CLIMATE CHANGE

▼ GLOBAL HEATING ▽ ▽

> You almost couldn't design a problem that is a worse fit with our underlying psychology. Climate change is not immediate, its causes are invisible, its consequences seem unrelated, and it is faceless. It has none of the features that evolution has taught to recognize as a threat. — paraphrase of Anthony Leiserowitz.

Climate change includes numerous phenomena. All of them come from an increase in the altitude of the Earth's 255°K (-1°F) radiation level. This temperature is governed by solar input and the albedo (reflectivity) of the Earth. Its altitude is controlled by the infrared optical depth, which depends upon ‘greenhouse gasses’. ‘Greenhouse gasses’ are any molecules with more than 2 atoms. They have many internal energy levels that interact with infrared photons. This means that they decrease the optical depth, which raises the altitude of the radiation level, warms the Earth's surface, and changes our climate.

△ △ THE FACTS ▽ ▽

> [Climate change] is the greatest and widest-ranging market failure

ever seen (*Stern Review* ⬆) — because the price of all things climate-related is based on current demand and supply, and takes no account of the distributed cost of global heating, floods and droughts, biodiversity attrition, agricultural losses, sea level rise, and other 'externalities'.

△ The Short Version ▽

For anyone who keeps up with the march of science, anthropogenic climate change was understood, anticipated, and noncontroversial a century ago:

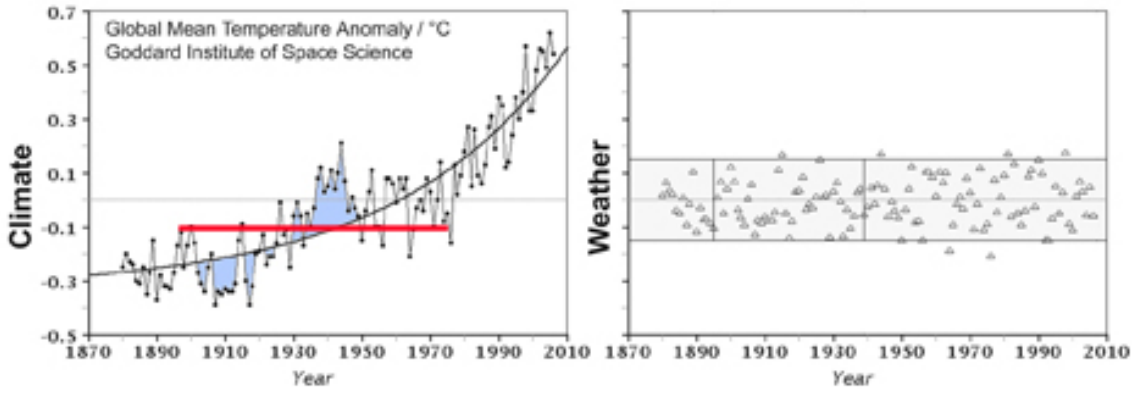
- 1824, Fourier: The atmosphere traps heat.
- 1861, Tyndall: Changes in CO_2 might explain climate change.
- 1896: Arrhenius outlines the effects of anthropogenic CO_2.
- 1936, Callendar: Doubling CO_2 will raise temperature 2°C.
- 1961, Keeling: Fossil-fuel use is steadily increasing CO_2.
- 7th-grade science known to everyone who has been paying attention:
  - Adding CO_2 increases the altitude from which infrared radiation can escape.
  - The radiation temperature of the Earth — a constant set by solar input — is at this altitude.
  - Below this altitude, temperature increases adiabatically with pressure.
  - This is why snow is found on mountain tops and the Dead Sea is hot.
- 1972, Sawyer: By 2000, CO_2 will increase by 25% and temperature by 0.6°C.
- 2003, Root: 1200 less intelligent species have responded to global heating by changing their behavior. **We are not among them. In fact, our ecocidal misbehavior is accelerating.**
- 2016, Hansen: Children are suing the government for the harm they will endure if we continue to use fossil fuels. The government moves to dismiss the case.

There was much we could have done with a century of advance knowledge. The problem is that known, profitable business-as-usual always seems more important than precautions against unknown dangers. We cannot predict the detailed dangers of climate change except in the broadest terms. This is because climate science is frontier science. It is perhaps the most complex problem that we have tackled. The number of disciplines that must be mastered is large. Their interactions (which produce the stochastic weather whose integration is climate) can be subtle and counterintuitive. The resulting

uncertainty, together with Leiserowitz's epigraph and Congress's vested interests, explain why limiting CO_2 production is understood as an emergency priority by a few and a scam by many.

Let me emphasize again that the heating is real. 1200 other species, more attuned to their environments than we are, have already altered their range or behavior. Europe is now warmer than it has been for 5300 years (if not 120,000 years). We know this because otherwise Ötzi the Ice Man would have thawed and decomposed. Climate is always changing. The Medieval Warm Period and Little Ice Age (local European events) had something to do with vulcanism and the circulation of the North Atlantic Ocean. The Sahara has been grassland. Coastal areas, once well below sea level, today hold our most socially and technologicaly advanced cultures. Such changes will happen again — but it is suicidal to help them happen!

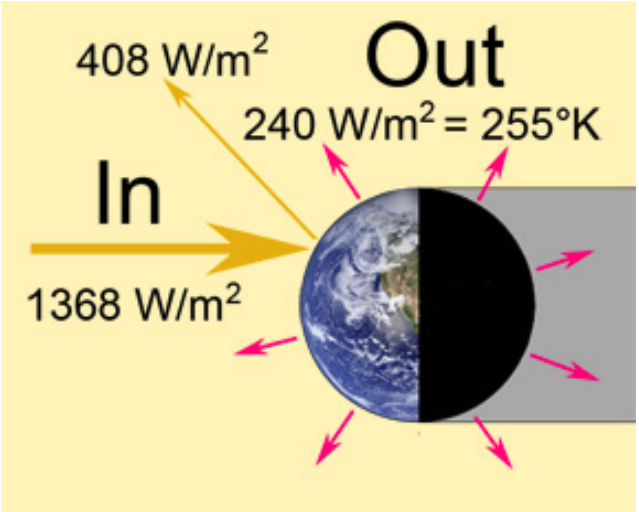
The superficial problem is shown in Fig. 0. The data is noisy, which makes it very hard to see small trends. The modeller's response is to separate noise from signal, which can be done by subtracting 2 simple equations from the 'climate' data on the left, leaving the 'weather' data on the right.



◀ Fig. 0. ▶ Global Heating. **Left:** The smooth curve is the best-fit exponential. It closely matches anthropogenic CO_2 production, with about half of the CO_2 absorbed by and acidifying the ocean. The shaded oscillation (1900–1950) was first spotted by oceanographer Wallace Broecker at a time when Big Oil pretended that the heavy horizontal line (an 80-year pseudo-stillstand) was real and claimed that the lack of increase between 1900 and, ultimately, the late 1970s, 'proved' that global heating was not happening. This was later admitted to have been a deliberate commercial lie, as their scientists were as competent as anyone's. After wartime ship records were digitized, it became clear that 'the sudden drop in [sea-surface temperatures (SST)] in late 1945 is consistent with' changes in the way SST was measured (bucket vs engine cooling-water intake). Correction can be as much as 0.3°C. **Right:** This is what would be happening in the absence of fossil-fuel consumption and

Wally's Wiggle, (both removed by subtraction of simple equations, implying simple underlying processes). Some of the low points are associated with large volcanic eruptions.

There are 2 important temperatures to consider in this discussion. The first is the radiation temperature of the Earth. Because energy is conserved (the First Law of Thermodynamics, and unlike human rules, a law that has never been observed to fail), energy leaving the Earth is equal to the energy it received from the sun. The energy is the same: the temperature of the energy is different because the receiving and exporting areas differ by a factor of 4, as shown in Fig. 1.



◀ Fig. 1 ▶ The Constant Radiation Temperature. The earth's steady-state *radiation* temperature depends upon 3 nearly invariant quantities: the incoming energy from the Sun, 1368±2 W/m^2 over the intercepted area; the fraction that is reflected (30±2%), and the emissivity of the earth (≈1). The reflected fraction, or albedo, amounts to some 400 W/m^2, leaving 960 W/m^2 to be radiated by the spherical area. The *radiation* temperature of the earth is then 255°K (-18°C or -1°F). The mean *surface* temperature is 33°C warmer; this difference is the 'greenhouse effect', and it is set by the altitude of the radiation level. The 2 temperatures differ by an average of 6.5°/km, the 'atmospheric lapse rate' (which varies as the humidity of the atmosphere varies).

99% of the visible (short-wave) solar and infrared (long-wave) earth radiation — the orange and red outgoing arrows in Fig. 1 — lie on opposite sides of the 4-micron wavelenth, and so are easily separable by satellites.) The CERES (Clouds and the Earth's Radiant Energy System) satellite recorded a mean long-wave energy emission of 239 W/m^2 for 2009 (compared to the 240 of Fig. 1), showing that this simple model is right on target. The 'radiative forcing' responsible for the observed 0.8°C increase in mean surface temperature is calculated (to 1 significant figure) in Table 0.

