, silicic, phosphoric, and other weak acids.

If these weak acids were not present, the excess positive charge from the fully dissociated ions would be compensated by negative hydroxyl ions, OH^- , which would make the oceans very alkaline indeed. Without atmospheric CO_2 to provide bicarbonate and carbonate ions, the oceans would have a pH of about 11.4, equal to that of household ammonia, and they would be very inhospitable to most life. Atmospheric CO_2 is essential to lowering the ocean's pH to a more moderate value. A representative value for the ocean surface is pH ≈ 8. Because its high alkalinity, the ocean sucks CO_2 from the atmosphere—not unlike the alkaline scrubbers use to extract CO_2 from spacecraft and submarine cabins.

The oceans contain about 50 times more CO_2 than the atmosphere. The laws of physical chemistry determine how ocean pH changes with CO_2. **Figure 15** shows how the computed pH of ocean water changes with atmospheric CO_2 (now about 400 ppm). Curves are shown for CO_2 alone—as well as for CO_2 plus the effect of naturally occurring boric acid, the next most important oceanic weak acid after CO_2. Ocean water would remain comfortably alkaline up to CO_2

concentrations of even several thousand ppm—far larger than would be produced by burning all economically available fossil fuels. The tiny effect of boric acid, the next most important weak acid in the oceans, demonstrates that atmospheric CO_2 is indeed the dominant factor in transforming oceans from highly caustic to mildly alkaline. As discussed below, the pH changes associated with increased CO_2 are small compared with normal pH variations in nature.

Figure 15. Computed pH of Ocean Water vs. Atmospheric CO_2 Concentration*



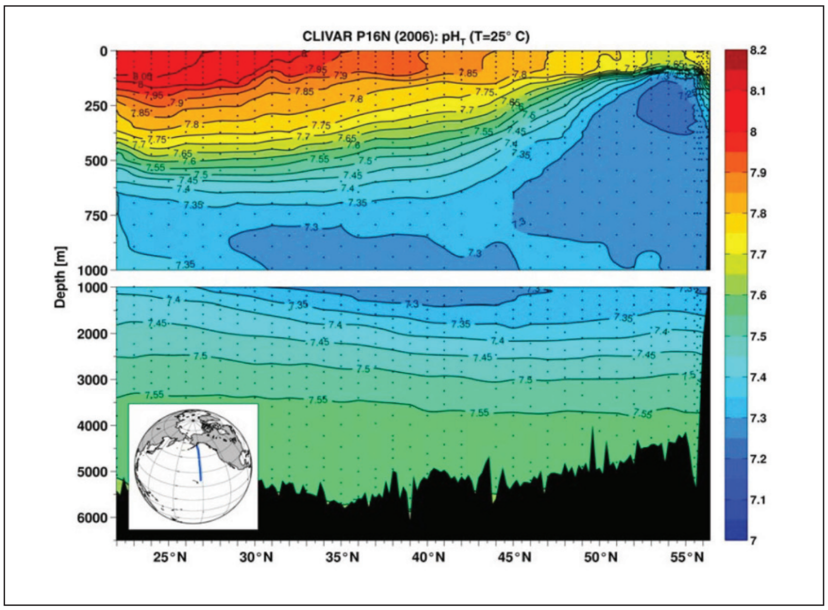
***Curves show the buffering effect of CO_2 alone and for CO_2 plus ocean boron content (0.42 x 10^{-3} M). The alkalinity of the ocean is assumed to be 2.3 mM. Increasing CO_2 from today's value, 400 ppm, to 500 ppm will reduce ocean pH by approximately 0.08; to 600 ppm will reduce pH by 0.15. The projected ocean pH reduction for a doubling of CO2 since the beginning of the industrial revolution (around 280 ppm in 1800) is 0.27, half of which has already occurred. A simple extrapolation of the current rate of increase of atmospheric CO_2 of 2 ppm per year would result in 600 ppm in the year 2100.

Source: R. W. Cohen and W. Happer, *Fundamentals of Ocean pH* (2015), http://co2coalition.org/fundamentals-of-ocean-ph/

For a CO_2 increase from the current 400 ppm to 600 ppm, the calculated decrease of average ocean pH is 0.15. Tans[42] projected a similar change—0.16 pH units—for an emissions scenario that would reach 600 ppm near the end of the 21st century, with pH gradually increasing again in succeeding centuries as emissions subside. As shown in **Figure 15**, the pH of ocean water in equilibrium with the atmosphere has already decreased by about 0.14 since the start of the Industrial Revolution.

