Climate Change in a Nutshell
by James Hansen, edited by Robert Hargraves
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Introduction. Climate has always been changing, but humans are now the principal driver of climate change, overwhelming natural climate variability. Rising atmospheric CO2 levels, primarily a result of fossil fuel emissions, have become the predominate cause of continuing climate change. Increasing CO2 is now responsible for about 80 percent of the annual increase in climate forcing by greenhouse gases. Climate change is driven by cumulative CO2 emissions, of which the United States historically contributed the largest share.

The extensive original article by James Hansen includes references to sources and a bibliography, at http://www.columbia.edu/~jeh1/mailings/2018/20181206_Nutshell.pdf

Climate Change Causes

Natural variability. Climate is described as the average weather over some period. Although climate is always changing, its variability is limited. Some climate variability results from the fact that the atmosphere and ocean are dynamical fluids that are slowly sloshing about. The ocean is about 4 km deep, so sloshing causes variability over long time scales. The most familiar variability is the El Niño cycle, the irregular occurrence of a warming in the tropical Pacific Ocean, which can affect weather globally.

Climate forcing is an imposed perturbation of Earth's energy balance of absorbed and emitted energy. Natural climate forcings include solar variability. For example, when the Sun, which is a variable star, becomes brighter, the added energy is a positive forcing. A positive forcing causes global warming, an increase of global average temperature. In contrast, a large volcanic eruption can inject large amounts of gas and dust into Earth's stratosphere at heights as great as 20-30 km. Most of the aerosols (fine particles) produced are sulfuric acid from sulfur dioxide gas. These aerosols remain in the stratosphere for one to two years, reflecting sunlight away from Earth, creating negative forcing. Temporary cooling was observed after large volcanic eruptions such as at Mt. Pinatubo in 1991.

Humans also cause climate forcings, some exceeding natural forcings in magnitude. The largest human-made climate forcing is a warming effect due to increases in atmospheric concentration of greenhouse gasses, such as CO2, CH4, and N2O that absorb Earth's emitted infrared (heat) radiation.

The second largest human climate forcing is a cooling effect due to human-caused increase of atmospheric aerosols. Aerosols increase reflection of sunlight to space, thus reducing solar heating of Earth's surface.

Additional human effects such as replacement of forests by cropland and building highways and cities can have large local and regional effects, but globally their climate effect is smaller than that of GHGs and aerosols.

CO2 climate forcing. French scientist Joseph Fourier described the greenhouse effect of gases that allow sunlight to pass unimpeded but absorb emitted heat radiation. In the 1850s Irish physicist John Tyndall made laboratory measurements of absorption of heat radiation by water vapor and CO2. Tyndall described the effect of these gases reducing heat radiation to space, causing an energy imbalance with more energy coming in than going out, causing

Earth's temperature to rise until Earth again radiates to space the same amount of energy that it absorbs from the Sun.

Climate forcings are measured in watts per square meter (W/m2). Earth absorbs about 240 W/m2 of energy from the Sun. The Sun's irradiance has been measured accurately since the late 1970s. The irradiance varies with the 11-year sunspot cycle, changing only about 0.1% from minimum to maximum, or only about 0.24 W/m2.

Absorption of heat radiation by CO2 is directly calculable from physics and confirmed by laboratory measurements. Increasing atmospheric CO2 from its pre-industrial concentration of 280 ppm to today's 407 ppm level causes a climate forcing over 2 W/m2. This CO2 climate forcing is an order of magnitude larger than the 0.24 W/m2 solar forcing. Solar forcing oscillates with the 11-year sunspot cycle, but the CO2 forcing is steadily, inexorably increasing.

Climate Feedback

Estimating climate change in response to climate forcings would be easy, if there were no climate feedbacks. However, there are climate feedbacks. For example, atmospheric water vapor increases as Earth warms, as we observe in water vapor increasing from winter to summer. Increasing water vapor is an amplifying feedback, because water vapor is a strong GHG that adds to the warming. Diminishing feedbacks can also occur. For example, some clouds might become thicker and reflect more sunlight to space as Earth warms. Climate feedbacks are critical to determining climate sensitivity, the change in temperature due to changes in climate forcing.

Climate sensitivity. Doubling CO2 from the pre-industrial level of 280 ppm to 560 ppm would be a large forcing, about 4 W/m2. Indeed, burning all fossil fuels would increase atmospheric CO2 by an order of magnitude.

