Climate Change in a Nutshell: The Gathering Storm

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James Hansen

Young people today confront an imminent gathering storm. They have at their command considerable determination, a dog-eared copy of our beleaguered Constitution, and rigorously developed science. The Court must decide if that is enough.

That is the final paragraph of my (thick) Expert Report written more than a year ago for Juliana v. United States. We are fortunate to have such a brilliant and dedicated group of attorneys who have assembled a score of Experts and are working to ensure that young people receive their day in court.

In the meantime, there are reasons why it may be useful to summarize the climate science story.

Albert Einstein once said that a theory or explanation should be as simple as possible, but not simpler. And it depends on who the audience is. My target is the level of a Chief Justice or a fossil fuel industry CEO.

This is a draft, because I want to be sure that there are no inconsistencies in my testimonies against the government, against the fossil fuel industry, and in support of brave people who have taken risks in fighting for young people. So I am seeking suggestions for how to make this science story clearer.

I should say something here about end-game strategy. We probably are getting close to the next opportunity for real progress. We blew the last opportunity, when Barack Obama was elected. It was not his fault. We had not really made the whole climate/energy/economics story clear enough.

Despite the sour turn toward increased global authoritarianism, the heart-warming sight of marching Australian children, defying their Prime Minister's instruction to stay in school, suggests that it may not be long until we have a chance at another day of reckoning. This time we must be clearer about what young people and other life on our planet need to assure their future. And thoughtful people at high government and industry levels must understand.

History of this understanding is not well reported, as I discuss in *Sophie's Planet*[a]. Already in 1982, E.E. David, President of Exxon Research & Engineering, in his keynote at the Ewing Symposium[b], presciently characterized the climate story: "faith in technologies, markets, and correcting feedback mechanisms is less than satisfying for a situation such as the one you are studying at this year's Ewing Symposium. The critical problem is that the environmental impacts of the CO_2 buildup may be so long delayed. A look at the theory of feedback systems shows that where there is such a long delay the system breaks down unless there is anticipation built into the loop. The question then becomes how to anticipate the future far enough in advance to prepare for it."

David recognized the ***delayed response of the climate system***, which is the critical factor that gives rise to intergenerational inequities. He concluded that this delayed response demands ***anticipation*** to avoid system breakdown, where, in the climate case, system breakdown would be catastrophic climate change for today's young people and future generations. David's conclusion began "To sum up, the world's best hope for inventing an acceptable energy transition is one that favors multiple technical approaches subject to correction - - feedback from markets, societies, and politics, and scientific feedback about external costs to health and the environment."

[a] A slightly revised draft of the Preface of Sophie's Planet is available here. [b] available here.

Response of the U.S. government and the fossil fuel industry was not policy that would move the energy industry gradually and efficiently toward clean carbon-free energy. Instead they chose very expensive investment in developing technologies such as hydraulic fracturing "fracking," an energy-, chemical-, water-, and resource-intensive process that allows extraction of more and more fossil fuels. E.E. David became a climate change denier. Government and industry concurred in this approach.

In assessing this failure of early government policy in Sophie's Planet I suggest that we, the scientific community, bear much of the responsibility. I disagree with the assessment in the dedicated issue on the New York Times last summer, that the greater public was the villain. I argue that President George H.W. Bush, in supporting the 1992 Rio Framework Convention on Climate Change, did what was appropriate at that time.

The failure has been not to advance policy in the subsequent 26 years. When I gave a talk to executives of an oil company that adorned its web site with windmills and solar panels, I learned that they actually had almost no investment in carbon-free energy, it was more a PR strategy. They could take advantage of the clout of "Big Green" environmental organizations, while not really getting serious about carbon-free energy.

That is the background, about why I believe there is value in trying to make the climate story as clear as possible to an industry CEO as well as a Chief Justice. There will be lawsuits against the fossil fuel industry, which may help bring them to their senses. However, I am not so much interested in 'reparations', the idea that we can extract a lot of money from the industry for its past sins. That potential pales in comparison to getting their cooperation on moving as rapidly as practical toward clean carbon-free energy of the future.

Therefore, I am interested in any suggestions for improving the clarity of 'Climate Change in a Nutshell'. I believe there is a good chance that the relevant CEOs have a heart, and they must be pretty smart or they would not have made it to the position they are in.

Well, o.k., we all know an exception or two, but this is no time for levity.

Climate Change in a Nutshell: The Gathering Storm

SECTION 1: Climate has always been changing, but humans are now the principal drive for climate change, overwhelming natural climate variability.

a. Rising atmospheric **CO_2 levels**, primarily a result of fossil fuel emissions, have become the **predominate cause** of continuing climate change. Increasing CO_2 is now responsible for about 80 percent of the annual increase in climate forcing by greenhouse gases (GHGs), the other 20 percent being from the combination of CH_4 (methane), N_2O (nitrous oxide) and other trace gases.

b. Climate change is driven by **cumulative CO_2 emissions**. The United States has contributed a disproportionately large share of cumulative global emissions, and thus the United States is, by far, the nation most responsible for the associated increase in global temperatures.

I. Climate Change Overview: Natural Variability vs. Human Effects

Natural variability. Climate is always changing. Climate is described as the average weather over some period, including the statistics of weather variability. Although climate is always changing, the range of variability is limited unless there is some mechanism, some ‘forcing,’ to drive climate change.

Unforced climate variability is mainly a result of the fact that the atmosphere and ocean are dynamical fluids that, in effect, are sloshing about. The ocean is deep, about 4 kilometers (km) or two and a half miles on average, so its ‘sloshing’ can cause variability on a large range of time scales. The most familiar variability associated with the ocean is the El Niño cycle, the irregular occurrence of a warming in the tropical Pacific Ocean, which can affect weather globally.

A **climate forcing** is an imposed perturbation of Earth’s energy balance. Natural climate forcings include solar variability. For example, when the Sun, which is a variable star, becomes brighter, that constitutes a ‘positive’ forcing. A positive forcing causes global warming, i.e., 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 by a volcanic eruption are sulfuric acid that forms from volcanic sulfur dioxide gas. These aerosols remain in the stratosphere for one to two years, reflecting sunlight away from Earth. This shading effect causes temporary cooling, as observed after large volcanic eruptions, such as the eruption of Mt. Pinatubo in 1991.

Human-caused climate forcing. Human-caused climate forcings now compete with natural forcings, with some exceeding natural forcings in magnitude.

The largest human-made climate forcing is a warming effect due to human-caused changes of atmospheric composition, specifically growth of **GHGs such as CO_2, CH_4, N_2O** and other trace gases that absorb Earth's infrared (heat) radiation. The second largest human climate forcing is a cooling effect due to human-caused increase of **atmospheric aerosols**. Aerosols, on net, increase reflection of sunlight to space, thus reducing solar heating of Earth's surface. There are additional human effects, e.g., changes in the characteristics of Earth's surface due to replacement of forests by cropland and the building of highways and cities. The local and regional effects of these surface changes can be large, but on global average their climate effect is smaller than the effect of GHGs and aerosols.

Benjamin Franklin understood climate forcings. He wrote about the likely effect of volcanic aerosols in cooling Earth[1], but he had no satellites to observe the global spread of aerosols or global temperature measurements to verify the climate response. In 1824, the French scientist Joseph Fourier described the greenhouse effect of gases that allow sunlight to pass unimpeded but absorb heat radiation: "The temperature [of Earth's surface] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air than in re-passing into the air when converted into non-luminous heat.

John Tyndall, an Irish physicist, made laboratory measurements of absorption of heat radiation by water vapor and CO_2. Tyndall described the effect of these gases as like that of a blanket or dam "by which the temperature of the earth's surface is deepened: the dam, however, finally overflows, and we give back to space all that we receive from the Sun." Tyndall was saying that a GHG, by reducing heat radiation to space, causes an energy imbalance, more energy coming in than going out – this imbalance causes Earth's temperature to rise until Earth again radiates to space the same amount of energy that it absorbs from the Sun.

Climate forcings, i.e., perturbations of Earth's energy balance, are measured in Watts per square meter (W/m^2). Earth absorbs 240 W/m^2 of energy from the Sun, so if the Sun's brightness were to increase 1 percent that would be a forcing of +2.4 W/m^2. The Sun's irradiance has been measured accurately since the late 1970s. The irradiance is found to vary with the sunspot cycle, with the amplitude of change, from solar minimum to solar maximum, about 0.1 percent. Thus this range of the Sun's forcing is only about 0.24 W/m^2.

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[1] For the sake of readability, I minimize references in this scientific summary, which is based mainly on four papers written in collaboration with relevant world experts. These papers, listed at the beginning of the Bibliography, are abbreviated in the text as: *Target CO_2* (2008), *Assessing Danger* (2013), *Ice Melt* (2016) and *Burden* (2017). Historical references are given in my Expert Report for the *Juliana v. United States* lawsuit, which will be available at trial, and in *Sophie's Planet* (in preparation).

Absorption of heat radiation by CO_2 is calculated accurately and confirmed by laboratory measurements. Increasing the amount of CO_2 from its pre-industrial level (280 ppm) to the 2018 amount (407 ppm) causes a climate forcing of more than 2 W/m^2. The CO_2 climate forcing is nearly an order of magnitude larger than the solar forcing. Also the CO_2 forcing is increasing monotonically whereas the solar forcing is oscillatory, which limits its climate effect.

II. Climate Feedbacks and Climate Sensitivity

Climate feedbacks. 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 change 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 thus a critical factor in determining climate sensitivity.

Climate sensitivity. Climate response to a specified climate forcing defines climate sensitivity. A standard climate forcing of doubled CO_2 is commonly used in discussions of climate sensitivity. Doubled CO_2, say from the pre-industrial level of 280 ppm (parts per million) to 560 ppm, is a large forcing, about 4 W/m^2.

Burning fossil fuels can yield such a large CO_2 increase. Indeed, burning all fossil fuels would much more than double atmospheric CO_2. Figure 1 shows that humanity has so far burned only a small fraction of fossil fuel reserves (proven resources) and total fossil fuel resources. Atmospheric CO_2 amount in 2018 is 407 ppm, which is a forcing of ~2.1 W/m^2. CO_2 absorption bands are partially saturated, so each additional 4 W/m^2 forcing requires another CO_2 doubling.

Doubled CO_2 was the forcing considered in 1979 in a study of the United States National Academy of Sciences, the Charney report. Charney concluded, based largely on climate model simulations, that doubled CO_2 likely would cause a global warming of about 3°C. However, because of limited understanding of climate feedbacks, the Charney study reported a large uncertainty in climate sensitivity, a range from 1.5°C to 4.5°C for doubled CO_2.

Charney's derived climate sensitivity of 3 ± 1.5°C, or 0.75 ± 0.25°C per W/m^2 of climate forcing, was the estimate for equilibrium (eventual) warming after the Earth's surface and ocean had warmed to restore planetary energy balance, with the assumption that ice sheet sizes remained unchanged. In reality ice sheets begin to shrink as the world warms, but if one's interest is in climate change on a time scale of a century or less, change of ice sheet size might be neglected.

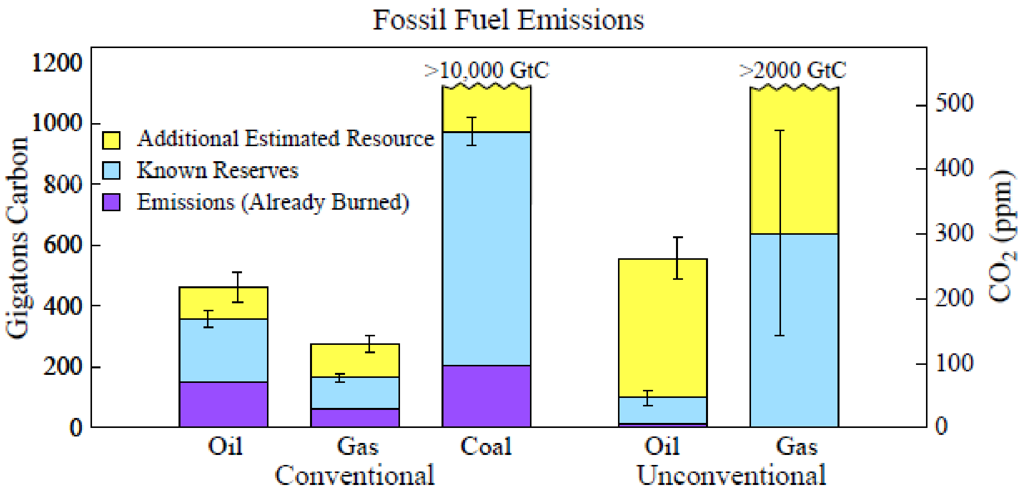

Fig. 1. Fossil fuel CO_2 emissions up to 2018 and carbon content (1 ppm CO_2 ~ 2.12 GtC, where a gigaton of carbon is the same as a picagram of carbon). Data are update of Fig. 2 in *Assessing Danger* (2013).

Charney's climate sensitivity thus includes effects of fast feedbacks, such as atmospheric water vapor and clouds, which respond quickly to changed climate, but it 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 an independent empirical evaluation of Charney's fast feedback climate sensitivity as well as information on the climate system's slow feedback response.

Slow feedbacks and the CO_2 control knob. Slow feedbacks include both amplifying and diminishing effects, but empirical evidence shows that the two principal slow feedbacks are both amplifying.

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, mostly by CO_2. It is an empirical fact that the ocean, soil and biosphere release more of these GHGs as the planet gets warmer. Part of this is the fact that CO_2 is less soluble in a warmer ocean, as in a warm Coca Cola, but more complex ocean chemistry and the rate of ocean overturning also affect the amount gases released to the air. GHGs are also released by melting tundra and by wetlands on a warmer planet.

A remarkable conclusion that emerged clearly from paleoclimate data in the 1980s is that the large glacial-interglacial climate changes are accounted for almost entirely by these two slow feedbacks. Glacial/interglacial climate cycles are instigated by small changes in Earth's orbit and the tilt of Earth's spin axis, but these orbital climate forcings are weak, involving only seasonal and geographical

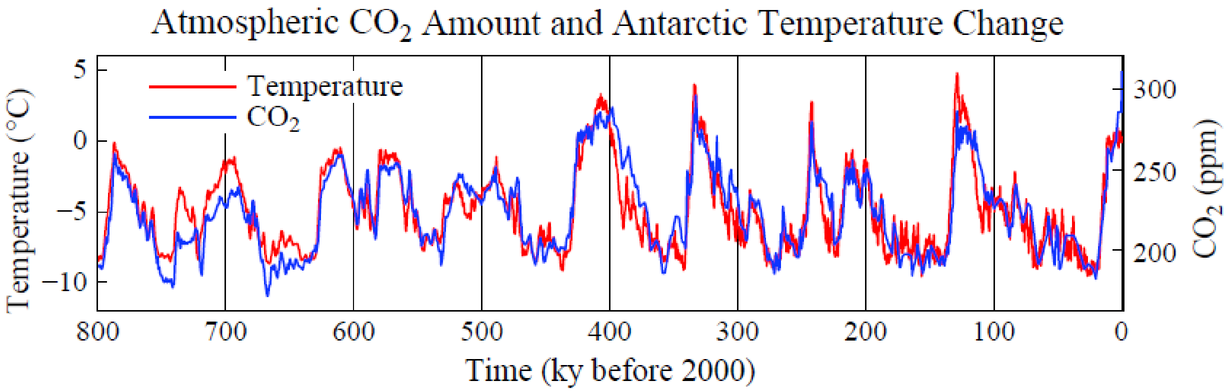

Fig. 2. Antarctic (Dome C) temperature for the last 800,000 years relative to the mean for the last 10,000 years and atmospheric CO_2 amount. Fig. 28 (a) of *Ice melt* (2016).

redistribution of sunlight on the planet. But the weak forcings are persistent, as the orbital changes are slow, changing on time scales of 20,000 to 100,000 years.

Figure 2 and the discussion that accompanies it (*Ice Melt*, 2016) show that CO_2 is a tight control knob on global temperature on millennial time scales. CO_2, temperature and sea level appear to change almost congruently on these millennial time scales, but close examination (Grant et al, 2012) shows that sea level (an indicator of ice sheet size) lags temperature by 1-4 centuries. This provides an indication of the time required for ice sheet size to adjust (and sea level to rise) in response to climate change.

The close correlation of CO_2, temperature and ice sheet size in the paleo record allows empirical evaluation of the (fast-feedback) climate sensitivity that Charney inferred, from climate models, to be 1.5-4.5°C for doubled CO_2. Paleo evaluation is obtained by comparing glacial and interglacial states; GHG amounts and ice sheet size are boundary forcings that maintain these climate states. These paleo data yield a narrower range (2.5-4°C for doubled CO_2) for the fast-feedback climate sensitivity [footnote 3 in *Ice Melt* (2016)].

