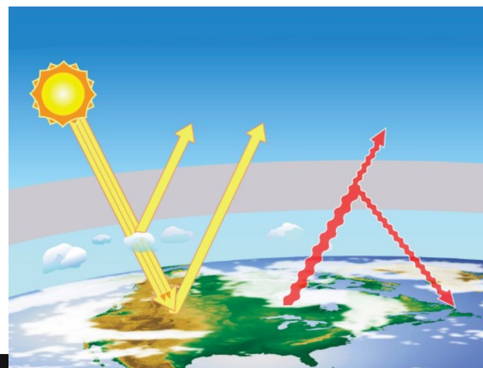
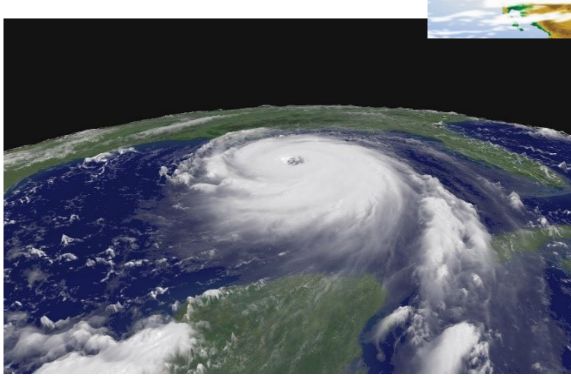
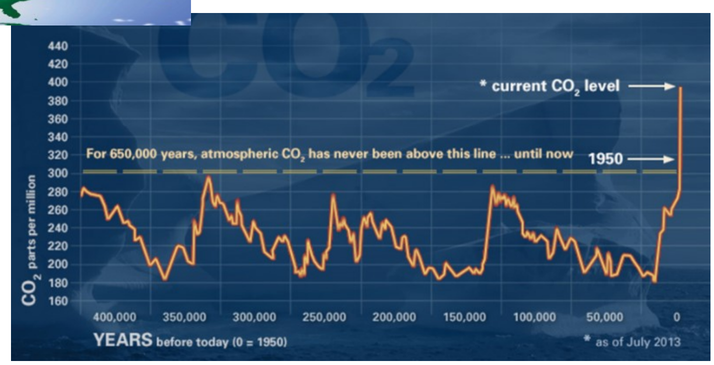
The Scientific Evidence on Climate Change

And the Ethics of Skepticism vs Denialism







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This is to acknowledge that Dr. Robert W. Haley has disclosed that he has no financial interests with commercial concerns related directly or indirectly to this program.

Biographical Information:

Robert W. Haley, M.D., is Professor of Internal Medicine, Distinguished Teaching Professor, and holder of the U.S. Armed Forces Veterans Distinguished Chair in Medical Research Honoring America's Gulf War Veterans endowed by Ross Perot and the Perot Foundation. After serving 10 years in Epidemic Intelligence Service at the U.S. Centers for Disease Control and Prevention (CDC), he joined the UT Southwestern faculty, founding the Division of Epidemiology, recently merged with the Division of Infectious Disease and Geographical Medicine. In addition to attending on the Parkland Internal Medicine Service and teaching a course in epidemiology for the clinical investigator and SAS computing for research fellows and young faculty, his research in over 200 scientific publications currently focuses on the neurological and genetic basis for sarin-related Gulf War illness and the possible role of paraoxonase in congestive heart failure, and he has led policy development on air pollution and climate change mitigation in the Dallas County Medical Society and the Texas Medical Association. While conducting an epidemiologic investigation of Dallas' 2012 West Nile encephalitis epidemic, he became interested in the problem of climate change which is playing an increasingly important role in the risks of infectious disease epidemics. Realizing from discussions with his academic peers that the scientific evidence on climate change is not well known in the medical profession, he conducted an intensive study of the scientific literature on the problem and began lecturing on the subject first to medical groups and then to lay audiences, reviewing the scientific evidence divorced from partisan political concerns.

Purpose and Overview:

The purpose is to introduce the main empirical evidence behind the scientific consensus that human-caused carbon emissions are warming the planet and threatening the health and survival of the world population. Following a "case report" of the role of climate change in causing the 2012 epidemic of West Nile encephalitis in Dallas, the presentation will summarize the evidence that addresses the 4 fundamental questions of the problem: Is the earth's surface warming? Is the warming due to human effects or natural phenomena? Is the warming climate a serious threat to humans? Should society invest in curtailing climate change? The first two are purely empirical questions which have been thoroughly answered. The last two involve value judgments and economic consequences which have provoked denial of the first two, stymying civilization-saving action. Finally the presentation will explain the distinction in scientific ethics between *skepticism* and *denialism* and some reasons that people confuse them. The conclusion will consider the moral imperative that physicians protect our patients and the rest of humanity by working toward a solution to climate change, just as the profession did 5 decades ago in leading opposition to world destruction by nuclear warfare.

Educational Objectives:

1. Explore the main evidence proving that the surface temperature of the earth has been warming since the beginning of the Industrial Era.
2. Review the main evidence establishing that human-related carbon emissions are the primary cause of global warming and climate change.
3. Consider the main scientific evidence showing important ways climate change is threatening the health and survival of humans.
4. Consider what measures our country must take to curtail and reverse climate change.
5. Understand the distinction between scientific skepticism and denialism and the moral imperative for physicians to protect our patients and the rest of humanity by working toward a solution to climate change, just as the profession did 5 decades ago in leading opposition to world destruction by nuclear warfare

“Case Report”

In 1999 West Nile encephalitis was imported into New York. It reached Dallas in 2002. For the next 10 years we had few cases, with a first small epidemic in 2006 (Fig. 1). In 2012 we had the largest epidemic in the country, with 173 encephalitis cases on ventilators in ICUs and 21 deaths. Since then we’ve had rare cases each year as before.[1] The main predictors of the number of cases were fewer number of hard freeze days and unusually warm springs (Fig. 2).

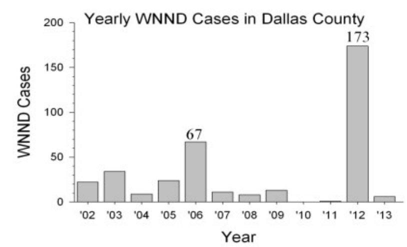


Fig. 1. Cases of West Nile neuroinvasive disease in Dallas County by year, 2002-2013. Credit: Chung, Buseman, Joyner, Hughes, Fomby, Luby, Haley. JAMA 2013;310:297.

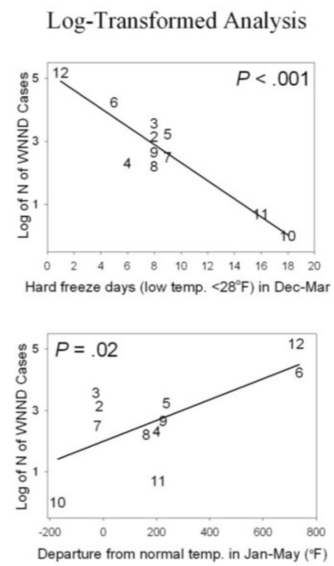


Fig. 2. Association of the yearly number of cases of WNND with lower number of hard freeze days and unusually warm springs. Credit: Chung, Buseman, Joyner, Hughes, Fomby, Luby, Haley. JAMA 2013;310:297.

These findings raised the question of whether this highly unusual epidemic might have been caused by global warming. In fact, our winters and springs have been getting warmer, and 2006 and 2012 were the warmest on record. Fewer hard freeze days increase over-wintering of infected mosquitoes and allow early virus introduction in the spring. Warmer spring temperatures speed viral replication and increase mosquito biting activity. So do we need to curtail global warming to prevent this from becoming more frequent? This brings us face to face with the question, “Do we believe in climate change?” and “If so, why?” To answer this we need to know the evidence the theory is base on.

To understand the scientific basis for climate change, it is important to realize that the issue really involves 4 separate questions, and failure to distinguish them is a major cause of confusion. The 4 questions are:

1. Is the earth’s surface warming?
2. Is the warming due to human effects or natural phenomena?
3. Is the warming climate a serious threat to humans?
4. Should society invest in curtailing climate warming?

The first 2 questions are purely empirical ones with definite answers strongly supported by evidence. The last 2 involve value judgments and economic consequences that spark debate. Unfortunately, the debate over the last 2 has been unfairly generalized to the first 2, stymying action.

Q1. Is the earth’s surface temperature warming?

Ten published studies have reconstructed longitudional surface temperatures back 1-2 thousand years by analyzing surrogates of temperature such as pollen counts in ice core samples from glaciers and ice sheets, tree rings, corals, lake or ocean sediments and historical data. One thousand-year reconstructions from 10 published sources agree that a slow decreasing trend in global temperature ended abruptly with the beginning of the Industrial Age in the late Nineteenth Century, followed by an initially gradual climb in temperatures (Fig. 3a).[2] These trends have been extended back to a 2000-year record and further confirmed (Fig. 3c).[3-5] Continuing into the 20th Century, after 1980 the rate of the increase abruptly accelerated, continuing to the present (Fig. 3b).[6] As of this year the global surface temperature has warmed a full 1ºC (1.9ºF) since the pre-industrial age.[7]

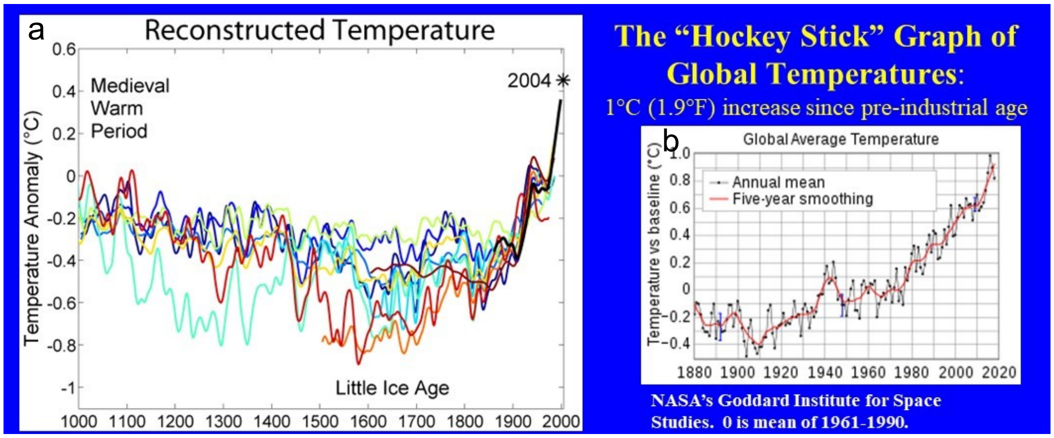


Fig. 3. Longitudinal trends in global temperature. Reconstructed from ice cores, tree rings, corals, sediments and historical data, decadally smoothed with a moving average. Redder lines are newer. Credit: a) Robert A. Rohde, CC BY-SA 3.0 http://creativecommons.org/licenses/by-sa/3.0/ ; b) NASA Goddard Institute for Space Studies Data.GISS: GISS Surface Temperature Analysis (GISTEMP v4) (nasa.gov)

This finding of a rapid rise in global surface temperature since the pre-industrial age is further verified by well characterized trends in other indicators that should be affected by the progressively increasing trend (Fig. 4).