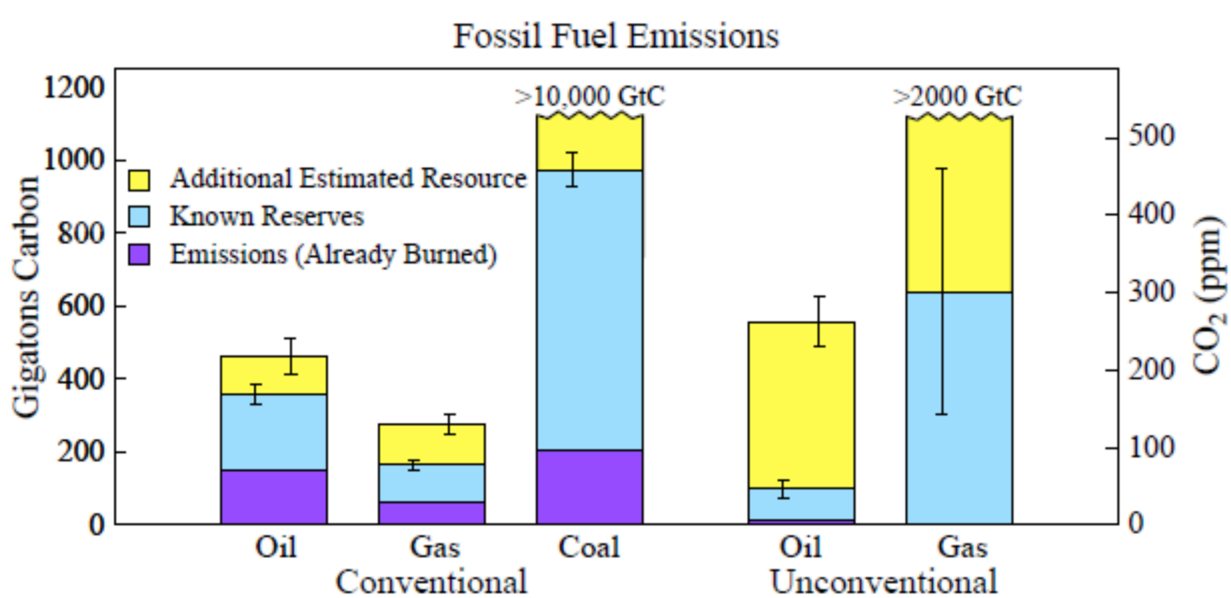

Fig. 1. Fossil fuel CO2 emissions up to 2018 (purple); burning all available fossil fuels could increase atmospheric CO2 by an order of magnitude.

Doubled CO_2 forcing was considered in 1979 in the Charney report of the US National Academy of Sciences. Based largely on climate model simulations, Charney calculated Earth's climate sensitivity to be 0.75°C per W/m2, leading to eventual global warming of about 3°C, after the Earth's surface and ocean eventually warm to restore planetary energy equilibrium. The uncertainty was ±50%, due to limited understanding of climate feedbacks and neglecting century-long ice sheet melting.

Fast feedbacks. Charney's climate sensitivity calculations include effects of fast feedbacks, such as atmospheric water vapor and clouds, which respond quickly to changed climate, but excludes slow feedbacks such as ice sheet size. As detailed information on Earth's paleoclimate history emerged, it became clear that the paleoclimate data provided independent empirical support of Charney's fast feedback climate sensitivity, as well as providing information on the climate system's slow feedback response.

Slow feedbacks include both amplifying and diminishing effects. The two principal slow feedbacks are both amplifying, making climate temperature unstable.

The first slow feedback is ice sheet size and albedo (literally its whiteness). Ice sheets shrink as Earth warms. The land thus exposed is darker than the ice, so it absorbs more sunlight, increasing the warming. Also, with warmer conditions an ice sheet is wet more frequently, from meltwater or rainfall, and wet ice is darker and more absorbing, again an amplifying feedback.

The second slow feedback is provided by CO_2, CH_4 and N_2O, but mostly by CO_2. The ocean, soil and biosphere release more of these GHGs as the planet gets warmer. CO_2 is less soluble in a warmer ocean, as in a warm Coca Cola. More complex ocean chemistry and the rate of ocean overturning also increase the gases released to the air. GHGs are also released by melting tundra and by warming wetlands.

A remarkable conclusion that emerged clearly from paleoclimate data in the 1980s is that these two slow feedbacks account for most of the large glacial-interglacial climate changes. They are instigated by small changes in Earth's orbit and the tilt of Earth's spin axis, but these orbital climate forcings themselves are weak, involving only seasonal and geographical redistribution of sunlight on the planet.

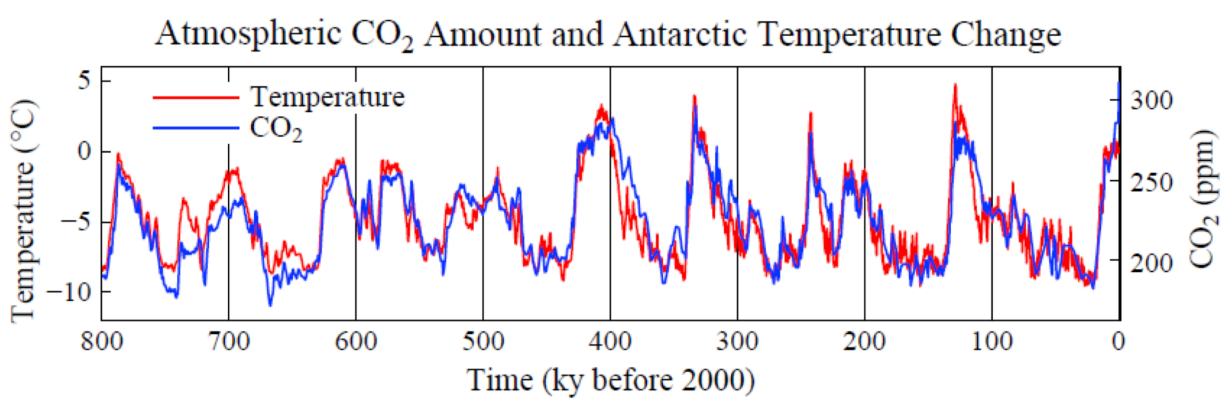

Fig. 2. Antarctic temperature and atmospheric CO_2 amount. Temperatures relative to 10,000-year mean.

CO_2 controls global temperature on millennial time scales. CO_2, temperature and sea level appear to change almost congruently on these millennial time scales. Close examination shows that sea level (an indicator of ice sheet size) lags temperature by 1-4 centuries, the time scale for ice sheet size to shrink (and sea level to rise) in response to climate change.

Observational evidence. The close correlation of CO_2, temperature and ice sheet size in the paleo record confirms the fast-feedback climate sensitivity that Charney inferred from climate models to be 1.5 to 4.5°C for doubled CO_2. Paleo evaluation is obtained by comparing glacial and interglacial states; GHG amounts and ice sheet size bound these two extreme climate states. These paleo data narrow fast-feedback climate sensitivity for CO_2 doubling to 2.5 to 4.0 °C

The Charney study used a climate model to estimate climate sensitivity. The paleoclimate data are empirical observations, independent of any climate model. They confirm the validity of a model-based approach to describe fast-feedback climate sensitivity. The fast-feedback climate sensitivity, which includes water vapor, cloud and sea ice changes, is the sensitivity employed in climate models used to interpret climate change of the past century, and by the models that the IPCC (UN Intergovernmental Panel on Climate Change) uses to project 21st century climate change. These climate models do not generally include the slow climate feedbacks.

