# The Case for Young People and Nature: A Path to a Healthy, Natural, Prosperous Future

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**Abstract.** Global warming due to human-made gases, mainly $CO_2$, is already 0.8°C and climate effects are growing worldwide. More warming is 'in the pipeline' because increasing $CO_2$ has driven Earth out of energy balance, absorbed solar energy exceeding planetary heat radiation by $0.75 \pm 0.25$ W/m$^2$ averaged over a solar cycle. Maintaining a climate that resembles the Holocene, the world of stable shorelines in which civilization developed, requires rapidly reducing fossil fuel $CO_2$ emissions. Such a scenario is possible, economically sensible, and has multiple benefits for humanity and other species. Yet fossil fuel extraction is expanding, including highly carbon-intensive sources. This situation raises profound moral issues as young people, the unborn, and nature, with no possibility of protecting their future well-being, will bear the principal consequences of actions and inactions of today's adults.

Humanity is now the dominant force driving changes of Earth's atmospheric composition and thus future climate (IPCC, 2007a). The principal climate forcing is carbon dioxide ($CO_2$) from fossil fuel emissions, much of which will remain in the atmosphere for millennia (Archer, 2005; IPCC, 2007a). The climate system's inertia, due mainly to the ocean and the ice sheets on Greenland and Antarctica, causes climate to respond slowly, at least initially, but in a very long-lasting way to this human-made forcing.

Governments have recognized the need to stabilize atmospheric composition at a level avoiding dangerous anthropogenic climate change, as formalized in the Framework Convention on Climate Change (FCCC, 1992). Despite this, the Kyoto Protocol, established in 1997 to reduce developed country emissions and slow the growth of emissions in developing countries, has been so ineffective that the rate of global emissions has since accelerated to almost 3%/year, compared to 1.5%/year in the preceding two decades (Reference).

There is a huge gap between rhetoric about reducing emissions and reality. Governments and businesses offer assurances that they are working to reduce emissions, but only a few nations have made substantial progress. Reality is portrayed in a New York Times energy supplement 'There Will Be Fuel' (Krauss, 2010), which describes massive efforts to expand fossil fuel extraction, including expansion of oil drilling to increasing ocean depths, into the Arctic, and onto environmentally fragile public lands; squeezing of oil from tar sands and tar shale; hydro-

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fracking to expand extraction of natural gas; and increased mining of coal via mechanized longwall mining and mountain-top removal.

Governments not only allow this activity, but subsidize fossil fuels at a rate of about 500 billion US$ per year[15]. Nor are fossil fuels required to pay their costs to society. Air and water pollution due to extraction and burning of fossil fuels kills more than 1,000,000 people per year and affects the health of billions of people (Cohen et al., 2005). But the greatest costs to society, also not reflected in the price of fossil fuels, likely will be the impacts of climate change, which are already apparent and are expected to grow considerably (IPCC, 2007b; Ackerman and Stanton, 2011).

Climate change is a moral issue of unprecedented scope, a matter of intergenerational injustice, as today's adults obtain benefits of fossil fuel use, while consequences are felt mainly by young people and future generations. In addition, developed countries are most responsible for emissions, but people in less developed countries and indigenous people in many nations will generally be burdened the most and will be less able to adapt to a changed climate.

The tragedy of human-made climate change, should the rush to exploit all fossil fuels continue, is that transition to clean energies and energy efficiency is not only feasible but economically sensible (Stern, 2007: Ackerman et al., 2009; Hsu, 2011). Assertions that phase-out of fossil fuels would be unacceptably costly can be traced to biased assumptions that do not account for the costs of fossil fuels to society or include the benefits of technology innovations that would emerge in response to an appropriate price on carbon emissions.

Our aim here is to expose the urgency to phase out fossil fuel emissions. We summarize the emission reductions required to restore Earth's energy balance, which is the basic requirement for stabilizing climate. We also draw attention to the moral issues, our obligations to young people, future generations, less developed nations, indigenous people, and our fellow species.

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[15] http://www.iea.org/weo/docs/G20_Subsidy_Joint_Report.pdf
and http://www.hedon.info/docs/GSI_The-Politics-Of-Fossil-Fuel-Subsidies.pdf