The pH of the ocean varies greatly with position and over time,[43] far more than the changes expected from increasing CO_2 levels. The pH, as measured on a series of cruises between Hawaii and Alaska, is shown in **Figure 16**: maximum values of about pH = 8.1 are measured in the warm, salty, surface water near Hawaii; minimum values, as low as pH = 7.3, are measured at depths of about 1,000 meters at mid-latitudes, or at a few hundred meters deep, off Alaska's south coast.

Figure 16. North Pacific pH Along Longitude 152° west (pH at 25 C), 2006

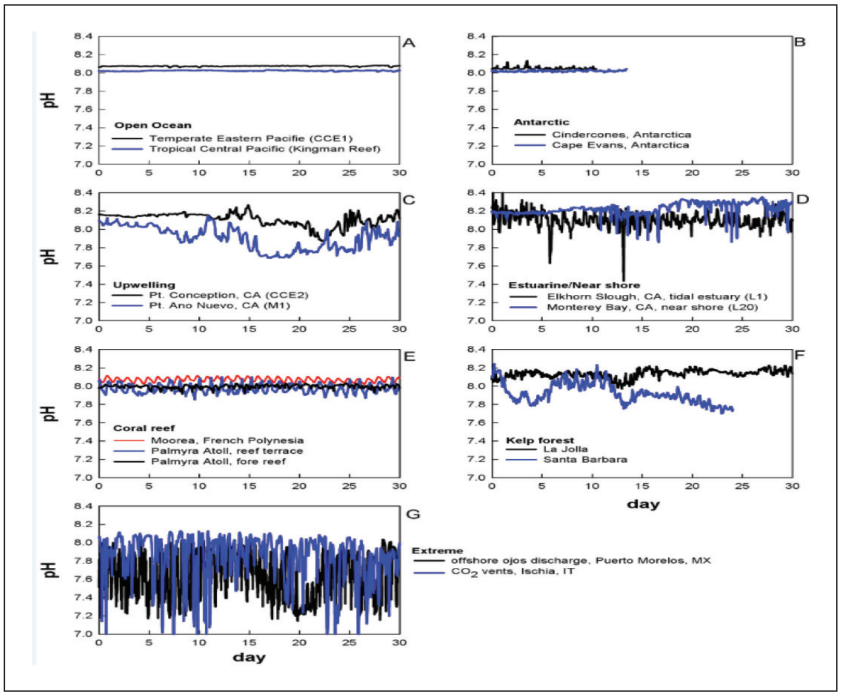


*Measured pH varies with position and depth, from 7.3 to 8.1.

Source: Robert H. Byrne et al, *Direct observations of basin-wide acidification of the North Pacific Ocean*, Geophysical Research Letters 37, L02601, 2010 doi:10.1029/2009GL040999, 2010)

The dramatic decrease in pH with increasing depth in the north Pacific is due to the "biological carbon pump"—the rain of organic material from photosynthesizing organisms near the sunlit surface to the dark depths where photosynthesis ceases, and where organic material decomposes back into CO_2. This process neutralizes more of the natural alkalinity of the oceans. Not only does ocean pH change with geographical location and ocean depth, it changes dynamically from day to day. **Figure 17** shows such variations, as measured in near surface water at 15 locations worldwide.[44]

Figure 17. Natural pH Fluctuations at 15 Locations Worldwide*



*Diurnal variations of one full pH unit are observed in some locations. Other locations experience changes of several tenths of a pH unit, over days and over weeks.

Source: G. E. Hofmann et al[44]

Only open ocean areas with insufficient nutrients for normal photosynthetic organisms have pH values that are stable from day to night. Otherwise, pH values tend to increase during the day, as photosynthesizing plankton convert dissolved CO_2, HCO_3^{-1}, and CO_3^{-2} into the organic matter of their tissues, leaving fewer bicarbonate and carbonate ions to neutralize the ocean's natural alkalinity. At night, the respiration of living organisms and the decay of dead organisms convert organic matter back into CO_2, and the pH decreases. Ocean life has adapted to these rapid natural variations of pH in time and space—variations far greater and faster than any projected slow change in ocean pH due to increased atmospheric CO_2.