The paleoclimate evaluation of climate sensitivity is important, because, unlike the Charney study, the climate sensitivity is extracted from empirical real-world data, independent of climate models. 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 Intergovernmental Panel on Climate Change uses to project 21st century climate change. It is important to remember that these climate models do not generally include the slow climate feedbacks. These slow feedbacks are already coming into play, and they will grow if global temperature rise continues.

III. Climate Response Time and Tipping Points

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, i.e., its slow warming in response to climate forcing by GHGs. Earth’s energy imbalance can now be measured, as I will describe. The global average imbalance is now +0.75 ± 0.25 W/m^2. Because climate sensitivity is about 0.75°C per W/m^2, this energy imbalance implies that more than 0.5°C [0.75 × 0.75] additional global warming is in the pipeline.

This additional warming (in the pipeline) will occur over coming decades and centuries, if atmospheric composition remains at today’s level. However, the stated value for warming in the pipeline is based on the fast-feedback climate sensitivity. Slow feedbacks will eventually cause further warming, if atmospheric GHGs stay at today’s level, as I will quantify.

Slow feedbacks will begin to come into play this century. As we have noted, paleoclimate data indicate that the response time of ice sheets and sea level to global warming is one to four centuries. The degree of slow feedback response this century, 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, as noticeable climate change is just beginning to rise above natural variability. In that regard, the ocean’s inertia and the slow climate feedbacks create a problem for young people. 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 neglected by Charney, 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. Thus as the ice shelves melt, the ice sheets expel ice into the ocean at a faster rate. This process is self-amplifying, because the melting icebergs freshen the ocean surface waters. Fresh water reduces the density of the ocean surface layer, thus reducing the ocean's vertical overturning, which in turn reduces the release of ocean 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. In that case, we say that a 'point of no return' is reached and it is too late to prevent discharge of massive amounts of ice, sufficient to raise sea level several meters. 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.

The concept of a 'tipping point' and a 'point of no return' may be easier to understand in the case of species extinctions. We are putting pressures on species in many ways as humans, in effect, take over the planet, the pressures including land use, overharvesting, nitrogen fertilization, exotic species introduction, and many others. Rapid climate change adds an overarching stress, as climate zones are shifting at a rate of several kilometers per year.

A tipping point for species can be reached, with acceleration of species loss, if climate zones shift so fast that species cannot migrate fast enough to stay within a hospitable climate, or if human development blocks their migration. Species are interdependent, so as some are stressed and eliminated, it is possible for an entire ecosystem to collapse. A point of no return is reached for a given species when its population is reduced and its environment diminished to the point that the species cannot recover, i.e., it is committed to extinction, to extermination.

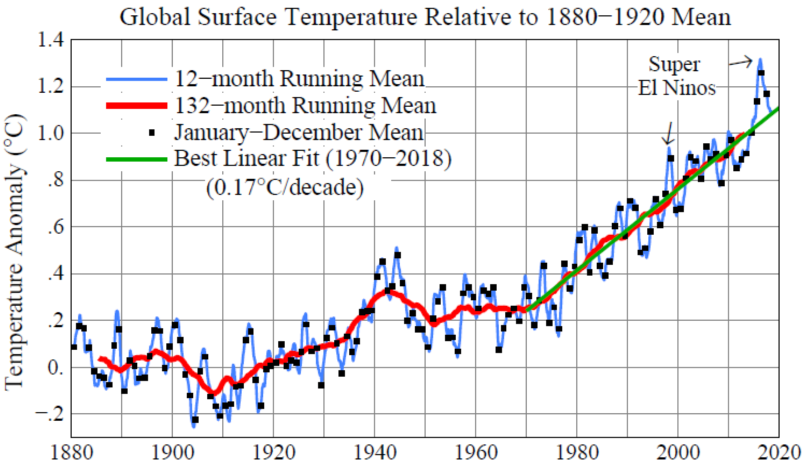

Fig. 3. Global surface temperature relative to 1880-1920 mean (Hansen et al., 2010; this figure is updated monthly and available at http://www.columbia.edu/~mhs119/Temperature/).

IV. Climate is Changing, Rapidly, and More Change is Coming

Global warming. Global temperature, despite its natural variability, has been rising rapidly for 50 years (Fig. 3), at a rate 0.17°C/decade (0.3°F/decade). This warming continues unabated and has accelerated in the past decade, as revealed by connecting the most recent El Niño maxima and La Niña minima (Fig. 3).

Global warming had 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.

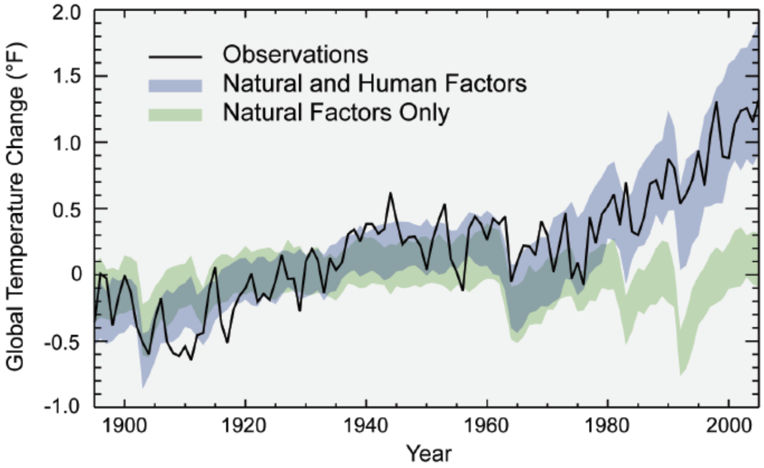

Fig. 4. Modeled and observed global temperature, from Melillo et al. (2014), who adapt the figure from Huber and Knutti (2012).

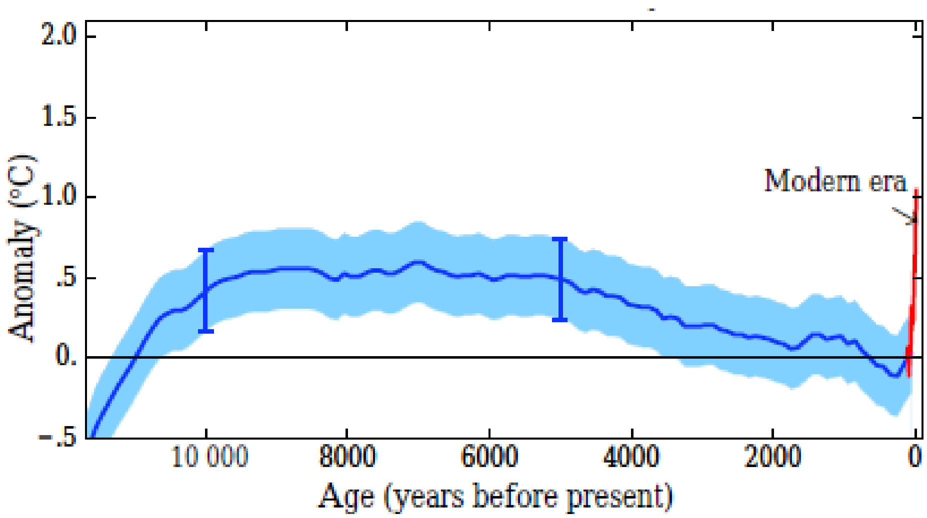

Fig. 5. Estimated global temperature during the Holocene era, i.e., the past 11,700 years and the 11-year running mean of modern data (red curve); Fig. 3 of *Burden* (2017).

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, the period in which civilization developed, a period in which sea level has been relatively stable for several thousand years. The temperature curve for the Holocene, the blue curve in Fig. 5, is 'centenially-smoothed', i.e., it necessarily has temporal resolution of about 100 years because of the nature of proxy temperature records used to construct it (Marcott *et al.*, 2013).

Modern era temperature (red curve in Fig. 5) 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, as I will discuss quantitatively, so it is certain that global warming will continue on decadal time scales.

How much further will temperature rise if we leave atmospheric CO_2 at its current amount (about 407 ppm) indefinitely? Paleoclimate data on millennial time scales provide a good estimate of the full response to CO_2 change, including the effects of both fast and slow climate feedbacks. Figure 2 reveals the tight control that CO_2 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 CO_2, 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.

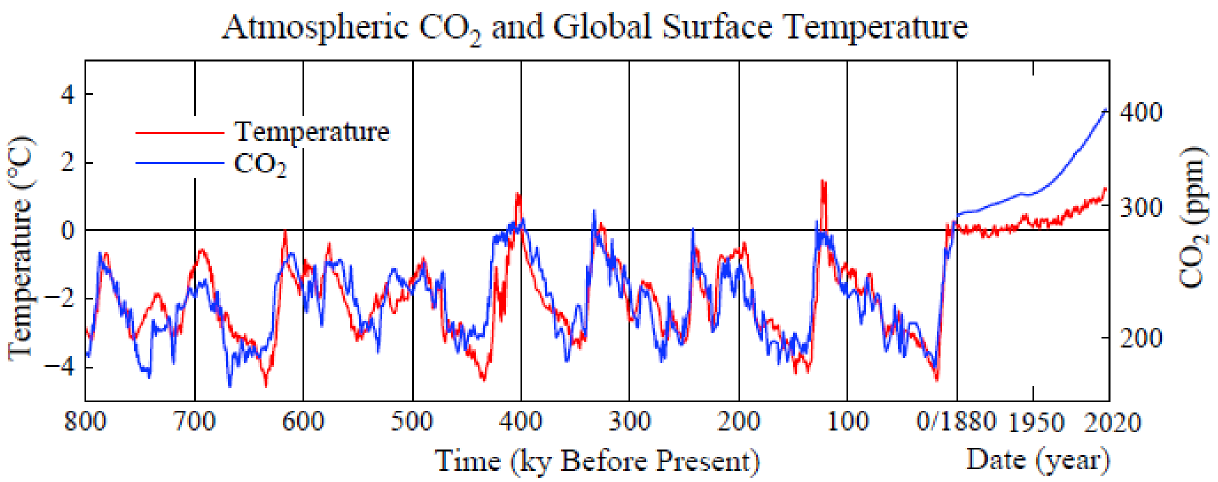

Fig. 6. CO_2 amount from Antarctic ice cores (Jouzel *et al.*, 2007). Paleo global surface temperature change is from ocean core data (Zachos *et al.*, 2008) via approximation to convert oxygen isotopic data to ocean temperature (Hansen *et al.*, 2013). CO_2 amount is plotted on a logarithmic scale, because the CO_2 climate forcing and thus expected temperature response are proportional to the logarithm of CO_2 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 CO_2 ice core dating, the results confirm the tight control of CO_2 on global temperature (Fig. 6). This figure implies that the eventual warming for 407 ppm CO_2 will be about 3.5°C, including the full effect of both fast and slow climate feedback processes. [Additional warming by non-CO_2 GHGs tends to be off-set by aerosol cooling; thus within the range of uncertainty CO_2 provides a good approximation of the net human-made forcing.]

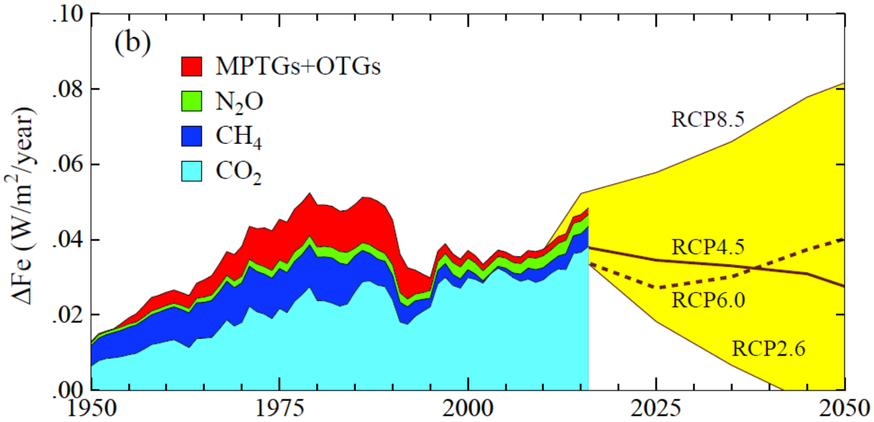

Fig. 7. Annual increase of greenhouse gas climate forcing has increased about 0.04 W/m^2 per year for the past 50 years. RCP scenarios were defined by the Intergovernmental Panel on Climate Change (IPCC). MPTG = Montreal Protocol trace gas, OTG = Other trace gas. [Update of Fig. 8b of *Burden* (2017)]

V. CO_2 Dominance in Growing GHG Climate Forcing

CO_2 change is the largest human-made climate forcing. In addition, the CO_2 climate forcing approximates the net human-made climate forcing. This is a coincidence. Non-CO_2 GHGs cause a climate forcing today, relative to pre-industrial conditions of more than 1 W/m^2 (the CO_2 forcing is over 2 W/m^2). Net (negative) aerosol forcing is poorly measured, but estimated to be about -1 W/m^2.

The GHG climate forcing has been increasing at a rate of approximately 0.04 W/m^2 per year for the past 50 years (Fig. 7). The net growth of GHG forcing was thus about 2 W/m^2 in those 50 years.

Until the 1980s trace gases (red area in Fig. 7), especially chlorofluorocarbons (CFCs), provided a significant fraction of the increasing GHG climate forcing. However, the Montreal Protocol has been successful in phasing out emission of ozone-depleting gases as well as some other trace gases. Because of the finite lifetime of these gases, with continued vigilance the future contribution of the red area in Fig. 7 may become zero or even slightly negative.

For the past 25 years CO_2 has provided about 80 percent of the growth of the GHG climate forcing (Fig. 7). However, the responsibility of CO_2 is even 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, and that global warming is largely due to increasing CO_2.

RCP (Representative Concentration Pathways) scenarios of IPCC (Intergovernmental Panel on Climate Change) 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. Below I define simpler scenarios to help reveal the relation of emissions to future global warming.

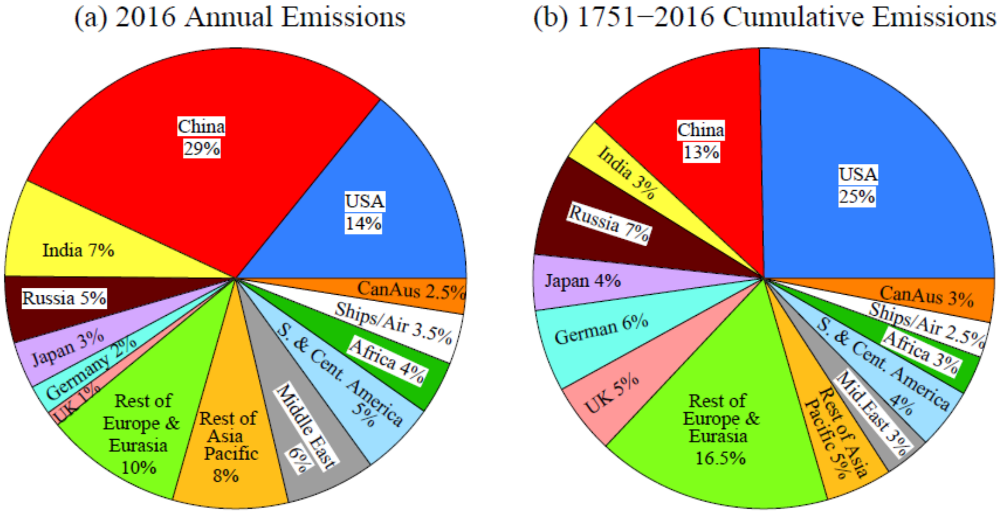

Fig. 8. (a) 2016 fossil fuel emissions by nation or region, and (b) cumulative 171-2016 emissions. Data sources, U.S. Carbon Dioxide Analysis Center and BP, are provided in detail by Hansen and Sato (2016).

VI. United States Responsibility for CO_2 Emissions

China passed the United States in fossil fuel CO_2 emissions several years ago and now has CO_2 emissions more than double those of the United States (Fig. 8a). However, we showed (Hansen et al., *Atmos. Chem. Phys.*, **7**, 2287-2312, 2007) that global warming is proportional to cumulative emissions and others have since confirmed that. Cumulative emissions by the United States substantially exceed those of any other nation (Fig. 8b). Thus the United States is, by far, more responsible than any other nation for the associated increase of global temperature.

Per capita emissions (Fig. 9) provide another useful perspective on emission responsibilities. Cumulative per capita emissions of China and India are an order of magnitude smaller than U.S. emissions.