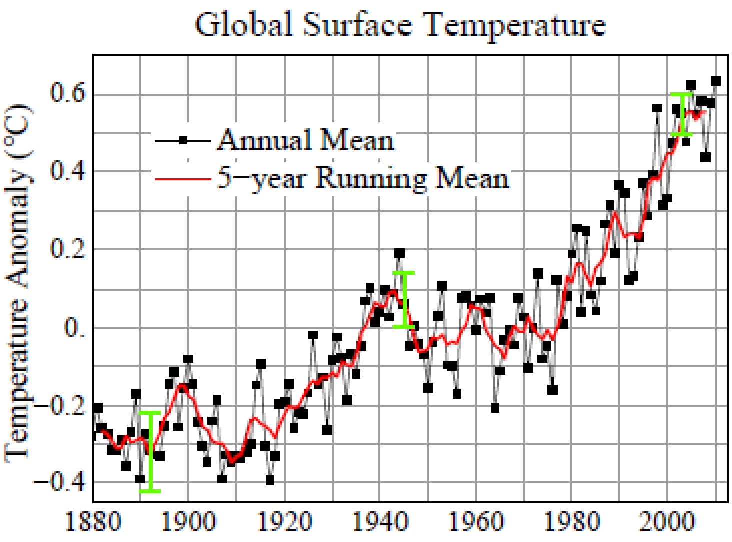

**Figure 1.** Global surface temperature anomalies relative to 1951-1980 mean for annual and 5-year running means. Green bars are 2-σ error estimates, i.e., 95% confidence intervals (Hansen et al., 2010).

## Global Temperature

Global surface temperature fluctuates chaotically within a limited range and also responds to natural and human-made climate forcings. Climate forcings are imposed perturbations of Earth's energy balance such as changes of the sun's luminosity, volcanic eruptions that inject aerosols (fine particles) into Earth's stratosphere, and human-caused alterations of atmospheric composition, most notably the increase of atmospheric carbon dioxide ($CO_2$) due to burning of fossil fuels.

**Modern Temperature.** Global temperature change over the past century (Fig. 1) includes year-to-year fluctuations that are partly unforced chaotic variability and partly forced climate change. Global warmth of 1998, e.g., was a result of the strongest El Niño of the century, a natural warming of the tropical Pacific Ocean surface associated with a fluctuation of ocean dynamics. Cooling in 1992 was caused by stratospheric aerosols from the Mount Pinatubo volcanic eruption, which temporarily reduced sunlight reaching Earth's surface by as much as 2 percent. The strong global warming trend over the past three decades is a forced climate change that has been shown to be a consequence of the rapid growth of human-made atmospheric greenhouse gases, predominately $CO_2$ from fossil fuel burning (IPCC, 2007a).

Basic physics underlying this global warming, the greenhouse effect, is simple. An increase of gases such as $CO_2$ makes the atmosphere more opaque at infrared wavelengths. This added opacity causes the planet's heat radiation to space to arise from higher, colder levels in the atmosphere, thus reducing emission of heat energy to space. The temporary imbalance between the energy absorbed from the sun and heat emission to space, causes the planet to warm until planetary energy balance is restored.

The great thermal inertia of Earth, primarily a consequence of the 4-kilometer (2½ mile) deep ocean, causes part of the global temperature response to a climate forcing to be slow. As a result, Earth is significantly out of energy balance – the solar energy being absorbed by the planet exceeds heat radiation to space. Measurement of Earth's energy imbalance provides the most precise quantitative evaluation of how much $CO_2$ must be reduced to stabilize climate, as discussed below.

However, we should first discuss global temperature, because most efforts to assess the level of climate change that would be 'dangerous' for humanity have focused on estimating a permissible level of global warming. Broad-based assessments, represented by the 'burning embers' diagram in IPCC (2001, 2007), suggested that major problems begin with global warming of 2-3°C relative to global temperature in year 2000. Sophisticated probabilistic analyses (Schneider and Mastrandrea, 2005) found a median 'dangerous' threshold of 2.85°C above global temperature in 2000, with the 90 percent confidence range being 1.45-4.65°C.

The conclusion that humanity could readily tolerate global warming up to a few degrees Celsius seemed to mesh with common sense. After all, people readily tolerate much larger regional and seasonal climate variations.

The fallacy of this logic became widely apparent only in recent years. (1) Summer sea ice cover in the Arctic plummeted in 2007 and again in 2011 to an area 40 percent less than a few decades earlier, showing an accelerating downward trend. Ice thickness is declining even faster, a decline underestimated by a factor of four in IPCC climate models (Rampal et al., 2011). Continued growth of greenhouse gas concentrations will likely cause the loss of all summer sea ice within the next few decades, with large effects on wildlife and indigenous people, increased heat absorption at high latitudes, and potentially the release of massive amounts of methane, a powerful greenhouse gas, presently frozen in Arctic sediments on both land and sea floor (e.g., Westbrook et al., 2009). (2) The great continental ice sheets of Greenland and Antarctic have begun to shed ice at a rate, now several hundred cubic kilometers per year, which is continuing to accelerate (Velicogna et al. 2009; Rignot et al., 2011). With the loss of protective sea ice and buttressing ice shelves, there is a danger that ice sheet mass loss will reach a level that causes catastrophic, and for all practical purposes irreversible, sea level rise. (3) Mountain glaciers, which provide fresh water to major world rivers during the dry season, are receding rapidly all around the world. As global warming removes glaciers and increases precipitation, including winter snowfall, spring floods become greater and dry seasons more damaging (Barnett et al., 2008; Kaser at al., 2010). (4) The hot dry subtropical climate belts have expanded, affecting climate most notably in the southern United States, the Mediterranean and Middle East regions, and Australia, contributing to more intense droughts, summer heat waves, and devastating wildfires (Held and Soden, 2006; Seidel and Randel, 2008; Westerling et al., 2008). (5) Coral reef ecosystems are already being impacted by a combination of ocean warming and acidification (a direct consequence of rising atmospheric $CO_2$), resulting in a 1-2% per year decline in geographic extent. Coral reef ecosystems will be eliminated with continued increase of atmospheric $CO_2$, with huge consequences for an estimated 500 million people that depend on the ecosystem services of coral reefs (Bruno and Selig, 2007; Hoegh-Guldberg et al., 2007; Veron et al., 2009). (6) So-called mega-heatwaves have become noticeably more frequent, for example the 2003 and 2010 heatwaves over Europe and large parts of Russia, each with heat-death tolls in the range of 55,000 to 70,000 (Barriopedro et al., 2011).