Climate models are complex calculations that elaborate the feedback effects of climate forcings. Overall global warming from increased CO_2 climate forcing is a certain consequence of physics. Climate models incorporating feedback attempt to describe the details of how, when, and where the climate changes. Climate models are subject to critical review, but the CO_2 climate forcing driver is basic physics. Detailed climate models may be imperfect, but global warming is a direct consequence of physics of CO_2 climate forcing.

Climate response time

The ocean has great thermal inertia, which delays the global climate response to a climate forcing. Thus even fast feedbacks are slow in developing, because they come into play in response to temperature change, not in direct response to climate forcing. Ocean-atmosphere models indicate that only about two-thirds of the equilibrium temperature change is realized 100 years after the forcing is introduced. The remaining one-third of the surface warming is still 'in the pipeline,' a result confirmed by Earth's observed energy imbalance.

Earth remains out of energy balance, more energy coming in than going out, because of the ocean's long response time; it warms slowly in response to climate forcing by GHGs. Earth's energy imbalance has been measured with a six-year study of ocean temperatures measured by multiple Argo floats at various depths to 2000 m.

The global average imbalance is now 0.75 ± 0.25 W/m2. Because climate sensitivity is about 0.75°C per W/m2, this energy imbalance implies that more than 0.5°C [0.75 × 0.75] additional global warming is in the pipeline even if atmospheric CO_2 remains steady. This additional pipelined global warming will occur over coming decades and centuries, just based on fast-feedback climate sensitivity.

Paleoclimate data shows that slow feedbacks from ice sheet and sea level changes occur with a response time of 1 to 4 centuries. In this century, the degree of this additional slow feedback response, such as ice sheet mass loss and permafrost melt, will depend on the magnitude of global warming and thus on the rate of continued GHG emissions.

The additional global warming from Earth's energy imbalance and from slow feedbacks can be increased or decreased, if atmospheric GHG amounts increase further or decrease. Warming in the pipeline need not occur, if emissions decrease at a rate that allows atmospheric GHG amounts to decline. The same is true for slow feedbacks: they will not occur to a significant degree, if emissions decrease rapidly such that atmospheric GHG amounts stabilize and then slowly decline.

The long response time of the ocean and slow climate feedbacks allows consequences for young people and future generations to build up while most of the public does not notice much happening. Noticeable climate change is just now beginning to rise above natural variability. However, this long response time also provides an opportunity to avoid the worst consequences, if emissions are decreased rapidly such that atmospheric GHG amounts are first stabilized and then decreased.

Climate tipping points. There is evidence that the slow climate feedbacks including ice sheet shrinkage, permafrost melt, and wetland emissions, are beginning to occur. The most important slow feedback is melting of the large ice sheets on Antarctica and Greenland, which causes the practical impact of large sea level rise.

As the ocean warms it begins to melt ice shelves, the tongues of ice that extend from the ice sheets into the ocean. These ice shelves buttress the land-based ice sheets. As the ice shelves melt, the ice sheets expel ice into the ocean faster. This process is self-amplifying, because the melting icebergs freshen the ocean surface waters and fresh water reduces the density of the ocean surface layer; this reduces the ocean's vertical overturning, leaving the warmer water below the cooler surface waters, not releasing heat into the atmosphere and space. Instead, this ocean heat stays at depth, where it accelerates the rate of ice shelf melting.

The danger is that the ice discharge will pass a tipping point such that the amplifying feedbacks cause rapid acceleration of the melting process. It is even possible that, for a vulnerable portion of the Antarctic ice sheet sitting on bedrock well below sea level, the melting process could become self-sustaining. If this happens, a 'point of no return' is reached and massive amounts of ice may be discharged, sufficient to raise sea level several meters. If this tipping point is reached, my colleagues and I estimate that this process could lead to multi-meter sea level rise in a period as short as 50-150 years, if GHGs continue to increase rapidly.