Measurements of average ocean pH over time are underway and are consistent with the slow rate of pH drop shown in Figure 14 and calculated in the Tans study.[42] For example, the North Pacific basin-wide measurements[43] found an average decrease, over 0m–800m depth, of 0.023 pH units in 15 years (0.0015 pH unit per year), with no observed change below 800m. Monitoring of pH in the waters around Hawaii, Bermuda, and the Canary Islands over the last two to three decades shows similar rates of decrease: approximately 0.0016-0.0019 pH units annually.[45]

Laboratory studies show that for the small levels of pH changes of interest, there is little significant impact on the dozens of organisms studied;[46] indeed, some changes appear to be positive. In the 200 years since the start of the Industrial Revolution, aquatic species have successfully adapted to the oceans' average pH decrease of about 0.14 pH units. It is extremely unlikely that such animals will have trouble adapting to similarly small, slow, further changes in pH. As discussed above, over the Earth's history, CO_2 levels have averaged many thousands of ppm—up to tenfold current levels or likely future levels—while aquatic life thrived.

4. The Benefits of More CO_2

During the past few decades, a remarkable, CO_2*-driven expansion of the Earth's plant biosphere has been discovered. It is already benefiting humanity and its positive impact will increase in future generations.*

More CO_2 in the atmosphere will benefit the planet generally —and humanity in particular. Few realize that the Earth has experienced a CO_2 famine for millions of years. In the past ~550 million years since the Cambrian period[47]—when abundant fossils first appeared in the sedimentary record—CO_2 levels have averaged thousands of parts per million (ppm), several times more than today's few hundred ppm. Preindustrial CO_2 levels of about 280 ppm were not much above the critical level (around 150 ppm) when many plants can die from CO_2 starvation.[48]

Land plants get the carbon they need from CO_2 in the air. Most plants draw other essential nutrients—such as water, nitrogen, phosphorus, and potassium—from the soil. Just as plants grow better in fertilized, well-watered soils, they grow better in air with several times higher CO_2 concentrations than present values.

Green plants grow faster with more atmospheric CO_2. Empirical studies show that their growth rate is approximately proportional to the square root of the CO_2 concentration. The increase in CO_2 concentrations, from about 300 ppm to 400 ppm over the past century, is thus expected to have increased their growth rate by about 15%. (Most crop yields have grown by far more than 15% over the past century, thanks to improved crop varieties, fertilizers, and water management, as well as more atmospheric CO_2.)

The low current relatively low CO_2 levels have exposed a "design flaw"—made by nature several billion years ago when the enzyme, Ribulose-1,5-bisphosphate carboxylase/oxygenase ("rubisco") first evolved. Rubisco is the world's most abundant protein. Using the energetic molecule adenosine triphosphate (ATP) produced by the primary step of photosynthesis, rubisco converts CO_2 to simple carbohydrate molecules with three carbon atoms in a process called the C3 cycle or Calvin cycle. These simple carbohydrates are subsequently elaborated into sugar, starch, amino acids, and all other molecules on which life depends. The last "c" in rubisco refers to rubisco's primary molecular target, CO_2, and the last "o" in rubisco refers to an unintended secondary target—the O2 molecule. Rubisco evolved at a time when CO_2 levels were far higher than today and O_2 levels were much lower. Nature did not foresee the exceptionally low CO_2 levels and high O_2 levels that have prevailed for the past tens of millions of years. At the current low levels of atmospheric CO_2, much of the CO_2 accessible to the leaf is used up during times of full sunlight. If rubisco, fueled by photosynthetically generated ATP, cannot find enough CO_2, it will settle for an O_2 molecule and produce toxic byproducts, such as hydrogen peroxide, instead of useful carbohydrates. This "photo-oxidation" is a serious problem. At current low CO_2 levels, it leads to a reduction of photosynthetic efficiency by about 25% in C3 plants, including rice, soybeans, cotton, and many other major crops.