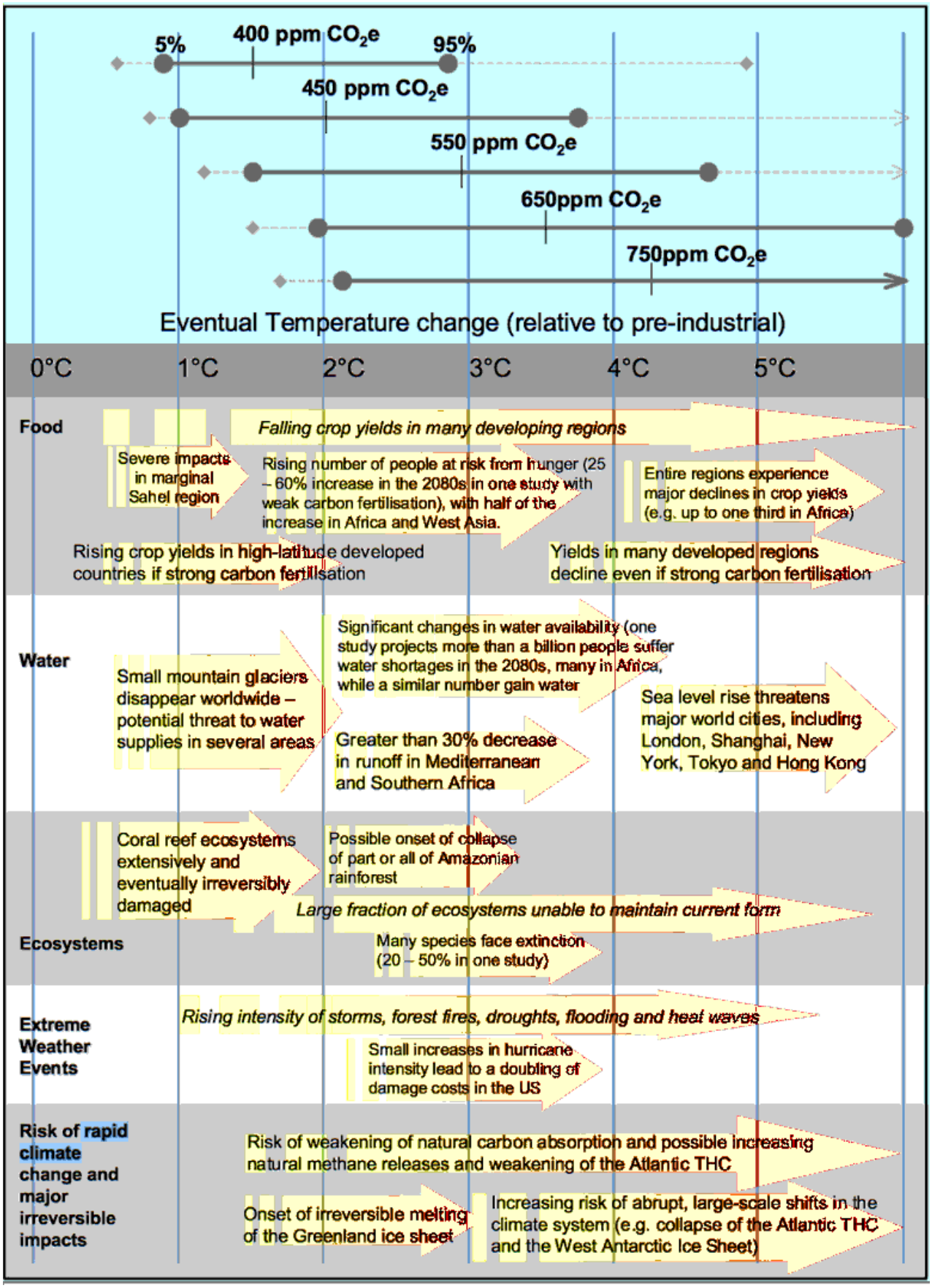
◄ Table 0. ► First-order calculation of energy density corresponding to an 0.8°C mean temperature increase.

	E/(W/M^2)		T/°K
THEN	1368·0.7·0.25 = 239.40	➡	254.91
INCREMENT			+0.8
NOW	242.42	⬅	255.71
INCREMENT	+ 3.02 or 1.26%		

The energy input is the 1368 W/m^2 of the solar constant measured at the top of the atmosphere, minus 30% for immediate reflection by clouds and snow cover, divided by 4 for the ratio of the areas of sphere and circle. Over the time period of interest, the maximum change in this number is 0.05 W/m^2, which is insignificant compared to the 3 W/m^2 radiative forcing estimated in Table 0. This means that whatever is changing is internal to the earth's atmosphere.

We are looking at changes on the order of 1% in measured and calculated values. Intuition tells us that 1% is not an alarming number. After all, the stock market — the most important number in the life of the power elite — fluctuates by 5.6% over the course of a quarter, and that is just noise compared to the 9.25% expected average profit. Why should we worry about 1% changes?

Figure 2 was Britain's attempt to answer to that question.



◀ Fig. 2 ▶ Consequences. The British Stern Review — the first comprehensive attempt to estimate the economics of climate change — produced this diagram. Later work has focussed on improving the new discipline of climate economics, and *The Stern Review Ten years on* should be read in

conjunction with the Stern Report itself. We are now at 400 ppm CO_2 and a temperature increase of 0.8°C, and all of the topics intersected by the 1° line are current problems. The extension of the 400-ppm line in the upper graph includes delayed effects, such as methane release as the surface temperature moves downward in permafrost. [THC is thermohaline circulation, the 10,000 year cycle from deep-water formation under ice shelves, ventilation of the ocean floor, gradual rising, and return to the poles in surface currents such as the Gulf Stream.]

The simplest linear extrapolation of business-as-usual to the end of the 21st century leads to an immediate temperature rise of 6.4°C, off the scale of Fig. 2. One of the major criticism of the Stern Report was that it paid scant attention to adaptation (living with climate change, the only course that 'realistic economists' consider feasible). Unfortunately, a 6.4°C increase is not something that we are likely to adapt to. It is a culture breaker of the sort that has brought down 100 previous advanced cultures of their day, catching them by surprise and leaving their ruins in the sand.

The 2016 US election installed people in government who deny the idea of climate change, so we will pobably get to observer many of these predicted effects. This should provide the 'empirical evidence' that deniers keep asking for.

△ How to tell ▽

Taking into account the discussion above, the simplest way to tell whether someone understands climate change is to ask the key questions. These are:

1. What is the radiation temperature of the Earth? — [255°K, -18°C, -1°F]
2. What is its mean annual surface temperature? — [288°K, 15°C, 58°F]
3. In a few words, why do these differ? — [They are at different altitudes, with temperatures related by the lapse rate.]

Equally acceptable answers to question 3 would include mention of '*photon path length*' and '*anthropogenic CO_2*'. The unadorned 'greenhouse effect' may be popular, but it is not an insightful answer. Keep reading.

△ △ THE FUD ▽ ▽

> Doubt is our product, since it is the best method of competing with the 'body of fact' that exists in the minds of the general public. It is also the means of establishing a controversy. — Unknown tobacco executive careless enough to write this prototypical

MBA-thinking in a memo.

The combination of frontier science and stochastic behavior makes the predictions of climatologists seem vague and unconvincing. It hasn't helped that 'To date [mid 2016], the Koch brothers have given more than $88 million to groups who regularly attack and undermine climate science. And that's just what's traceable.' Nor has it helped the public to understand the serious nature of what is happening, when the 3 main cable 'news' networks are unable, or unwilling, to report climate-related material accurately.

Fox's errors are apparently financially motivated, by both network and speakers. CNN seems to have no axe to grind, but it still gives air time to those who do. MSNBC's mistakes are the ones we all make when records fall, even though there is no *direct* connection to known forcing agents. Climate scientists are touchy about this, because such direct connections are impossible to demonstrate. Experts are still exploring scores of small specialized models of subsystems that are not yet incorporated into the 40-odd Earth System Models (ESMs) running at various universities and climate centers. An ESM requires some hundred million calculations per simulated day. Climate, being the long-term integration of weather, requires simulations of 3-century periods, meaning months-long runs on the world's most powerful supercomputers. Only when aspects of the various models learn to agree (statistically) with eachother and with the data, do we begin to think that we understand those aspects of climate.

◄ Table 1 ► Accuracy of Climate Reportage. According to the Union of Concerned Scientists, ⬆ the fraction of segments containing misleading statements in 2013 was as shown.

CABLE CHANNEL	% ERRORS	COMMENT
MSNBC	8	Mainly attribution of specific extreme events to climate change
CNN	30	Mainly FUD by guests
Fox	72	Mainly FUD by commentators

I came across, on You Tube, a commentator who couldn't tell me what the Earth's mean temperature is, or what it would be in the absence of greenhouse gasses, if his life depended on it. Yet on national TV he feels competent to spew raucous, climate-change-denying FUD to an audience that appears to reach the halls of Congress, where Representative Joe Heck (NV), Senator Pat

Toomey (PA), Senator Ron Johnson (WI) and others agree with him. He presents as rude (interrupting his guests), ignorant (unaware of the data), and stupid (impervious to rationality) — apparently because this appeals to his audience. Considering the millennial effects of global heating, any responsible organization with a minimal concern for the future of humanity — which in an ideal world might even include his TV network, the Federal Communication Commission, and the Supreme Court — would require equal time for a factual presentation.

There is minority in the Senate smart enough to understand the situation — but it is something of an embarrassment that the majority is intent on leading us into a preventable disaster. One gets the impression that the feudofascist 1‰ understand full well that public awareness of global heating will reduce the market value of their corporations. Assuming that their billions will shield them for the remainder of their lives, their response is Nasrudic business as usual. They get two last decades of profits (or campaign contributions) — 'and maybe the horse will sing' ⬆. In the meantime, they deny anything is happening, and quietly prepare for martial law as things go pear-shaped.

In the process, so much FUD and misinformation — both deliberate and ignorant — is broadcast about global heating and climate change that it seems worthwhile to provide a reliable tutorial. Suffice it to say that I have no financial interest in the question, and am professionally competent in 2 or 3 of the score of disciplines involved. The climate scientists are doing the best they can, but — like anyone in the field — I can poke holes in the IPCC (Intergovernmental Panel on Climate Change) reports and the programs and data sets they are based on, simply because the problem is so complex, no data set is as long or complete or reliable as we would like, and no computer program can include everything of importance with the precision and detail of the real world. But year by year we incorporate complexity more accurately in the models, the data sets get longer and more precise, and computers get bigger and faster. Meanwhile, it takes no more brains than those of a plant to recognize and respond to global change.

△ Biased Data? ▽

> [Rejecting authority, the Americans] fall to denying what they cannot comprehend. — A philosophical consequence of democracy in America, observed as early as 1831 by Alexis de Toqueville.

Ignoranti (such as Rush Limbaugh) claim that there are no data supporting

climate change. This is not true. The American Meteorological Society offers 14 time series, supported by 257 pages of detail, showing 8 things increasing that one expects to rise with global heating (e.g., land surface temperature, ocean heat content, …), and 6 things decreasing that one expects to fall (glacier volume, soil moisture, …). One has to be stupid, purblind, or bought, not to recognize that global heating is real.

The Intergovernmental Panel on Climate Change's *IPCC Reports* lag the data by about 5 years, but provide our best assessment of climate change. The current set draws on nearly every relevant research paper written through 2012. The *Physical Science* volume has 2 companions of similar import and size: *Impacts, Adaptation and Vulnerability*, and *Mitigation of Climate Change*. All are available for download here.

Ameliorating global heating will cost money. It will generate business opportunities for some, and reduce them for others. Consequently, much tobacco-style FUD is aimed at the interpretation of temperature proxies such as tree rings, marine sediments, ice cores, coral reefs, stalactites, &c. In particular, there were indignant claims that the Medieval Warm Period (c. 950–1250) was just as hot as today (not true), so all is well (not true). The rationale seems to be this:

> If we just ignore the data, global heating will go away. Let us declare paleothermometry to be junk science and the Weather Bureau (and 100 other research centers) incompetent. They are clearly doing what we learned to do in expensive MBA courses: spread Fear, Uncertainty, Doubt, and Lies to keep the research money rolling in.