Climate is Changing, Rapidly, and More Change is Coming

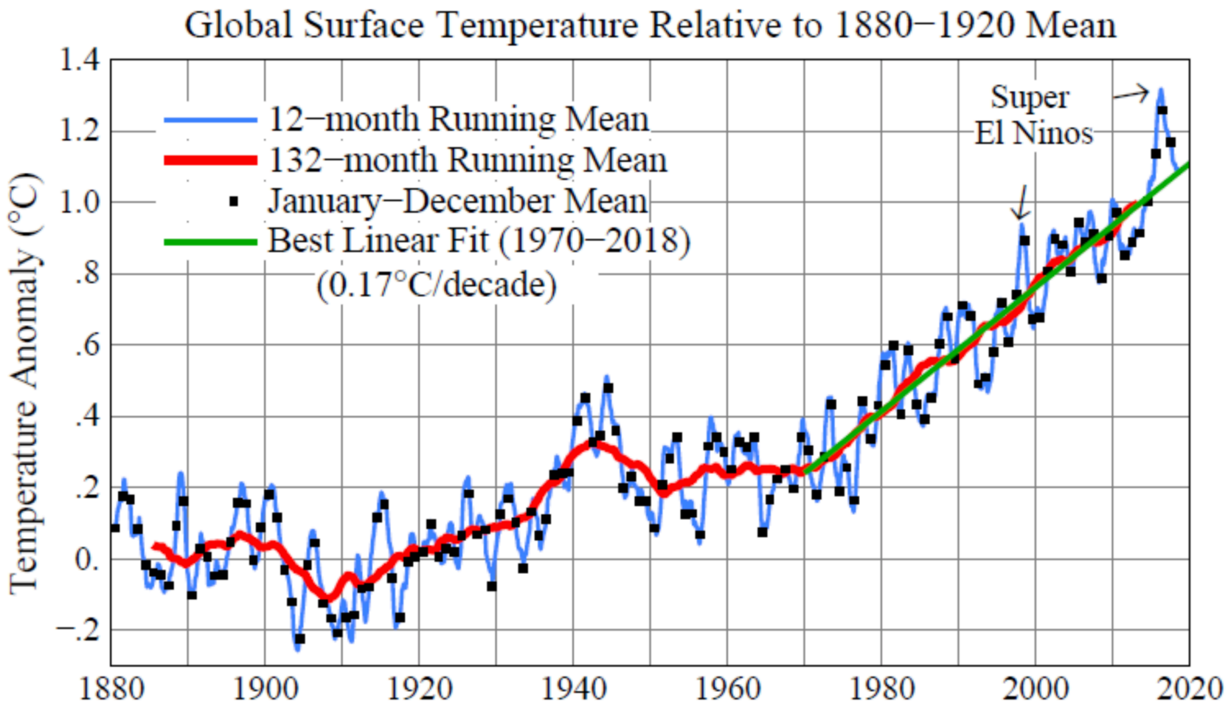

Fig. 3. Global surface temperature relative to 1880-1920 mean.Updated monthly at http://www.columbia.edu/~mhs119/Temperature/.

Global temperature, despite its natural variability, has been rising rapidly for 50 years at 0.17°C per decade (3°F/century). This warming continues unabated and may have accelerated in the past decade, as revealed by connecting the most recent El Niño maxima and La Niña minima (Fig. 3).

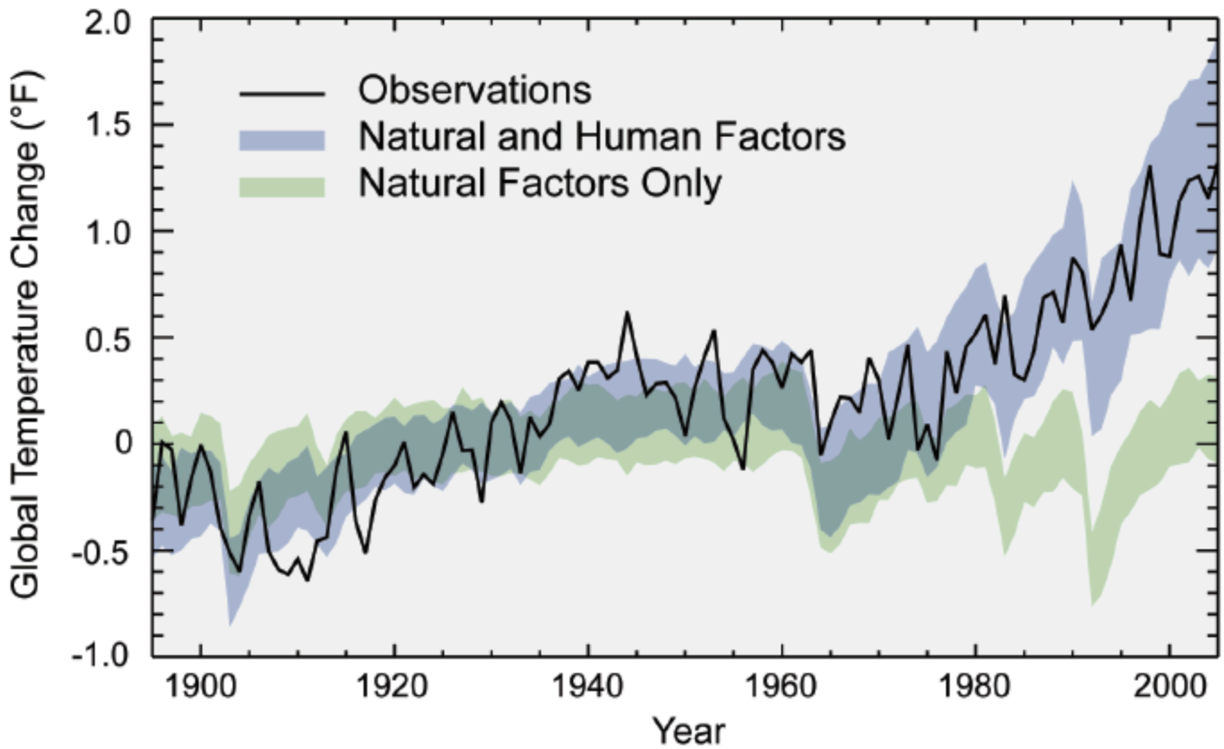

Fig. 4. Modeled and observed global temperature.

Global warming has risen out of the range of natural variability (Fig. 4). The green band shows how global temperature would have changed due to natural forces alone, as simulated by climate models. The blue band shows model simulations for both human and natural forcings (including solar and volcanic activity). The black line is observed global temperature. Only with the inclusion of human influence can models reproduce the observed temperature changes.