The United States has outsize responsibility for human-made climate change. The United States also has exceptional technical potential to reduce its emissions and work in mutually beneficial ways to reduce emissions of other nations.

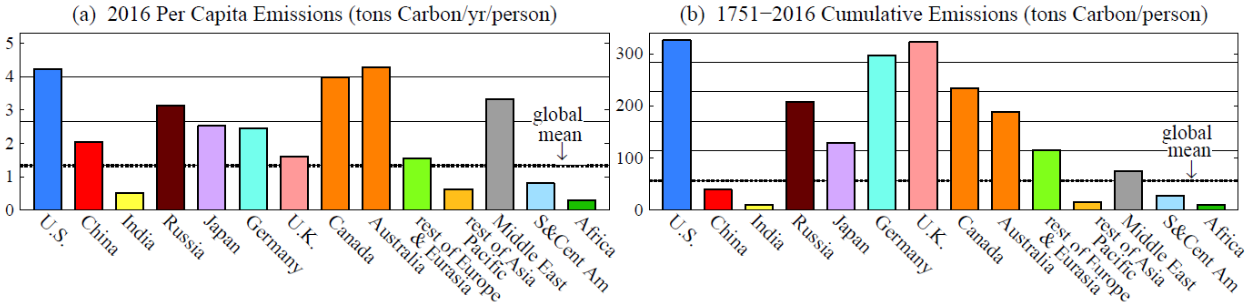

Fig. 9. Per capita fossil fuel CO_2 emissions in 2016 and cumulative emissions (data sources: see Fig. 8).

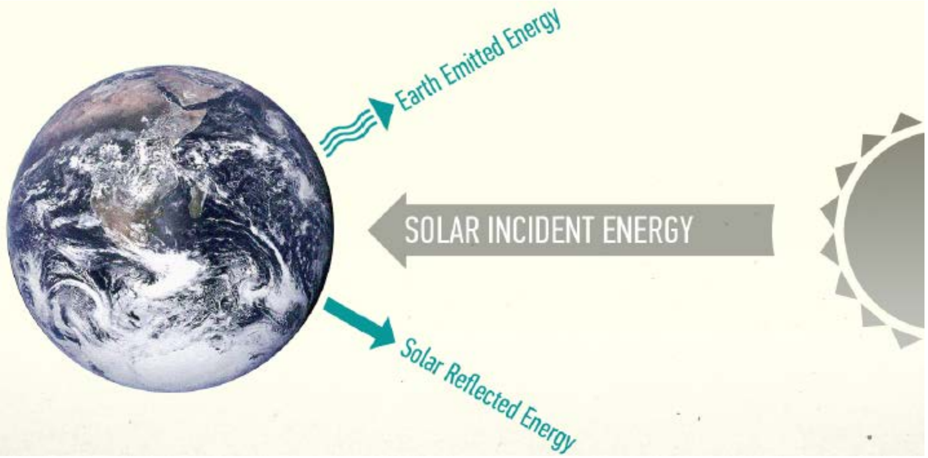

Fig. 10. Earth's energy balance: about 30% of the solar energy reaching Earth is reflected away. The absorbed 70% warms Earth until it is hot enough to radiate away all the absorbed energy as heat radiation.

SECTION 2: Current levels of long-lived atmospheric GHGs, mainly CO_2, cause Earth to be out of energy balance. This imbalance, with Earth absorbing more solar energy than it radiates back to space, is driving climate change.

a. Earth's energy **imbalance is now measured and large**, consistent with expectations based on physics. As long as Earth remains out of energy balance, more energy coming in than going out, the planet will continue to get hotter.

b. Earth's energy imbalance is the **immediate drive of climate change**, which has deleterious climate impacts that are now beginning to emerge. If GHG amounts continue to rise unabated, the energy imbalance will drive global warming to levels with climate impacts beyond the pale, as delineated in OPINION 3.

I. The Scientific Method and Tools in a Scientist's Tool Box

Earth's energy balance (Fig. 10) is the most basic physics determining Earth's temperature and climate. A crucial quantitative question is: how far out of balance is Earth's energy budget and how much will Earth warm to reestablish balance?

That was a question posed to high school and college students, as well as their teachers and professors, during the 1990s *Summer Institute on Planets and Climate* at NASA Goddard Institute for Space Studies. Our concept of 'research education' was that students and educators could learn the scientific method best by working on teams with scientists on real ongoing research.[2] One of the student/educator/ researcher teams published a paper[2] on precisely the topic of my OPINION 2.

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[2] Hansen, J., C. Harris, C. Borenstein, B. Curran & M. Fox: Research education. *J. Geophys. Res.* **102**, 25677, 1997. The success of this approach was demonstrated by tracked career successes of participating students.

This team used the scientific method and useful tools from the scientific toolbox to analyze Earth's energy balance, and to thus expose a planetary energy imbalance.[3] Their study serves as an introduction to the science in OPINION 2, and it also illustrates the scientific method used in forming other OPINIONS.

The scientific method is simple in principle: (1) Study all available data on the matter, (2) Be very skeptical of your interpretation, (3) Reassess from scratch with any new data. However, it comes with one strong caution: Your preference, your ideology, must not affect your assessment. Skill in the scientific method is the highest achievement in science, but in practice it is not easy to achieve.

Developments in understanding of Earth's energy imbalance, chronicled below, demonstrate the scientific method and how the most relevant tools in the scientific toolbox are employed. These tools are: (1) Earth's paleoclimate history, which contains information about how Earth responded to climate forcings in the past, (2) modern observations of how Earth is responding to natural and human-made climate forcings, and (3) climate models, which aid interpretation of observations and allow projections of future climate change constrained by laws of physics.

The following developments also illustrate a common practice of scientists. A given problem is analyzed with existing data, conclusions published if warranted, and then the material is set aside. Several years later new data become available that warrant reassessment, as dictated by the scientific method. As this procedure is repeated, if the scientific method is adhered to with skill, understanding evolves.

II. First Analysis of Earth's Energy Imbalance: The Concept

We called Earth's energy imbalance 'disequilibrium forcing' in our first attempt to quantify it, i.e., in the *Summer Institute* study published in *J. Geophys. Res.* in 1979 by the 'Forcings & Chaos' research team. 'Disequilibrium forcing' is good scientific terminology, as the imbalance constitutes a global forcing pushing the climate system toward energy balance with space. Later we decided that 'Earth's energy imbalance' was an easier concept for most people to grasp.

In the Forcings & Chaos research paper we used a global climate model to make climate simulations for the period 1979-1997. If the model started in equilibrium in 1979, i.e., in energy balance with space, and was forced by observed GHG increases the modeled global warming rate was much less than observed in

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[3] Hansen, J. and 42 coauthors, Forcings and chaos in interannual to decadal climate change, *J. Geophys. Res.*, **102**, 25,679-25,720, 1997. This team, dubbed 'Forcings & Chaos,' aimed to distinguish forced climate change from unforced variability. High school teachers and students came from schools ranging from Bronx School of Science to Far Rockaway and college educators and students from City University's flagship City College to York College.

the real world. In a happy accident, we started some of the computer simulations with an energy imbalance of 0.65 W/m^2. We found that this initial disequilibrium forcing, or planetary energy imbalance, was just what was needed for the model to produce a global warming rate in agreement with observations.

We realized that an energy imbalance in 1979 made sense. An imbalance is expected because of the steadily increasing GHGs during prior decades and the great thermal inertia of the ocean. We used these model runs to make a prediction for the Earth's energy imbalance at the end of the 20th century: 0.85 ± 0.15 W/m^2.

Our inferred, substantial, planetary energy imbalance emboldened us to make another prediction. Such a large disequilibrium forcing meant that Earth's global temperature should soon set a new record for the period with instrumental data. The prediction had a purpose: confident prediction, if its accuracy was confirmed, would draw attention to implications of the continuing energy imbalance.

A new record global temperature was set the next year (1998, we submitted our paper in February 1997). It was a fluke that a record occurred so quickly: given the underlying, forced, global warming trend, we expected the record would occur during the next El Niño year, but the timing of El Niños is difficult to predict. What we can say with confidence is that, as long as a large Earth energy imbalance continues, each decade will almost surely be warmer than the prior decade.

III. Second Analysis of Earth's Energy Imbalance: Measurement Exists

Earth's energy imbalance is the most fundamental diagnostic of Earth's climate. If we know the value of Earth's energy imbalance, that informs us of the direction that global climate is headed, and, if used with a tested climate model, it can provide a good estimate of the likely rate of climate change.

Our first evaluation of Earth's energy imbalance was only an indirect inference, based on Earth's observed global warming rate. Actual measurement of Earth's energy imbalance was needed. Unfortunately, it is very difficult to measure. With an expected energy imbalance of the order of 1 W/m^2 or less, the measurement accuracy required is of order 0.1 W/m^2. This is less than 0.01% of the solar irradiance striking Earth, measured perpendicular to the Earth-Sun direction.

Direct measurement of energy imbalance to an accuracy 0.1 W/m^2 is thus implausible. Sunlight reflected by Earth to space and heat radiation emitted to space are highly dependent on direction and temporally variable. Accurate measurement would require a swarm of satellites making observations with stable absolute calibration accuracy far beyond state-of-the-art of satellite instruments.

Fortunately, an alternative approach exists: measure the changing heat content of Earth's heat reservoirs. The largest heat uptake, by far, is into the ocean. Some energy is also going into net melting of ice, warming of the continents to depths of a few tens of meters, and warming of the atmosphere. However, most of Earth's heat gain, 90 percent or more, is by the ocean.

The difficulty is the large ocean volume and the need for precise temperatures. Ocean data compiled by NOAA were limited by large regions without observations, especially in the Southern Ocean and the deep ocean, and by an assumption of no temperature change in regions without data. Even in regions with data, uncertainties were introduced by occasional change of instrumentation without cross-calibration.

However, in 2004 a consistent analysis of temperature change in the upper 750 meters of the ocean for 1993-2003 became available (Willis *et al.*, 2004). This, clearly, was the time to dust off our pile of research papers on Earth's energy imbalance and make a new study. Available computer power had grown such that we could begin the climate simulations in the 19th century with an essentially preindustrial atmosphere. Any energy imbalance in 1993-2003 would be generated by known changes of GHGs.

We found that our climate model (Hansen *et al.*, 2005) results were in excellent agreement with the observations taken at face value. The model yielded an average energy imbalance of 0.75 W/m^2 for 1993-2003, ending with an imbalance of 0.85 W/m^2 in 2003. Observed heat gain in the upper 750 meters of the ocean corresponded to a global heat gain rate of 0.60 W/m^2. Based on our climate model's vertical profile of warming in the ocean, we estimated that the deeper layers of the ocean were sequestering heat at a rate of about 0.1 W/m^2. Energy required for observed atmospheric warming, ground warming, and observed loss of sea ice and land ice required a total energy of 0.04 W/m^2 averaged over Earth.

Unfortunately, it soon began to appear that this close agreement of observations and model may have been fortuitous. The rate of warming in upper ocean layers seemed to decline for a few years and experts in the instrumentation used for ocean temperature measurements described various uncertainties in the data due to changing instrumentation and inadequate calibrations. Also there were too few data on changes below 750 meter depth. Without better ocean data we could not be sure of whether the model was consistent with the real world.

Fortunately, the oceanographic research community recognized the need for more comprehensive and accurate global ocean monitoring data. An international program with deep-diving floats was initiated in the early 2000s.

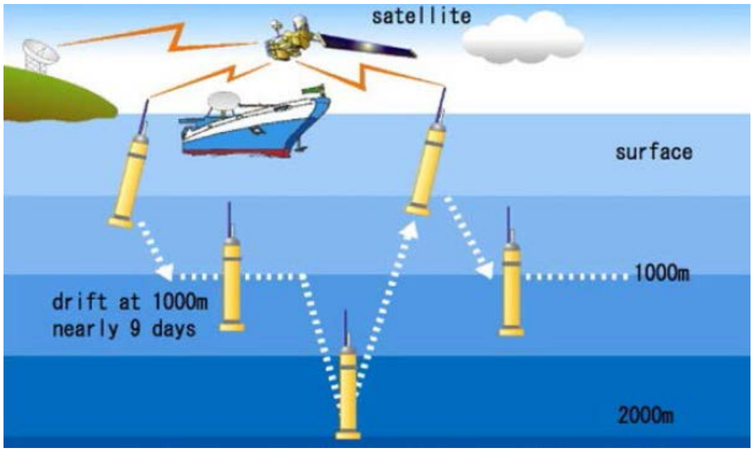

Fig. 11. An Argo float is deployed from a ship, then operates autonomously, spending most of its time drifting at depth 1000 meters, diving once every 10 days to a depth of 2000 meters, then briefly surfacing to radio its measurements to a satellite. Image: Japan Agency for Marine-Earth Science & Technology.

IV. Third Analysis of Earth's Energy Imbalance: Argo Float Data

By 2005 more than 3000 floats were distributed around the world's oceans, about half provided by the United States. The floats descend to a depth of two km, drift with the currents, ascend while making measurements, and radio the data to a satellite (Fig. 11). Argo data were limited to the top two kilometers of the ocean, but that is where most of the heat is expected to be absorbed.

By 2011 Argo provided a six-year (2005-2010) record of ocean heat gain. This timing was propitious, coinciding with the deepest solar minimum in the period of accurate measurements (Fig. 12). Climate change deniers argue that the Sun is the main cause of climate change. However, Argo data show that Earth was gaining energy, more energy coming in than going out. The increasing greenhouse effect due to increasing atmospheric CO_2 overwhelms the effect of solar variability.

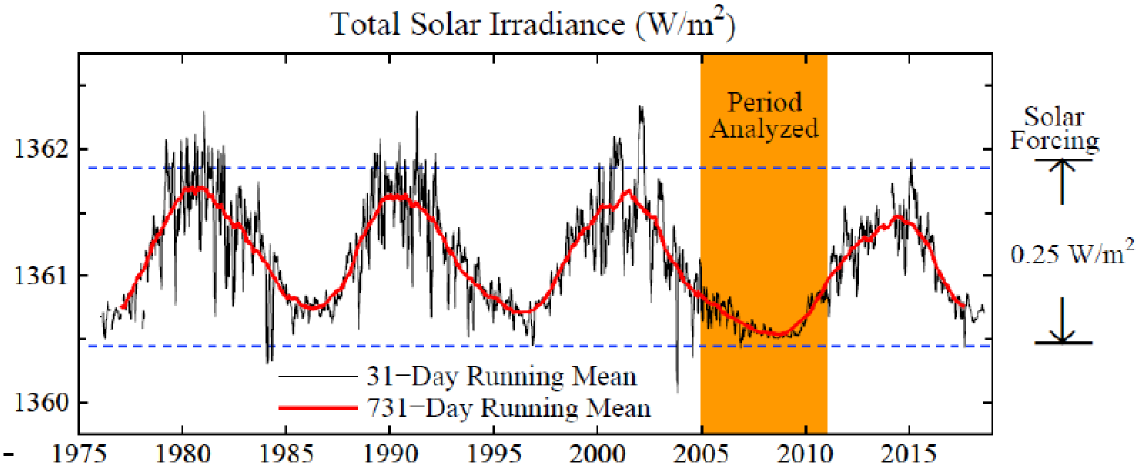

Fig. 12. Solar irradiance from composite of satellite-measured time series (Hansen *et al*., 2011).

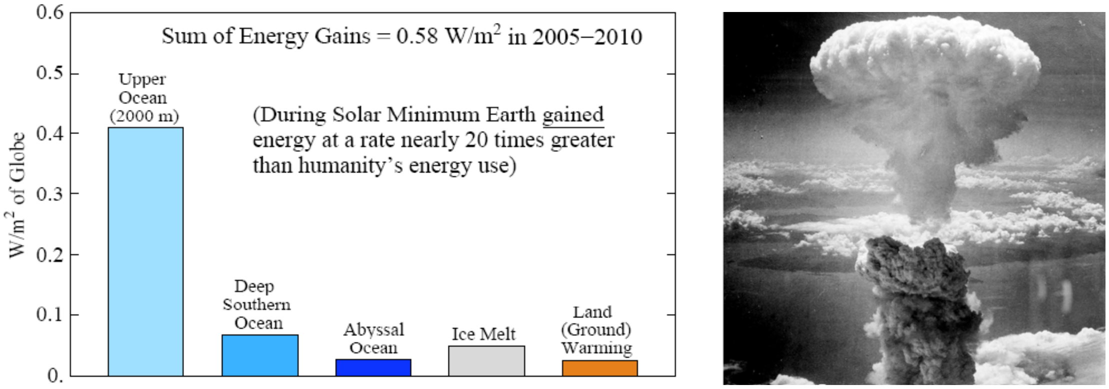

Fig. 13. Earth's energy imbalance during the solar minimum period 2005-2010. Excess energy absorbed by Earth was equivalent to that in 400,000 Hiroshima atomic bombs per day, 365 days per year.