Low CO_2 levels of the past tens of millions of years have driven the development of so-called C4 plants—such as corn and sugar cane—that cope with the oxygen poisoning of rubisco by protecting it in special structures within the leaf. CO_2 molecules are ferried into the protective leaf structure by molecules with four carbons, which give the C4 pathway its name. The extra biochemical energy for the more elaborate C4 photosynthetic pathway comes at a cost, but one worth paying in times of unusually low CO_2 concentrations, such as the present.

In short, thousands of experiments leave little doubt that all plants—both the great majority, with the old-fashioned C3 path, as well as those with the novel C4 path—grow better with more CO_2 in the atmosphere.[48-50] This benefit comes from the basic biophysics of photosynthesis. CO_2, H_2O and sunlight are the most essential nutrients of plants, and more CO_2 suppresses the poisonous effects of O_2 to photosynthesizing plants.

But the nutritional and oxygen-detoxifying value of additional CO_2 is only part of its benefit to plants. Of equal or greater importance is the fact that more CO_2 in the atmosphere makes plants more drought-resistant. Plant leaves are perforated by stomata—tiny holes in the gas-tight surface skin that allow CO_2 molecules to diffuse from the outside atmosphere into the moist interior of the leaf, where they are photosynthesized into carbohydrates. A leaf in full sunlight can easily reach a temperature of 30 C, where the concentration of water molecules in the moist interior air of the leaf is about 42,000 ppm, more than one hundred times greater than the 400 ppm concentration of CO_2 in fresh air outside the leaf.

CO_2 molecules, which are much heavier than H_2O molecules, diffuse more slowly in air. Because of the relatively sluggish diffusion of CO_2 molecules compared to H_2O molecules, and because of the much higher concentration of H_2O molecules in the leaf, as many as 100 H_2O molecules can diffuse out of the leaf for each CO_2 molecule that is used in photosynthesis. This is the reason that most land plants need at least 100 grams of water to produce one gram of carbohydrate. Water use efficiency (WUE), the ratio of water that participates in plant metabolism to water lost, via transpiration, is a vitally important parameter in agronomy and other areas of plant biology. And WUE is increased by more atmospheric CO_2.

In the course of evolution, land plants have developed finely-tuned feedback mechanisms that allow them to grow leaves with more stomata in CO_2-poor air (such as today's atmosphere), or with fewer stomata for CO_2-rich air, like that which prevailed over most of the geological history of land plants. If the amount of CO_2 doubles in the atmosphere, plants reduce the number of stomata in newly grown leaves by about a factor of two. With half as many stomata to leak water vapor, and with other conditions held constant, plants require significantly less external water supply.

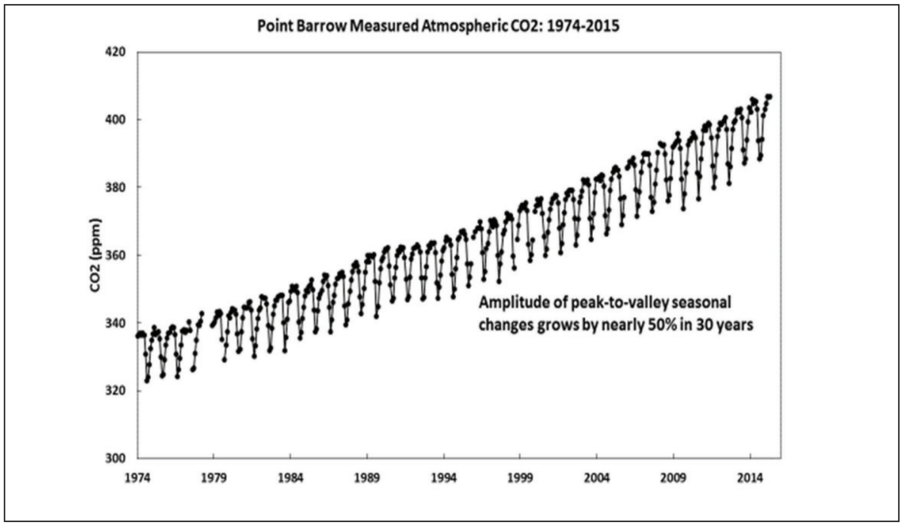
The recent modest increase in atmospheric CO_2 is already having a significant positive impact on plant life: the same kinds of results obtained under controlled conditions of greenhouses and laboratories are being observed in the natural world. Satellites, aircraft, and ground observations over the past few decades confirm an ongoing, significant expansion of the Earth's vegetation.