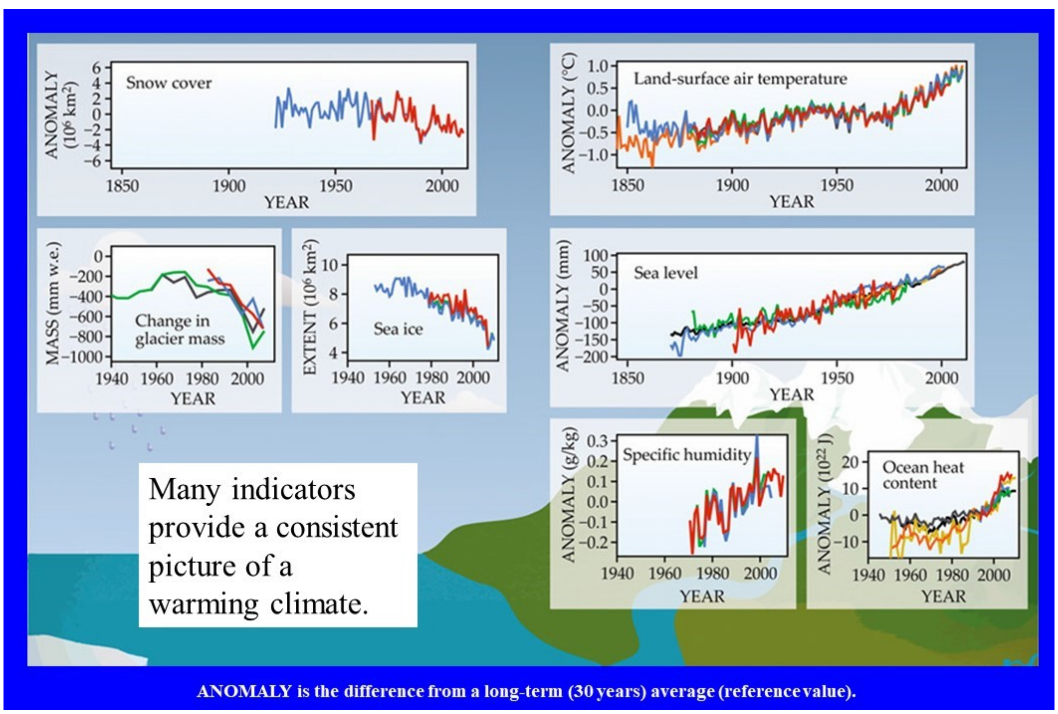


Fig. 4. Longitudinal trends in other indicators that should be affected by rising global temperatures. Credit: US National Oceanic and Atmospheric Administration: National Climatic Data Center., Public domain, via Wikimedia Commons

An important feature of global warming is that the degree of warming is geographically highly variable. This is a major determinant of the great geographical differences in the effects on climate. For example, land areas are warming faster than oceans; the Northern Hemisphere is warming faster than the Southern Hemisphere, and the Arctic region is warming the fastest of all (Fig. 5). Whereas the average global temperature has increased 1ºC since the pre-industrial age, the average temperature of the Arctic region has warmed more than 3ºC, and the adverse effects on the region are likewise disproportionately worse.

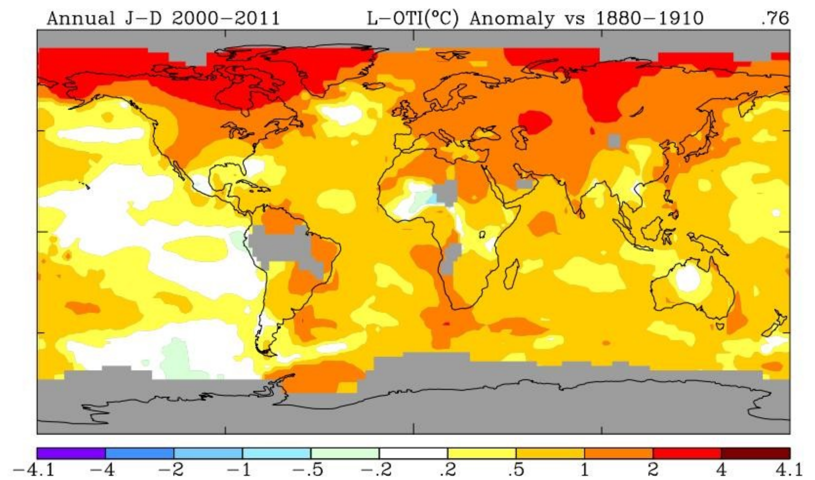


Fig. 5. Regional differences in the degree of atmospheric warming.
Credit: NASA/GISS

The conclusion for question 1 "Is the Earth's surface temperature increasing?" is clearly yes.

Q2. Is the warming due to human influences or natural phenomena?

Prediction of the Greenhouse Effect

The idea that the buildup of certain gases in the atmosphere would warm the atmosphere at the earth's surface, known as the "greenhouse effect," was first described by Joseph Fourier in 1824. In 1859 John Tyndall measured the radiative properties of many gases. In 1896, Svante Arrhenius quantified the effect as what is known as the Greenhouse Law:

$$\Delta F = \boldsymbol{\alpha} \ln(C/C_0)$$

A simple matter of physics, the atmospheric temperature (*F*) will increase as a function $\boldsymbol{\alpha}$ of the logarithm of the increase in the atmospheric CO_2 concentration C/C_0. As a consequence of this equation, Arrhenius predicted that industrial CO_2 emissions were sufficient to affect the average global temperature, and a doubling of the current atmospheric CO_2 (280 ppm) would increase average global temperature by 5ºC (9ºF). However, in 1896 he felt that industry could never emit enough CO_2 to make a detectable difference in temperatures. Arrhenius received the Nobel Prize in chemistry in 1903, the first Swedish scientist to receive the honor.

How the Greenhouse Effect works

The sun's light heats the earth (Fig. 6). Its light is partially reflected back into space by clouds, air pollution, and light land surfaces such as ice, while the rest is absorbed by the surface, thus generating heat. At night some of the heat absorbed during the day is radiated back into space as infrared radiation, thus cooling the earth overnight. Greenhouse gases, such as CO_2, methane (NH_4), nitrogen gases (N_2O), ozone (O_3), chlorofluorocarbons (CFCs) and water vapor (H_2O), trap some of the outgoing infrared radiation and reflect it back to earth, thus acting as a blanket keeping the earth warmer.

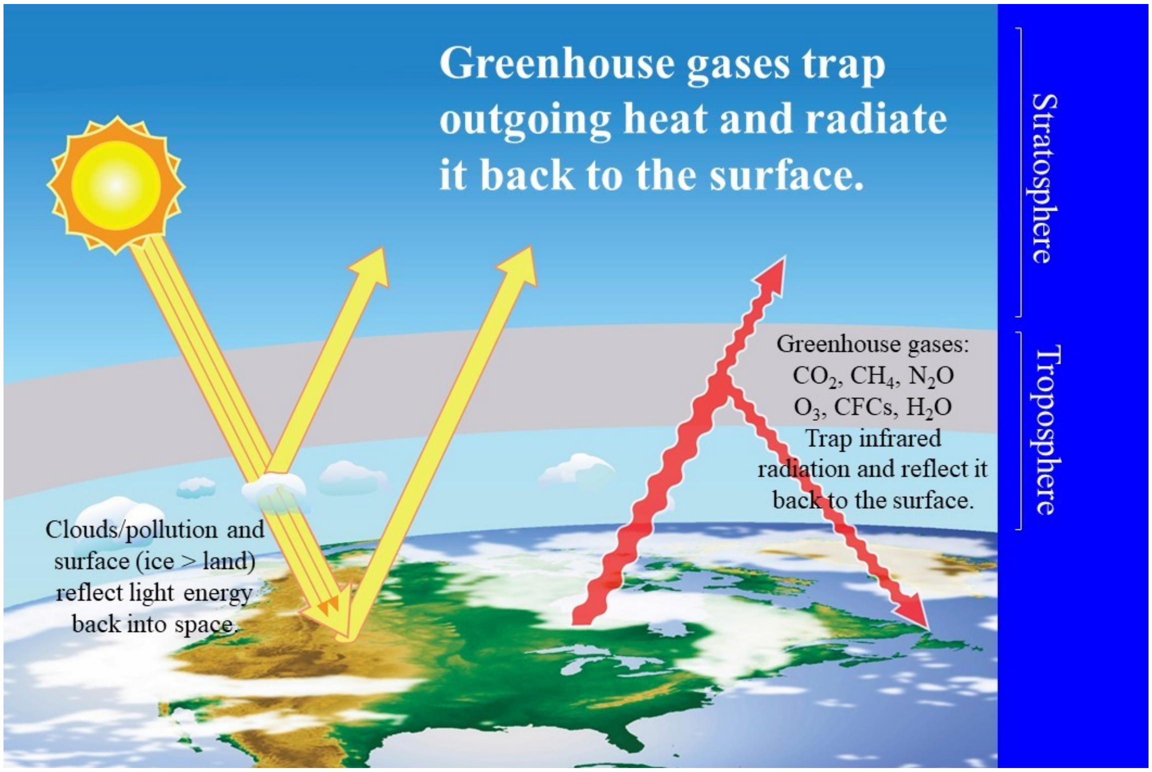


Fig. 6. The Greenhouse Effect.

Atmospheric CO_2 concentrations and carbon emissions

CO_2 emissions. CO_2 is a potent greenhouse gas, which, once emitted, remains in the atmosphere for hundreds or thousands of years. The average annual CO_2 concentraton in the atmosphere has been estimated from ice core sampling up to 1960; thereafter, it has been measured directly in an atmospheric station at the top of Mt. Mauna Loa in Hawaii, where it is exposed only to the winds from the vast Pacific Ocean to its west, which accurately measure the average global CO_2 concentration of air (Fig. 7a). The annual level of carbon emissions from human activity since 1850 follow exactly the annual level of the average global temperature (Fig. 7a,c). The same tracking is apparent in comparing annual levels over the past 1,000 years (Fig. 7d).

Altogether since the pre-industrial age, man has emitted an estimated 1,000 gigatons (Gt) of CO2 into the atmosphere (a Gt is 1 billion tons). Presently roughly 45% is in the atmosphere, and 30% is dissolved in the oceans. The rest is sequestered in unknown sites, referred to as the "missing sink."