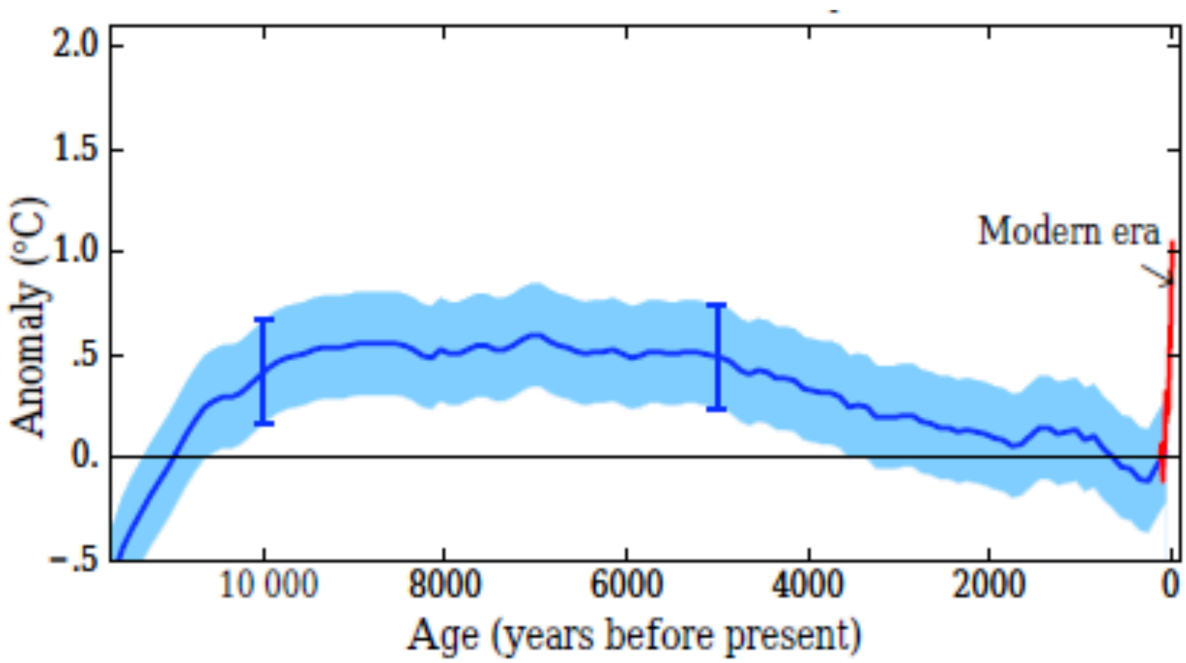

Fig. 5. Estimated global temperature during the past 11,700 years and the 11-year running mean of modern data (red curve).

Paleoclimate context. The rapid global warming of the past 50 years has raised global temperature out of the prior range during the Holocene (Fig. 5), i.e., the past 11,700 years. In this period in which civilization developed sea level has been relatively stable.

Modern era temperature (red curve) crossed the early Holocene (smoothed) temperature maximum in about 1985. We know the modern era temperature will continue to rise. Earth is out of energy balance, with more energy coming in than going out.

How much further will temperature rise if we leave atmospheric CO2 at its current amount (about 407 ppm) indefinitely? Paleoclimate data on millennial time scales provide a good estimate of the full response to CO2 change, including the effects of both fast and slow climate feedbacks. Figure 2 reveals the tight control that CO2 exerts on Antarctic temperature on millennial time scales. Antarctic temperature change is shown because it can be placed accurately on the same time scale as CO2, as both quantities are recovered from analysis of the same Antarctic ice core. Antarctic temperature change on millennial time scales is expected to be about twice as large as global mean temperature change.

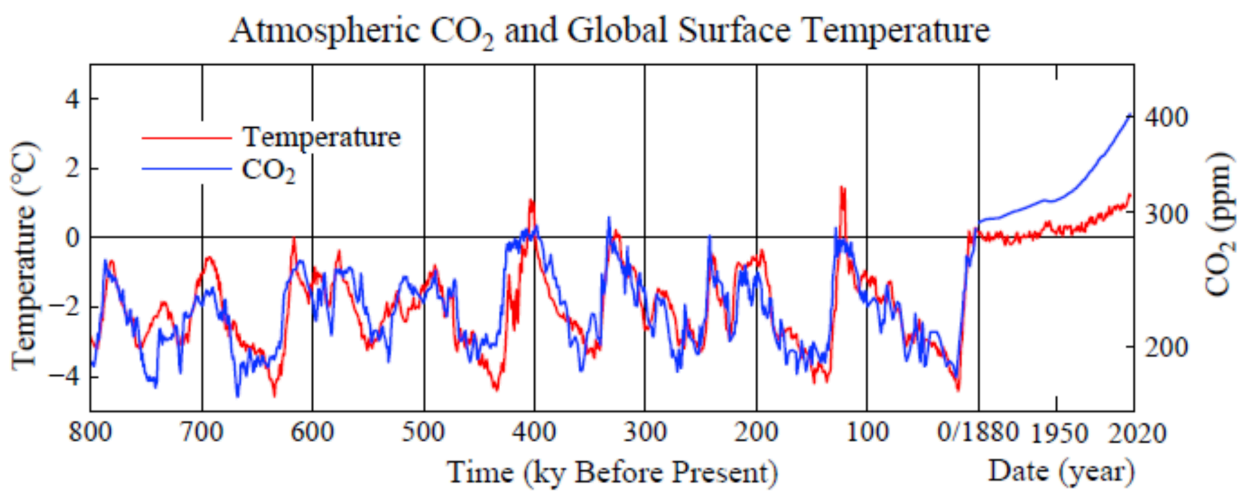

Fig. 6. CO2 amount from Antarctic ice cores. Global surface temperature change is from ocean core data. CO2 amount is plotted on a logarithmic scale, because CO2-forced temperature response is proportional to the logarithm of CO2 amount.

Global mean temperature change on millennial time scales can be estimated using ocean cores from many locations around the world. Although this introduces uncertainty in the dating compared to the CO2 ice core dating, the results confirm the tight control of CO2 on global temperature (Fig. 6). This figure implies that the eventual warming for 407 ppm CO2 will be about 3.5°C, including the full effect of both fast and slow climate feedback processes.