The Argo data provided the basis for improved analysis of Earth's energy imbalance (Hansen *et al.*, 2011). The inferred planetary energy imbalance for 2005-2010 was 0.58 ± 0.15 W/m^2. Because the data were for solar minimum, we estimated that the imbalance averaged over an entire solar cycle would be 0.75 ± 0.25 W/m^2.

This continual energy gain by Earth is significant (Fig. 13). Even during the solar minimum it was equivalent of the energy of 400,000 Hiroshima atomic bombs per day every day of the year. Such continued energy input to the ocean will affect ice shelves around Antarctica, coral reefs, and the ocean's biology.

The energy imbalance measured by Argo, even when increased to account for the solar cycle, was on the small side of our climate simulations. Our global climate model (Hansen *et al.*, 2005) had an imbalance of 0.85 W/m^2 in 2003. The imbalance would be close to 1 W/m^2 for 2005-2015, for the assumed climate sensitivity. So the climate model was predicting a somewhat larger energy imbalance than reported in the Argo data.

Thus in this third analysis of Earth's energy imbalance we studied the likely implications of this moderate discrepancy between the climate model and Argo data. We used a simplified climate model that allowed us to vary both the uncertain climate forcing (aerosols) and the most uncertain model characteristics.

We had reasons to believe that the GISS ocean model, and other ocean models, were too diffusive[4], mixing heat downward too efficiently, thus exaggerating the planet's energy imbalance. The surface manifestation of excessive ocean mixing is greater time needed for surface temperature to reach its new equilibrium after a climate forcing occurs. Specifically, the GISS ocean model mixed surface heat

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[4] Hansen, J., Climate Threat to the Planet: Implications for energy policy and intergenerational justice, Bjerknes lecture, American Geophysical Union, San Francisco, CA, 17 December 2008.

into the deeper ocean so rapidly that after 100 years the surface temperature response to a climate forcing was still only 60 percent of the eventual response.

The new tool in our data toolkit in 2011, thanks to Argo, amounted to a single data point: an accurate measure of Earth's energy balance during the recent solar minimum. Argo data confirmed our suspicion that our climate model's surface temperature response was too slow. The Argo-derived energy imbalance, accepted at face value, suggested a faster surface climate response, with about 75 percent of the equilibrium response achieved in 100 years.

Earth's energy imbalance inferred from Argo data had practical significance. It implied that, if other climate forcings were unchanged, atmospheric CO_2 must be reduced to about 350 ppm to restore planetary energy balance. Energy balance is a first approximation for the change needed to stabilize climate. The social and economic significance of implied policy actions makes further analyses essential.

V. **Further Analyses of Earth's Energy Imbalance**

Improvements have been made to historic ocean temperature data records, especially via bias corrections of expendable bathythermograph data. Data now yield heat content change that is temporally more self-consistent and agrees better with Argo (Ishii et al., 2017). Ocean heat data now provide a better test of climate models for the entire period of rapid global warming, i.e., back to the 1970s.

An independent evaluation of ocean heat uptake has recently been achieved, based on the temperature dependence of gas solubilities and precise measurement of abundances of atmospheric oxygen (O_2) and CO_2. The initial report (Resplandy *et al.*, 2018) from this study was an average rate of heat uptake by the entire ocean of 0.83 ± 0.11 W/m^2 over the period 1991-2016. In a correction that the authors have submitted to *Nature*, the result is changed to 0.75 ± 0.45 W/m^2. This value for ocean heat uptake, when augmented by the heat going into land, ice and atmosphere, yields a central estimate for planetary energy imbalance in the range 0.80-0.85 W/m^2, but with its large uncertainty ('error bar').

The large error bar on this oxygen-based energy imbalance means that it is not inconsistent with the moderately smaller energy imbalances inferred from Argo and other in situ measurements of ocean temperature change. However, this new approach provides a valuable independent verification of ocean heat uptake that will become more valuable as the record becomes longer and the analysis method is refined. It also provides support for upward revisions in the rate of increase of ocean heat, such as those of Ishii et al. (2017).

Two important model uncertainties must be addressed in refined analyses of Earth's energy imbalance: (1) climate sensitivity, and (2) ocean mixing rates.

A larger measured energy imbalance would favor a higher climate sensitivity, as suggested by Resplandy et al., if all other quantities were known and fixed. However, climate sensitivity may not be the most uncertain variable. Independent paleoclimate data indicate that climate sensitivity is probably not far from 3°C for 2×CO_2. It would be particularly satisfying if that canonical climate sensitivity yielded good agreement with Earth's measured energy imbalance.

Ocean mixing is crucial, but it is imperfectly represented in climate models. The lethargic response of early GISS climate models, achieving only 60 percent of the equilibrium (long-term) response after 100 years, was characteristic of other contemporaneous American and British climate models a decade ago, leading to a suggestion that excessive subgrid-scale mixing may be a common model problem.[6]

Ocean models are improving, however, as a result of both higher resolutions and more realistic treatments of turbulent mixing. The current GISS climate model, which has a more realistic subgrid-scale mixing parameterization, yields a moderately faster surface response time, achieving about 65 percent of the equilibrium response in 100 years. This model continues to yield a climate sensitivity close to 3°C for 2×CO_2.

Overall, uncertainties about climate sensitivity and ocean surface response time seem to be narrowing, so it is of interest to check their consistency with current estimates of Earth's energy imbalance. A Green's function calculation using observed GHG histories, a climate sensitivity 3°C for 2×CO_2, and a climate response function that achieves 2/3 of its equilibrium response in 100 years, yields agreement with both the observed global temperature history and the best estimate for Earth's energy imbalance averaged over the last solar cycle, 0.75 ± 0.25 W/m^2.

Much more can be learned from the depth and geographic distribution of observed heat penetration into the global ocean. Given the large number of global climate models that now exist around the world, it would be informative if all of these models were used to simulate the past century with precisely the same climate forcing, based on observations, and extended through the 21st century with a standard scenario. To be most useful, all models should also do a step-function 2×CO_2 run to define the model's equilibrium sensitivity and response function.

VI. 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 solar cycle 2005-2016 Earth's energy imbalance is 0.75 ± 0.25 W/m^2.

The range 0.5 to 1 W/m^2 is substantial. For example, in order to restore Earth's energy balance by reducing atmospheric CO_2, which is the principal cause of the imbalance, CO_2 would need to be reduced from its 2018 407 amount to 373 ppm if the imbalance is 0.50 W/m^2, but to 342 ppm if the imbalance is 1 W/m^2.

In reality CO_2 is not only continuing to increase, its rate of growth is increasing. The reason is that global population and energy demands continue to increase, and about 85 percent of global energy is provided by fossil fuels. Nevertheless, it is conceivable to achieve a decreasing atmospheric CO_2 amount, because the ocean, soil and biosphere absorb CO_2, presently about 45 percent of annual emissions.

However, 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.

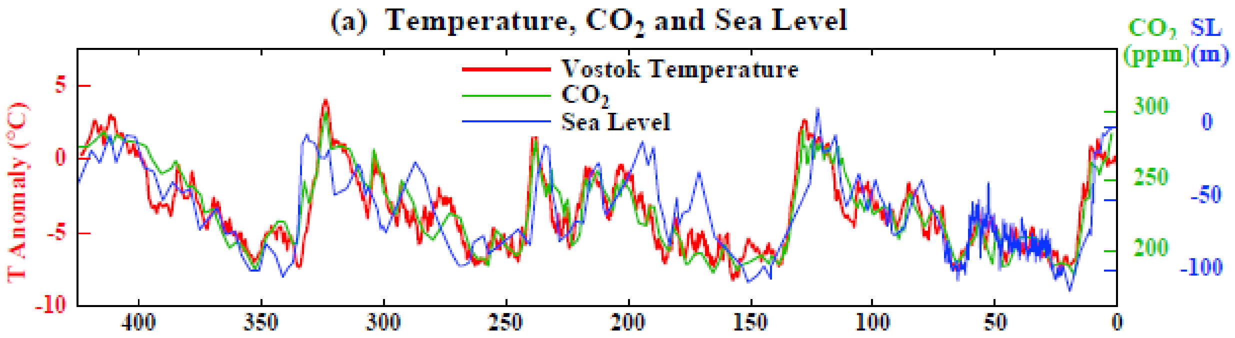

Fig. 14. Antarctic temperature (Vimeux *et al*. 2002), atmospheric CO_2 (Petit *et al.* 1999) and sea level (Siddall *et al.* 2003) over past 420,000 years. Figure is from Hansen *et al.* (2007).

SECTION 3: If high fossil fuel emissions continue, global warming will have predominately negative consequences for humanity, especially for young people.

a. Sea level: 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, with economic consequences that are incalculable.

b. Species exterminations: Rapid shifting of climate zones is a significant stress for many species. Continued global warming, in combination with other human-caused stresses, threatens to commit a substantial fraction of species to extinction, leaving the prospect of a more desolate planet for young people.

c. 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, at best, would be an increasing challenge.

I. Sea level changes sensitively with global temperature

Paleoclimate sea level change. As Earth becomes warmer the ice sheets shrink and sea level rises. Sea level history for the past several hundred thousand years (Fig. 14) provides an indication of how much ice sheet size (as measured by sea level) adjusts in response to global temperature change on these time scales. Sea level change is of order 100 meters for a global temperature change of at most 5°C (Antarctic temperature change of about 10°C), thus 20 meters (about 65 feet) for each degree Celsius of warming.

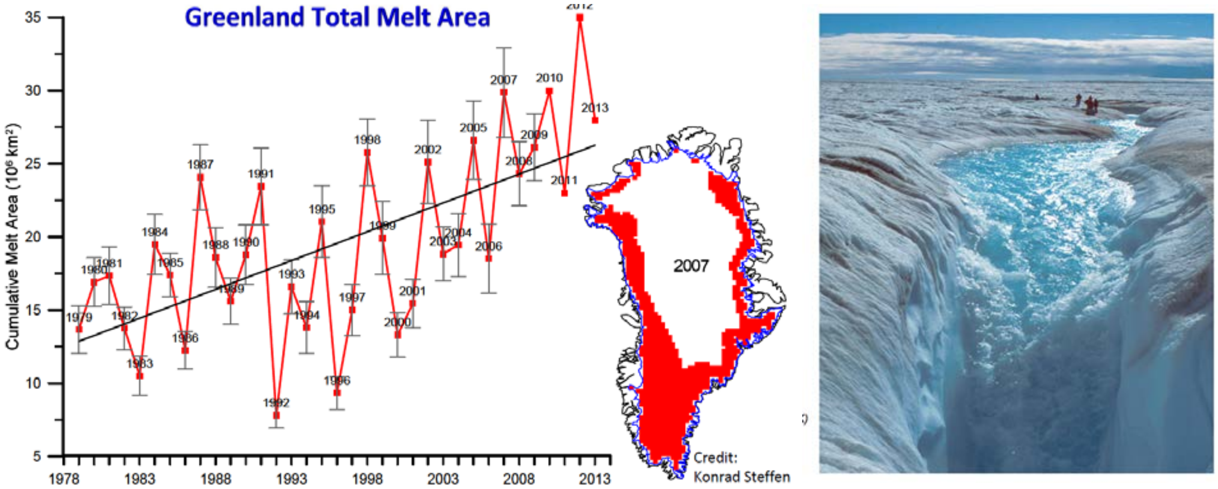

Fig. 15. Greenland area with surface melt in summer has more than doubled in recent decades. Update of chart used in Bjerknes lecture[4], courtesy of Konrad Steffen and Russell Huff, CIRES, Univ. Colorado.

Sea level rise in Fig. 14 was mainly from ice ages, when there were ice sheets on North America and Eurasia as well as Greenland and Antarctica, toward warmer climate, so there were more ice sheets to provide meltwater. Sea level will not be as sensitive in going from today's climate toward warmer conditions.

However, 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. During the early Pliocene, several million years ago, when global temperature was at most about 3°C warmer than pre-industrial conditions, sea level probably reached as high as 15-25 meters above today's level.

In other words, there is plenty of vulnerable ice available to cause eventual sea level rise that would inundate today's coastal cities, in response to a warming level that we could produce this century. 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).

Modern ice sheet processes. Greenland is at a lower latitude than Antarctica and thus has much more surface melt in the summer. The area of surface melt has more than doubled since satellite measurements began in the late 1970s (Fig. 15).

Snowfall on Greenland is also increasing because atmospheric water vapor increases as Earth warms. Increased snowfall is a positive term in the ice sheet's mass balance that partially offsets increased melting. However, not surprisingly, the net effect is that the Greenland ice sheet is shrinking as the world gets warmer.

The climate forcing introduced by humanity's use of fossil fuels is large and growing faster than any natural forcing in Earth's history, at least any that we

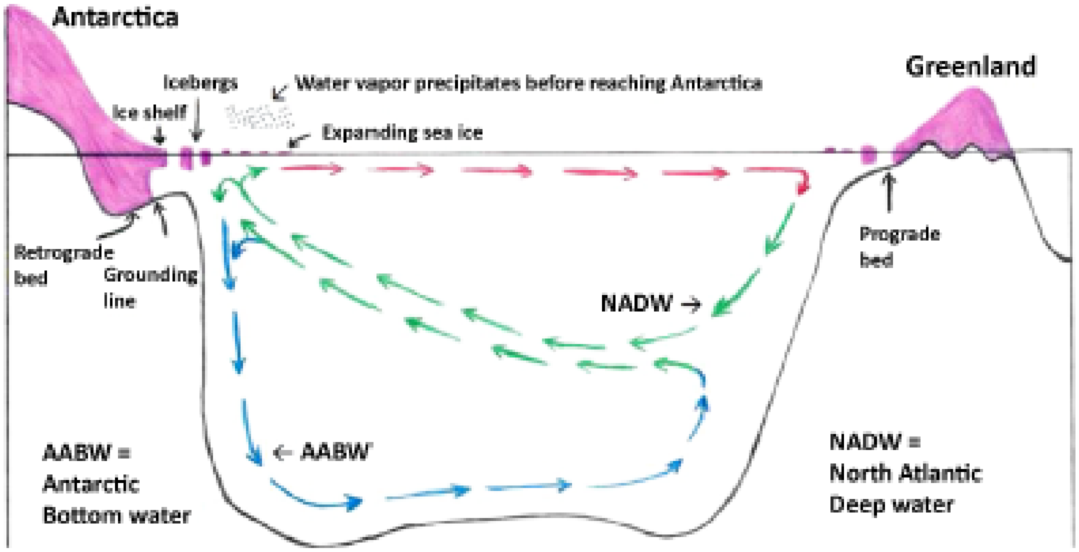

Fig. 16. Diagram of stratification and precipitation amplifying feedbacks that affect ice sheet mass loss. Stratification: increased freshwater on Southern Ocean reduces surface density, reducing AABW formation, trapping NADW heat and increasing ice shelf melt. Precipitation: increase freshens and thus cools ocean surface, increasing sea ice area and causing precipitation to fall before it reaches Antarctica.

know about. Ice is frangible. It can be broken up by thaw-freeze cycling. Ice sheet mass loss will not grow linearly, simply proportional to the temperature increase. The existence of amplifying feedbacks implies that mass loss from the most vulnerable portions of the ice sheets is likely to be a very nonlinear process that can be approximated by a doubling time for the rate of mass loss.

The characteristic time for Greenland mass loss, approximated as a doubling time, may be longer for Greenland than for Antarctica, because Greenland does not have as much ice as Antarctica in direct contact with a warming ocean. However, Greenland does have several fjords with ice streams that terminate in the ocean, so Greenland is not immune to marine interactions that can speed up mass loss.

Antarctica has extensive ice shelves extending into the ocean, which are now melting faster as the ocean warms. Ice shelf loss is beginning to cause increased discharge of land-based ice, which tends to freshen the surface waters around Antarctica and produce feedbacks that will amplify continental ice loss. Important feedbacks are illustrated in Fig. 16, which is taken from the Ice Melt (2016) paper. As yet the rate of freshwater injection onto the Southern Ocean may not have yet reached a level large enough to counter the loss of sea ice due to global warming, as judged from the large sea ice area reduction that has accompanied the warming of the past few years (http://www.columbia.edu/~mhs119/SeaIceArea/).