The additional carbon has increased the atmospheric CO_2 level to 416 ppm as of summer 2020. In the

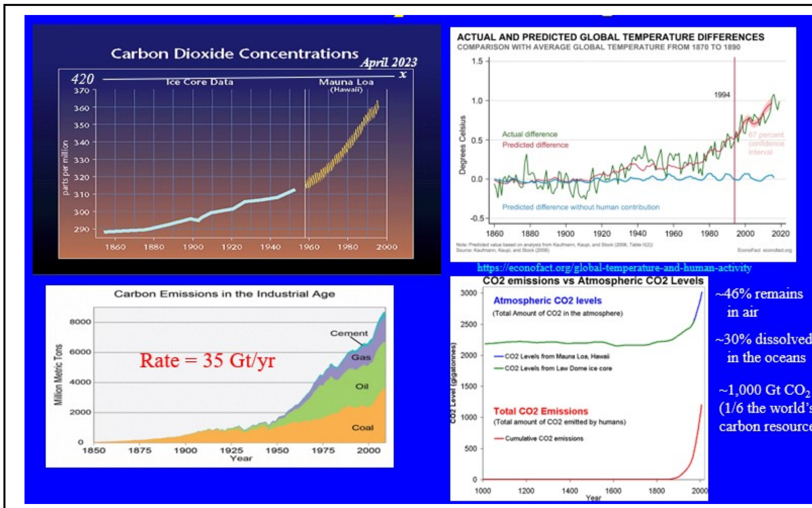


Fig. 7. Longitudinal trends in atmospheric CO_2 levels and CO_2 emissions.
Credit: a) U.S. Government, public domain; b) N.O.A.A.; c) U.S. Global Change Program, GlobalChange.gov public domain; d) The Skeptical Science Website, Creative Commons attribution 3.0. https://skepticalscience.com/print.php?r=45

pre-industrial age, the CO_2 level averaged 280 ppm, and over the prior 650,000 years, it had never exceeded 300 ppm.

Methane (CH_4) emissions. Methane is natural gas. Human-caused emissions are mainly from leaking natural gas wells and pipelines. Natural emissions are mainly from anaerobic decomposition of plant matter, rice production, livestock belching, and forect fires. CH_4 is a greenhouse gas which, once emitted, remains in the atmosphere only 10-20 years. Although its atmospheric concentration is far lower than that of CO_2, it is important because its global warming potential (GWP) is far greater than that of CO_2. The GWP100, measured over 100 years, is 28-36 times that of CO_2; wherease, its GWP20, over 20 years from emission, is 86 times that of CO_2. So methane emissions are of greater importance when the concern is for the near-term effects of global warming on climate.

Paleoclamatic fluctuations of the atmospheric CO_2 concentration. Atmospheric CO_2 levels have been measured by ice core sampling, etc., over at least the past 800,000 years[7,8] (Fig. 8). The longitudinal plot shows a dramatic cyclical fluctuation between 180 ppm and 300 ppm, which has been recurring for the past 34 million years. At its low points the earth plunges into an ice age (called a "Glacial" period); while at its high points, the earth experiences temperate climate (called an "Inter-glacial" period). The fluctuations occur irregularly at intervals of between 75,000 and 125,000 years. **The main point is that the atmospheric CO_2 level has not exceeded 300 ppm for at least the last 650,000 years (almost certainy many times further back than that), and the dramatic rise since the pre-industrial age to the present level of 416 ppm has not happened for millions of years.**

Notice particularly the abrupt rise that ends each ice age and brings in the temperate period.[9] Somehow massive stores of carbon are mobilized and released into the atmosphere in a relatively short time. A recent study indicated that this happens when small changes in earth's orbit (possibly from the earth's wobble) cause melting of the Arctic ice cap, dumping fresh water into the northern Atlantic, blocking the Atlantic circulation, heating the Antarctic, and causing CO_2 to bubble up from the southern oceans, causing a runaway greenhouse effect (more about this below). Thus, having artificially pushed the CO_2 level far above what it has been, we have entered uncharted waters where it is impossible to predict what might result. We know there are still massive stores of carbon sequestered away which once were in the atmosphere, but we do not know if the present rise could trigger positive feedback systems and a massive carbon release.

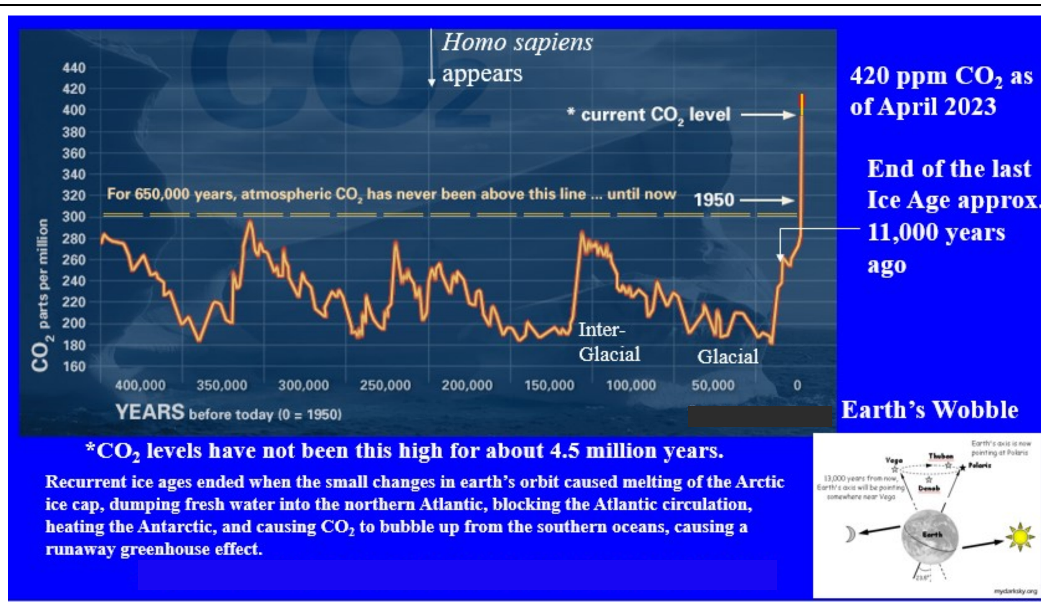


Fig. 8. Paleoclimatic fluctuation of the atmospheric CO_2 level from ice core sampling, etc., emphasizing the singularity of today's level.
Credit: Basic graphic from *https://climate.nasa.gov* from data at Luthi et al. *Nature* 2008; 453:379-382.

Could the recent rise in CO_2 levels be caused by an increase in the sun's energy output?

One theory of CO_2 rise is that the sun has recently gotten hotter thus heating up the earth's atmosphere. Two sets of measurements have ruled out this possibility.

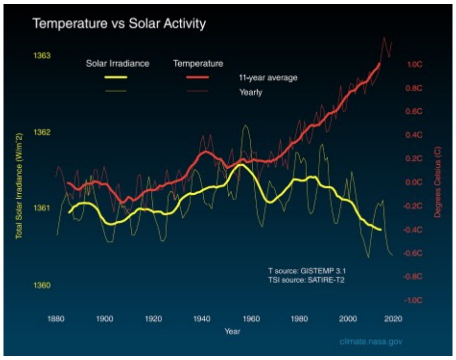


Fig. 9. Since 1960 solar irradiance (yellow line) has remained stable while global temperature (red line) has steadily climbed. Credit: https://climate.nasa.gov

First, measurements back to the pre-industrial era show that since the 1950s, the total solar irradiance has remained approximately stable while the earth's atmospheric CO_2 level has relentlessly climbed (Fig. 9).

Second, satellite measurements have demonstrated that, as the average global temperature of the earth's surface (the troposphere) has been warming, the temperature of the stratosphere, above the concentration of greehhouse gases, has been cooling[10] (Fig. 10). Solar heating would progressively warm the stratosphere as well as the troposphere.

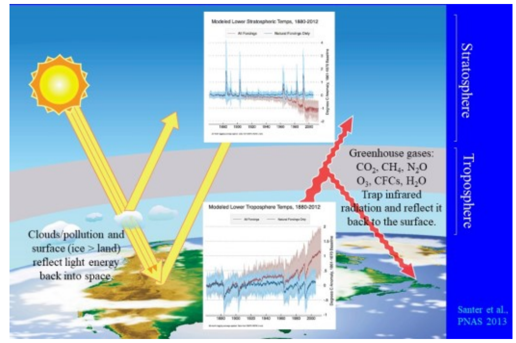


Fig. 10. Global temperatures of the troposphere and the stratosphere since 1880. The blue lines (error bars) are from super computer models excluding anthropogenic forcings, and the red lines (error bars) are the observed values. Credit: Hausfather Z. https://yaleclimateconnections.org/2013/09/vertical-human-fingerprint-found-in-stratospheric-cooling-tropospheric-warming/

Direct evidence of the Greenhouse Effect

Decisive evidence of the Greenhouse Effect has come from measurement of the energy being reflected back to earth at night and from that escaping into space (Fig. 11).

First, measurement and spectral analysis of infrared energy at the earth's surface at night has shown that the energy reflected back to the earth's surface at night is almost entirely confined to the wave lengths that are absorbed and reflected back by the greenhouse gases: CO_2, CH_4, O_3, N_2O and CFCs[11,12] (Fig. 11a).

Second, a long-term satellite study found that from 1970 to 1996 the amount of energy escaping into space declined only for the wave lengths absorbed by the greenhouse gases[13] (Fig. 11b).