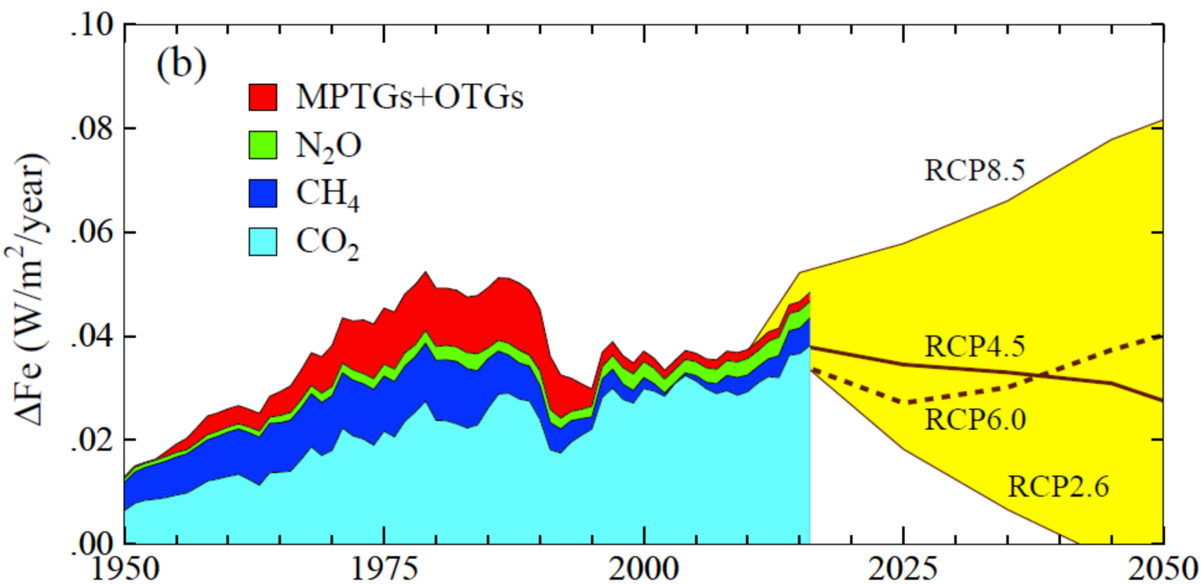

Fig. 7. Greenhouse gas climate forcing has increased about 0.04 W/m2 each year for the past 50 years. Representative Concentration Pathways scenarios (RCP) were defined by the IPCC.

CO_2 Dominates GHG Climate Forcing

The Montreal Protocol has been successful in phasing out emission of ozone-depleting gases as well as some other trace gases. CO_2 change is the largest human-made climate forcing, alone equal to the net human-made climate forcing; other GHG forcing is about balanced out by aerosol forcing. The GHG climate forcing has been increasing at a rate of approximately 0.04 W/m^2 per year for the past 50 years, summing to about 2 W/m^2 (Fig. 7). The full effect of CO_2 is greater than suggested by the figure, because part of the growth of CH_4 and N_2O is the amplifying feedbacks from wetlands and tundra changes that occur with global warming, largely due to increasing CO_2.

RCP (Representative Concentration Pathways) scenarios of IPCC in Fig. 7 are arbitrary, but note the steep reduction of forcing growth in scenario RCP2.6, a scenario chosen to keep global warming under 1.5°C. It peaks GHG emissions by 2020 and drops radiative forcing to 2.6 W/m^2 by 2100.

Summary

Earth is now substantially out of energy balance. The amount of solar energy that Earth absorbs exceeds the energy radiated back to space. The principal manifestations of this energy imbalance are continued global warming on decadal time scales and continued increase in ocean heat content.

Quantitative understanding of Earth's energy imbalance has improved over the past decade. The upper two kilometers of the ocean, where most of the excess energy is stored, has been well-monitored by the international Argo floats program since 2005. Over the full sunspot cycle 2005-2016 Earth's energy imbalance is 0.75 ± 0.25 W/m^2.

In order to eventually restore Earth's energy balance, cumulative atmospheric CO_2 would need to be reduced from 407 ppm to 342-373 ppm. Ocean, soil and biosphere do absorb about 45 percent of annual CO_2 emissions. Restoring energy balance requires both stopping emissions that add to cumulative CO_2 and also removing CO_2 relying on natural ocean, soil and biosphere absorptions.

In reality CO_2 cumulative emissions continue to increase; annual emissions increase; even their rate of growth is increasing. Global population and energy demands continue to increase, and about 85 percent of global energy is provided by fossil fuels.

Impact of continuing to burn fossil fuels

Before considering the potential for phasing down CO_2 emissions and atmospheric CO_2 amount, it is appropriate to consider the practical impacts of climate change, if fossil fuel CO_2 emissions are not phased down.

Sea level. Sea levels are now rising at only about 3 mm per year, but this will accelerate if the climate reaches a tipping point. Sea level rise in the past century has been due to the combination of several processes, the most substantial being (1) thermal expansion of the ocean, (2) melting of glaciers and small ice caps, and (3) mass loss of Greenland and Antarctic ice sheets. The first two processes are relatively linear with increasing global temperature, compared with disintegration of the great ice sheets, which threaten multi-meter sea level rise and the loss of coastal cities.

Ocean warming is melting ice shelves that buttress the Antarctic and Greenland ice sheets. If global warming continues unabated, portions of the ice sheets will become unstable, ice sheet disintegration will accelerate, and sea level will rise continuously. A majority of large U.S. and global cities are coastal. Continued high fossil fuel emissions will lead to eventual sea level rise that makes these cities dysfunctional

Sea level reached heights as great as 6-9 meters during the prior interglacial period, the Eemian about 120,000 years ago, when global temperature was only about 1°C above the pre-industrial level, i.e., similar to today's global temperature. Burning all of the readily available fossil fuels would eventually melt almost all the ice on the planet, raising sea level 65-75 meters (more than 300 feet). We must expect several meters of sea level rise for each degree Celsius of global warming, if warming is left in place indefinitely.

Species extermination. Rapid shifting of climate zones is a significant stress for many species. CO2 is increasing today at least 10 times faster than any change in Earth's history. On a regional basis this global warming causes a shifting of climatic zones. Since 1970 the average rate of poleward migration of a given temperature line has been about 60 kilometers per decade, more than 3.5 miles/year, for Northern Hemisphere land areas. This rate of change can exceed the rate at which many species are able to migrate. Species can generally survive only within some specific climate zone.

Regional climate anomalies will become more extreme and costly. The subtropics in summer and the tropics all year will become dangerously hot, if global warming continues. Living and working outdoors would become difficult. Most jobs are outdoors, agricultural or construction. Populations would be driven to emigrate; governance would be an increasing challenge.

Avoiding Dangerous Climate Change

Science can specify an initial target for atmospheric CO2, about 350 ppm, which is sufficient to define near-term policy needs. Emission reductions must begin promptly. Otherwise climate can be pushed beyond the tipping point at which changes proceed out of possibility of human control. Leisurely reductions of 1-2 percent per year will not suffice.