Perhaps the earliest signal that extensive "greening" of the planet was underway was the observation of large progressive increases in the amplitude of seasonal oscillations of CO_2 at measurement stations in high northern latitudes. In the early 1990s, Charles D. Keeling, a pioneering chemist, noticed that seasonal oscillations were indeed increasing in northern latitudes.[51]

A later study, led by the National Center for Atmospheric Research (NCAR), found that "seasonal CO_2 variations have substantially increased in amplitude over the last 50 years. The amplitude increased by roughly 50 percent across high latitude regions north of 45° N, in comparison to previous aircraft observations from the late 1950s and early 1960s."[52] Heather Graven, lead researcher at the Scripps Institute of Oceanography, reported: "This means that more carbon is accumulating in forests and other vegetation and soils in the Northern Hemisphere during the summer, and more carbon is being released in the fall and winter."[53]

In other words, the observation of larger seasonal CO_2 oscillations is a fingerprint of a plant biosphere that is expanding significantly—the plant biosphere is taking "deeper breaths" as it inhales more nourishment. **Figure 18** shows the results of CO_2 measurements at Point Barrow, Alaska, since 1974: the increase over time in the amplitude of seasonal oscillations is readily apparent.

Figure 18. CO_2 Measurements at Point Barrow, Alaska, Since 1974*



*The increase in seasonal CO_2 variations is readily discernible and an early indicator of terrestrial greening due to more CO_2 in the atmosphere.

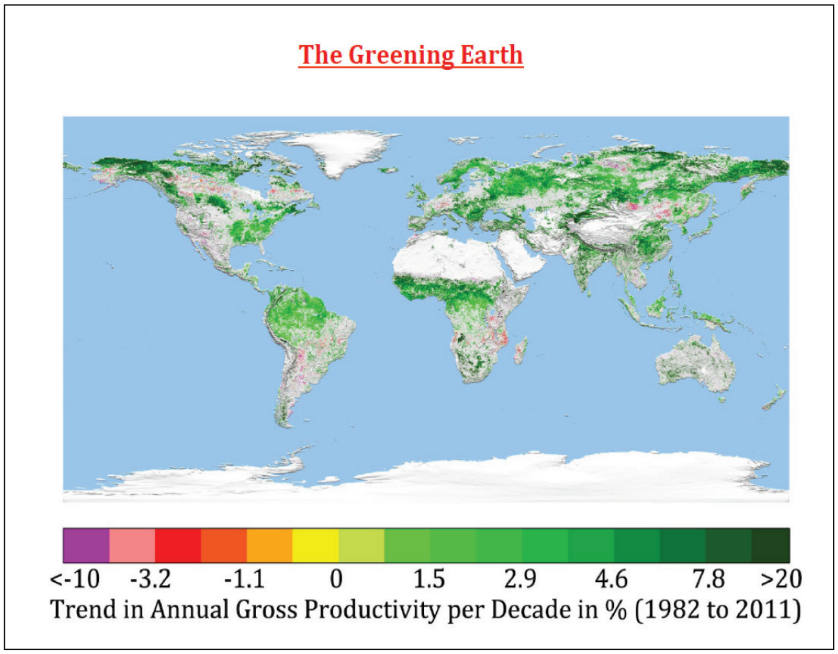
Source: Scripps Institute of Oceanography; Scripps CO_2 Program

The results of the NCAR study were published in the journal *Science,* where the authors stated: "None of the CIMP5 [IPCC climate] models can account for the increase in amplitude north of 45 deg between 1958–61 and 2009–11 and tend to underestimate both the CO_2 amplitude change and [net ecosystem production] amplitude changes in northern ecosystems."[53] Thus the same climate models that have failed to project global temperatures during the past 20 years have also failed to predict the response of the biosphere to increased atmospheric CO_2.

It is now clear that both the Earth's northern latitudes and its entire plant biosphere are greening as a result of increased CO_2 in the atmosphere. While there may be multiple causes of greening in any particular location or region—including increased moisture, temperature, sunlight, and the availability of ground nutrients—statistical techniques can isolate the effect of increasing CO_2 from these other influences.