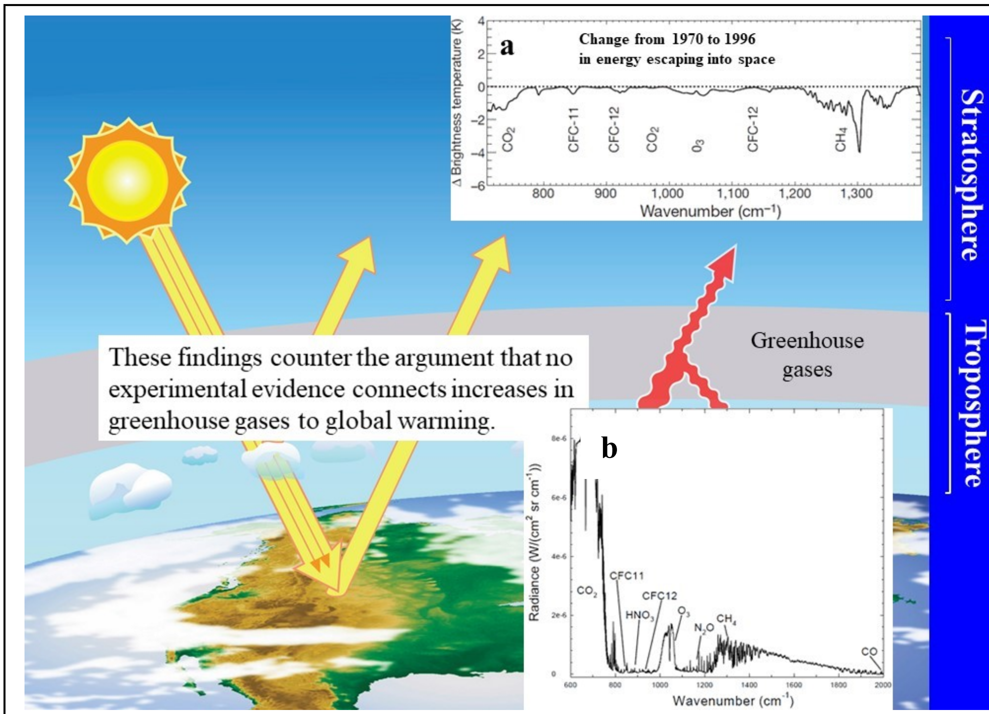


Fig. 11. Wavelengths of infrared energy reflected back to earth's surface at night and blocked from escaping into space. Credit: a) Harries et al. *Nature* 2001;410:357; b) Evans and Puckin. 18th Conference on Climate Variability and Change extended abstract. P1.7. 30 Jan 2006. https://ams.confex.com/ams/Annual2006/techprogram/paper_100737.htm

Evidence that the added CO_2 is from burning of fossil fuels: 1. O_2 decline

There is a finite number of possible sources for the additional CO_2 that has warmed the planet over the past 100 years. The major ones are volcanos, putrefacton of organic material, and anthropogenic burning of fossil fuels: coal, oil and natural gas. While the volcanos and purefaction generate CO_2 anaerobically, only fossil fuel burning does so by oxidation. Burning involves combining oxygen with carbon to produce CO_2 and heat by:

$$C + 2O = CO_2 \quad (\nearrow \text{Heat})$$

Consequently, as burning fossil fuels adds 1 molecule of CO_2 to the atmosphere, 2 atoms of oxygen must disappear. Long-term measurements of atmospheric gas composition have demonstrated that, at least since 1990 (the era of the geometric increase in global temperature), the concentration of oxygen has been declining at exactly twice the rate that CO_2 has been increasing[14,15] (Fig. 12). This excludes natural sources of CO_2 and by elimination confirms the role of fossil fuel burning.

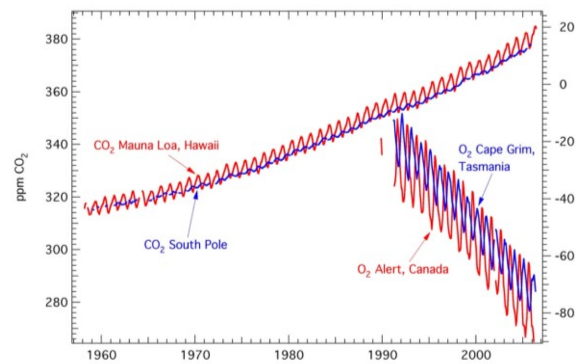


Fig. 12. The oxygen concentration of the atmosphere has been declining at exactly twice the rate that CO2 has been increasing, supporting causation by fossil fuel burning.
Credit: IPCC AR4, The Physical Science Basie, 2.3.1, p. 138.

Evidence that the added CO_2 is from burning of fossil fuels: 2. Atomic fingerprint

Two isotopes of carbon predominate in the atmosphere: carbon 12 (^{12}C) and carbon 13 (^{13}C). Carbon 12 has 6 neutrons, and carbon 13 has 7 (Fig. 13 top).

Carbon in fossil fuels, which were formed by a primitive photosynthesis process millions of years in the past, has a lower $^{13}C/^{12}C$ ratio than that in the natural atmosphere. Consequently, if the CO_2 that has recently been added to the atmosphere is from fossil fuel burning, the atmospheric $^{13}C/^{12}C$ ratio should have fallen since the pre-industrial era.

Ice core sampling demonstrates that the $^{13}C/^{12}C$ ratio was stable for >1,000 years until the start of the industrial age when it began falling in direct proportion to the increase in the atmospheric CO_2 level[16] (Fig. 13 bottom). Moreover the rate of change in the $^{13}C/^{12}C$ ratio is strongly correlated with the rate of increase in anthropogenic CO_2 emissions[17] (Fig. 13 inset).

Thus the change in the atomic fingerprint of the atmosphere further supports an anthropogenic source of the recent atmospheric CO_2 rise.

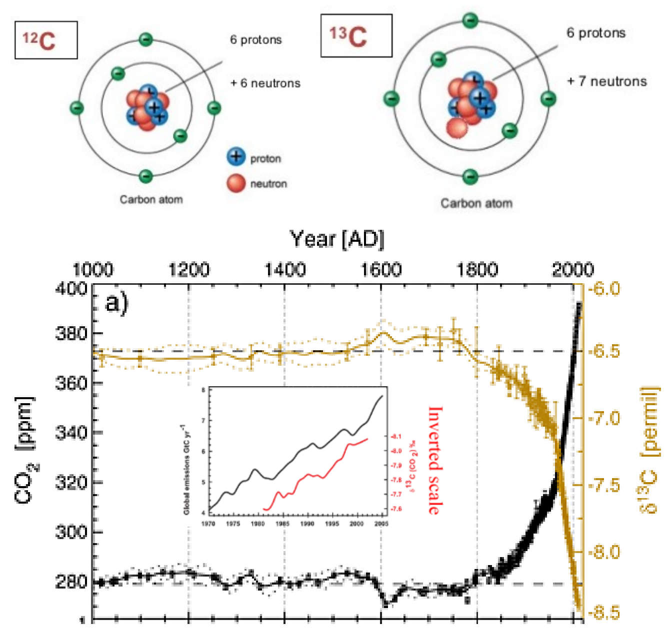


Fig. 13. Since the beginning of the post-industrial age, the atmospheric $^{13}C/^{12}C$ ratio has been falling as the CO_2 concentration has been rising, and the 2 trends are highly correlated (inset). $\delta^{13}C$ = change in the $^{13}C/^{12}C$ ratio.
Credit: **Rubino, Etheridge, Trudinger et al. *J Geophys Res Atmosph* 2013;118:8482. *Doi:10.1002/jgrd.50668*.**
Insert from Forster et al. IPCC ar4-wg1-chapter2, section 2.3.1, p 138.

The conclusion for question 2 "Is the warming due to human influences or natural phenomena?" is the latter: it is from human (anthropgenic) influences, primarily fossil fuel burning.

Q3. Is the warming climate a threat to humans?

The average global temperature has now increased by 1.02ºC (1.84ºF) since the pre-industrial era (Fig. 14). Already we are seeing dramatic effects from this small change. The most recent IPCC report urges keeping the warming below 1.5ºC to avoid severe damage, finding that reaching 2ºC warming would be catastrophic to:

- Food production
- Water supplies
- Human health
- Coastal cities
- Energy production
- National security
- Continued economic prosperity

Current patterns of anthropogenic release of CO_2 and methane, if not curtailed, will reach the point of irreversability between 2036 and 2046, if not sooner, and 3ºC warming by 2,100.

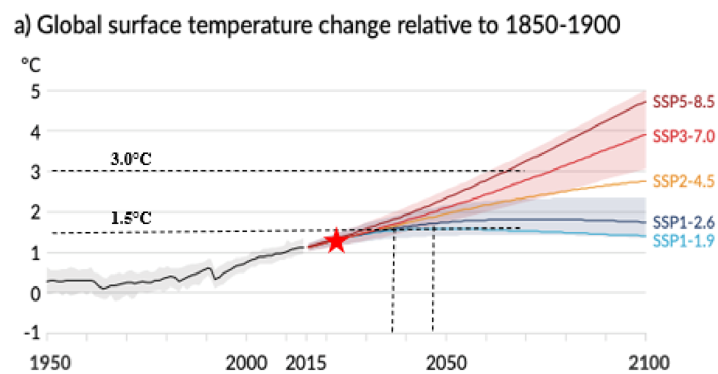


Fig. 14. Four scenarios for the degree of climate warming by 2,100. The true course depends on 2 uncertainties: the degree of climate sensitivity and the extent of human action to curtail it. SSP = Shared Socioeconomic Pathway.
Credit: ***IPCC AR4 Working Group 1, 2021***

The effects of climate change

The major effects of climate change have been widely discussed[4] and will only be listed here to allow more time to discuss the lesser known mechanisms underlying the changes.

- Extreme heat waves for longer
  - Threats to health, energy, agriculture, etc.
- Changes in precipitation patterns
  - More droughts in the Southwest reducing crop yields
  - More wildfires
- Longer frost-free season/fewer freezes
  - Longer growing season
  - Increasing disease vectors and earlier epidemic conditions
  - Increasing tree diseases, die-offs and deforestations
- Ocean acidification
  - Fish species migrate out of traditional fisheries.
  - Species that cannot adapt to rapid change decline.
  - Species extinctions constrain food supply
- Disappearing glaciers
  - Threaten water supplies to major cities
- More rainfall in the Midwest
  - Death and property losses from flooding
  - Water quality loss and increased water-borne diseases
- Stronger storms
  - Tornadoes and hurricanes of higher grades, more hail storms
- Sea level rise
  - Higher storm surges
  - Eventual loss of coastal cities

Disease-causing effects of climate change[18]

https://www.cdc.gov/climateandhealth/effects/default.htm

- Increased numbers and efficiency of vector transmission (e.g., West Nile)
- Expanded range of vector-borne diseases (e.g., dengue, Chagas, leishmaniasis)
- More rapid emergence of novel infectious diseases (e.g., “bird flu”)[19]
- More asthma and COPD exacerbations and heart attacks from ozone & particulate pollution
- Increased allergies and asthma from higher pollen production and longer allergy season
- Greater risk of food-borne and water-borne diseases (e.g., cholera)
- More extreme heat waves and heat-related illness (e.g., heat stroke, deaths)
- Increased severity of extreme weather events (e.g., hail, tornados, hurricanes)
- Growing forest fires and deforestation from intensifying drought, winds and insect infestations
- Famines & water shortages from drought, glacial shrinkage and reduced aquatic abundance

Examples of infectious diseases already affected[20]

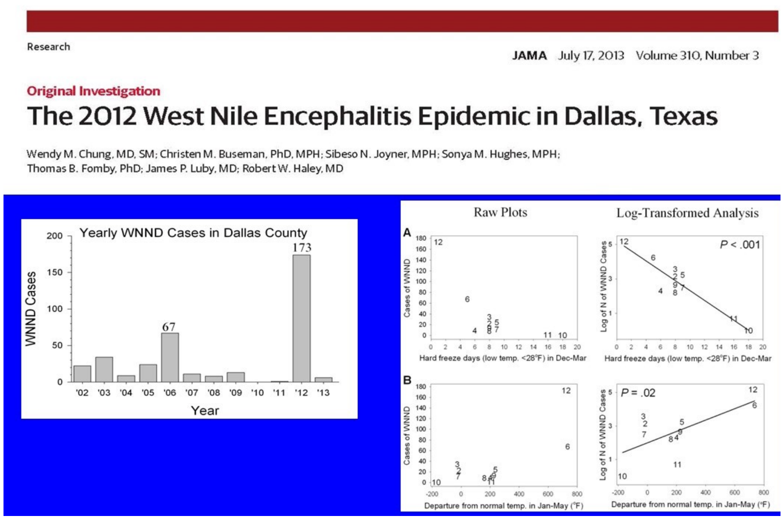
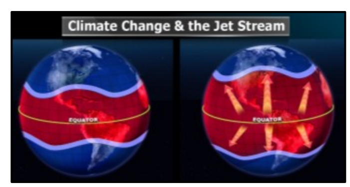


Fig. 15. The effect of higher temperatures with fewer hard freezes in winter and an earlier, warmer spring were apparent in the 2012 Dallas epidemic of West Nile encephalitis.