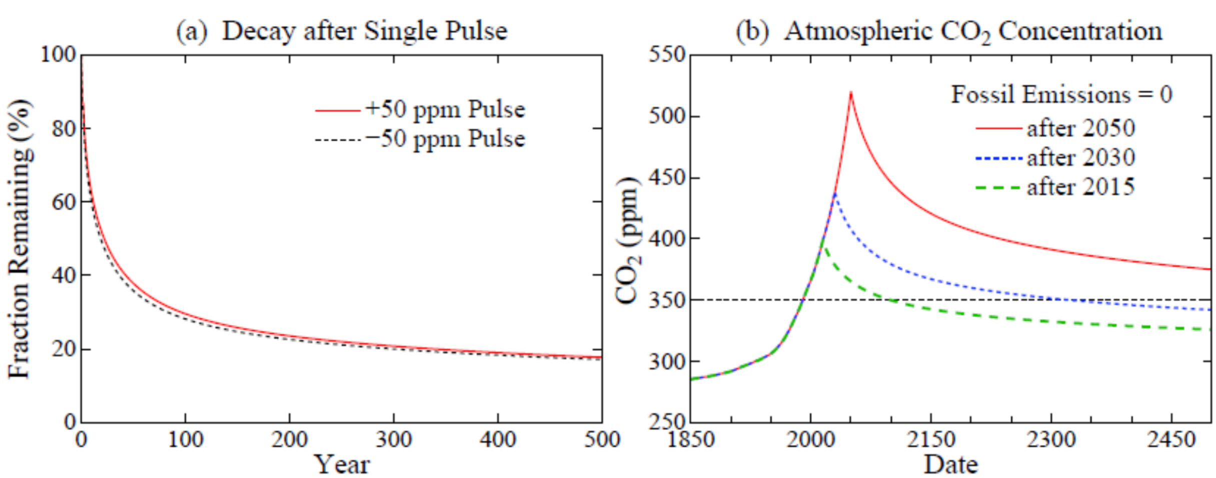

Fig. 25. Decay of atmospheric CO2 perturbations. (a) Instantaneous injection or extraction of CO2 with initial conditions at equilibrium. (b) Fossil fuel emissions terminate at the end of 2015, 2030 or 2050 in these three scenarios.

Earth's slow response to energy imbalance. Earth responds by growing warmer, until it radiates to space as much energy as it absorbs from the Sun. However, it takes at least several decades for the ocean to achieve most of its warming. Meanwhile, ice sheets and tundra are melting, providing amplifying feedbacks that increase the warming and stretch the response time.

Long life of CO2. Much of the fossil fuel CO2 injected into the air remains in the atmosphere for centuries (Fig. 25a). Fig. 25b shows how difficult the problem becomes if high emissions continue. Even with emissions terminated entirely in 2030, CO2 in the air does not decline to 350 ppm until 2300.

Lifetime of energy infrastructure. Fossil fuel energy infrastructure is extensive and valuable. Fossil fuels provide 85 percent of the world's energy, which has raised standards of living. Energy is needed to support a still growing global population. These expensive capital investments will not be easily abandoned. Replacement of fossil fuels by carbon-free energy sources will require several decades.

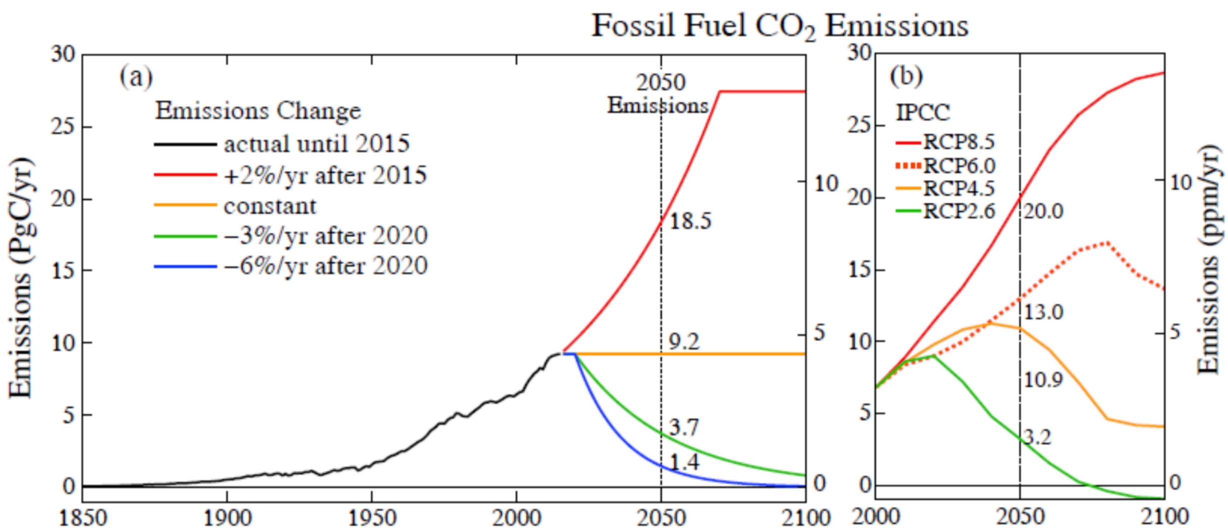

Fig. 26. Fossil fuel emission scenarios. (a) Scenarios with simple specified rates of emission increase or decrease. (b) IPCC (2013) RCP scenarios.

Fossil fuel CO2 emission scenarios. IPCC provides several RCP (Representative Concentration Pathway) scenarios for fossil fuel emissions (Fig. 26b). For ease of interpretation, we define simpler scenarios in Fig. 26a by the annual growth rate of emissions: +2%, 0% (constant emissions), – 3% and – 6%.