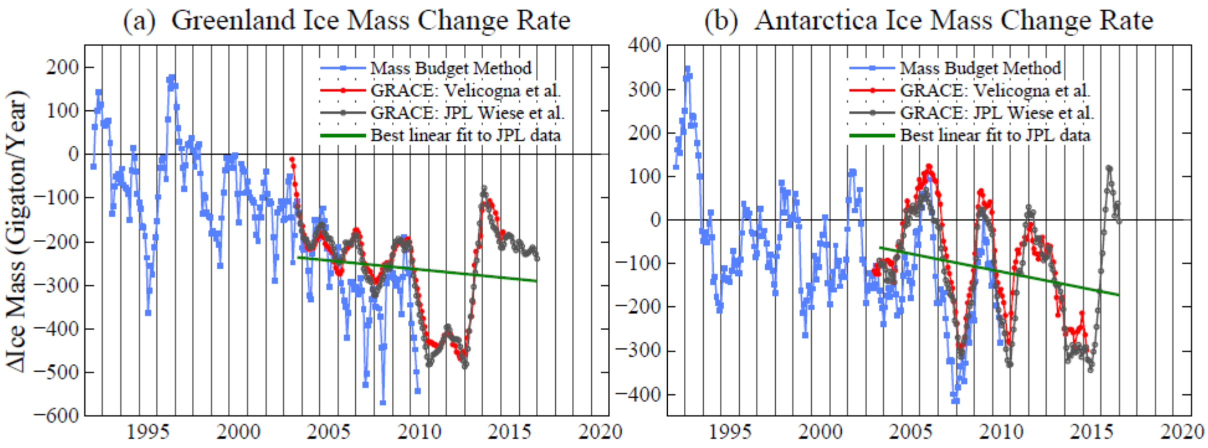

Fig. 17. Greenland and Antarctic ice mass change. GRACE data is extension of Velicogna et al. (2014) gravity data. MBM (mass budget method) data are from Rignot et al. (2011). Red curves are gravity data for Greenland and Antarctica. Update of Fig. 30 of *Ice Melt* (2016) paper.

Nevertheless, it is clear that amplifying feedbacks will produce increasingly rapid sea level rise if fossil fuel emissions and global temperatures continue to increase unabated. Even in the case of slowly changing paleoclimate forcings, ice sheet disintegration on a number of occasions achieved a rate that produced meter and multi-meter sea level rise in a century, confirming the existence and the potential large magnitude of amplifying feedbacks. Once the global warming effect on ice sheets is sufficient to strongly spur the amplifying feedbacks, we would expect the rate of mass loss by the ice sheets and the rate of sea level rise to grow nonlinearly, at a faster and faster rate.

A capable means of assessing possible Greenland and Antarctic ice sheet mass loss became available with the first precise monitoring of Earth's gravitational field from a satellite (Fig. 17). Early results from the gravity satellite showed shockingly rapid growth of the mass loss rates for both the Greenland and Antarctic ice sheets, for Greenland through 2012 and for Antarctica through 2015 (Fig. 17). Doubling times for mass loss rates were only of the order of a decade for both Greenland and Antarctica. However, in Greenland in 2013 and Antarctica in 2016 the rapid growth of mass loss was interrupted by a negative feedback: increased precipitation (snowfall).

Decreased summer melt and increased snowfall over Greenland were associated with a change of summer weather patterns. The 2012 summer was characterized by sunny weather and a steady stream of warm air streaming from the south over Greenland, but subsequent summers have had a high proportion of cloudy days with moist marine air. Increased snowfall over Antarctica in the past two years was associated with reduced sea ice in the adjacent Southern Ocean, which coincided with rapid global warming during that period. The magnitude of the sea ice loss may have been related to the coincident strong El Niño. On the longer run,

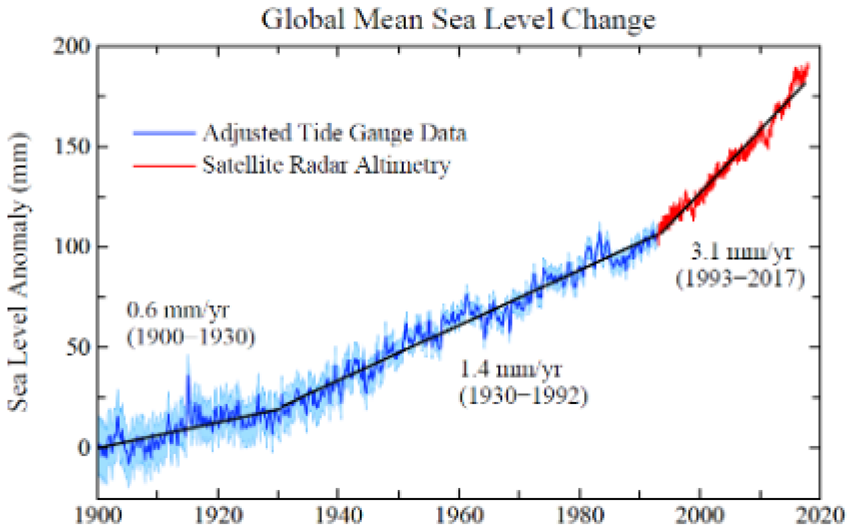

Fig. 18. Sea level change (*Ice Melt* paper) based on satellite altimetry, Cazenave and Le Cozannet https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/references.html and tide gauge data (Church and White, 2011) with the latter change rate multiplied by 0.78, so as to yield a mean 1901-1990 change rate 1.2 mm/year (Hay et al., 2015).

it has been predicted that increasing ice discharge from Antarctica, especially in the Western Hemisphere from the Ross to Weddell seas, will tend to cause an increase of sea ice cover, altering the precipitation feedback (see Fig. 16).

Amplifying feedbacks win out eventually in a warming climate. The magnitude of eventual sea level rise for a given global warming is indicated by the repeated examples in paleoclimate records. We must expect several meters of sea level rise for each degree Celsius of global warming, if warming is left in place indefinitely.

Assessment of doubling time. One estimate for the characteristic time for acceleration of ice sheet disintegration and sea level rise is provided by sea level rise itself. Fig. 18 shows that the rate of sea level rise has more than doubled twice in the past century, suggesting a doubling time of the order of 50 years.

The mean rate of sea level rise in the past 25 years has been 3.1 mm/year, which is just over a foot per century. Only a few more doublings are needed to reach multi-meter sea level rise in a century.

However, 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. Thus the empirical doubling time based on net sea level change is an upper limit for the doubling time for sea level change from the Greenland and Antarctic ice sheets.

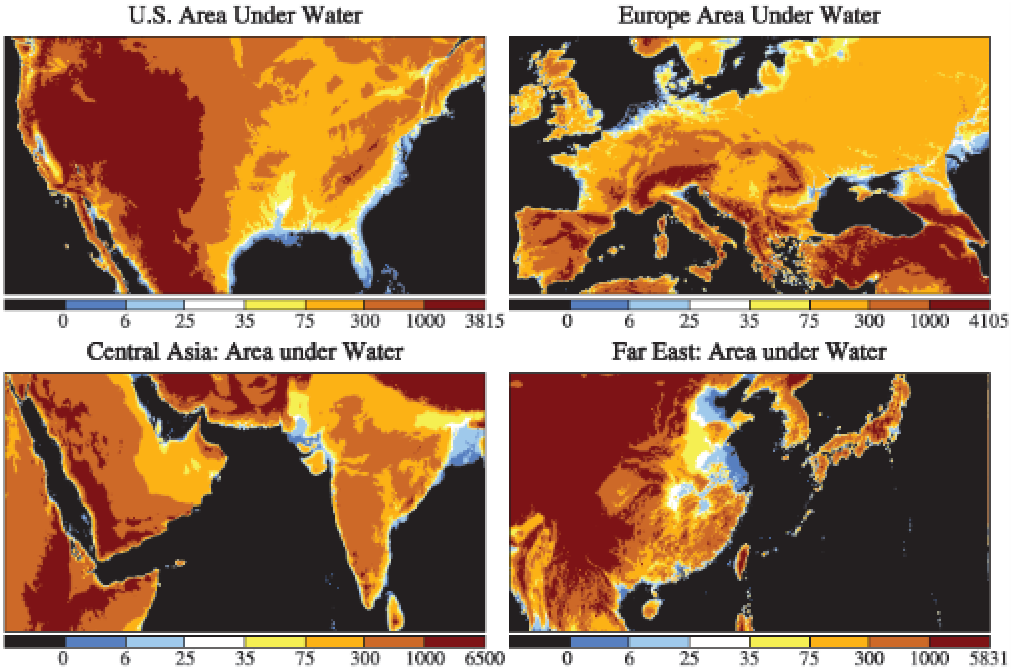

Fig. 19. Areas (light and dark blue) that nominally would be under water for 6 and 25 m sea level rise.

It is only the ice sheets that threaten multi-meter sea level rise and the loss of coastal cities. As the ice sheet contribution to sea level rise takes over, the doubling time for sea level rise will tend to become that for ice sheet mass loss. A case has been made that the doubling time for ice sheet mass loss, assuming continued growth of fossil fuel emissions, may be as short as 10-20 years, based on evidence from the combination of paleoclimate data, modern observations, and ocean-atmosphere modeling. In that case, multi-meter sea level rise would occur on a time scale of 50-150 years.

Sea level threat to young people. Sea level rise is beginning to be noticed in places. People in Miami are surprised to see high tides lapping onto some of their streets. However, effects so far are trivial inconveniences, compared with what is in store if high fossil fuel emissions and global warming continue.

Sea level reached at least six meters greater than today during the Eemian period, when global temperature is estimated to have been about 1°C warmer relative to pre-industrial, i.e., little warmer than today, if at all. Projections for end-of-century warming reach 3°C, if business-as-usual fossil fuel use continues, a global warming that could yield eventual 15-25 meter sea level rise.

Figure 19, showing areas underwater with large sea level rise, fails to convey the staggering implications of sea level rise. True, it shows that Netherlands and Bangladesh would be under water, as well as a portion of China now occupied by a few hundred million people. But most of the world remains above water, so people can just move, right?

Think of the implications. All of the large cities on the East Coast of the United States – Boston, New York, Philadelphia, Washington, Miami – would become dysfunctional and abandoned, even though parts of a city stuck out of the water. The infrastructure in our coastal cities is a large fraction of our infrastructure. Much of our transportation system in the Eastern United States, including railroads and highways, would be dysfunctional. Our largest airports would be under water, including all of those serving New York. It would not be sensible to rebuild on the shore, as there would be no stable shoreline.

If ice sheets are allowed to go unstable, shorelines will be experiencing continual sea level rise for centuries, a consequence of the slow response time of ocean temperature and ice sheet dynamics. Ice sheet disintegration is a process that is slow to get started, but exceedingly difficult to stop once it is well underway. The great danger of young people is that they will be handed a situation that is out of their control.

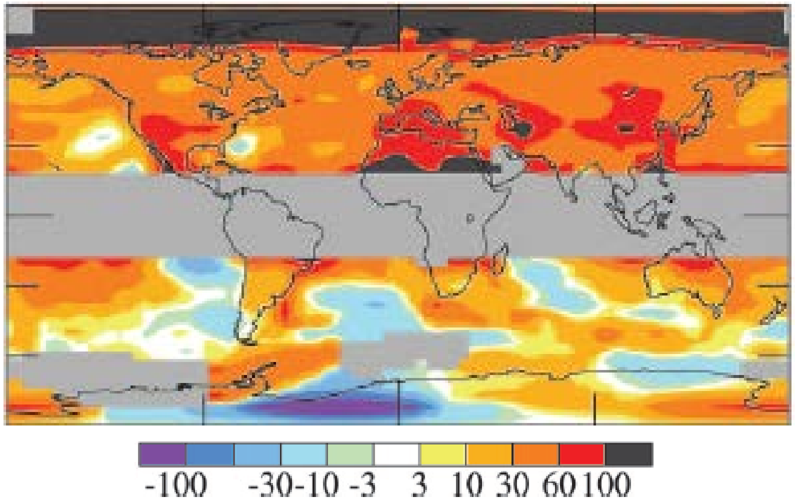

Fig. 20. Poleward migration of surface temperature isotherms in km/decade (Hansen *et al*., 2006).

II. Species Exterminations

Humans are putting stresses on other species and whole ecosystems as humanity, in effect, takes over the planet. The IPCC report *Climate Change 2014: Impacts, Adaptation, and Vulnerabilities*, focuses on the potential loss of ecosystem services that humanity will suffer from the combined effect of climate change and the other stresses on all species.

Many young people, instead, emphasize simply the potential extermination of species, if greenhouse gas emissions continue unabated and climate change grows unfettered. Young people's right to enjoy the full range of life on Earth that their forefathers cherished may not be enumerated in the Constitution, but yet the basic concepts on which our nation was founded seem relevant.

The idea in our Declaration of Independence that the right to life, liberty and pursuit of happiness warranted risking the comforts of life and life itself; the idea in our Constitution that all citizens have a right to life, liberty and property – these concepts seem at odds with one generation being allowed to knowingly eliminate a substantial fraction of the lifeforms on the planet left to young people and future generations. That is the issue raised by young people, who are concerned with the morality and practical effects of massive, witting species exterminations.

Shifting of climate zones. CO_2 is increasing today at least 10 times faster than the most rapid known prior change in Earth's history, which occurred during the Paleocene-Eocene Thermal Maximum. As a result, global average temperature is rising rapidly (Fig. 3). On a regional basis this global warming causes a shifting of climatic zones. Although temperature fluctuates from year to year, the isotherms on a map, *i.e.*, lines of given average temperature are rapidly shifting poleward.

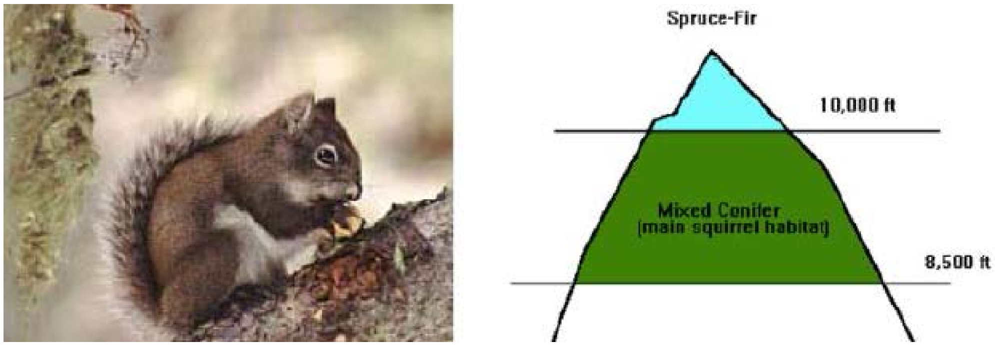

Fig. 21. Mount Graham red squirrel (credit: Claire Zugmeyer) survives on a single mountain in Arizona.

Since 1970 the average rate of poleward migration of a given temperature line (Fig. 20) has been about 60 kilometers per decade, more than 3.5 miles/year, forNorthern Hemisphere land areas. This rate of change is an order of magnitude faster than isotherm movement during periods of natural climate change, and can exceed the rate at which many species are able to migrate. Species can generally survive only within some specific climate zone. So if the total migration distance of isotherms exceeds the size of the natural habitat, or the habitat fragment that remains in the face of human land use, the species survival is threatened.

Species interactions and ecosystem survival. Multiple pressures on species include habitat loss, overhunting, pollution, and invasive species, with humanity's increasing land expropriation the most important factor. When these stresses are combined with rapidly shifting climate zones in can lead to species extinctions, and, because of interdependencies among species, to ecosystem collapse.

The Mount Graham red squirrel (Fig. 21) is an example. It survives on a single Arizona mountain, an "island in the sky,' an isolated green spot in the desert. Like polar species, life in many biologically diverse alpine regions is in danger of being pushed off the planet. As a given temperature range moves up a mountain, the area with those climatic conditions becomes smaller and rockier, and the air thinner, resulting in a struggle for survival. Heat-stressed alpine forests are vulnerable to beetle infestation and fires that burn hotter, leaving lower reaches of the forest that cannot recover. Loss of the red squirrel alters the forest, because its middens are a source of food and habitat for chipmunks, voles and mice.

Mass extinctions have occurred during Earth's history as a result of climate change. New species evolved, but that required millennia and longer spans of time. Young people will face life on a more desolate planet, if rapid climate change is allowed to proceed.