Credit: Chung, Buseman, Joyner, Hughes, Fomby, Luby, Haley. JAMA 2013;310:297.



Credit: https://www.climatecentral.org/

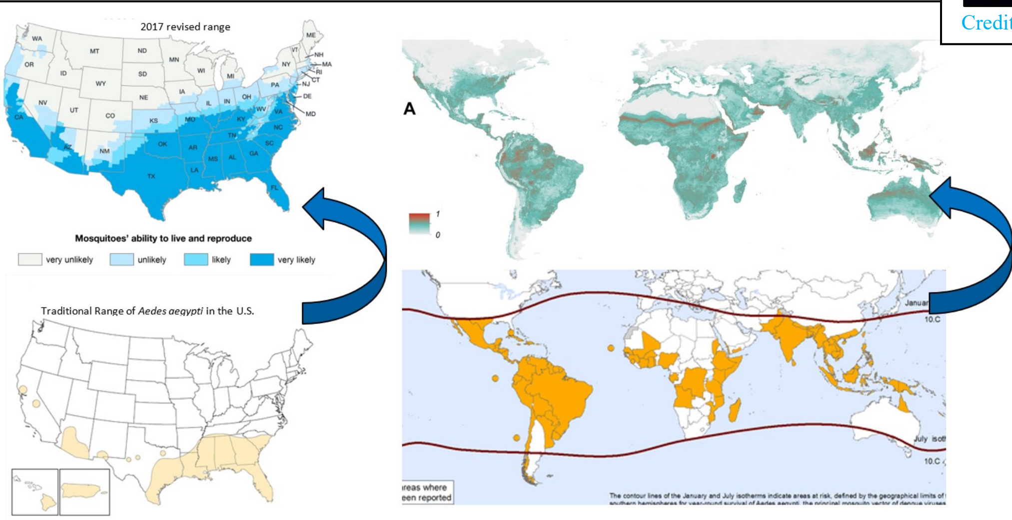


Fig. 16. The warming climate is moving the jet streams poleward (inset), expanding the tropical zone and moving the northern geographical limits of *Aedes aegypti* overwintering further northward. Zika-carrying mosquitos now survive winter further north than ever.

Credit: **CDC https://www.cdc.gov/zika/pdfs/zika-mosquito-maps.pdf; WHO http://www.climatecentral.org/gallery/graphics/climate-change-the-jet-stream**

Threats to National Security from climate change

U.S. military planners have long taken threats from climate change seriously and addressed them in forward plans for protection of national security. Dramatic effects on regional environmental conditions have had profound effects on the stability of governments that have involved the U.S. in costly military operations. Instability and conflict from climate change are expected to increase.[21]

The Arab Spring (2011-2014) was immediately preceded by a once-a-century wintor crop failure in China that inflated global wheat prices. The top 9 wheat importing countries are in the Middle East, and 7 of these had price protests involving deaths and ignited revolutions over pent-up stresses.

The Syrian civil war was entirely unexpected; that country with its educated population, steady economy and generally optimisic economic outlook was thought to be immune to the civil wars of its Middle East neighbors. However, the highly destructive civil war still in progress was preceded by 4 years of the worst drought and crop failure in its history. Crop losses reached 75%. Sheep herders lost 85% of their sheep. Hundreds of thousands of wells were drilled for water, draining the aquifers. These conditions caused a massive migration of rural populations to the cities, and poor government management led to open civil war.

The major economic powers, the U.S., Russia and China, are competing for control of commercial passages and mineral rights opened up by the melting Arctic ice.

Climate change is driving immigration from Central America to the U.S. border

Accelerating crop failures in Central America are accelerating northward immigration to the U.S. (e.g., the 2018 carvans of "drought refugees").[22] The most severely affected countries are Guatamala, El Salvador, Honduras, and Nicarogua (Fig. 17). By 2018, 29% of all asylum applications to all U.S. ports combined were from Guatamala, El Salvador and Honduras; only 7% were from Mexico (U.S.CIS report, April 2018). The U.N. Food and Agriculture Organization reports that 1.6 million Central Americans face food insecurity, and the World Food Program surveyed immigrants who recently left Central America and found that half had left because of lack of food.

Fig. 17. Central American countries currently experiencing severe, prolonged drought.
Credit: **NOAA early warning system**

Climate change is thought to drive immigration from Central America both directly by its negative impact on the food supply and indirectly by driving migration from the dominant rural farming economiy to rapidly growing cities. There over-crowding and poverty fuel crime and exploitation, which out of fear drive immigration northward ("step immigration") (Fig. 18).

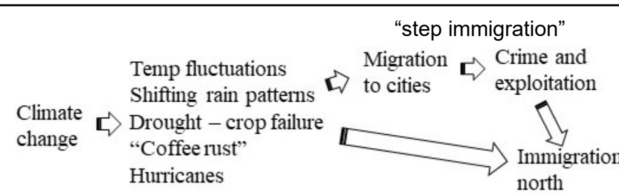


Fig. 18. How climate change is driving immigration both directly and indirectly from Central America northward.

Rising sea levels

One of the most widely publicized adverse effects of climate change, along with increasing forest fires and hurricanes, is rising sea levels. Since 1870 global mean sea level has steadily risen 3.3 mm per year, presently totaling 9 inches (230 mm).[7] Worldwide 8 of the 10 largest cities are located on the coastline and are experiencing increased flooding. In Miami street flooding at high tide that used to happen once or twice a year is now occurring many times a year, and property values and insurance rates are being affected. Many low-lying coastal regions and islands are facing inundation. In the U.S. approximately 40% of the population lives in relatively high-populatin-density coastal areas where rising sea level is causing increased flooding, shoreline erosion, and serious damage from storms.

There are 2 major causes of sea level rise: thermal expansion of sea water and melting of the land-based ice masses, mainly glaciers and ice sheets. At present 90% of increases in atmospheric heat from global warming is absorbed by the oceans. Thermal expansion accounted for most of the rise before the exponential rise in global temperatures in the early 1980s. Since then melting of land ice has accounted for 80%.

Melting ice sheets

The world has 3 massive ice sheets: the Arctic, Greenland and Antarctic ice sheets (Fig. 19). Together they contain approximately 80% of the world's fresh water. They have existed for approximately 34 million years. For decades scientists believed that ice sheet melting would happen slowly, giving us plenty of time to control global warming and curtail melting. However, in the past 3 years improved satellite imaging has revealed far more rapid melting of all 3 ice sheets. Melting of the Arctic ice sheet will not increase sea level directly since melting of floating ice does not increase sea level (more on this below), but melting of land-based ice will.

The Antarctic ice mass is composed of the massive East Antarctica ice sheet and the thinner West Antarctica sheet. Scientists have been observing the progressive melting of the West Antarctica ice sheet for decades, as floating ice shelves at his periphery have been dropping off and large fissures have been appearing in its land-based ice sheet. Recent evidence indicates that the brittle ice shelves play a crucial role in stabilizing the ice sheets and preventing them from slipping into the ocean where they would melt rapidly. When West Antarctica melts completely, sea level is expected to rise an estimated 10 feet. New evidence now shows that the massive East Antarctic ice sheet, which was thought to be stable, is also losing ice more rapidly than previously thought. According to the National Snow and Ice Data Center, complete melting of the Greenland ice sheet would increase sea level by 20 feet, and of the East Antarctic ice sheet, by over 190 feet—a total of 220 feet altogether.

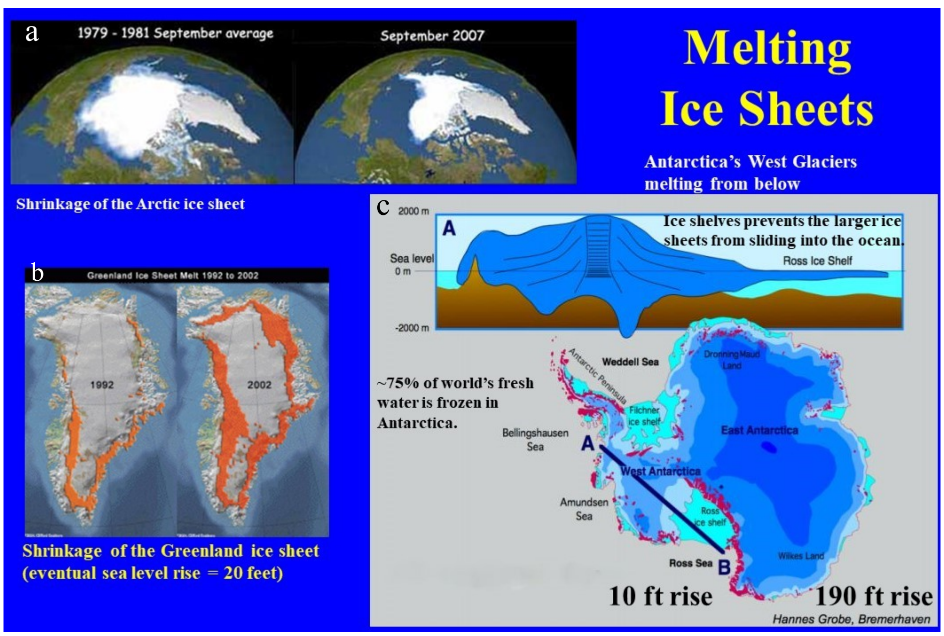


Fig. 19. Melting ice sheets. Complete melting of the land-based Greenland and Antarctic ice sheets would raise global mean sea level by approximately 220 ft. Melting of the floating Arctic ice will not raise sea levels directly.