Granted, each paleothermometer presents unique subtleties and is subject to confounding influences. This is why professionals devote their careers to testing and refining techniques and interpretations.

Granted, the Weather Bureau cannot predict weather 2 weeks in advance, because the atmosphere is chaotic and weather happens at random in the right half of Fig. 1. This is why we focus on the smooth curve drawn through the left half of the figure.

'Figures don't lie, but liars do figure'. Here are some misleading things one could truthfully say about Fig. 1:

- The mean temperature was the same in 1926 and 1978.
- 1944 was the hottest year of the [or 'a'] century.
- The record shows 60 years of mean temperature decrease.

— and none of them changes the 0.8°C rise.

△ Some Confusions ▽

It might seem strange that 'belief' in an established fact like climate change should separate political parties sharply. Yet psychologically it makes sense that Democrats should try to limit climate change, and that Republicans would obstruct them. ('Latent ideology lies in psychology.') ⬆ This follows from the Moral Foundations ⬆ parameters that best distinguish conservatives from liberals: Liberals score higher on Concern for Others (ie, Care + Fairness); Conservatives on Loyalty, Authority, and Purity. Rs ask themselves, 'Has climate change — if it isn't just weather variability — hurt me?', and the answer is 'No. The Ds just like to spend other peoples' money', and 'They're not getting mine!' Ds looks at the world and see that climate change is already hurting people, that the damage will not be undoable in any human time frame, that is going get worse if we continue business as usual, and to minimize damage, want to limit what Rs are allowed to do to the world in pursuit of money.

Common sources of confusion include:

1. Water vapor

Water vapor has absorption bands all over the spectrum and so it is more important as a greenhouse gas than CO_2, with its single deep absorption in the middle of an H_2O band. This is perfectly true — in the lower troposphere where radiation is trumped by turbulent mixing. Water vapor pretty much freezes out (at the snow line) well below the radiation level (which is above 5 km), and so makes a very minor contribution to global heating.

2. Saturation

Noticing that all the available energy in the infrared CO_2 band is absorbed in about 10 m, a voluble subset of deniers has fastened on this fact as meaning — erroneously — that adding CO_2 to the atmosphere cannot warm us further, because, obviously, all the IR is already being absorbed.

But saturation is a function of the number of CO_2 molecules per meter, and thus a function of pressure. Higher in the atmosphere there will less CO_2/ m, and added CO_2 will absorb outgoing IR. The troposphere is well mixed, so that CO_2 added at at the bottom finds its way to the top quickly. As Fig 22.12 shows, it is CO_2 at the top of the atmosphere that raises the radiation surtace and the ground temperature.

3. Satellite Measurements

Perhaps the most frequent denial of global heating is based on the fact that satellite measurements 'have shown that temperature has not risen in 17 years'. This is true but *irrelevant*: what satellites measure most easily and uncontroversially is the *radiation* temperature of the Earth, which is constant, rather than its *surface* temperature, which is changing. The radiation temperature is set as indicated in Fig. 22.11, the surface temperature in Fig. 22.12.

4. Time Scales

A typical denialist complaint is that a while back, climate scientists were predicting another ice age. Now they're predicting heat waves, so obviously they don't know what they are talking about. (Denialists are uncomfortable with change, but clearly on speaking terms with fraud, since it is the first thing they think of to explain the erratic progress of science.) If you look at the temperature-vs-time curves from the 4 km of ice at Vostok in Antarctica, you see Fig. 3, with a sawtooth curve and a steep rise at the beginning of an interglacial, followed by a slow cooling into the next ice age. (There are now ice cores from 3 dozen sites, showing both general agreement and interesting local variation.) The sawtooth pattern was exciting news in 1999 when it was first published. Checking their algorithms against this new data, climate models suggested that by now, 12,000 years into the interglacial, eastern Canada would be accumulating ice again. Hence the concept of a new ice age **90,000 years down the road**.

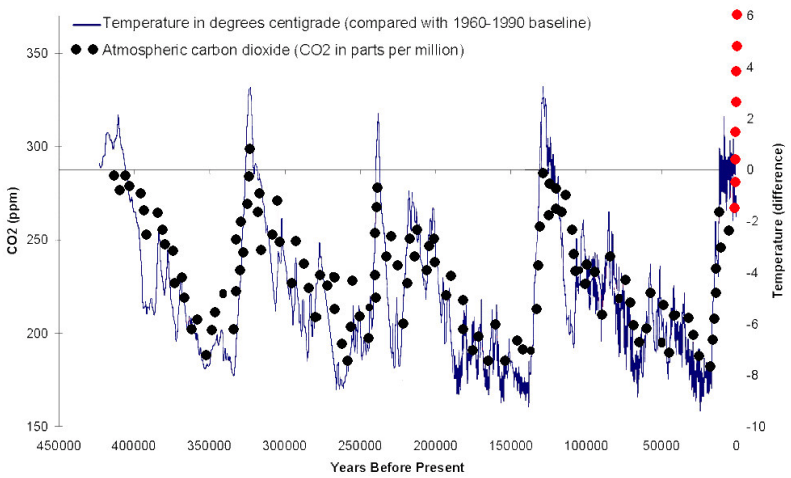
5. 'Alternative Facts'

A typical FUD paper claims that instrumental records suffer from urban heat islands, land-use change, relocation of stations, missing data, poorly placed thermometers, and undocumented 'adjustments' that have left a record with a warming bias and no reliable way to correct it. The subphrase of its title, 'Policy-based deception?', again suggests psychological projection of the authors' own *modus operandi*. The paper is part of a long carping suite of disinformation from the Heartland Institute, a raucous denier of climate change supported by and speaking for the Koch coal billionaires. In contrast to the FUD, careful analysis showed a slight *cooling* bias in US data, corresponding not to the suggested problems, but to the replacement of mercury thermometers by thermistors. This bias was removed by pairwise comparisons of trend lines spanning the period of replacement. The US Climate Reference Network (with some duplicate stations and triply redundant instrumentation) shows

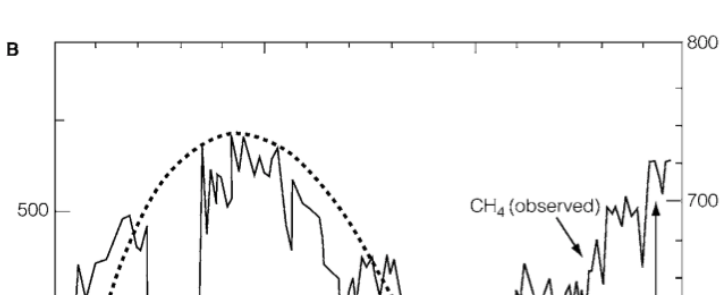
intercomparison uncertainties comparable to the precision of thermistors, in the millikelvin range (±0.001°C). 'We find no evidence that the US average temperature trends are inflated due to poor station siting'.

6. 'You don't stand by a cold stove to get warm!'

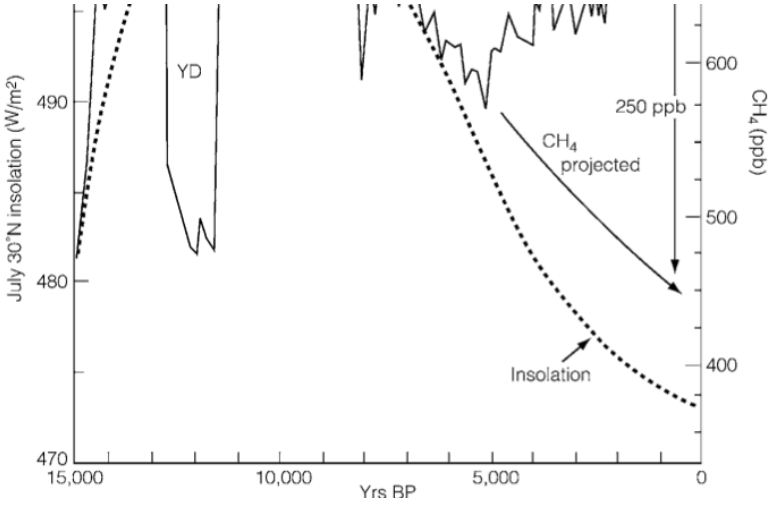
This the argument of Dr Peter L. Ward, a retired USGS vulcanologist with an idiosyncratic grasp of physics. He is responding to Fig. 1.1 of *IPCC Climate Change 2013*: p 126) which shows a big downward arrow labelled 'Back Longwave Radiation'. Recognizing that this shorthand cannot be the actual warm.ing mechanism, misconstruing the Bohr-Einstein relation, and seeing a correlation between stratospheric ozone and the temperature record, Ward tells Republican Senators what they want to hear: 'CO_2 is not the culprit. The ozone hole is letting in more UV, which has 48 times as much energy as CO_2's IR radiation.' This is wrong; Bohr and Einstein added 'per photon' to that sentence, and there are very few UV photons and many IR photons. Despite numerous efforts, no one has been able to correct Ward, who points to Galileo as justification for contradicting the established physics of the last century.



◀ Fig. 3 ▶ Vostok Temperature Data. (The CO_2 data is continuous, and as noisy as the temperature data. For clarity it has been replaced by discrete samples, mostly at local extrema.) The accumulation of ice begins as soon as insolation and the greenhouse between them are too weak to melt all of the winter's ice during the summer, approximately at the 0 line of temperature difference. The earlier ice ages suggested that we should be seeing year-old snow in eastern Canada by now, and some climate models agreed. This is not happening, so our interglacial is not like the previous ones. Why not?



◀ Fig. 4 ▶ Early Methane. Ruddiman noticed that CO_2 began inceasing ~6,000 BCE, when we started clearing European forests for agriculture. Methane



began increasing ~3000 BCE, when the Chinese started making rice paddies. (The dip labelled 'YD' is the Younger Dryas, a millennial cold dry period resulting from Laurentide icemelt inhibiting the Atlantic thermal circulation.) The coupling between low-latitude insolation and methane is probably through monsoon rains and lowland floods (stagnant water being a common source of methane). In short, Ruddiman suggests that we began changing the climate long before the Industrial Revolution.

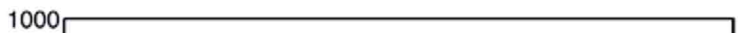
But Canada is *not* accumulating ice. In 2003, Ruddiman suggested that land clearance for Neolithic agriculture, beginning 8000 years ago, had injected enough anthropogenic greenhouse gases to make our interglacial different from the prototypes — a hypothesis he himself described as 'provocative and controversial', although I don't see why. Figure 3 shows the expected and actual changes in methane over the period in question, with methane being much more effective than CO_2 as a greenhouse gas. The graph for CO_2 shows a similar change of direction starting 8000 years ago.