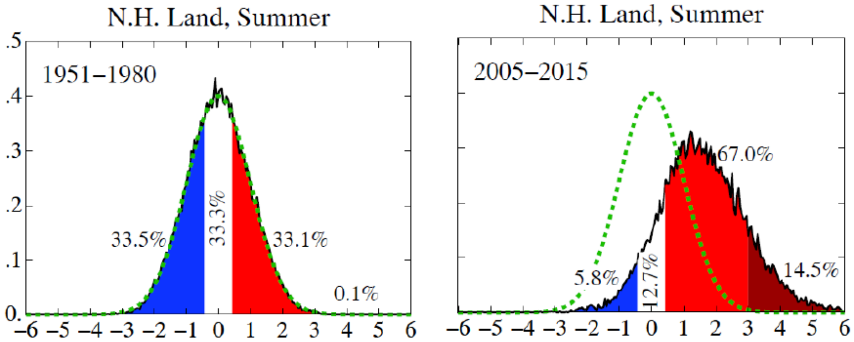

Fig. 22. Frequency of occurrence of local temperature anomalies in Northern Hemisphere land areas in period of climatology (1951-1980) and in recent years. Horizontal axis is the local standard deviation, the typical annual variability, which is greater at high latitudes than at low latitudes. [Hansen and Sato, 2008]

III. Regional Climate

The human species may be more adaptable than most, in part because humans can control conditions within their living quarters. That does not mean, however, that humans will escape direct effects of global warming – far from it.

Overheating of low latitudes. Weather, even when averaged over a 3-month season, varies from year to year. Fluctuations of local seasonal mean temperatures about the 30-year mean during the period 1951-1980 formed a symmetric bell curve, as shown for the Northern Hemisphere summer on the left side of Fig. 22.

The warming of the past several decades has caused the bell curve defining the probability of a given anomaly to shift, and the bell curve to become asymmetric with anomalies defined relative to the base period climate (Fig. 22, right side). Extreme hot summers, of a degree that seldom occurred last century, have become much more common, as the bell curve now has a long tail on the hot side.

The bell curve shift depends upon season and location. At middle latitudes climate change is not so obvious in the winter, but the chance of having an extremely hot summer has increased noticeably (Fig. 23).

The largest change from the normal climate of last century is in the subtropics in summer and the tropics year-round. Subtropics includes the Southwest United States and the Mediterranean/Middle East region. Every summer in these regions is now hotter than the average summer of last century.

The subtropics in the summer and the tropics year-round were already hot, before the rapid warming trend of the past 50 years. These areas will become dangerously hot, and an unpleasant place to live, if global warming continues. Living and working outdoors would become difficult. Most jobs are outdoors, either agriculture or construction. At present, these increasingly difficult working conditions are already beginning to have a measurable effect on economies.

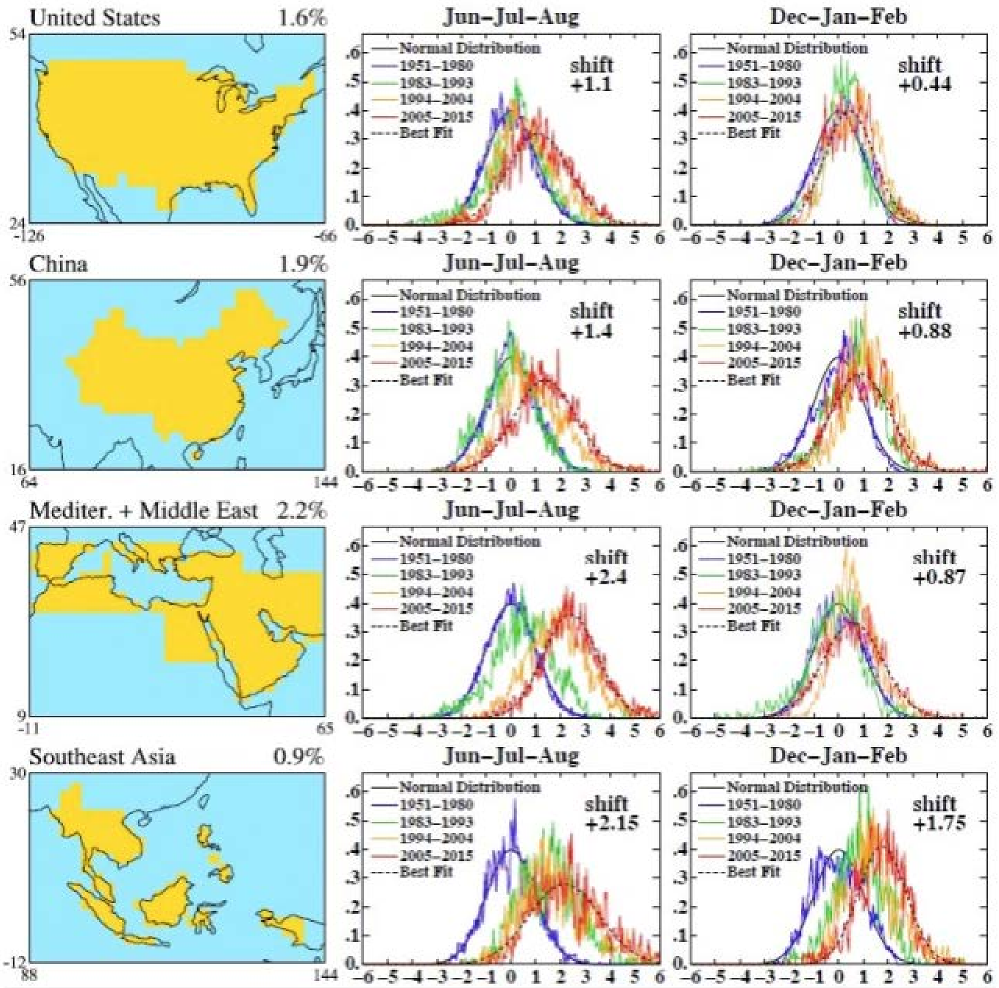

Fig. 23. Shifting bell curves that define the frequency of local temperature anomalies relative to the 1951-1980 base period for four regions. [Hansen and Sato, 2008]

<u>Regional climate extremes.</u> The principal effect of global warming on regional climate is to increase climate extremes, at both ends of the hydrologic cycle. Places and times when it is dry can have stronger droughts, because of greater heat. Fire seasons will be more intense and longer. Dry subtropics, such as the Southwest United States and the Mediterranean and Middle East, will in general, become still hotter and drier, if fossil fuel emissions and global warming continue unabated.

Even such regions, however, will have more extreme rainfall events and floods during the rainy season or the occasional storm. The reasons for this are that warmer air holds more water vapor and the sea surface is warmer. Water vapor is fuel for thunderstorms, tornadoes, and tropical storms, and with a warmer sea surface tropical storms are able to reach higher latitudes and to come onshore with greater strength. Rising sea level adds to the height of storm surges. The greatest damage is often caused by the increased rainfall and thus greater flooding associated with higher temperatures.

Global warming can also slow the translational movement of tropical storms in some situations. Slow storm movement greatly increased rainfall totals and flood damage from recent hurricanes hitting the United States, specifically the Houston area in 2017 (Hurricane Harvey) and the Carolinas in 2018 (Hurricane Florence).

Emigration pressure. Low latitudes will become hotter and less hospitable, if fossil fuel emissions and global warming continue unabated. Evidence of this trend is beginning to emerge already in tropical regions and in the subtropics.

Recent scientific research confirms what common sense suggests: violence and conflicts increase in regions that become hotter and less livable. Interpersonal violence and conflicts between groups and nations are both found to rise significantly with excessive temperature.

Pressures to emigrate from low latitudes will increase, if global temperature continues to increase. Continued global warming will also cause sea level to rise more rapidly, which will be another source of pressure to emigrate.

The world already has enough difficulty caring for refugees. If these potentially huge numbers of climate refugees should become reality, it is possible that young people will inherit a planet in chaos.

IV. Summary: Intergenerational Justice

Continued high fossil fuel emissions would hand young people a situation with consequences that are beyond the pale. Impacts of fossil fuel burning, on sea level, on extermination of species, and on regional climate, raise great practical and moral issues on a global scale. This topic can be addressed effectively only by governments. However, it is not being effectively addressed.

Human-made climate change is now a matter of justice, predominately a matter of intergenerational justice, which must be considered by the courts.

Thomas Jefferson and James Madison were concerned about the possibility that their generation, newly empowered by the establishment of the democratic United States, with a government constrained by a remarkable but imperfect Constitution, might not have adequately protected the rights of young people and future generations. They were considering the proposed Bill of Rights to supplement the Constitution when, on 6 September 1789, Jefferson wrote to Madison:

"The question whether one generation of men has a right to bind another…is a question of such consequences as not only to merit decision, but place also among the fundamental principles of every government…I set out on this ground, which I suppose to be self-evident, 'that the Earth belongs in usufruct to the living'."

Jefferson, a scientist and farmer, was concerned especially about the fertility of the soil, which, he argued, should not be left in depleted condition. More generally, he was saying that the present generation can enjoy the fruits of the land, but with an obligation to leave Earth in equally good condition for the next generation.

Young people today, as they learn about human-made climate change, realize that they are confronting a moral issue of a scope that had never been imagined. Using the language of Jefferson and Madison we can write:

(1) one generation is wittingly binding young people and posterity,

(2) developed nations are wittingly binding the rest of the world, and

(3) one species, the human species, is wittingly binding all others.

These potential injustices might seem to reach well beyond the thoughts of Jefferson, Madison, and the other Founders of the United States of America. But is that so? Might the fundamental considerations that they were debating provide the path that is needed to address the enormity of these potential injustices?

The fundamental considerations of the Founders can be imagined while reading the draft of the Unanimous Declaration of the Thirteen United States of America, in Jefferson's hand (http://www.historyplace.com/unitedstates/revolution/decindep.htm), with additions and deletions by John Adams and Benjamin Franklin. The second paragraph reads:

> "We hold these truths to be self-evident, that all men are created equal, that they are endowed by their creator with certain unalienable rights, that among these are life, liberty, and the pursuit of happiness. That, to secure these rights, governments are instituted among men…"

Below we consider the words chosen for the Constitution by the Founders, including the Bill of Rights and other Amendments. However, the above words in the Declaration of Independence, written as the Founders were about to risk their lives, liberty and sacred honor in a long war of independence, ring with clarity, especially the "unalienable rights" that they chose to enumerate ("life, liberty and pursuit of happiness") and "to secure these rights, governments are instituted…".

Do not the three great injustices enumerated above – intergenerational, international, and interspecies -- infringe upon young people's unalienable rights to life, liberty and pursuit of happiness?

Governments were instituted to protect these unalienable rights. Policies are the province, largely, of the Executive and Legislative branches of government.

Yet it is the task of the third branch, the Judiciary, the courts, to assure that the policies do not infringe upon the people's unalienable rights.

The Founders realized they could not imagine all issues of justice that would arise in the future, so the Constitution and its Amendments described rights in a general way to allow future interpretation. The most relevant statements concern 'due process' and 'equal protection', but the Ninth Amendment is also relevant.

The Fifth Amendment states "No person shall be…deprived of life, liberty or property without due process of law."

The Fourteenth Amendment states "…nor shall any state deprive any person of life, liberty or property, without due process of law; nor deny to any person within its jurisdiction the equal protection of the laws."

The Ninth Amendment states "The enumeration in the Constitution, of certain rights, shall not be construed to deny or disparage others retained by the people."

Application of these rights to attainment of justice for young people will be considered by the legal experts. However, the science provides conclusions that will bear upon discussion of the three potential injustices enumerated above.

First the climate change that drives all three of these injustices is caused mainly by cumulative fossil fuel emissions. Young people and the world realize that the United States is much more responsible for those emissions than any other nation.

Second, the United States possesses sufficient fossil fuel resources, in coal and other conventional and unconventional fossil fuels, through development, use and exportation, could substantially push the climate system, causing young people to inherit a climate system with consequences running out of their control.

Third, cooperation among nations is needed for global phasedown of fossil fuel emissions at the rate needed to stabilize atmospheric composition and climate. Scenarios to stabilize climate require United States technical and political leadership. United States withdrawal from climate discussions and retreat within our borders cannot achieve protection of the public. The United States needs a plan for climate mitigation.

The actions needed by the United States are achievable, as discussed quantitatively in subsequent Opinions.

Note regarding references. For readability, scientific references are minimized in the text. A bibliography is included after the final Opinion.

SECTION 4: Actions required to avoid dangerous climate change are guided by Earth's climate history and by the need to restore Earth's energy balance.

a. Science can specify an **initial target for atmospheric CO_2**, about 350 ppm, which is sufficient to define near-term policy needs.

b. Emission **reductions at a substantial rate must begin promptly**. Our ability to turn back the dial will not long persist, as climate can be pushed beyond a point at which changes proceed out of human control. Leisurely reductions of 1-2 percent per year will not suffice.

I. Initial target for atmospheric CO_2

Earth's climate history shows the eventual climate effect of different levels of atmospheric gases. CO_2 is dominant, by far, of the long-lived greenhouse gases, and thus CO_2 operates as a control knob on global temperature.

Earth does not respond instantly to CO_2 changes. **First**, there is a lag due to the ocean's large thermal inertia: 100 years after a change of atmospheric greenhouse gases Earth's surface only achieves about two-thirds of its eventual ('equilibrium') response. **Second**, the ice sheets on Antarctica and Greenland shrink as Earth becomes warmer, but melting takes time: paleoclimate data show that sea level change lags global temperature change by 1-4 centuries. However, we cannot count on a long ice sheet lag, because the human-made CO_2 change is large and must faster than natural CO_2 changes that drove paleoclimate sea level changes.

The good side of the ocean and ice sheet lags is that, despite the large size of the atmospheric CO_2 increase, global warming has been limited (just over 1°C, or about 2 degrees Fahrenheit) and sea level rise is small (about 20 cm, which is about 8 inches). The bad side is that more temperature rise, and a lot more sea level rise, are 'in the pipeline', unless we reduce the amount of CO_2 in the air.

Paleoclimate guidance. Global warming of +2°C relative to preindustrial climate would make Earth warmer than it was in the Eemian interglacial period. The Eemian was the last interglacial prior to the current one, the Holocene. During the Eemian sea level reached 6-9 meters (20-30 feet) higher than today.

If global temperature reaches +2°C, ocean temperature will remain elevated for centuries, so sea level rise of many meters almost certainly would be locked in. Most coastal cities would be lost, although we cannot say how soon. Civilization is adapted to today's shorelines, with more than half of today's largest cities being coastal (Fig. 24). Clearly a 2°C lid on warming would be a foolish target to set, highly dangerous for young people and future generations.

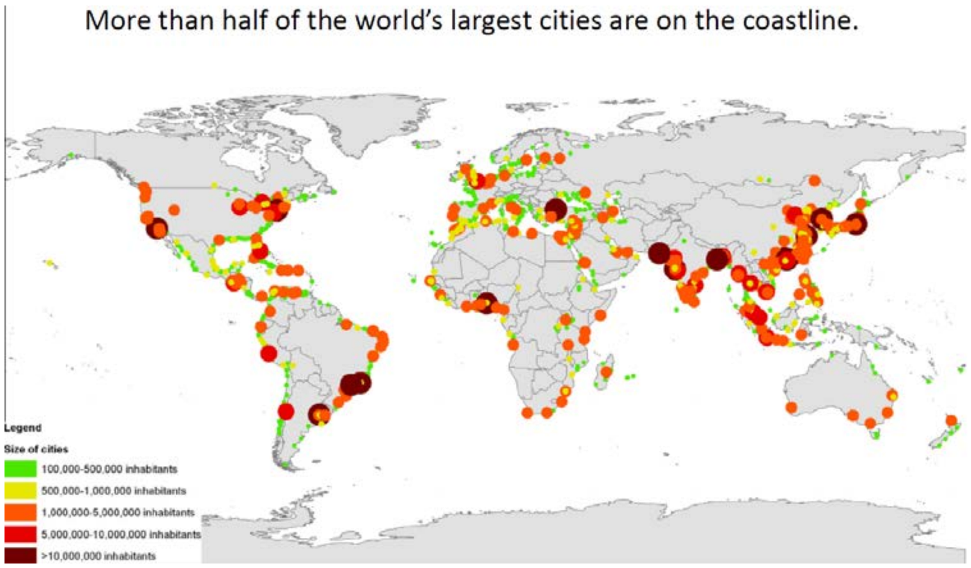

Fig. 24. World's largest cities. More than half are located on coastlines.

Guidance from today's climate change. Civilization is adapted to the climate of the Holocene. Human-caused global warming of about 1°C already has effects, especially in areas that were already warm such as the American Southwest, the Mediterranean, Southeast Asia and the Tropics. If global warming were doubled to 2°C many of these regions would become difficult to live and work in.

Further warming in cold regions is also undesirable, judging from changes that are beginning, such as the melting of tundra. If fossil fuels are allowed to cause 2°C global warming, the CH_4 and CO_2 released from melting tundra and methane hydrates will amplify that warming to still greater levels. Arctic summer sea ice is already much diminished with 1°C global warming and might pass a tipping point leading to much larger loss with major impacts on Arctic ecosystems.