Credit: a) NASA *http://www.nasa.gov/topics/earth/sea ice nsidc.html,* b) ©2004, Clifford Grabhorn, c) Hannes Grobe 21:51, 12 August 2006 (UTC), Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany (Own work) [CC-BY-SA-2.5 (www.creativecommons.org/licenses/by-sa/2.5)], via

The dire effects of feedback

A critical unanswered question that gets to the issue of how fast global warming will progress is what explains the huge, rapid swings in the atmospheric CO_2 concentration that have ended every ice age for the past 34 million years (Fig. 20)? Where was all that carbon coming from, why was it released so rapidly, what might trigger such a release now, and how much sequestered carbon is there? It had to have been from massive feedback between rising temperatures and biological ecosystems, triggered by rapid increases in global temperature. Although such rapid shifts have been conjectured for decades, they have not yet been incorporated into the large super computer climate models used to predict the course of warming and climate change. If they were, projections would be more dire, with climate shifts sudden and large.

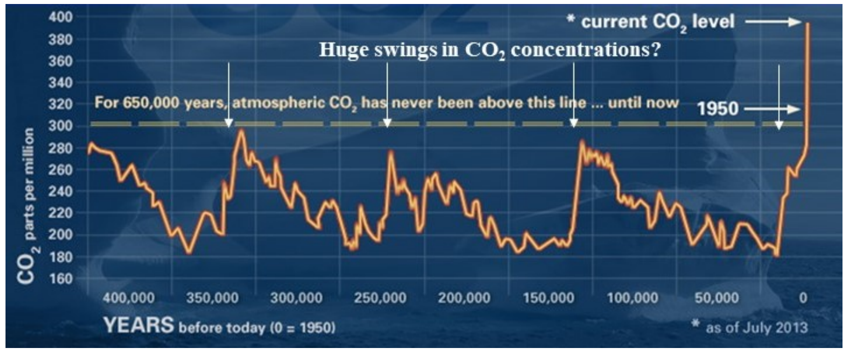


Fig. 20. What explains the huge, rapid swings in CO_2 (vertical arrows) that ended each ice age for the past 34 million years?
Credit: https://*climate.nasa.gov*

One example of positive feedback from global warming relates to the melting of snow and ice-covered land. White ice and snow-covered surfaces reflect sunlight back into space and counteract warming (albedo effect); whereas, dark land masses absorb more light energy. Melting ice exposes land, more light is absorbed, and melting accelerates. This exposes more land, which absorbs more light energy, and so on.

Another example involves the major role of vegetation in absorbing CO_2 and sequestering it underground in its root systems. When drought, fires or human development cause deforestation, the roots decompose and release sequestered carbon, mostly as methane (CH_4), which has 86 times the heat trapping potency of CO_2 in the short term. The resulting warming encourages more fires and thus more deforestation. For example, increasing temperature and human development have deforested 17% to 20% of the Amazon rain forest and reduced its resilience to recover from frequent stresses, nearing a tipping point beyond which it will convert to a savanna, releasing many gigatons of carbon.[23]

Melting of the Arctic permafrost

Permafrost is a thick layer, from several feet to a mile thick, composed of plant and animal matter deposited and frozen there over millions of years (Fig. 21).[24] Permafrost covers approximately a quarter of the land mass of the Northern Hemisphere, stretching around the globe from Northern Canada to Northern Scandinavia and on to Siberia. Recall that global warming of these northern climes is 2-3 times that of lower latitudes and thus is melting the permafrost rapidly. The National Center for Atmospheric Research has estimated that up to 90% of the Northern Hemisphere's topmost layer of permafrost could thaw by 2100, posing a threat to the structural stability of buildings.[25] When the vast amounts of organic matter thaw, they putrify, releasing CH_4 and CO_2 into the atmosphere, further warming the atmosphere in a positive feedback loop.

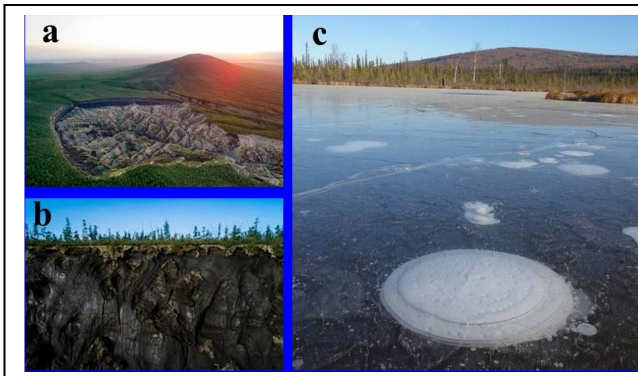


Fig. 21. Melting permafrost in Siberia. a) melting permafrost "crater". b) cross-section of Arctic permafrost containing vegetation and animal matter frozen for millennia. c) methane bubbling up from a new Arctic lake in thawed Siberian tundra.
Credit: a & b) Welch c, Orlinsky K. *National Geographic* Sep 2019 https://www.nationalgeographic.com/environment/article/arctic-permafrost-is-thawing-it-could-speed-up-climate-change-feature; c) Katey Walter Anthony/ University of Alaska Fairbanks, https://www.space.com/41533-abrupt-permafrost-melting-carbon-climate-impact.html

The Thermohaline Circulation and the polar ice sheets

In an effort to develop a better understanding of climate sensitivity to warming and thus to predict how rapidly global warming could accelerate and how climate will be affected, James Hansen, leading a multidisciplinary team of scientists, compiled the existing evidence on the rapid warming and CO_2 rise that ended the glacial period 120,000 years ago and their effects on the climate of the ensuing interglacial temperate period[26] (Fig. 22). They found, contrary to predictions, when global temperature reached only slightly higher than today, large chunks of polar ice disintegrated, producing a rapid rise in sea level of 20-30 ft. It has been generally agreed this will happen, but gradually over several centuries. The new finding is that it will happen more abruptly over the next 50 years, inundating most of the world's large coastal cities.

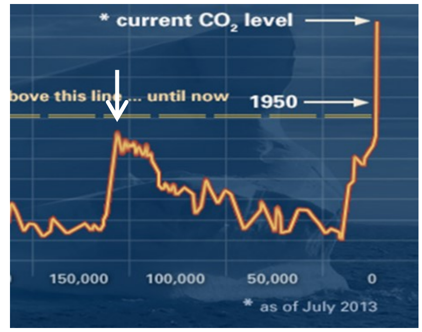


Fig. 22. The 2016 paper by James Hansen's team of multidisciplinary scientists to explain the rapid warming that ended the ice age 120,000 years ago (arrow).
Credit: https://*climate.nasa.gov*

The Thermohaline Circulation. Presently a massive underwater current in the Atlantic Ocean connects and sustains the large Arctic and Antarctic ice sheets (Fig. 23). Warm surface currents are driven northward by temperature and salinity gradients, cooling them en route. Reaching the Arctic Ocean, salinity increases and they become very cold and dense and sink to the bottom, forming the North Atlantic Deep Water, which flows southward. Reaching Antarctica, they circulate around the land mass, rise and maintain the cold temperature of the frozen Antarctic ice shelf.

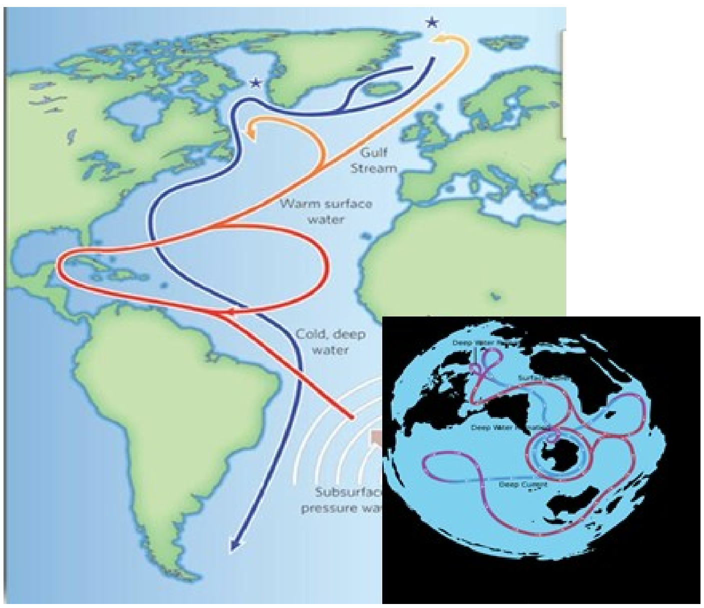


Fig. 23. The Thermohaline Circulation* (the "Ocean Conveyor Belt") brings warm surface water northward to the Arctic where it cools and dives to the bottom, then transits southward to circle Antarctica, cooling and maintaining the Antarctic ice shelf.
***Known by scientists as the Atlantic Meridional Overturning Circulation (AMOC)** Credit: Avsa (CC BY-SA 3.0 [https://creativecommons.org/licenses/by-sa/3.0] or GFDL [http://www.gnu.org/copyleft/fdl.html]), via Wikimedia Commons

The combined paleoclimatic and modern geological evidence suggests that 120,000 years ago the initial melting of the Arctic ice sheet released large caps of fresh water between the Arctic and Greenland. This slowed or stopped the Thermohaline Circulation that distributes heat around the planet and allows some of it to escape into space. Warmth then accumulated in the deeper ocean and greatly accelerated melting of the Antarctic ice sheets. Geological methods in the study found evidence of immense storms, many times stronger than storms during human history, simultaneous with the accelerated polar ice melt, driven by large north-south temperature gradients. During these storms massive bolders the size of buildings were thrown up onto cliffs above the shore by violent wave activity[26,27] (Fig. 24).

Fig. 24. Megaboulders at the crest of a 65 ft high ridge (person pictured for size perspective). Examination of underlying soil strata confirmed that the boulders were wave-transported.
Credit: Hansen et al. *Atmosheric Chemistry and Physics.* 2016;16(6):3761-3812 *doi:10.5194/acp-16-3761-2016.*

Applied to the present, the Hansen team's evidence predicts abrupt catastrophic sea level rise and extremely violent storm activity by **50 years from now**.

This theory was raised and examined 10 years earlier with the existing research methods and found to overstate the degree of slowing of the ocean currents. But this new paper uses multidisciplinary research methods to generate novel evidence from paleogeological history that reopens it.

Implications of rapid increases in the atmospheric CO_2 concentration

Since the beginning of the industrial era, humans have released into the atmosphere more carbon in 100 years than was mobilized in a period of over 1,000 years at the abrupt ending of each of the past ice ages, and we have now forced the CO_2 level to heights not seen in millions of years (Figs. 8 and 22 above). This anthropogenic outpouring of CO_2 has occurred in the present interglacial temperate era on top of the abrupt increase in atmosphieric CO_2 that ended the last ice age 11,000 years ago (Fig. 8). This raises the question of what positive feedback loops might now be triggered, possibly irreversibly, and whether they might trigger the outpouring of additional masses of carbon from sequestered sources to further accelerate global warming.