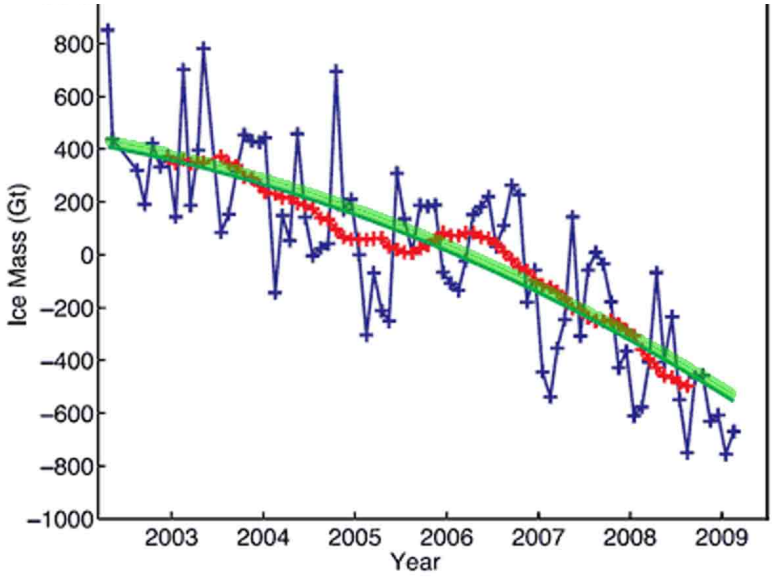
Nor does the conservative FUD change the reality of global heating. 'Climate sceptics', apparently terrified of taxes, regulation, and loss of business, continue to exaggerate imaginary failings in the hope of discrediting scientists who study global heating. Accordingly, we look at a pair of indirect records whose data and interpretation — while still subtle — are independent, based on different techniques, and are perhaps more persuasive to the by-stander. These are the loss of Arctic sea ice and Antarctic land ice.

△ Melting the Ice ▽

> Virtually all [climatologists] are now convinced that global warming poses a clear and present danger to civilization. — glaciologist Lonnie Thompson

The loss of ice is unarguable. Antarctic land-ice loss is accelerating at the rate of 28 Gtons/yr², as shown by the parabolic green trend line in Fig. 5. (The red line smooths seasonal variability.) Unlike the melting of Arctic sea ice, this loss contributes directly to sea-level rise.





◀ Fig. 5 ▶ Antarctic Ice Loss, measured by gravity changes, integrating over the area without needing detailed ice-thickness measurements. The heavy wiggly line is seasonaly adjusted; the smooth parabolic line is the trend, widened to include a 33 Gt/yr error estimate. including isostacy (the solid crust rises in the fluid mantle as the ice melts).

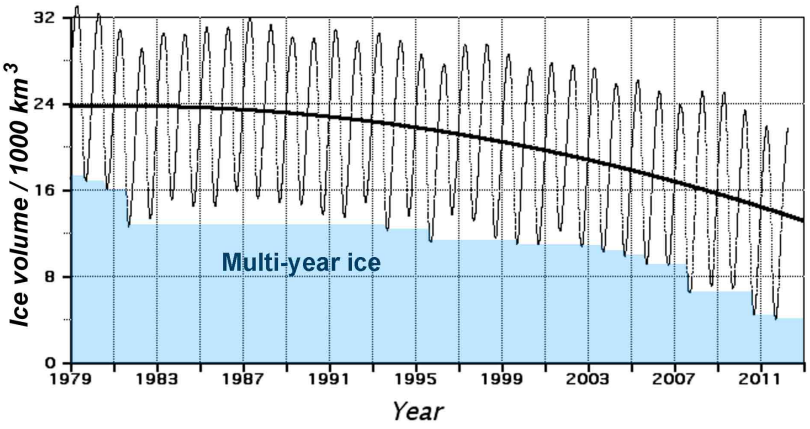
As of 2007, the best interpretation led the IPCC to say:

> Current global model studies project that the Antarctic Ice Sheet will remain too cold for widespread surface melting and is expected to gain in mass due to increased snowfall.

This did not happen, and perversely, Antarctic *sea* ice is *increasing*. Poorly informed sceptics misinterpret this to deny global heating and display the incompetence of scientists, but the projection was from models that did not include circumpolar fluid thermodynamics with sufficient subtlety. Warmer water north of the Antarctic Convergence evaporates. Naïvely expected to increase precipitation on the land mass, it instead snows out before it reaches the coast, creating a fresh-water input that reduces the salinity and density of surface seawater, while raising its freezing point and increasing its vertical stability. This produces a cold, thin, quickly frozen surface layer. The present balance (not necessarily permanent) results in more sea ice. (After all, ‘warming’ in Antarctica can mean going from -20°C to -17°C, and ice still forms.)

The major concern in Antarctica is the West Antarctic Ice Sheet. Ice sheets are what glaciers turn into when they hit the ocean, and their size is a balance between glacial input and ice-edge calving of icebergs and melting. The Larsen A Ice Shelf (at the warm end of West Antarctica) collapsed in 1995, the adjacent Larsen B, about the size of Rhode Island, having been stable for 12,000 years, disintegrated in 3 summer weeks of 2002. The Ross Ice Shelf, about the size of France, showed signs of instability by May 2014. Its disintegration would not raise sea level (because it is floating ice), but it would unblock the glaciers that feed it, which have the mass to raise sea level by 3

meters in, say, a century.



◀ Fig. 6 ▶ Arctic sea-ice volume from a validated model by University of Washington's Polar Science Center. Inspired by Fig. 5, I have added the parabolic trend line. The loss of multi-year ice (shaded) and its summer infra-red reflectivity increase the rate of loss.

Up in the north, the loss of thick multi-year Arctic sea ice was 50 km^3/yr in 1972 and has increased at 10 km^3/yr^2 since, as shown in Fig. 5. The Northwest Passage, sought by navigators for centuries, is now open and raising diplomatic questions about whether it is international water or an internal Canadian waterway.

△ The 'Denatured' Among Us ▽

> Meanwhile, back on SPACESHIP EARTH, the crew are:
> — Plundering the ship's supplies
> — Tinkering with the temperature and life-support controls
> — Still looking for the instruction manual
> — Engaging in bloody skirmishes in every corner of the vessel
> — Increasing the size of the crew by 2 million PER WEEK. — P Creola

Another observation which undermines the attempts of climate sceptics to deny global heating comes from the biological world. By 2002, Gian-Reto Walther could cite 97 papers describing climate-induced behavioral change in different groups of organisms. 1200 species (lacking thermostats and air conditioning) had altered their behavior a decade ago. Some have moved poleward at 6 km/decade, or 80 m up the mountain. Others flower or mate earlier, by 2.3 days/decade. Systems such as bird reproduction in which one component responds to day length (migration) and another to temperature (insect food for nestlings) are confused: evolution will be rapid here. Heat- and drought-resistant alleles have spread into populations that never needed them.

One of the more striking examples is the circumpolar Arctic walrus. Normally, walruses use ice floes to rest, sleep, raise their young, and scan the

bottom for molluscs. By October of 2014 there was so little sea ice that 35,000 walruses hauled out on Alaska beaches — a habitat they had abandoned long ago because of predation by humans.

Put bluntly, **those who know what is going on have been adjusting for decades.** (Oddly, this includes trees and bugs — but not bankers, CEOs, or politicians.) The world of nature is exquisitely aware of what is happening 'out there', posessing a perspective known only to humans who are similarly in touch with the real world — bird-watchers, backpackers, gardeners, ecologists, field biologists, climatologists, and their ilk. The challenge of climate change has driven human evolution in the past. At the 10^5-year scale, it forced cranial growth of *Saharapithecus tchadensis* and relatives. At the 10^3-year scale, it drove us to new techniques for dealing with the ice-age and its retreat. At the 10^1-year scale, might it thin out the ranks of the unadaptive climate-change deniers — people who subsist in heated/air-conditioned space, so insulated from the natural world that we might call them 'denatured'? In the absence of technology (and the financial ability to protect themselves artificially), they would be the first to succumb to natural change. Biologically speaking, they are dead fossils walking.

△ △ THE DETAILS ▽ ▽

Can we stabilize population by reducing fertility before nature takes over and stabilizes our numbers by raising mortality? — Lester Brown. [Curiously, the mortality ratio of Ebola in Africa approximates the sustainable/current population ratio. Might this be an answer to Brown's question? Global warming also means that 'tropical' diseases are migrating poleward.]

Global temperature regulation is so complex, relevant information so remote from the non-scientist, the abhorrence of taking responsibility so ingrained, and the thought of spending corrective money so appalling, that it is easy for the denatured to deny:

1. That global heating is happening;
2. That it is caused by human activity;
3. That we can alter its course; and
4. That we could afford amelioration.

Having established sufficient FUD, purblind economics can show that:

5. In defiance of Zoroaster and evolution, we owe our descendants nothing, and

6. They will be better able to cope.

The Cato Institute suggested that in 100 years the per-capita GDP will be $321,684, so:

7. The only rational course of action is to get rich as fast as possible.

This is Instinct-I talking. The most generous interpretation one can put on denial is that it is tightwad comedian Jack Benny's response to a mugger's repeated 'Your money or your life!': 'I'm thinking, I'm thinking.'

Despite smear campaigns — fueled by ignorance and greed — against people like James Hansen (the NASA researcher who first publicized climate change) and Al Gore (apparently a rare politician capable of understanding the science), the scientific consensus on global heating is now well established. Point by point:

△ *1. It's Happening* ▽

> Recent observations confirm … the worst-case IPCC scenario trajectories are being realized. — J. Romm (2012) ⬆.

An obvious indication of heating is the new discipline of 'ice-patch archaeology', resulting from the thawing of areas frequented by early man, from which organic artefacts have been recovered that decay in unfrozen sites. Ötzi, the trans-Alpine Ice Man, frozen in an Alpine glacier, is the poster boy for the field. The cautious IPCC said only:

> Palaeoclimatic reconstructions show that the second half of the 20th century was likely the warmest 50-year period in the Northern Hemisphere in the last 1300 years. — IPCC (2007)

Despite all the FUD about the Medieval Warm Period, Ötzi showed that the Alps are appreciably warmer today than they have been since he froze to death 5,300 years ago.

In the Arctic, the situation is even clearer. Moss clumps recently exposed by melting ice caps are a minumum of 44,000 years old, by C-14 dating. But only about 0.5% of the original radiocarbon remains by this time, so experimental error is high, and the moss could be much older. In fact, ice was thick at 44 ka, and combined data suggest that Baffin Island is warmer today than it has been for 120,000 years.

The question to ask deniers is 'If we are burning buried carbon, what mechanism do you suggest that might *prevents* global heating?'.