Regional climate extremes are already enhanced at 1°C global warming, including more extreme floods, storms, heat waves and wildfires. Observed climate impacts from 1°C global warming point to the conclusion that it is dangerous to push ahead to still greater global warming.

Earth's energy imbalance. There is more global warming on its way, even if greenhouse gases were stabilized at today's amounts, because Earth is out of energy balance, more energy coming in than going out. That imbalance is our best quantitative guide for what needs to be done to stabilize climate.

Today Earth is out of balance by 0.75 ± 0.25 W/m^2. The cause of the imbalance, of course, is the excess amount of greenhouse gases, principally CO_2, in the air. It is easy to calculate how much CO_2 must be reduced to allow a given increase in radiation to space. It is only a radiation calculation; it does not require knowledge of uncertain factors such as climate sensitivity. The uncertainty in this radiation calculation is only of order 10 percent.

If Earth's energy imbalance is 0.50 W/m^2, CO_2 must be reduced from its present 407 ppm to 373 ppm. If the imbalance is 1 W/m^2, CO_2 must be reduced to 342 ppm to restore energy balance.

Energy balance at the present global warming level of more than +1°C relative to preindustrial (Fig. 3) may not be sufficient to prevent eventual multi-meter sea level rise, so the eventual target probably needs to be a CO_2 amount slightly below that needed for energy balance. The target <350 ppm for CO_2 set in 2008, when CO_2 was 385 ppm and global warming was +0.9°C, emphasized that 350 ppm was only an initial target that must be refined once CO_2 actually begins to decline and approach 350 ppm.

Earth's energy imbalance was only one of several reasons for choosing the initial target <350 ppm. Other reasons included paleo data on climate and sea level for larger CO_2 amounts, effects of ocean acidification, and climate impacts already emerging in 2008 when the global temperature anomaly was +0.9°C.

Why is the appropriate target not 280 ppm, the preindustrial CO_2 amount? Because humans have made many other changes that affect Earth's energy balance, such as replacing forests with farmland, highways and cities. Also there are other changes to the atmosphere that cause both cooling (aerosols) and warming (other greenhouse gases). Earth's energy imbalance provides a comprehensive diagnostic of the system, because it incorporates all effects.

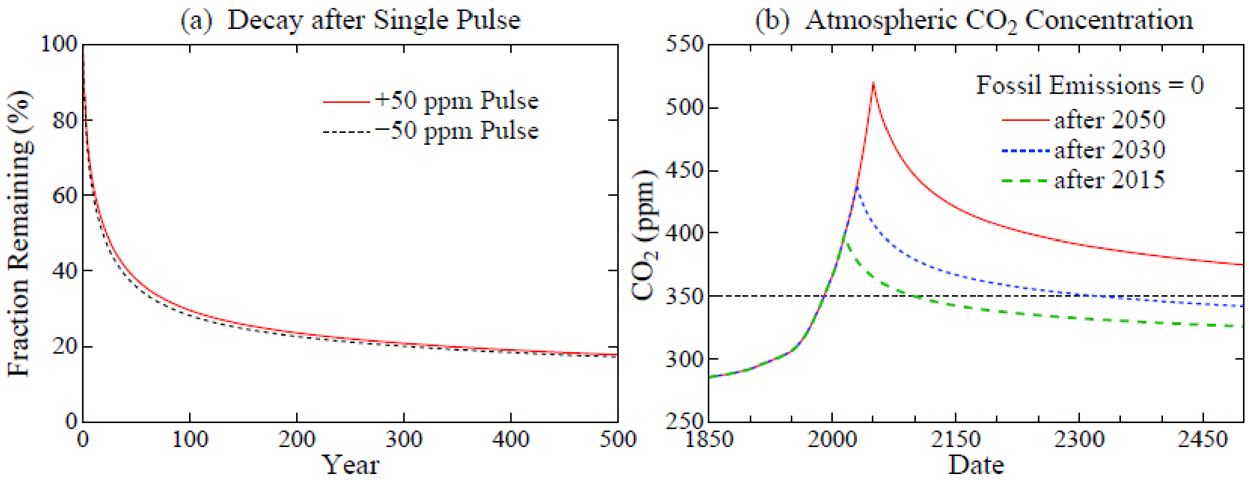

Fig. 25. Decay of atmospheric CO_2 perturbations. (A) Instantaneous injection or extraction of CO_2 with initial conditions at equilibrium. (B) Fossil fuel emissions terminate at the end of 2015, 2030 or 2050 in these three scenarios. This is Figure 4 in *Assessing Danger* (2013) paper.

II. Emission reductions, at a substantial rate, must begin promptly

CO_2 released in fossil fuel burning remains in the climate system for millennia (Archer, 2005). The portion of CO_2 remaining in the air declines rapidly at first (Fig. 25). Half of the emitted CO_2 is taken up in the first 25 years by the ocean, soil and biosphere, but uptake then slows such that almost one-fifth is still in the air after 500 years. Chemical weathering eventually deposits the fossil fuel carbon on the ocean floor as carbonate sediment, but that process requires millennia.

Thus all together there are three slow processes that characterize the climate and energy problem, creating a difficult situation for young people. Unless urgent actions are undertaken, climate consequences will run out of humanity's control.

(1) First, 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.

(2) Second, the long life of CO_2. Much of the fossil fuel CO_2 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, CO_2 in the air does not decline to 350 ppm until 2300.

(3) Third, the 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. Replacement of fossil fuels by carbon-free energy sources will require several decades, even with effective planning that so far has been absent.

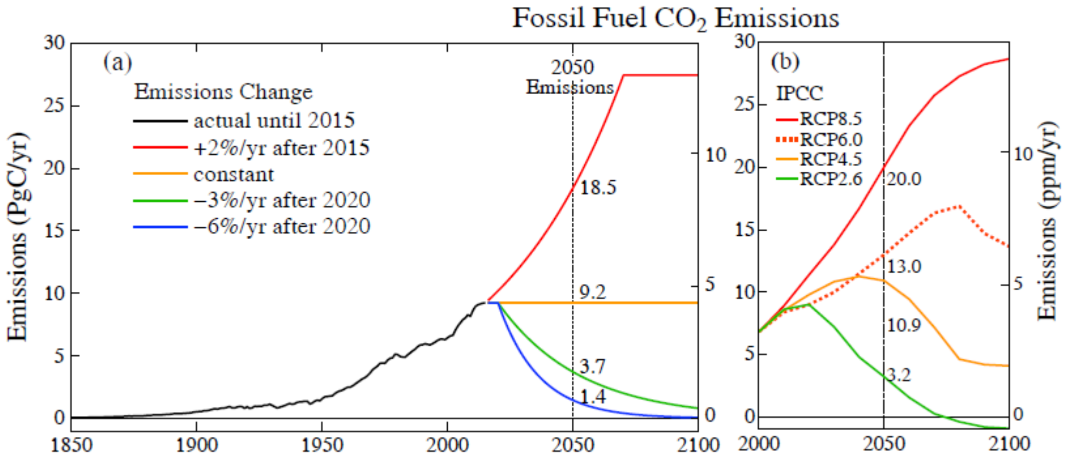

Fig. 26. Fossil fuel emission scenarios. (a) Scenarios with simple specified rates of emission increase or decrease. (b) IPCC (2013) RCP scenarios. Note:1 ppm atmospheric CO_2 is ~2.12 GtC. This is Figure 9 in *Burden* (2017) paper.

The first two of these three slow processes – (1) restoration of Earth's energy balance via planetary warming, and (2) uptake of CO_2 by the ocean, biosphere and soil – are under control of nature. To be sure, propositions for 'geoengineering,' altering the natural processes, now arise because of the climate urgency. The severe limitations and extreme costs of these schemes are discussed below.

The process controlled by humans, fossil fuel emissions, will dominate the climate outcome. Climate impacts of global warming are beginning to appear and are growing. The potential danger of this situation if high emissions continue, predictable catastrophic consequences in future decades, is manifest. The task is to reduce emissions faster than Earth responds to the energy imbalance. As we will see, there is no time for delay in reducing emissions.

Fossil fuel 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%.

Atmospheric CO_2 amount resulting from each emission scenario can be computed with confidence using carbon cycle models for the uptake of CO_2 by the ocean, biosphere and soil. The model used here is a convenient well-tested version of the Bern model (Joos et al., 1996) as also described by Kharecha and Hansen (2008) and references therein. The model, also used for Figure 25, was tested and found to yield a good fit to observed atmospheric CO_2 over the industrial era.

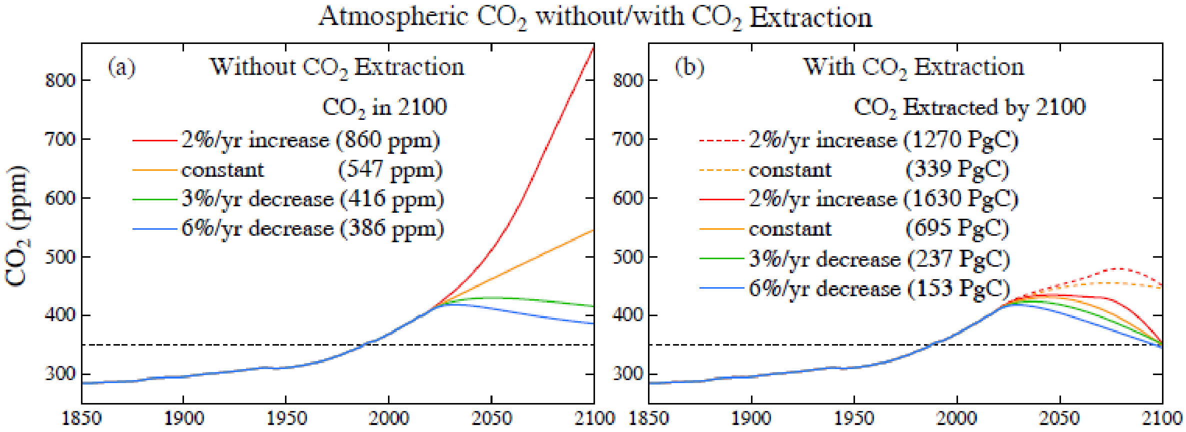

Fig. 27. (a) Atmospheric CO_2 for Fig. 9a emission scenarios. (b) Atmospheric CO_2 including effect of CO_2 extraction that increases linearly after 2020 (after 2015 in +2%/year case). [from *Burden* (2017)]

Atmospheric CO_2 scenarios. Atmospheric CO_2 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, which is probably the earliest conceivable date for a substantial downward trend in global emissions to begin, given the denial of science by the current Executive Branch of the United States government and the slow pace of the Judicial Branch.

Rapid emission reduction, at least 3 percent per year, is needed just to keep CO_2 in the neighborhood of 400 ppm (Fig. 27a). Constant emissions lead to CO_2 above 500 ppm this century. Emissions growth at 2 percent per year, typical of recent decades, leads to CO_2 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. We, the scientific community, responded oddly to absence of effective international energy and climate policy. Instead of sounding a strong alarm, we added climate scenarios with massive ‘negative emissions’ to IPCC documents. These are imaginary emissions that might be produced if fossil fuel power plants were replaced by power plants burning biofuels and if the CO_2 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 CO_2 is enormous. NIMBY opposition to CO_2 pipelines CO_2 storage would be great. The decisive factor likely would be cost. Why would developing countries, the principal source of future emissions, submit to the added cost? After all, developed countries raised their standards of living by burning fossil fuels and dumping refuse CO_2 in the air without penalty.

Cost of CO_2 extraction. Consider the case of constant emissions, which would result in CO_2 of 547 ppm in 2100 without CO_2 extraction (Fig. 27a). That constant emission scenario can still achieve the goal of 350 ppm CO_2 in 2100, provided that 695 PgC[5] of CO_2 is captured and permanently stored, as shown in Fig. 27b.

The amount of CO_2 that must be extracted from the air to achieve 350 ppm CO_2 at the end of the century is calculated with the same carbon cycle model used for other calculations above, as described in the *Burden* (2017) paper, which includes extensive references to the relevant scientific literature. Alternative representations of the carbon cycle would not qualitatively alter the results.

The *Burden* (2017) paper includes reference to and discussion of a paper on biophysical and economic limits to negative CO_2 emissions by P. Smith and 40 co-authors (Smith *et al.*, 2016). Smith *et al.* provide an optimistic estimate for cost of extraction and storage of CO_2, specifically \$150-350/tC, where tC is tons of carbon. A ton of C is 44/12 tons of CO_2, so this cost range is about \$40-95/tCO_2.

This low cost range of Smith *et al.* is obtained for biophysical extraction methods with economic co-benefits, such as energy production, that reduce the cost. In contrast, the lowest cost for direct air capture of CO_2 based on technology demonstration (Keith *et al*., 2018) is \$113-232/tCO_2 and that cost does not include cost of CO_2 storage, which has been estimated as \$10-20/tCO_2.

Now, let us accept the low cost range of Smith *et al*., \$40-95/tCO_2, and calculate the cost of extracting the 695 GtC that must be removed under the ‘constant emissions’ scenario, if atmospheric CO_2 is to be brought down to 350 ppm by 2100. The result is \$104-243 trillion, or \$1.3-3.0 trillion/year if the cost is divided uniformly over 80 years.

Such extraordinary cost, along with the land area, fertilizer and water requirements (Smith *et al*., 2016) suggest that, rather than the world being able to buy its way out of climate change, continued high emissions would likely force humanity to live with climate change running out of control with all the consequences that would entail.

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[5] A PgC (picagram of carbon) is the same as a GtC (gigaton of carbon), i.e., one billion tons of carbon. Note that if one prefers to use the mass of CO_2, these numbers must be multiplied by 44/12 ~ 3.67, to account for the atomic mass of carbon being 12 and the mass of oxygen being 16.

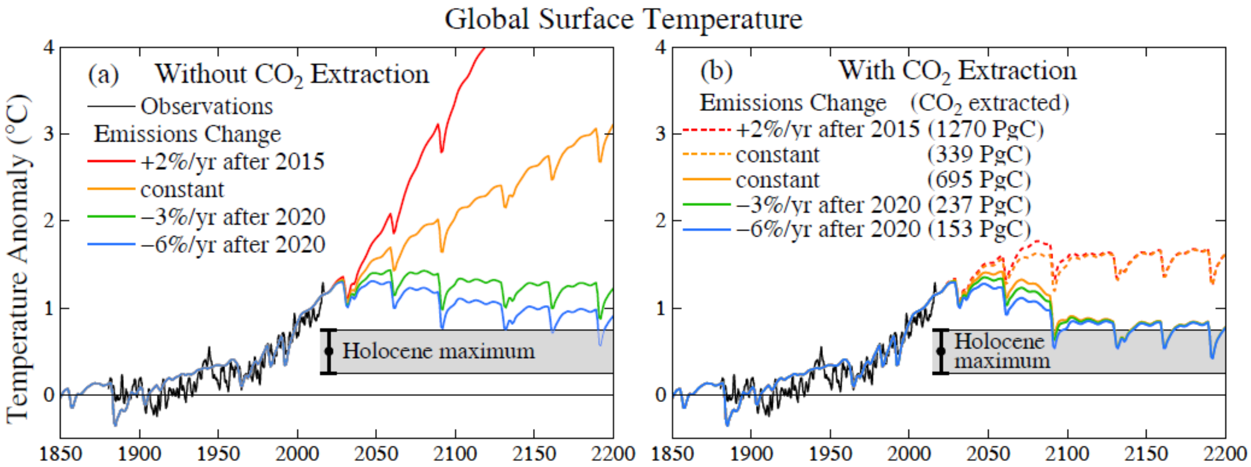

Fig. 28. Simulated global temperature. Temperature zero-point is the 1880-1920 mean temperature for both observations and model. Gray area is 2σ (95% confidence) range for centennially-smoothed Holocene maximum, but there is further uncertainty about the magnitude of the Holocene maximum, as noted in the text and discussed by Liu et al. (2014). [Figure 12 from *Burden* (2017) paper]

Mitigation alternative. These considerations reveal the unlikely prospects for CO_2 extraction, negative emissions, becoming a panacea for the climate problem.

Similarly, the other popular geoengineering idea, solar radiation management, SRM, has fundamental issues. The idea with SRM is to reflect sunlight away from Earth, perhaps by putting mirrors in space or continually sending up airplanes to dump sulfur dioxide into the stratosphere, making a permanent human volcano. SRM does not address ocean acidification caused by increasing CO_2. Also, undesirable side effects would grow as the magnitude of SRM increased. Some level of geoengineering may be necessary as the world continues to drag its feet on addressing climate change, but geoengineering can and should be minimized.