Computer modeling of geologic data and counting of stomata of fossilized leaves have constucted a record of the atmospheric CO_2 levels back more than 500 million years (Fig. 25). It shows repeated spikes of CO_2 coinciding with the 5 mass extinctions of species.[28,29] Finally in the last 35 million years, the CO_2 level has declined to critical levels below 500 ppm (green arrow in Fig. 25) which allowed the large mammals to evolve (Fig. 8 above), formed the polar ice sheets, and supported all of hominid evolution. Thus, humans have lived entirely in the lowest CO_2 environments of geological time. And yet, anthropogenic fossil fuel burning has produced CO_2 levels, today 416 ppm, unseen throughout this hominid evolution. Were this stimulus to trigger some new biological feedback cycle for further release of long sequestered carbon, it is apparent that there are sufficient carbon sources, released in prior geologic epochs, that, if even minimally mobilized, are likely to extinguish human life.

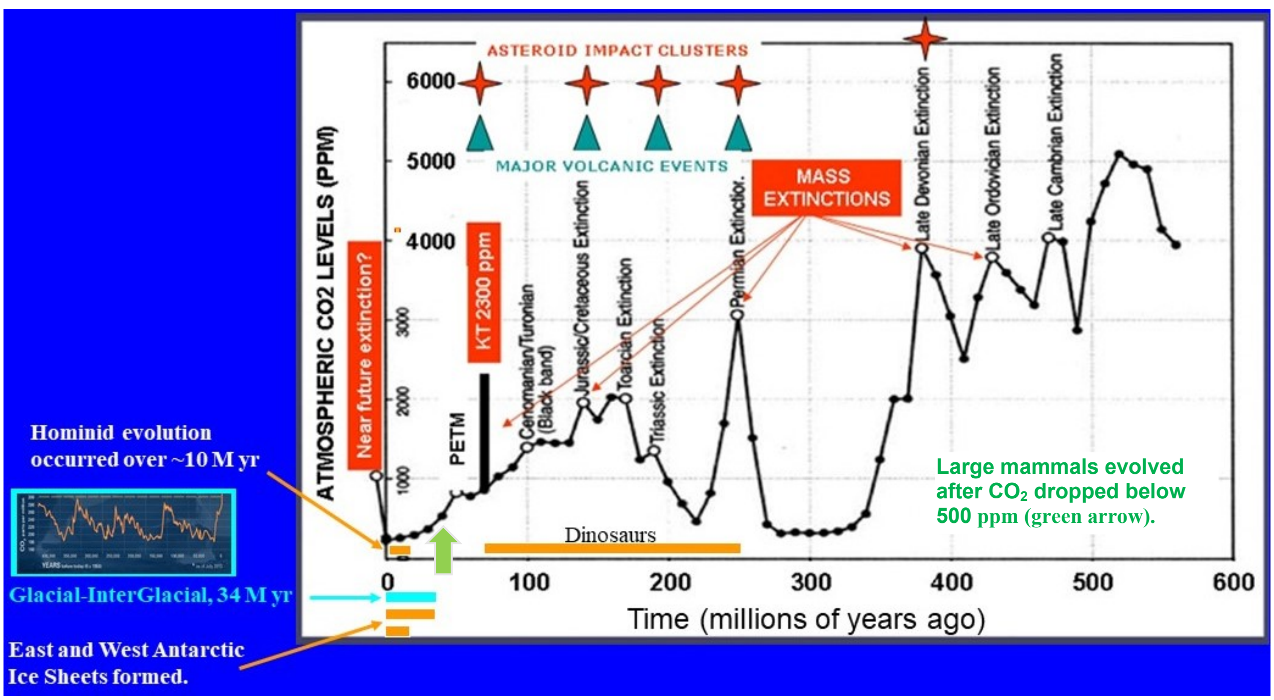


Fig. 25. Massive shifts in atmospheric CO_2 levels and mass extinctions of species through time when atmospheric CO_2 levels reached several thousand ppm (compared with a high of 416 ppm today). CO_2 levels are estimated by mathematical modeling (GEOCARB) and counting CO_2-sensitive stomata on fossilized leaves.

Credit: Glikson A. *Countercurrents.org*. 2010. CO2 Mass Extinction Of Species And Climate Change By Andrew Glikson (countercurrents.org)

The conclusion for question 3 "Is the warming climate a threat to humans?" is yes, global warming with climate change from human emissions of CO_2 and other greenhouse gases:

- *Is no longer a debate within the scientific world.*
- *Is not an issue of faith that you "believe in" or not. (It is science that you believe in or not.)*
- *Is a rapidly growing threat to our children's future (Fig. 26).*
- *Can be constrained by radical action only for the next 11 years.*

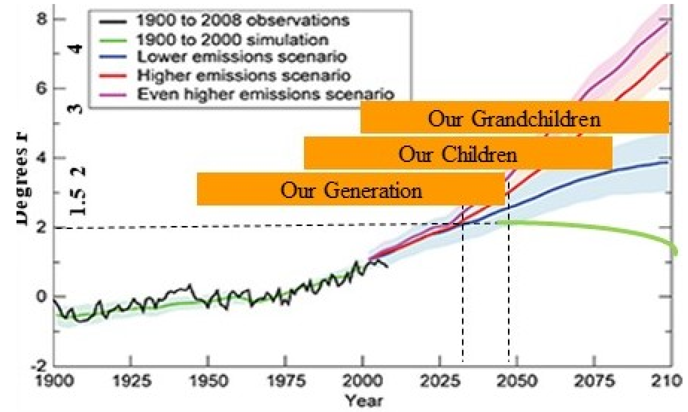


Fig. 26. Scenarios of climate sensitivity in relation to the life span of 3 generations alive today. Dire effects of our actions are likely to play out in the lifetimes of our children and grandchildren.
Credit: ***IPCC AR4 Working Group 1, 2021***

Q4. Should society invest in curtailing climate warming?

Main strategies for halting and rolling back climate change

To prevent catastrophic intensification of the effects of climate that we are already seeing, it is crucial to focus our national efforts on the strategies that will have the most impact. These are:

1. *Transition from fossil fuel burning to non-polluting renewable sources of power* (to slow the rate of warming – when trapped in a deep hole, the first priority is to stop digging).
2. *Remove CO_2 from the atmosphere by Negative Emissions Technologies (NETs)* (to slow the rate and then reverse warming – remember the CO_2 we have emitted will remain in the atmosphere for hundreds of years unless we draw it down).
3. *Adaptation to the most damaging effects of climate change* (to forestall the impact on some humans until relentless climate change eventually overwhelms them – we should minimize investment here to invest maximally in #1 and #2 above).

Transition from fossile fuel burning to nonpolluting renewable sources of energy

The remaining reserves of fossile fuels dwarf extracted amounts (Fig. 27). Fortunately, the revolution in fracking has allowed rapid move away from coal and oil burning to natural gas as a transitional fuel, which is beginning to be replaced by nonpolluting renewables (Fig. 28).

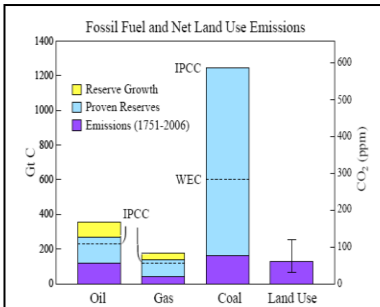


Fig. 27. Sources of past and future CO_2 emissions (Gt C).
Credit: Hansen et al.
arxiv.org/abs/0804.1126

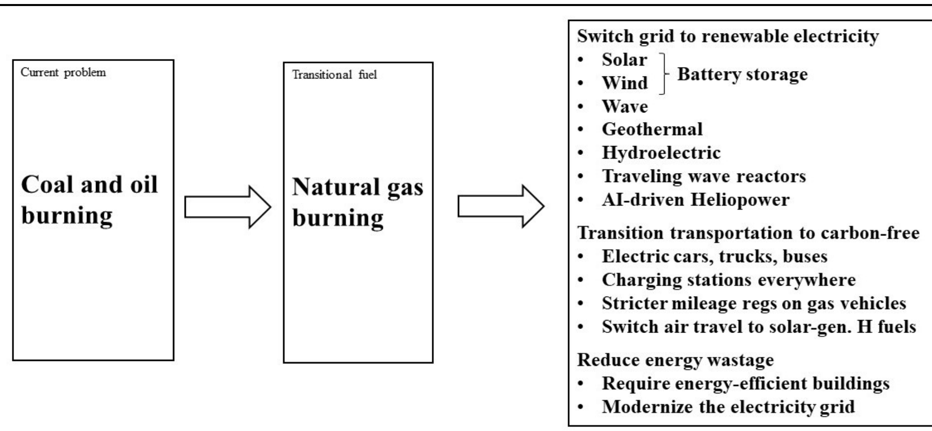


Fig. 28. Transition from fossile fuel burning to renewable sources of energy

The new goal is to limit warming to <1.5ºC to avoid catastrophe, and we have only 10 years to put the infrastructure in place to phase out fossil fuel emissions by 2030, replace them with nonpolluting renewables, and remove CO_2 from the air. Here is what we must do to get there.

- Major federal **infrastructure** investment to reduce energy wasteage and increase R&D to improve efficiency and scale up of renewable soures, just as done with solar and wind in past decades.
- Tighten **standards** in sectors that emit the most carbon: utilities and transportation.
- Transition current fossil fuel **subsidies** (presently $5 trillion, 6% of GDP, per year worldwide) to renewables.
- A national plan to provide new jobs to coal, oil and gas **workers** who are put out of work.
- Restructure **U.S. foreign policy** to persuade other countries to emit less.
- Non-regressive **price on carbon** (e.g., carbon tax) to realign incentives, if politically feasible. The quantitative modeling of Willialm Nordhaus supporting carbon pricing won the 2018 Nobel Prize.

Removal of existing CO_2 from the atmosphere

Even if we completely stop releasing CO_2 into the atmosphere, atmospheric CO_2 levels would remain above 400 ppm for 2 centuries before the CO_2 degrades. The ongoing ice sheet loss and feedback systems would prove increasingly catastrophic. The science reflected in the IPCC reports concludes that to hold atmospheric CO_2 rise to <1.5°C will require both the rapid phase-out of fossil fuel burning and large-scale removal of CO_2 from the atmosphere.

Forestry and agriculture. One of the most efficient ways to remove CO_2 from the atmosphere is to increase forested areas. This can be done in three ways: 1) preserving existing forested regions (e.g., Amazon rain forest); 2) reforestation of clear-cut areas previously forested, and 3) afforestation of land not previously forested. It is estimated that forested area could be increased enough to reduce the atmospheric CO_2 level by 60 ppm. Additional useful agricultural approaches include growing special crops to burn for energy production while copturing and storing the emissions (bioenergy with carbon capture and storage, BECCS); managing farmland and coastal wetlands to trap more CO_2; and grinding up certain minerals that absorb and lock in CO_2. Drawbacks include the large amounts of land required and potential reversibility from later deforestation.