△ *2. We Are Causing It* ▽

> The most dangerous worldview, is the worldview of those who

have not viewed the world. — Alexander von Humboldt

The timing, distribution, and isotopic composition of atmospheric CO_2 increase matches anthropogenic production, similar to the exponential of Fig. 1. The flatness of the data in the right-hand graph of Fig. 1 suggests no non-anthropogenic contributions to global heating on a centennial time scale. The grey band is the background noise, or 'weather'. Global heating is not caused by solar activity, because the Goddard Institute for Space Science reports that the 'new record temperature in 2010 is particularly meaningful because it occurs when when the recent minimum of solar irradiance … is having its maximum 'cooling effect'. Whatever else is happening, anthropogenic CO_2 will make a bad situation worse, so **under any scenario** it is to our advantage to minimize CO_2 emissions. Consuming less than half of the remaining fossil-fuel reserves will take us well above the 2°C temperature rise accepted by 100 countries as the tolerable limit.

△ *3. We Can Take Corrective Action* ▽

Ignoring public health [ie, the Ebola epidemic, with 50% mortality and a transmission factor of 1.7] is the cure for ignoring climate change. — G2geek

In 50 years the US spent G$21 on nuclear fusion (always 50 years away). The problem is trying to do civil engineering at the temperature of stellar cores, in the absence of a gravitational field powerful enough to force charged nuclei together. Theoretical solutions fail to unexpected instabilities.

In the same period we spent only M$80 on sustainable satellite solar power. Eventually, the National-Security Space-Office Advanced-Concepts Office (aka 'Dreamworks') published a 75-page recommendation for space-based solar power (SBSP). This collects energy in orbit, where solar-power density is 10 times the average from stationary ground-based collectors, and transmits it by microwave to the ground. The major problems are a long development time and a practical need for factories (and infrastructure) on the moon, but as Fig. 7 indicates, this is the probably the best option for sustainability.

Source	Clean	Safe	Reliable	Base-load
Fossil Fuel	No	No	Decades remaining	Yes
Uranium fission	No	No	Finite fuel supply	Yes
Thorium fission	Yes	Yes	Breeder	Yes
Wind				

◀ Fig. 7 ▶ Space-Based Solar Power. This is the official assessment of the advantages of SBSP. Recent data suggests that

WIND POWER	Yes	Yes	Intermittent	No
GROUND SOLAR	Yes	Yes	Intermittent	No
HYDRO	Yes	Yes	Drought; Complex scheduling	Yes
BIOFUELS	Dubious	Yes	Limited quantity; Competes with food	?
SPACE SOLAR	Yes	Yes	Yes	Yes

producing biofuels is not as clean as hoped. Source: JD Rouge (2007).

The estimated cost for a 10 MWe demonstration SBSP pilot plant is G$9, which is 10% of what our banksters paid themselves in bonusses in 2013. It is astonishing that no intelligent, forward-thinking, socially indispensible paragon of entrepreneurial capitalism has had the wit to build a prototype for himself. A national commitment to such a project should (like a moon landing) generate enough cost overruns and boondoggles to satisfy corporate interests, and unlike the Military-Industrial-Complex wars, actually accomplish something useful. An attractive aspect is that much of the infrastructure is now standard aerospatial engineering. Low lunar gravity may mean that we need O'Neill habitats to house the workers.

In 2011 Andrea Rossi began promoting a Low-energy Nuclear Reaction (LENR) system called E-Cat, which purported to extract nuclear energy by adding a proton to nickel to make copper. The fact that it didn't produce enough gamma rays to kill him should have alerted visiting scientists, but the lure of cheap energy overwhelmed suspicion. By November of 2016, all but a few with more hope than shrewdness were convinced that Rossi had managed another a 6-year energy scam. It was his third.

Wally Broeker (who coined the term 'global warming' in 1975) suggested that we could remove CO_2 directly from the atmosphere by chemical reaction with common rocks. The problem is one of scale: this requires a larger industrial plant than coal mining and power generation together. The US produced 1.8 gigatons of CO_2 in 1999, or 5 megatons/day from 1.35 Mt of coal. Experimental CO_2-removal reactors run at 185°C and 150 atmospheres, using powdered rock. This is a daily need for mining, transporting, pulverizing, heating, and processing 13 megatons of rock, adding 6 megatons of water, and disposing of 24 megatons of magnesium carbonate and silica slurry (moving 29 tons for every ton of coal).

Another approach separates CO_2 from flue gas and injects it into exhausted oil fields, where it can force more oil to the surface, allowing us to increase CO_2 production even further. Alternatively, captured CO_2 is fed to engineered *Synechococcus elongatus* protoctists, who convert it photosynthetically to

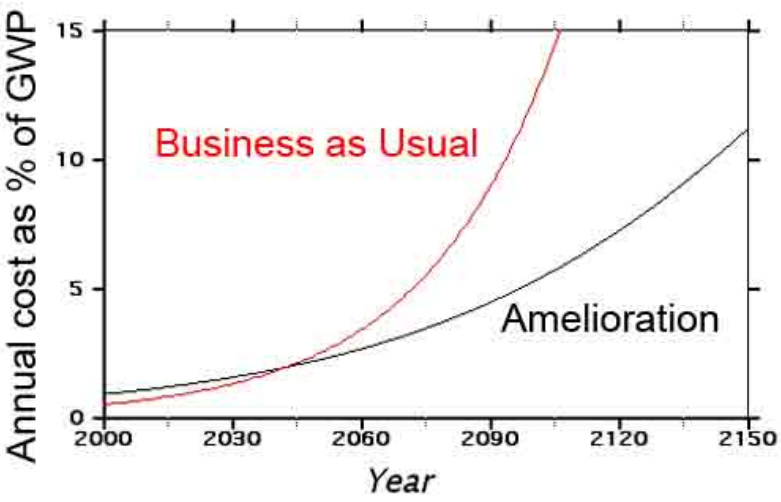
isobutanol (usable as fuel) and other chemical feedstocks. This is elegant, but once again, the problem is one of scale: we are talking about plant investment many times the size of all the world's oil refineries.

△ *4. Immediate Action is Cost Effective* ▽

> [T]he costs of switching will be paid for in fuel savings between now and 2050. — *MIT Technology Review* 2014-05-19.

The 700-page *Stern Review* ⬆ — independent of the IPCC — initially concluded that the cost of 'reducing greenhouse gas emissions to avoid the worst impacts of climate change' would be 1% of the GWP. However, this 1% comes disproportionately out of the income of the 'elite', while the initial costs of global heating fall upon what are commonly called 'useless eaters'. Some of the 'elite' see this as a benefit (possibly reducing the numbers of the eaters — while overlooking the irreversible, global nature of the process), so nothing has happened. (The later costs, when mitigation will have little effect, will fall on developed countries and cities.)

Delay can raise the cost above 20% of GWP 'now and forever', as sketched in Fig. 8. It is expensive to remove greenhouse gases from the atmosphere, and the number of problems increases rapidly with warming. (A new one is coastal erosion of, and salinity intrusion into, the agricultural Nile Delta as sealevel rises {*GW* 2009-09-18. p25} — in a nation so unsustainable that it already imports half its food.) Stern suggested in late 2009 that the cost had risen to 2% of GWP {*GW* 2009-09-18 p17}, already above the black curve of Fig. 8. Unfortunately, Fig. 8 provides all the incentive some need to postpone action until the curves cross. The only effective response to the political argument, 'We'll be dead by then: why pay for something that won't benefit us?' is political death now, by a recall election. Or some faster method.



◀ Fig. 8 ▶ Annual cost of alternatives as a function of starting date of amelioration. The longer we wait to take protective action against global heating, the more costly and less effective our action becomes. (These simple curves are guesses that ignore fossil-fuel exhaustion and

'tipping points' such as melting of methane clathrate as the arctic warms.)

△ *5. They're Your Grandchildren* ▽

> An ounce of prevention is worth a pound of cure — but a lot of people want your pound, and will encourage you to wait.

The disruption in the 2nd half of the century will be comparable to the World Wars and Depression. Energy will be expensive, and at the rate things are going, infrastructure will be in worse shape than today. Your grandchildren will take the brunt of these changes. For cultures that never really left the Neolithic, this will be a less difficult transition than for us. Already tractors are too expensive to use in Rajasthan except during the short planting season, so the price of camels has risen 5-fold in 4 years {*GW* 2008-07-25 p 31}.

Economists' commonly minimize future values by 'discounting'. As nearly as I can tell by examining events in my own lifetime, this is both unrealistic and unethical. Computers may have decreased in real price, but a cast-iron skillet, $2 in my youth, still works. A slightly fancier replacement costs $88 (of which $20 is inflation) and the cheaper 'high-tech' versions are inferior. Recycled, 100-year old, hand-carved furniture beats Ikea on esthetics, utility, price, durability, and repairability. In other words, in life as I live it, the future value of well made real items often *exceeds* their present value. Every item that I have claimed householder insurance on has been over-depreciated by the adjuster (a small sample, but sufficient so that I usually prefer to 'self-insure').

So too with climate change. The future costs (of action or inaction) will be, *and be seen as*, larger than the present costs.

△ *6. Grandchildren will be Poorer* ▽

The idea that our grandchildren will be richer than we are is based upon the assumption of cheap oil (never again!) plus zero inflation (when the Consumer Price Index rises at 2%, inflation is running 6–8%). Wishful thinking to the contrary, this idea is not realistic.

△ *7. Inaction is Stupidity + Greed* ▽

— because

> [we need not] choose between averting climate change and promoting growth and development. … Action on climate change will also create significant business opportunities, as new markets are created in low-carbon energy technologies and other low-carbon goods and services. These markets could grow to be

> worth hundreds of billions of dollars each year, and employment in these sectors will expand accordingly. — Stern Review: Executive Summary ⬆

One might have thought that this government-sponsored study would have had some effect, at least in the UK. But no. Like any pioneering effort, it had some flaws which deniers siezed and used to discredit it, to the extent that as her first official act, Prime Minister Theresa May could shut down the Department for Energy and Climate Change and moved responsibility for the environment to a new Department for Business, Energy & Industrial Strategy, essentially guaranteeing that nothing will be done to disturb business as usual.

△ *8. Armoring* ▽

A psychological consequence of global heating that has received no attention is the likelihood of its induction of Reichian armoring. As desertification spreads and life becomes more difficult, Instinct-I increasingly dominates Instinct-II. The aspects of religion which make it worthwhile — altruism and compassion — are replaced by tribalism (at best) and selfishness. Islam, the least useful of the tribal markers because it began as a cult of psychologically armored marauders, is likely to spread as soil desiccates.