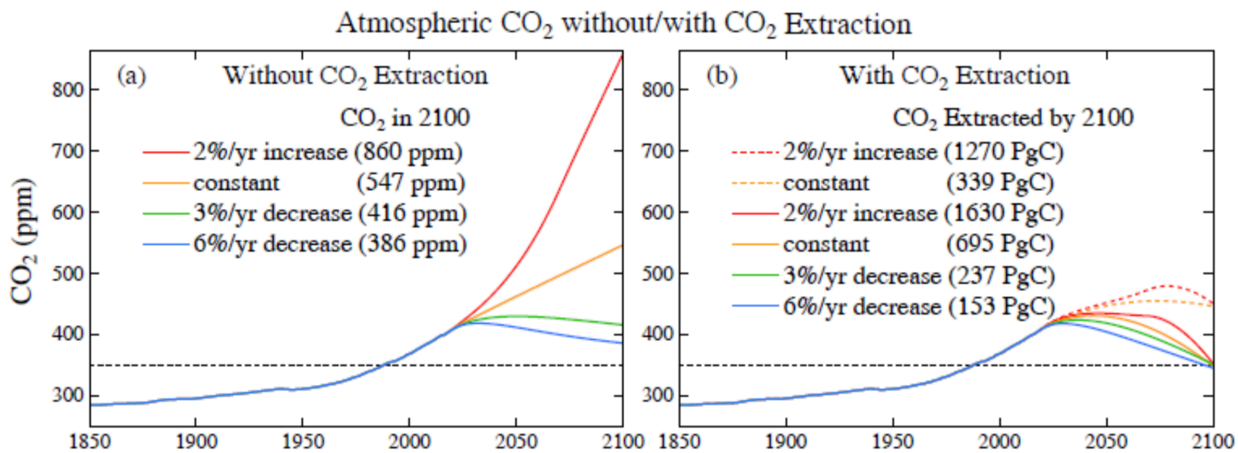

Fig. 27. (a) Atmospheric CO2 for Fig. 9a emission scenarios. (b) Atmospheric CO2 including effect of CO2 extraction that increases linearly after 2020 (after 2015 in +2%/year case).

Atmospheric CO2 scenarios. Atmospheric CO2 resulting from the emission scenarios of Fig. 26a is shown in Fig. 27a. Emission reductions in scenarios with declining emissions (reductions of 3% and 6% per year) begin in 2021.

Rapid emission reduction, at least 3 percent per year, is needed just to keep CO2 in the neighborhood of 400 ppm (Fig. 27a). Constant emissions lead to CO2 above 500 ppm this century. Emissions growth at 2 percent per year, typical of recent decades, leads to CO2 exceeding 800 ppm! Constant emissions is about the best that can be hoped for with current global policy discussions, in which developed countries reduce their emissions while emissions from developing countries are still growing. In other words, current global policies yield a path that leads to certain disastrous consequences for young people and future generations.

Negative emissions. Some scientists proposed imaginary negative emissions that might be produced if fossil fuel power plants were replaced by power plants burning biofuels and if the CO2 emitted by the power plants were captured and buried permanently. Implausibility of negative emissions on the required scale is readily apparent. Land to grow biofuels must compete with land needed to grow food. The task of capturing, transporting and storing the CO2 is enormous. NIMBY opposition to CO2 pipelines CO2 storage would be great. The decisive factor likely would be cost.

Cost of CO2 extraction. The constant emissions scenario, which would result in CO2 of 547 ppm in 2100 (Fig. 27a), might still achieve the goal of 350 ppm CO2 in 2100, provided that 2500 Gigatons of CO2 is somehow captured and permanently stored, as shown in Fig. 27b. The lowest, optimistic estimate for cost of extraction and storage of this much CO2 is $104-243 trillion, or at least $1.3-3.0 trillion/year if the cost is divided uniformly over 80 years. This extraordinary cost makes CO2 extraction infeasible.

Conclusion

Climate science described above shows unambiguously that global fossil fuel emissions must decrease rapidly over the next few decades, if we are to avoid climate calamities.

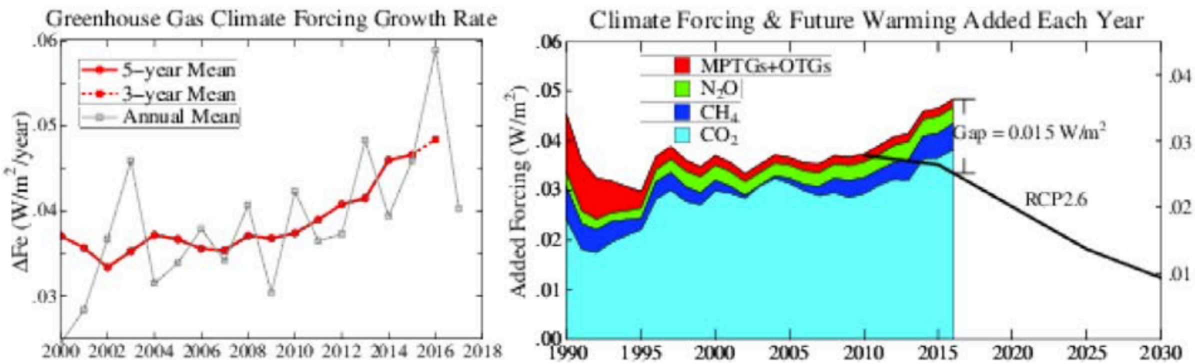

Fig. 31. Annual increase of greenhouse gas climate forcing. Right graph: contribution of each gas. RCP2.6 scenario is designed to keep global warming below 1.5°C, but the gap is being widened.

Paris Agreement. Negotiators seemed optimistic, even self-congratulatory, upon reaching the 2015 Paris Agreement. But the truth is that the accord does little to change the world's energy and climate trajectory. Figure 31 compares reality with IPCC scenario RCP2.6, the pathway to cap global warming at about 1.5°C. Already the gap between that scenario and reality has grown to 0.015 W/m2 and measurements so far in 2018 show that the gap is continuing to grow.

Climate science shows unambiguously that global fossil fuel emissions must decrease rapidly over the next few decades, if we are to avoid climate calamities.