Satellite observations have provided data for plant cover of the entire globe. Biologist Ranga Myneni has quantified global greening on a grid of 8 km square pixels during 1982–2011. He found that more than 30% of the Earth's land area greened during this period—for a 14% overall increase in total gross vegetative productivity (**Figure 19**).[54] Greening was observed in all 12 vegetation types examined across the Earth's land surface, with about half of observed greening ascribed to the greater supply of CO_2**.**

Figure 19. Global Trends in Gross Vegetative Productivity, 1982–2011*



*As recorded by satellite optical measurements.

Source: R. Myneni, *The Greening Earth*, "Probing Vegetation Conference, From Past to Future," July 4-5, 2013 (Antwerp, Belgium)

Recognizing that assigning cause and effect for greening can be difficult when more than one factor changes simultaneously, R. J. Donohue and colleagues focused their study on arid and semi-arid areas, including desert margins, where water supply is the strongest limitation on plant growth:[55] "The direct CO_2 effect on vegetation should be most clearly expressed in warm, arid environments where water is the dominant limit to vegetation growth."

The stomata response, discussed above, was tested with real-world empirical data. During the period of observation, Donohue and colleagues found that vegetative cover across these dry environments increased by 11%. They concluded: "Our results confirm that the anticipated CO_2 fertilization effect is occurring alongside ongoing anthropogenic perturbations to the carbon cycle and that the fertilization effect is now a significant land surface process."

Regional studies also confirm the Earth's ongoing greening, including sensitive regions of concern, such as the Amazon rainforest ("Satellite data have indicated higher greenness levels, a proven surrogate for carbon fixation, and [higher] leaf area during the dry season, relative to the wet season");[56] China ("Our… estimates suggest that, at the country scale, China's greening was chiefly driven by rising atmospheric CO_2 concentrations (contributing 85%), although the dominant factor varies across different provinces");[57] and the central African forest and northern Savannah ("We find that the increase of atmospheric CO_2 by 52.8 ppm during the period of the study explains 30–50% of the increase in [inherent water use efficiency] and >90% of the [light use efficiency] trend over the central African forest…The [inherent water use efficiency] increases by 10-20% per decade during the 1982–2010 period over the northern savannahs").[58]

Though there is little doubt that the Earth's CO_2-induced greening boosts crop productivity, disentangling the various influences on crops is complicated by direct anthropogenic interventions, such as fertilization, irrigation, and the development of superior crop varieties. Nevertheless, an extensive database has been compiled on thousands of CO_2-enrichment experiments, conducted on hundreds of different crops grown under a variety of conditions.

Using the crop database, an extensive bottoms-up analysis has been developed to estimate the recent and future economic impact of increasing CO_2, based on data for 45 key crops that comprise 95% of the world's agricultural food supply.[59] The analysis assumes that agricultural practices, under changing conditions, have adapted to capitalize fully on the fertilization and water-use efficiencies made available by increased atmospheric CO_2.

The study found that annual benefits during 1961–2011 easily reached $100 billion (in 2004–06 dollars) late in the study period, with a total present value exceeding $3 trillion. Future increases in CO_2 will likely further improve crop productivity, helping feed humanity's growing population. An additional benefit from rising productivity is that some land currently under cultivation will return to a more natural state.[60]

Conclusion

Empirical data on global warming and carbon dioxide lead to an optimistic outlook for the Earth and its inhabitants. People everywhere can look forward to a greener, lusher, slightly warmer planet. More food can be grown while using less land to do so. Longer growing seasons are likely, and insecurity about hunger will decline.

Hundreds of millions of desperately poor people stand on the cusp of benefiting from the same advances in prosperity that affluent nations have already achieved. Moral and economic justifications intersect to argue that the available, reliable, and inexpensive sources of energy be used to foster development and modernization across the globe. Yes, there will be mild climate change, and it will benefit the world.

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The mission of the CO2 Coalition is to promote broader understanding of the beneficial effects of more carbon dioxide in the atmosphere around the world. The Coalition fosters informed debate on the scientific evidence, as summarized in this Primer. The Coalition's initial paper, published in the fall of 2015, urged the public to "see for yourself."

CO2 COALITION

1621 North Kent Street, Suite 603
Arlington, Virginia 22209
www.co2coalition.org
info@co2coalition.org
571-970-3180

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