△ △ MODELS AND DATA AGREE ▽

▽

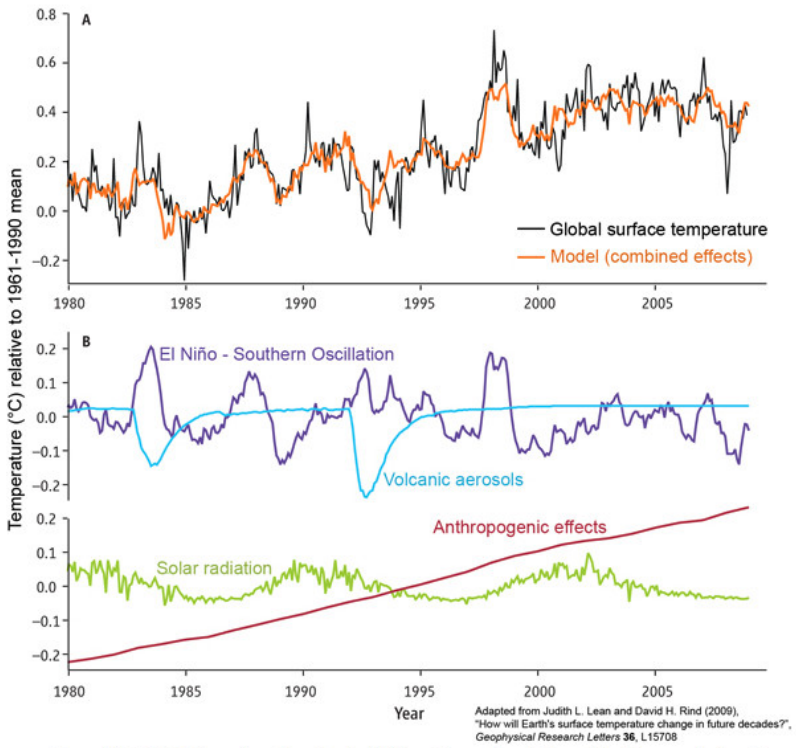
> I am never content until I have constructed a … model of the subject I am studying. If I succeed in making one, I understand; otherwise I do not. — Lord Kelvin (1904), who said 'mechanical' at the ellipsis, but most models today are computational.

The *fact* of global heating may be well established, but the *cause* is not quite so certain. The details above are based on 20 years of work by some 800 researchers and 2500 reviewers. Received wisdom has been that climate is the product of many influences. As is evident from Fox 'News', a major, if illogical, complaint of the 'climate deniers' is that all of the predictions of future change are based on computer models instead of data. Ignoring the difficulty of obtaining future data in time to make use of it, the important feature is that **until one can model climate, one cannot pretend to understand it**. Our current grasp of short-term effects is shown by the detailed agreement of the two lines in the upper graph of Fig. 9.

The frequent statement by climate deniers, that they 'haven't seen any

data', may mean that they don't want to look, that they lack the analytic ability to read Fig. 9, or that they do not understand that 'Anthropogenic effects' is synonymous with 'fossil-fuel CO_2'. All natural processes that affect the Earth's surface temperature are cyclic (solar output) or episodic with a return to normal (vulcanism, El Niño), or random around a zero mean (the spikes).

Figure 9 was drawn too early to show the effect of arctic methane.



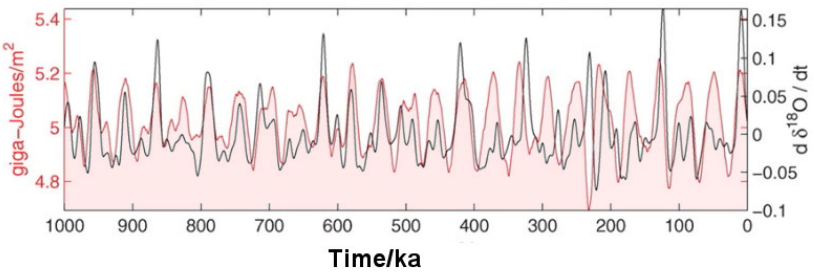
◀ Fig. 9 ▶ 25 Years of Modelled Climate. Perhaps surprisingly, the 4 processes in the lower panel account for all but a series of sharp 0.1° spikes in the temperature record — and of these 4, anthropogenic effects make the largest contribution and the only one with a trend. Note that the solar-radiation curve shows only the short-term sun-spot cycle, and is too short to notice the millennial Milankovitch cycles.

Contrary to expectations, detailed timing of the fast warming at the end of ice ages (Fig. 3) showed that ocean temperature rose first, followed by air temperature, *then* CO_2, followed 7000 years later by glacial melting and sea level rise. One suggestion is solar forcing, since the ocean is the principal absorber of solar energy. The sequence would then be a:

> Northern Hemisphere summer-insolation-intensity [Milankovitch] trigger for an initial retreat of northern ice sheets. Meltwater and icebergs entering the North Atlantic alter oceanic and atmospheric circulation and associated fluxes of heat and carbon, causing increases in atmospheric CO_2 and Antarctic temperatures that drive the termination in the Southern Hemisphere. Increasing CO_2 and summer insolation drive recession of northern ice sheets, with probable positive feedbacks between sea level and CO_2. — Cheng &7a 2009

While this description is a bit short on details, the correlation between

insolation at 65°N and ice volume is good, as shown in Fig. 10. The major problem is that 100-kyr ice ages survive any number of potential Milankovitch triggers, so something else appears to set the major periodicity.



Black: Time rate of change of ice volume

Red: Summer high latitude sunlight

◄ Fig. 10 ► Ice Volume. During WW II, the Serbian mathematician Milutin Milankovitch, interned as prisoner of war, solved the problem of ice ages by relating them to changes in insolation as the Earth's orbit changed quasi-periodically from the gravitational effects of the other planets. While Milankovitch periodicities show up in climate proxies, it is hard to see a direct correlation between insolation and proxy data. The process is more subtle: There is good correlation between the rate of ice-volume change (inferred from oxygen-isotope data) and high latitude *summer* insolation over the last million years.

One recent supplementary suggestion is P/IAH, the Peatland/Ice Age Hypothesis, which might cycle enough carbon to account for a climate forcing of 5 W/m^2.

I suggest that a prime candidate is the interaction of shallow-sediment methane clathrate, ice volume, sea level, and Milankovitch.

Start with a warm interglacial climate like today's, but without anthropogenic CO_2 input. Phytoplankton slowly but steadily draw down atmospheric CO_2, die, increase organic carbon in sediments, and thence methane clathrates. The gradual loss of atmospheric CO_2 cools the climate, with (as the models show) major effect in the arctic zones. Milankovitch willing, land ice accumulates, sea level drops, but exposed Arctic-basin sediments are cold enough to preserve the methane ice. The process continues until there's a mile-thick glacier in the northern hemisphere, and sea-level fall has exposed several hundred vertical meters of clathrate-rich sediments on continental shelves and slopes. This situation is thermodynamically metastable; all it needs now is a Milankovitch insolation peak to produce a warm Arctic summer, and it

releases a 50,000-year accumulation of a greenhouse gas with many times ⬆ the warming potential of CO_2. This methane pulse will *not* be trapped in air bubbles in the ice, because methane is oxidized to CO_2 in a few years, and summer temperatures at the beginning of the interglacial — as in Greenland currently — would melt winter accumulation. The metastability is continuous throughout the glaciation, and episodes of local melting might account for the sharp oscillations seen in ice-age temperatures.

Modelling this hypothesis requires more computational power than I have available, so I content myself with describing it. It accounts nicely for the rise of temperature before CO_2, for the sawtooth nature of the isotopic temperature record, and it offers a plausible driver for the 100-kyr glaciation cycle. The fact that methane is currently escaping from Arctic sediments might seem contradictory: Why did it not all boil off 12,000 years ago at the start of the interglacial? All I can suggest is that additional warming from the 100 ppm of anthropogenic CO_2 is reaching deeper into the permafrost, again making this interglacial different from all others.

△ The Permian Extinction, 252 Ma ▽

> The opposite of an Ordinary Truth is a lie, but the opposite of a Great Truth is another Great Truth. — Niels Bohr.

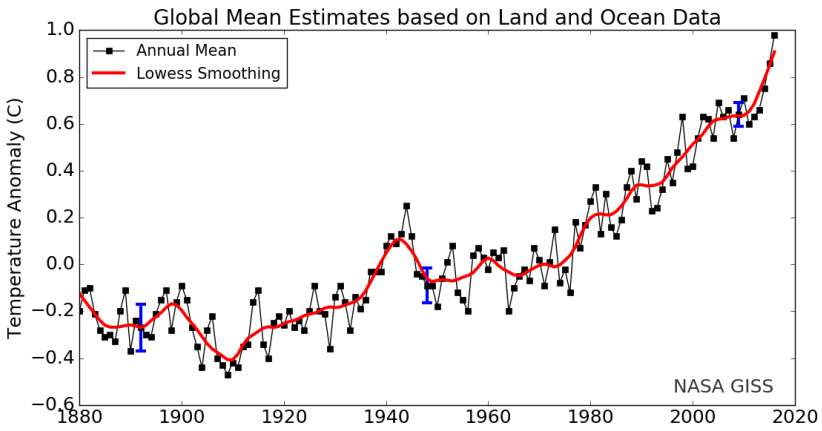
A prime example of Bohr's paradox is the Medea Theory of paleontologist Peter D. Ward of the University of Washington. Medea is the polar opposite of the Gaia Theory of Lovelock and Margulis. If Gaia is the archetype of the Good Mother, Medea is the archetype of the Evil Mother, who murders her own children. Medea Theory sees the universe as malignly inhospitable to advanced life, blames all but one of the 5 great extinctions on climate change, and notes how easily the next catastrophe (natural or incidental to purblind profit-seeking) can wipe us out.

Loss of polar ice shelves is probably sufficient to prevent bottom-water formation and ventilation of the deep ocean. Sulfur bacteria then extract oxygen from sulfate, leaving poisonous H_2S, which kills everything else. This happened at the end of the Permian, when we lost 90% of marine families and 70% of terrestrial vertebrates.

The first 4 extinctions were caused by climate change. We might want to minimize global heating lest the 6th take us with it. Climate-change deniers will point out that deep-sea ventilation is a myriennial process, so there is time

to *make* money, rather than spend it — but what is the (evolutionary) point of making money if so doing destroys your descendants?

As an example of half-truth FUD, consider Fig. 11, an update of Fig. 1.



◀ Fig.11 ▶ Mean temperature to 2016. The rapid rise in the last 3 years should put an end to denialist talk of 'constant temperature since 1998'. We are now 0.2°C from the 1.5° 'tolerable limit' — one decade at the linearized increase — and the US just elected a denialist and coal enthusiast to the Presidency. The foreseeable future looks uncomfortably warm. Source.