Almost all economist agree that mitigation of emissions is not only possible, it is the economically sensible approach. Specific policies should be determined by elected officials, but it is appropriate to point out general principles, as discussed in section 9.2 of *Burden* (2017), for the sake of making clear that rapid rates of fossil fuel phasedown are not only possible, they make the most economic sense.

The crucial requirement is to make the price of fossil fuels honest by including costs to society in their price, rather than letting the atmosphere be used as a free waste dump. Economic studies show that a steadily rising carbon fee provides incentives for entrepreneurs, businesses and the public to move to clean energies, decreasing emissions at rates of 3 percent per year and faster.

Minimal reduction rates. Climate simulations of global temperature change provide valuable guidance about the rate at which CO_2 emissions must be reduced to stabilize climate. The results in Fig. 28 are from a Green's function calculation of global temperature under the assumption that climate sensitivity is 3°C for $2\times CO_2$. The calculations are described in more detail in the *Burden* (2017) paper.

An important point to note about our simulations in Fig. 28, and those of the models used in the IPCC reports, is that results do not include slow feedbacks such as ice sheet disintegration. Reason for exclusion is poor understanding of the response time of ice sheets and other slow feedbacks. Yet slow feedbacks can and should drive our interpretation of the alternative emission scenarios in Fig. 28.

The scenario with constant emissions, the orange line in Fig. 28, provides an indication of the global temperature tendency that should be expected under the lackadaisical policies of the Paris Agreement, a precatory accord in which it is hoped that developed countries will reduce their emissions and developing countries will try to at least limit their growth rate. The net effect will surely be that fossil fuel emissions remain high, perhaps slightly decreasing or increasing.

The climate impact of this constant emission case is certain disaster for young people and future generations. Global temperature, rising far above that in the Eemian, would drive amplifying slow feedbacks, including ice sheet disintegration, sea level rise, and emigration from increasingly torrid low latitudes.

Emission reductions of 3 percent/year, the green line in Fig. 28, or more are needed to stay below 1.5°C global warming and achieve a downward temperature trend. Decreasing temperature would tend to limit slow feedback amplifications.

Extraction of CO_2 from the air is required, in addition to emission phasedown, in order to bring global temperature back close to the Holocene range (Fig. 28b). Without extraction, global temperature remains well above the Holocene level for centuries, as shown in Fig. 28a, leaving a danger of consequences such as large sea level rise, albeit such consequences are not as certain as with constant emissions.

Extraction of as much as approximately 100 PgC is possible via improved agricultural and forestry practices, which store more carbon in the soil and biosphere, based on estimates discussed in the *Burden* (2017) paper. Some researchers have suggested that such potential quasi-natural extraction could be as high as 150 PgC (Robertson, 2018). This greater extraction, in combination with 6 percent per year reduction of fossil fuel emissions, would return global temperature close to the Holocene range by the end of this century (Fig. 28b).

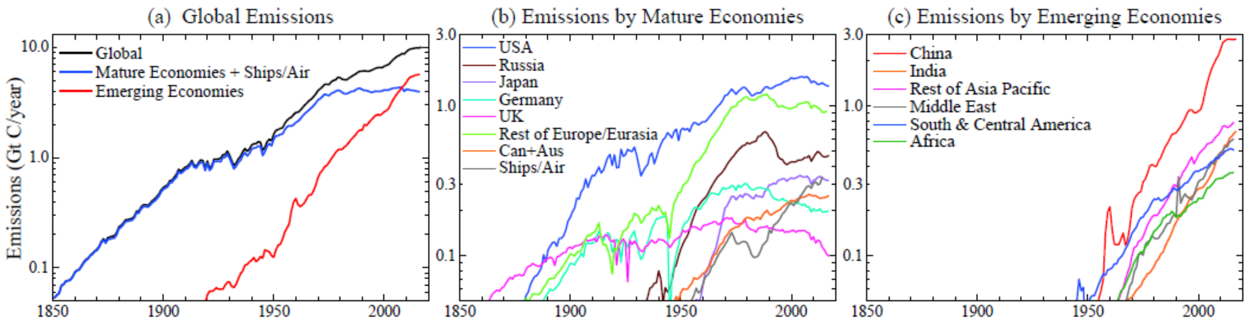

Fig. 29. Fossil fuel CO_2 emissions (note log scale), update of *Burden* (2017) Fig. 1, where countries in the different regions are defined. Ships/Air is bunker fuels of all nations. Can+Aus is Canada+Australia.

SECTION 5: The United States government, via both actions and inactions, is behaving with flagrant disregard of the rights and wellbeing of young people.

a. Actions include authorizing, permitting and subsidizing massive fossil fuel extraction, which will only compound the disproportionate responsibility of the United States for global climate change.

b. Inactions include absence of any coherent, effective program to reduce emissions, which, unless remedied, unarguably sentences young people to either a massive, implausible cleanup or growing deleterious climate impacts or both.

Framework Convention. In 1992 the United States, under President George H. W. Bush, exercised global leadership at the "Earth Summit" in Rio de Janeiro, helping draw up the United Nations Framework Convention on Climate Change. The objective of the Framework Convention is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The United States is among 197 nations that signed the Framework Convention, which went into force in 1994.

The Framework Convention states that Parties should act to protect the climate system on the basis of "common but differentiated responsibilities" and that developed country Parties should "take the lead" in addressing climate change. The Convention outlines how specific international treaties, called Protocols or Agreements, may be negotiated to specify limits on greenhouse gas emissions, but it has no enforcement mechanisms, and the United States has not agreed to any emission reductions.

The United States did not join the 1997 Kyoto Protocol, which established "binding" targets for national emissions, but with no enforcement mechanism. The reality of emission changes is shown in Fig. 29. Emissions from mature economies, on average, declined very slightly. Emissions from emerging economies continued to increase.

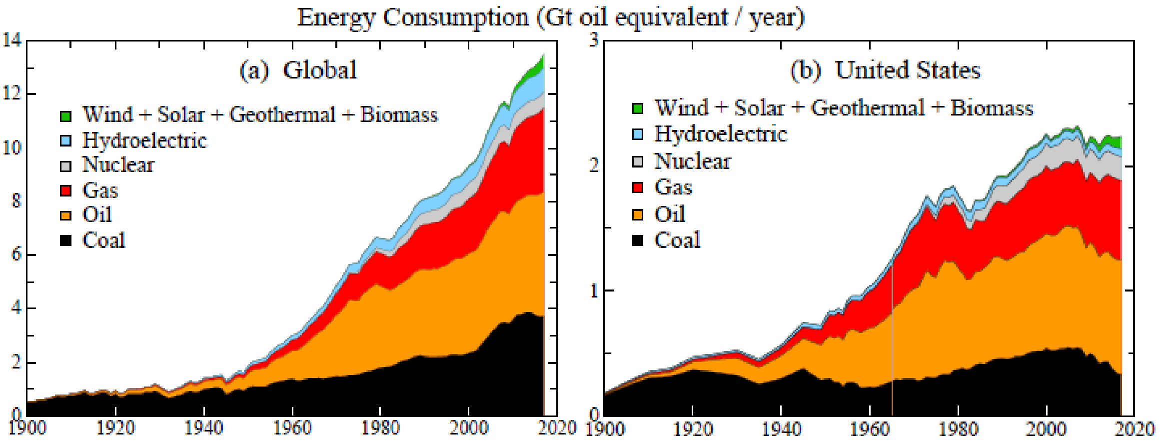

Fig. 30. Global and United States energy consumption by fuel type.

<u>United States emissions in context.</u> Emission histories vary from nation to nation, but the global picture is simple (Fig. 29a). Emissions from mature economies continue at a high level, as emissions grow from emerging economies. The need to raise living standards is the underlying reason for emissions growth. Fossil fuels continue to supply more than 80 percent of energy use in the U.S. and worldwide (Fig. 30). Global fossil fuel use continued to increase after the 1997 Kyoto Protocol, indeed, faster than in preceding decades (Fig. 30a).

United States fossil fuel use increased in the last 50 years (Fig. 30b), despite the fact that manufacture of many products for the United States shifted overseas. The United States is, by far, the nation most responsible for the excess CO_2 in the air today and thus the United States is most responsible for global climate change (see Fig. 8b and discussion thereof), even though China is the largest source of greenhouse gas emissions today (Fig. 8a).

Participation of the United States is required to phase down global emissions as the United States is still the second largest emitter of greenhouse gases. Moreover, the United States retains great potential for innovative technological development of carbon-free energy. Studies reveal economic and social benefits of revitalizing the nation with modern energy infrastructure. Instead, the government and fossil fuel industry have doubled down on extraction of even more fossil fuels, including the dirtiest, most carbon-intensive unconventional fossil fuels.

<u>United States actions.</u> The United States government has allowed, permitted and subsidized fossil fuel interests to exploit fossil fuel reserves, so that the fossil fuels are processed, transported and burned with little or no control on emissions. They allow the atmosphere to be treated as a free dumping ground for waste CO_2. The government does this even while knowing the consequences thereof.

This deference to the fossil fuel industry, violating the rights of young people, is not a problem that can be solved at the ballot box. Both political parties in the U.S. have a sycophantic relationship with the fossil fuel industry, differing only in degree. Both parties receive large sums of money from the fossil fuel industry.

The Obama Administration, for example, in 2011 opened up hundreds of millions of tons of coal on public lands to new lease sales. Moreover, the sales were at prices far below market value, continuing a practice of federal subsidy of coal titans amounting, through those sales alone, to tens of billions of dollars.

The Trump Administration's astounding recent efforts to accelerate fossil fuel CO_2 emissions are pressing the world more rapidly toward the climate precipice. Straight-faced lies about the facts of climate change, whether borne of simple ignorance, desire for fossil fuel money, or political expediency hoping for votes from people dependent on coal and other fossil fuel industries, cannot be allowed to trample on the rights and the future of young people.

United States inaction. The United States has no plan to phase down fossil fuel emissions and move to clean energy alternatives, even though the government itself has produced numerous reports showing that such planning is urgent.

President George H.W. Bush did more than support the Framework Convention on Climate Change, which acknowledged the need to avoid dangerous human-made interference with climate. Via a presidential initiative in 1989 he established the U.S. Global Change Research Program (USGCRP) to coordinate and integrate federal research on changes in the global environment and implications for society. Congress codified USGCRP with the Global Change Research Act of 1990.

On 23 November 2018 the Fourth National Climate Assessment, on *Impacts, Risks and Adaptation in the United States* was issued by the U.S. Global Change Research Program. The assessment began "Earth's climate is now changing faster than at any point in the history of modern civilization, primarily as a result of human activities. The impacts are already being felt in the United States and are projected to intensify in the future – but the severity of future impacts will depend largely on actions taken to reduce greenhouse gas emissions…"

President Trump's response, reported by *USA Today* on 26 November was that it makes no sense for the U.S. to take drastic steps to combat climate change when other countries, such as China and Japan, have not done so. "Right now we're at the cleanest we've ever been. It's very important to me," the president told reporters. "If we're clean and everyone else is dirty, that's not so good."

The fact of the matter is that, as far as responsibility for climate change is concerned, the United States is the dirtiest of them all, by far, as quantified above.

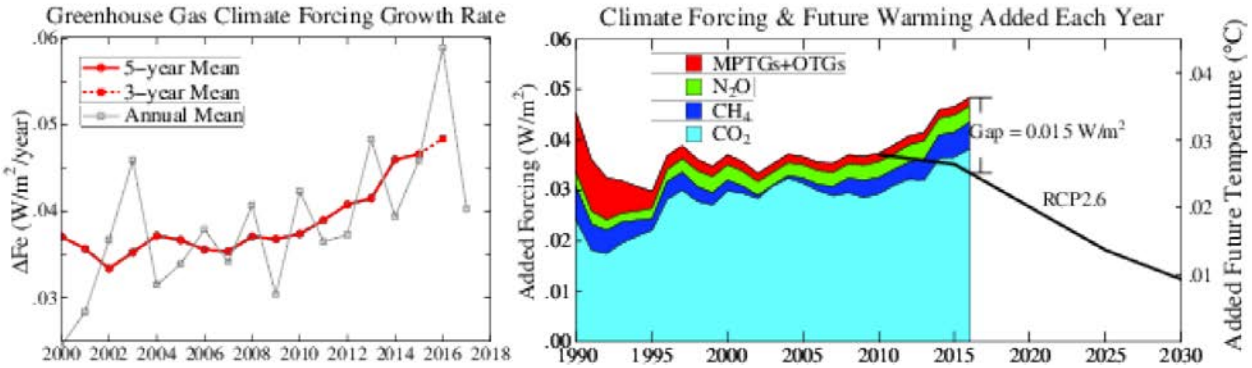

Fig. 31. Annual increase of greenhouse gas climate forcing. Right graph: contribution of each gas. RCP2.6 scenario is designed to keep global warming below 1.5°C, but it is being exceeded. Added future warming (scale on right) is based on climate sensitivity 3°C for 2×CO_2, i.e., it excludes slow feedbacks.

SUMMARY: Climate science described above shows unambiguously that global fossil fuel emissions must decrease rapidly over the next few decades, if young people are to avoid climate calamities. Economists say that such a change is not only possible but makes economic sense, because economies are more efficient if subsidies are eliminated and externalities are included in prices.

Urgency is exposed by one last graph: the annual addition to the human-caused increase in radiative forcing (Fig. 31). This forcing (measured in W/m^2) caused by the greenhouse gas increase is known accurately and based on a simple radiation calculation that does not depend on climate models or climate sensitivity. It is, instead, a function of the reduction of Earth's heat radiation to space, which reduction increases Earth's energy imbalance.

Negotiators seemed optimistic, or 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. Accordingly, a cold dose of reality, which Fig. 31 delivers, is now important, especially for people, groups and nations who are determined, as we must be, to convert the spirit of Paris into meaningful action.

Figure 31 compares reality with IPCC scenario RCP2.6. RCP2.6 is the pathway for climate forcing that the United Nations Intergovernmental Panel on Climate Change (IPCC) identified as required to cap global warming at about 1.5°C. Already the gap between that scenario and reality has grown to 0.015 W/m^2 and measurements so far in 2018 show that the gap is continuing to grow.

Let's reflect upon how we got to this point, before we examine implications of what the (growing) gap of 0.015 W/m^2 per year means for young people. The UN scientific group, IPCC, realized that unfettered fossil fuel emissions would cause growth of atmospheric greenhouse gases to outstrip scenarios in which global warming is limited so as to avoid dangerous consequences. Thus they devised a scenario, RCP2.6, in which large quantities of CO_2 are assumed to be stripped from the air, so as to make up for any failure to achieve emission reductions.

How much CO_2 must be extracted from the air today to offset the excess growth of greenhouse gas forcing in a single year, i.e., to reduce climate forcing by 0.015 W/m^2? Atmospheric CO_2 must be reduced almost exactly 1 ppm CO_2 to increase heat radiation to space by 0.015 W/m^2. [We actually need to suck more than 1 ppm from the air, because the ocean reacts to the reduction of atmospheric CO_2 by increasing the net backflux of CO_2 to the atmosphere. However, we can make our point without including this added difficulty in achieving CO_2 drawdown.]

One ppm of CO_2 is 2.12 billion tons of carbon or about 7.77 billion tons of CO_2. Recently Keith *et al.* (2018) achieved a cost breakthrough in carbon capture, demonstrated with a pilot plant in Canada. Cost of carbon capture, not including the cost of transportation and storage of the CO_2, is \$113-232 per ton of CO_2. Thus the cost of extracting 1 ppm of CO_2 from the atmosphere is \$878-1803 billion.

In other words, the cost, in a single year, of closing the gap between reality and the IPCC scenario that limits climate change to +1.5°C is already about \$1 trillion. And that is without the cost of transporting and storing the CO_2, or consideration of whether there will be citizen objection to that transportation and storage.

This annual cost will rise rapidly, unless there is a rapid slowdown in carbon emissions. This annual cost is not being paid, and common sense tells us that it will not be paid in the future as the cost rises to astronomical levels. Instead the mess is left for young people. Continued high fossil fuel emissions sentences young people to a massive and likely implausible cleanup and growing deleterious climate impacts.

The tragedy of this situation is that it is unnecessary. Honest pricing of energy, economists and common sense concur, would move us toward carbon-free energy. Economists caution that the carbon fee or tax should be imposed gradually but surely, so as to both minimize short-term disruption and provide a price signal that spurs an effective response from our technologic and industrial sectors.

Human-made climate change presents an intergenerational issue. What rights will we accord to young people and the unborn? Was Thomas Jefferson right in writing ‘that the Earth belongs in usufruct to the living’?

What is clear is that young people today confront an imminent gathering storm. They have at their command considerable determination, a dog-eared copy of our beleaguered Constitution, and rigorously developed science. The Court must decide if that is enough.

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