Direct air capture and sequestration. Technology is rapidly advancing to capture CO_2 from the air and either sequester it permanently underground or develop it into products to make the extraction process economical.[30] Large public and private investments in direct air capture (DAC) are required to scale it up to industrial levels. Following demonstration of its feasibility, a number of start-ups are now operating DAC plants using one of two basic absorbants, *hydroxide* absorbants and *amine* absorbants. These absorb CO_2 out of the air and are then heated to high temperatures to release the CO_2 for deep underground storage in rock formations that store it permanently. Hydroxides, used by the Canadian firm Carbon Engineering are cheaper but require more energy to release the CO_2. Plants using amines, used by the Swiss firm Climeworks, though more expensive, have a modular design that could be more easily and cheaply proliferated worldwide.

This technology will have to be scaled up at approximately the same rate that photovoltaic (solar) technology has been, approximatley 30% per year, which will require similar government investment and incentives. While underground space to store the extracted CO_2 is not a limiting factor, the vast amounts of energy required to release the CO_2 from the absorbant could be, although Climeworks is presently fueling its new Iceland facility—sequestering 4,000 tons of CO_2 per year—entirely with geothermal power.

A major danger in committing to CO_2 removal is that it will be seen as a panacea and the phase-out of fossil fuel burning will be delayed; for example, Exxon recently announced a major new investment in carbon capture. Realistic scenarios for holding global temperature rise to <1.5°C require both rapid fossil fuel phase-out and CO_2 removal.

The essential role of the U.S. federal government

While efforts at the individual and local/state levels are helpful and should be encouraged, they will not accomplish the goal alone. Only full commitment of the U.S. federal government, leading our domestic program and the world's other national governments, can get us to where we need to be (Paul Romer, 2018 Nobel Prize in Economics). The federal government is the collective force of all Americans to accomplish the greatest tasks that are beyond local or individual abilities. Federal leadership is essential to invest in rapidly scaling up the required technologies and to lead and incentivize other countries to follow expeditiously.

To reiterate, there are only 2 unknowns in predicting how bad the climate situation will get: the sensitivity of the climate to the rise in greenhouse gas concentrations and whether humans will take sufficient actions to curtain the problem. In the past several years, evidence has been growing that the climate is far more sensitive than previously assumed and is likely to respond with consequences on the most severe end of all the modeled scenarios. Consequently, human action through national governments is the only force that will save the human species.

From the Ethics of Scientific Integrity: Skepticism vs Denialism

Definitions

Skepticism = Withholding belief because the evidence does not live up to the standards of science. (This is an essential attitude of scientists that furthers the self-correcting advance of scientific knowledge.)

Denialism = Refusing to believe something in the face of what most other people would consider compelling evidence.

Without denigrating fellow citizens who presently deny the science of climate change, it is important to understand some of the main reasons that well meaning people might deny:

- Taking no interest in the issue, assuming nothing can destroy our comfortable environment.
- Withholding belief makes us feel rigorous and superior to those “naïve believers.”
- Feeling that no matter how strong the evidence, the scientists could be wrong.
- Having to deny to belong to a social group or a political party.
- Being unwittingly influenced by wealthy fossil fuel interests that have bombarded us with doubt about the science, much as the wealthy tobacco interests and others have done.

“But . . . when we withhold belief long past the point at which the overwhelming cascade of evidence should have convinced us, particularly when inertia will condemn our children and grandchildren to a miserable life, we have moved beyond skepticism to *willful ignorance* . . . *extreme gullibility*.”

Conclusion

"What do we do about this monster that we have created, nourished, and developed to a point where its nefarious power today is literally a million times greater than in 1945? We all know that we are the first generation of humans since Genesis that can totally destroy the human species and make our beautiful planet uninhabitable."

Father Theodore J. Hesburgh
President Emeritus, University of Notre Dame
May 12, 1988
From his speech “The Nuclear Dilemma: The Greatest Moral Problem of All Time”

. . . We are now the second generation of such humans.

References

1. Chung WM, Buseman CM, Joyner SN, et al. The 2012 West Nile encephalitis epidemic in Dallas, Texas. *JAMA.* 2013;310(3):297-307 doi:https://dx.doi.org/10.1001/jama.2013.8267.
2. Moberg A, Sonechkin DM, Holmgren K, Datsenko NM, Karlen W, Lauritzen SE. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature.* 2005;433(7026):613-617 doi:10.1038/nature03265.
3. National Research Council. *Surface Temperature Reconstructions for the Last 2,000 Years.* Washington, DC: The National Academies Press; 2006. https://www.nap.edu/catalog/11676/surface-temperature-reconstructions-for-the-last-2000-yearsAccessed.
4. Ljungqvist FC. A New Reconstruction of Temperature Variability in the Extra-Tropical Northern Hemisphere during the Last Two Millennia. *Geografiska Annaler Series a-Physical Geography.* 2010;92a(3):339-351 doi:DOI 10.1111/j.1468-0459.2010.00399.x.
5. Mann ME, Zhang Z, Hughes MK, et al. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc Natl Acad Sci U S A.* 2008;105(36):13252-13257 doi:10.1073/pnas.0805721105.
6. Mann ME, Bradley RS, Hughes MK. Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters.* 1999;26(6):759-762 doi:10.1029/1999gl900070.
7. NASA. Global Climate Change: Vital Signs of the Planet. 2020. https://climate.nasa.gov/. https://climate.nasa.gov/.
8. Lüthi D, Le Floch M, Bereiter B, et al. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature.* 2008;453(7193):379-382 doi:10.1038/nature06949.
9. Shakun JD, Clark PU, He F, et al. Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature.* 2012;484(7392):49-54 doi:10.1038/nature10915.
10. Santer BD, Painter JF, Bonfils C, et al. Human and natural influences on the changing thermal structure of the atmosphere. *Proceedings of the National Academy of Sciences.* 2013;110(43):17235 doi:10.1073/pnas.1305332110.
11. Evans WFJ. Observations of Climate Radiative Forcing from Ground and Space. *Advances in Imaging, Optical Society of America, Vancouver, OSA Technical Digest (CD).* 2009:FWA4 doi:10.1364/FTS.2009.FWA4.
12. Evans WFJ, Puckin E. Measurements of the radiative surface forcing of climate. *18th Conference on Climate Variabiity and Change, American Meteorological Society, Atlanta, GA.* 2006:1-8. https://ams.confex.com/ams/Annual2006/techprogram/paper_100737.htm.
13. Harries JE, Brindley HE, Sagoo PJ, Bantges RJ. Increases in greenhouse forcing inferred from the outoing longwave radiation spectra of the Earth in 1970 and 1997. *Nature.* 2001;410:355-357.
14. Keeling RF, Shertz SR. Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle. *Nature.* 1992;358(6389):723-727 doi:10.1038/358723a0.
15. Manning A, Keeling RF. Global oceanic and land biotic carbon sinks from the Scripps atmospheric oxygen flask sampling network. *Tellus B: Chemical and Physical Meteorology.* 2006;58(2):95-116 doi:10.1111/j.1600-0889.2006.00175.x.
16. Rubino M, Etheridge DM, Trudinger CM, et al. A revised 1000 year atmospheric δ13C-CO2 record from Law Dome and South Pole, Antarctica. *Journal of Geophysical Research: Atmospheres.* 2013;118(15):8482-8499 doi:10.1002/jgrd.50668.
17. Ghosh P, Brand W. Stable isotope ratio mass spectrometry in global climate change research. *International Journal of Mass Spectrometry.* 2003;228(1):1-33. https://www.sciencedirect.com/science/article/pii/S1387380603002896?via%3Dihub.
18. Haines A, Patz JA. Health Effects of Climate Change. *JAMA.* 2004;291(1):99-103 doi:10.1001/jama.291.1.99.

19. Jones BA, Grace D, Kock R, et al. Zoonosis emergence linked to agricultural intensification and environmental change. *Proceedings of the National Academy of Sciences of the United States of America.* 2013;110(21):8399-8404.
20. Paz S, Semenza JC. Environmental drivers of West Nile fever epidemiology in Europe and Western Asia--a review. *International Journal of Environmental Research & Public Health.* 2013;10(8):3543-3562.
21. *Global Trends 2040: A More Contested World.* Vol NIC 2021-02339. Washington DC: National Intelligence Council; March 2021. https://www.dni.gov/files/ODNI/documents/assessments/GlobalTrends_2040.pdf.
22. United Nations World Food Programme. Food security and emigration: why people flee and the impact on family members left behind in El Salvador, Guatemala and Honduras. 2017. https://docs.wfp.org/api/documents/WFP-0000019629/download/.
23. Boulton CA, Lenton TM, Boers N. Pronounced loss of Amazon rainforest resilience since the early 2000s. *Nature Climate Change.* 2022 doi:10.1038/s41558-022-01287-8.
24. Welch C, Orlinsky K. Arctic permafrost is thawing fast. That affects us all. *National Geographic.* 2019(September). https://www.nationalgeographic.com/environment/2019/08/arctic-permafrost-is-thawing-it-could-speed-up-climate-change-feature/.
25. Hjort J, Karjalainen O, Aalto J, et al. Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications.* 2018;9(1):5147 doi:10.1038/s41467-018-07557-4.
26. Hansen J, Sato M, Hearty P, et al. Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. *Atmosheric Chemistry and Physics.* 2016;16(6):3761-3812 doi:10.5194/acp-16-3761-2016.
27. Velasquez-Manoff M, White J. In the Atlantic Ocean, Shifts in Atlantic hint at dramatic dangers. *New York Times.* 2021;3March:A1. https://www.nytimes.com/interactive/2021/03/02/climate/atlantic-ocean-climate-change.html.
28. Ward PD. *Under a Green Sky: Global warming, the mass extinctions of the past, and what they can tell us about our future.* NY: HarperCollins; 2007: 135Accessed.
29. Glickson A. CO2 mass extinction of species and climate change. *Countercurrentsorg.* 2010. https://www.countercurrents.org/glikson220210.htm. Published 22 February 2010.
30. Realmonte G, Drouet L, Gambhir A, et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat Commun.* 2019;10(1):3277 doi:10.1038/s41467-019-10842-5.

General overview: Mann ME, Kump LR. *Dire Predictions: Understanding Climate Change: The Visual Guide to the Findings of the IPCC*. 2nd Ed., Penguin Random House: New York, 2015.

Good website: *https://climate.nasa.gov*

Intergovernmental Panel on Climate Change (IPCC) reports:

6th Assessment Report: The Physical Science Basis (AR6, 2021)
https://www.ipcc.ch/report/ar6/wg1/

6th Assessment Report: Synthesis Report (AR6, 2023)
https://www.ipcc.ch/report/ar6/syr/