There is a powerful lobby that is extremely anxious to make discussion of global heating go away, and after the 2016 election, some of its members were chosen to run RELEVANT GOVERNMENT DEPARTMENTS. 91 foundations, supported as surreptitiously as possible by corporations and billionaires, paved the way for this by spending a billion dollars lying to you about climate. This turns out to be a normal psychological response when people are overpaid: characteristic of the criminogenic environment of unregulated Wall Street and a result of inadequate parenting by the 1‰. 'Social class negatively predicted probability of telling the truth, … and positively predicted favorable attitudes toward greed ….' The 1‰ have spent 45 years perverting the system to work for them, and do not welcome anything that would change their rules and reduce their profit.

△ Contrarians ▽

Because science progresses by falsifying bad ideas, those who practice it pay thoughtful attention to the arguments of contrarians in their field. And there are a number of useful contrarians who call attention to weaknesses in the debates about climate (in addition to any number of zealous deniers who contribute only noise). In the usual case, they have hold of a half-truth. A favorite: H_2O has absorption bands all over the spectrum and so is more important as a greenhouse gas than CO_2, with its single deep absorption in the middle of an H_2O band. This is perfectly true — in the lower troposphere where radiation is trumped by turbulent mixing. Water vapor pretty much

freezes out (at the snow line) well below the radiation level (above 5 km), and makes a very minor contribution to global heating.

Unfortunately, deniers often find the explanations opaque or too subtle to register. As a result, only the most patient of my friends still try to sort such people out. Unsorted, they populate the web with plausible but misleading blogs.

△ Leave It in the Ground ▽

One doesn't need super computers to see how seriously we are in trouble. An approach accessible to middle-school students is to extrapolate the 20th century linearly into the 21st, in terms of population, per-capita energy use, and anthropogenic temperature increase. This is the business-as-usual approach — understood, approved, and planned for by CEOs, bankers, and politicians.

Think of a square pyramidal oil tank with base (population x * annual per-capita oil use y) and 100 years tall. It holds a volume $v = x*y*100/3$, which (from the data in Table 2) is 1 trillion barrels (1 Gbbl), almost exactly what we burned in the 20th century, and it raised the mean temperature 0.8°C. Now double each dimension, and the volume is 8 trillion bbl. If 1 Gbbl raised the temperature 0.8°C, 8 Gbbl will raise it 6.4°C — and world agriculture is essentially dead.

◄ Table 2. ► Extrapolating the 20th century linearly is a culture breaker. (Assumption: there are still 2 billion people living on solar energy today.) *Bbl* is the abbreviation for the standard oil barrel of 42 US gallons, about 159 liters, and a common wine barrel in the first US oil field. As the prompt temperature increase moves downward into the permafrost, it will release additional greenhouse gasses, making the ultimate temperature increase larger by an unknown amount.

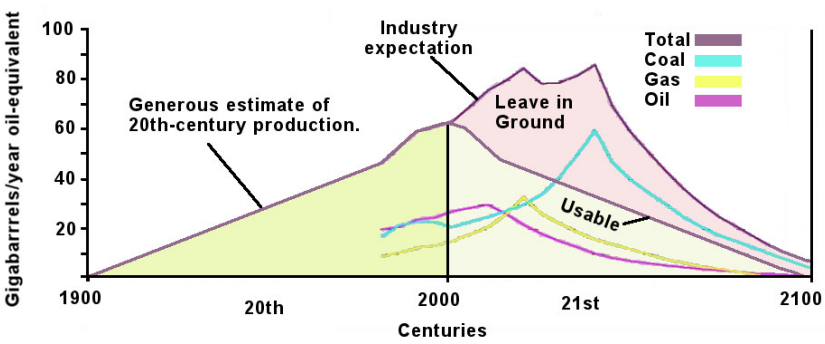
Date	Years	Population / Billion	Annual Per-capita Oil Use / Bbl	Total Oil Burned / Trillion Bbl	Prompt Temperature Increase
	t	$x = pop - 2$	y	$v = xyt/3$	$\Delta T = 0.8°C \cdot v$
1900	0	0	0	0	0
2000	100	4	7.5	1	0.8°C
2100	200	8	15	8	6.4°C

The 2 billion people alive in 1900 were the sustainable population of the

day, living off of solar energy in its many natural forms (wind, wood, water, and whale oil) — except that they nearly drove the whales extinct. Given improvements in agriculture and extension of cropland, the sun may now support 3 billion people,l but oil supports the rest. Much of the current unrest in the world arises from our inability to keep up with their expectation of an ever-increasing standard of living — showing that the simple linear extrapolation is already too optimistic.

The 2°C temperature increase once assumed to be acceptable is proving to be too much, and the consensus is that 1.5°C will stress our civilization as much as it can bear. Today's wars and mass migrations may be exacerbated by US bombings, but they are a harbinger of more to come as temperature increase and water shortages spread in desert areas.

There is still discourse in which 'growth' and 'sustainability' occur together, often with the premise that the first is necessary for the second. For a century, economic growth has meant increased oil usage. Table 2 tells us that we can no longer do this. There is another trillion barrels of conventional oil in the ground: using this will raise the temperature to the acceptable limit. Using all known fossil reserves (coal, tar sands, heavy oil) will raise the temperature by 4.4°C (based on the linear extrapolation, not on computer simulation). Fracking will take it even higher. *We do not want to do this*. We want to keep the Koch Brothers and Exxon-Mobil and Big Oil from doing it to us. Corporations, deliberately ignoring science, see only agitators trying to keep them from making money. Not being a CEO, I find this suicidally irrational. If it were just suicide, this would be splendid; the problem is Tom Lehrer's: 'we all will go together when we go'.



◀ Fig.12 ▶ Unrealistic Expectations. The 20th-century production of CO_2 (yellow) is mirrored in the 21st century (tan). This is the most CO_2 that we can release and keep the immediate temperature rise to ~1.6°C. The upper (reddish) area is what energy companies are planning to market. This must be left in the ground unless feasible and economical methods of Carbon Capture and Sequestration (CCS) are found to keep it out of the atmosphere. Data from J Busby (2010). (His estimates of future production differ from those used in the text, but the conclusions are the

same.)

'Sustainable' means that (Population · per-capita energy use) is less than (Usable incoming solar energy). The 3 things we can do are to lower the population, use less energy, and increase solar energy and molten-salt breeder reactors.

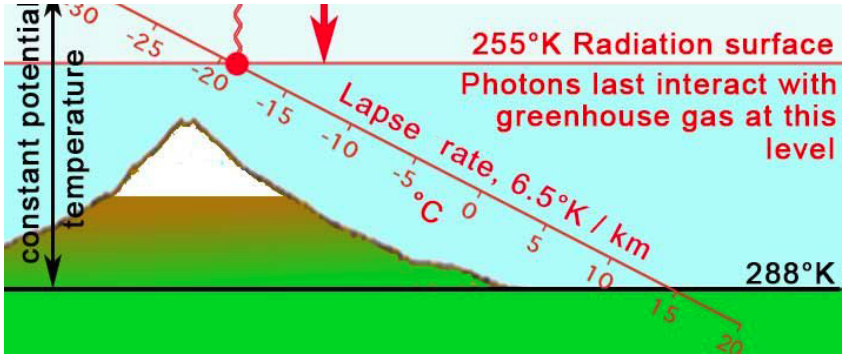
Population reduction, and less fossil-carbon-energy-use, are not concepts that our current politicians can deal with. We have yet to commit to meaningful sustainable energy. This means that the transition to a sustainable world will probably depend painfully upon the 3 Malthusian standbys. *Moral restraint* (chastity and late marriage) has never worked, *Vice* (contraception and abortion) we decry as evil, and this leaves *Misery* (starvation, war, pandemics, bad government, …) to do the job. 'All of the children born beyond [the supportable limit], must necessarily perish.' As always. Those who do not solve their problems with intelligence will have them solved by stupidity.

△ △ THE GREENHOUSE ▽ ▽

Perhaps the most frequent denial of global heating is based on the fact that satellite measurements 'have shown that temperature has not risen in 17 years'. This is true but *irrelevant*: what satellites measure most easily and uncontroversially is the *radiation* temperature of the Earth, which is constant, rather than its *surface* temperature, which is increasing. The radiation temperature is set as indicated in Fig. 12, the surface temperature in Fig. 13.

Figure 1 is a toy thermodynamic model in which the earth is a blackbody. The model is rigorous, simple, and depends upon 3 numbers only, 2 of which are uncomplicated and one that is not. It ignores minor variables, packs all of the incredible difficulties into that single recalcitrant quantity (τ = infrared optical depth), and still covers everything important (to first order). It depends on the First Law of Thermodynamics (Energy is conserved), the Perfect Gas Law ($PV=RT$), and the standard well mixed, constant-composition, troposphere. It starts from a steady state in which all the energy that the earth receives from the sun is reradiated to space at the same rate (otherwise the earth warms or cools). These are all valid assumptions, and they are where the ~40 supercomputer models also started.

◀ Fig.13 ▶ The Changing Surface Temperature: The infrared optical depth τ



(which shortens as greenhouse gasses increase) determines the altitude at which 255°K photons last interact with molecules and can escape to space. All the red lines are attached to the red dot, and move up as τ shortens. (Note that water mostly freezes out at the snow line, and does not have much effect on τ.) The intersection of the lapse rate line with the ground then determines the mean surface temperature. (Using the scale-height atmosphere lets us put a conceptual top on the atmosphere, and so define a radiation level. It also confounds the modelled lapse rate, which in fact is curved and depends upon the pressure changes with height in the real atmosphere. *All* models simplify: their utility comes from knowing which simplifications are permissible in aid of practicality.

Satellites have been measuring the albedo and 15 other contributions to surface temperature since March 2000. Animated maps of the results can be watched here.

To avoid having to deal with the lack of a top to the atmosphere, we ignore gravity and compress the entire atmosphere to its scale depth of 11 km, at which size it is all at a pressure of 1 atmosphere. This compression makes very little difference to anything in the model, and it lets us give a precise meaning to the optical depth τ, which is the lowest depth from which infrared photons can escape without interacting with any more gas molecules. Having found the optical depth, we unscale the atmosphere and let gravity restore the pressure gradient.

We now need the concept of 'potential temperature'. Think of air as existing in 'parcels' about the size of weather balloons surrounded by infinitely elastic membranes which prohibit mixing or energy exchange. Motion is then adiabatic (no heat enters or leaves the parcel). The parcel changes pressure, volume, and temperature in accordance with the perfect-gas law as it rises or descends, but it is always at the same temperature at the same altitude. For climatologists, it makes sense to define the potential temperature at the optical-depth/radiation-level (near 500 mb): its actual temperature after being compressed to 1 bar is then the surface temperature of the earth. Notice once again: no heat is required to raise its temperature during this process, and below the radiation level, back-radiation from greenhouse gasses can be included as part of the turbulent mixing that maintains a constant composition

troposphere.

The surprising effect of greenhouse-gas absorption of long-wave energy is that the earth's surface receives nearly as much long-wave energy from the atmosphere as it does short-wave energy from the sun. This sounds as though energy were not being conserved, but it is just being trapped temporarily, as by an insulating blanket.

If, on a sunny day, one points a $10 pocket bolometer (infrared thermometer) at the blue sky, the sun, the road, a river, a cloud, vegetation, a passing dog, a sunny wall, and a shaded wall, all will report different radiation temperatures. *The* temperature (as reported by a mercury thermometer in a shaded, ventilated, space, is not any of the various radiation temperatures. The 'blue-sky' measurement, typically a bit above 0°C, is the lapse-rate temperature at the upward optical depth. We don't notice this cold radiation because it is overwhelmed by the denser radiation from the sunny wall, and the higher kinetic temperature of the air around us. The sun itself has 2 temperatures from Earth, a 'color temperature' that defines 'white' for us, determined by its spectrum, and a thermal temperature set by the temperature of the Sun's radiation level (high in its atmosphere!) and attenuation by r^2. These various temperatures are never in equilibrium, but co-exist just as sun and shadow coexist. Deriving a meaningful average global surface temperature from this stew is something of a challenge!

△ Some Complexities ▽

> This presentation is the '30-page' version. For the '600-page' version, see ScienceofDoom, a level-headed and thorough collection of tutorial discussions of all aspects of climate science, which responds to rude skeptics with serious attempts explain the view of climate scientists on the issue in question.

If the simple thermodynamic model is rigorous, why is so much effort put into IPCC? The easy answer is that the thermo model is a concise description of what the IPCC has discovered. Obtaining the 288°K annual mean surface temperature from the observed daily 100°C range of ground temperatures required a long and painstaking international effort. The 255°K radiation temperature is a function of the albedo (fraction of energy reflected), which required worldwide data about land-surface reflectivity, aerosol composition and cloud droplet size, concentration, and distribution, and gas-photon interactions. Explaining and predicting the future of the optical depth is an immensely complex chemical, physical, and mathematical problem, requiring

6D integration (3D spatial + composition + concentration + wavelength) over the spectrum of interactions (with light, and with eachother) of some 200 time-varying chemical species.

The supercomputer models become trustworthy only when they reproduce historical climate from historical data — and our records are never as complete as we might like. The attempt to predict future values of the optical depth τ draws in economic historians, futurologists, demographers, anthropologists, and sociologists. The verbal input of these experts must be converted to numerical parameters before the computers can use them: this is one of the subtlest of skills, fraught with uncertainties. Political sensitivities preclude public discussion of realistic events, such as the consequences of a climate-induced population crash, or the probabilty that preparations for martial law and militarization of police forces are in expectation of serious disorder when global heating, energy shortages, and crop failures arrive simultaneously.

By far the easiest use of increased computer power is to reduce the size of the geographical step, and over the years this has gone from 500-km steps in 1970 to 110-km steps in 2007, and from 1 fluid layer (atmosphere or ocean) to 30 in each. (Sometimes this reduction produces unexpected results, for reasons that are not completely understood.) New processes have been added, in the sequence: CO_2 and rain in 1970s, then clouds and ice, a shallow 'swamp' ocean, volcanoes, sulphates, a deep ocean, the carbon cycle, rivers, aerosols, an overturning ocean, interactive vegetation, and UV-induced atmospheric chemistry.

The bottom line, in terms of 'radiative forcing' (which is measured in W/m^2, like the incoming energy, is shown in Table 3. CO_2 contributes 1.7 W/m^2. Everything else sums to almost zero:

Note the small effect of water vapor. Although often cited as 'the most important greenhouse gas' this is true only below the radiation level. Below cloud level, it blocks most IR radiation, and transports the latent heat of condensation up to the clouds. But most water freezes out by 5 km, and what is found in the stratosphere is newly formed from oxidized methane. Much of the effect of 'other GHG' is from meat-production methane, generated in the rumens of cattle during the bacterial digestion of cellulose. Although the carbon in this methane was removed from the atmosphere by photosynthesis of cattle fodder, methane, with 4 C-H bonds to absorb energy, is a much more powerful GHG than CO_2. With a 12.5-year half-life, it make an appreciable contribution to global warming.

◀ Table 3. ▶ Greenhouse Radiative Forcings (IPCC AR5 WG1 Table 8.6). 'GHG' is 'greenhouse gas'.

GHG	Radiative Forcing / (W/m^2)
CO_2	1.66
Other GHG	1.17
Tropospheric ozone	+0.40
Stratospheric ozone	–0.05
Stratospheric Water vapor	+0.07
Aerosol, radiation	–0.45
Aerosol, cloud	–0.45
Surface albedo	–0.15
Contrails+cirrus	+0.05
Black carbon	+0.04
Total	+2.3
Solar irradiance	+0.05

Science fiction might come to the rescue at this point, with something like a realization of 'Chicken Little', a fast-growing (cancerous?) tissue culture fed alga-derived glucose, producing chicken meat quickly, with no methane production.

One final question is 'Where does the additional energy to warm the earth come from if everything is in balance?'. I *told* you that we lied to you: it isn't quite in balance. NASA's Jim Hansen ⬆ showed that the earth absorbed (0.58 ± 0.15)W/m^2 more than it radiated over the 2005–2010 period, with 71% of the energy going into the ocean (in proportion to its fractional area), confirming 'the dominant role of the human-made greenhouse effect in driving global climate change'. This value is less than 1/4 of the 2.3 W/m^2 calculated above and 1.6 ofthat estimated in Table 0. There is still a mismatch of numbers and so deeper understanding to be sought here.

A discouraging aspect is the effective permanence of adding CO_2 to the atmosphere. If you look only at geochemistry (with a geological timescale), you see atmospheric CO_2 in equilibrium with dissolved CO_2, and the latter

reacting with carbonate sediments to form harmless bicarbonate ions, so there is a steady drawdown of atmospheric CO_2 leading to a return to today's equilibrium. But most of the ocean does not come in contact with enough solid carbonates to matter *on a human timescale*. There are no carbonates on the deep sea floor (because sinking foraminifera tests dissolve by a pressure effect before reaching the bottom), and it takes 10,000 years for water to make the thermohaline circuit (sinking under polar ice shelves to form bottom water, flowing slowly around the globe, rising imperceptibly to the surface — most distantly in the North Pacific — and flowing by surface currents back to the poles. It can make many circuits without contacting shallow-water carbonates on continental slopes. What we have already done to the atmosphere and climate may outlive our tenure on the planet.

△ △ THE PLANETARY LIMITS ▲

> The Anthropocene raises a new question: 'What are the non-negotiable planetary preconditions that humanity needs to respect in order to avoid the risk of deleterious or even catastrophic environmental change at continental to global scales'? — J Rockström &28a (2009) ⬆

Climate change may be our first priority among threats, but it is not alone. Outranking all the popular political and military alarms, the collection in Table 4 includes the phenomena most likely to become culture breakers.

In closing, we again come to frontier science, this time in the attempt to recognize planetary boundaries, and — drawing upon multidisciplinary understanding — to quantify them. Like climate change (which presents one of the boundaries) this requires immense collaborative effort. Boundaries are not obvious, their effects are insidious, their consequences diffuse, and their causes impersonal. To individuals, they are not recognizable as either threats or things that can be changed. Avoiding these boundaries often requires governmental regulation, to prevent people from doing as they please when the cumulative consequences are culture breaking. The conservative wing of the Senate apparently exists to oppose such regulations. If crossing a boundary is 90-day profitable, it is acceptable — whatever its long-term consequences.

◄ Table 4. ► Planetary Boundaries. The calculated limits are subject to better estimation as knowledge accumulates. The repercussions of exceeding any of these boundaries include the cultural collapse that has ended the careers of a hundred prior civilizations. The 'miners' canary' is merely the best understood aspect of a boundary.

BOUNDARY	MINERS' CANARY	LIMITING PARAMETER	STATUS
Climate Change	Polar ice sheets	Atmospheric CO_2 < 350 ppm and/or radiative forcing < +1 W/m^2	**400 ppm 2.88 W/m^2**
Ocean Acidification	Coral reefs	Mean surface seawater saturation state with respect to aragonite ≥ 80% of pre-industrial levels	Approaching boundary
Stratospheric Ozone	Skin cancer	< 5% reduction in O_3 concentration from pre-industrial level of 290 Dobson Units	
Biogeochemical Nitrogen Flux	Terrestrial dystrophication	Limit industrial and agricultural fixation of N_2 to 35 Tg N/yr	**Exceeded**
Biogeochemical Phosphorus Flux	Anoxic seas	Annual P inflow to oceans not to exceed 10 times the natural background weathering of P	Close to boundary
Global Freshwater use	Civil unrest	<4000 km^3/yr of consumptive use of runoff resources	
Land system change	Soil loss	< 15% of the ice-free land surface under cropland	
Biological diversity loss	Ecosystem loss	Annual rate of <10 extinctions per million species	**Greatly Exceeded**
Chemical pollution	Environmental cancers; Surprises await	Limit not yet known	
Atmospheric aerosol loading	Monsoon system	Limit not yet known	
Wealth inequality	Civil unrest	When Rome collapsed, 1800 people owned nearly everything. Or vice versa.	Even odds this one wins.

The eleven planetary boundaries of Table 3 have so far been recognized. The idea of a boundary is that potential catastrophes lie ahead. In some cases their approach seems slow but inexorable; in others, possibly sudden and disastrous. Given Lao Tzu's startling observation that 'If we do not change direction, we may end up where we are heading', it seems smart to put a

notional fence between us and the disasters. Since we know what worked during the Holocene (11,700 BCE–1760), a good bet is that we might be able to extend the Anthropocene (1760–??) indefinitely by maintaining conditions similar to those of the Holocene. Table 3 presents some boundaries we should not cross if we hope to do this. Note that every boundary is at least as complex as the discussion of global heating above. Rockström did not mention the final entry.

Work continues on refining the limits. Table 4 is just the beginning: population — the principal driver of the entries above — has not been mentioned, nor have social limits, such as wealth distribution. Web searches for papers by Johan Rockström, Will Steffen, and Paul Crutzen will lead to bibliographies of hundreds of detailed papers behind Table 4 — few of which will seem alarming by themselves. ■

Last update: Thu, 2017-Mar-16, 20:38 GMT. Last update: 2017Mar16 21:25 CET