Reassessment of the dangerous level of global warming has been spurred on by realization that large climate effects are already beginning while global warming is less than 1°C above preindustrial levels. A valuable tool for assessment is provided by paleoclimate, the history of ancient climates on Earth.

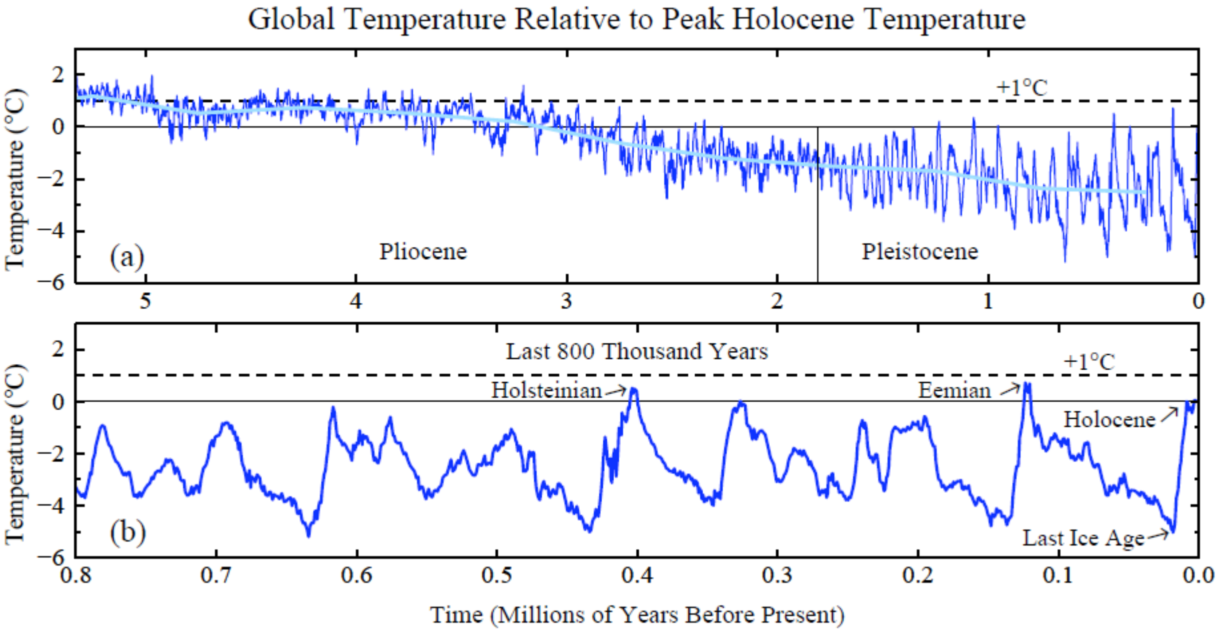

**Figure 2.** Global temperature relative to peak Holocene temperature (Hansen and Sato, 2011).

**Paleoclimate Temperature.** Hansen and Sato (2011) illustrate Earth's temperature on a broad range of time scales. Figure 2(a) shows estimated global mean temperature[16] during the Pliocene and Pleistocene, approximately the past five million years. Figure 2(b) shows higher temporal resolution, so that the more recent glacial to interglacial climate oscillations are more apparent.

Climate variations summarized in Figure 2 are huge. During the last ice age, 20,000 years ago, global mean temperature was about 5°C lower than today. But regional changes on land were larger. Most of Canada was under an ice sheet. New York City was buried under that ice sheet, as were Minneapolis and Seattle. On average the ice sheet was more than a mile (1.6 km) thick. Although thinner near its southern boundary, its thickness at the location of the above cities dwarfs the tallest buildings in today's world. Another ice sheet covered northwest Europe.

These huge climate changes were instigated by minor perturbations of Earth's orbit about the sun and the tilt of Earth's spin axis relative to the orbital plane. By altering the seasonal and geographical distribution of sunlight, the orbital perturbations cause small temperature change. Temperature change then drives two powerful amplifying feedbacks: higher temperature melts ice globally, thus exposing darker surfaces that absorb more sunlight; higher temperature also causes the ocean and soil to release $CO_2$ and other greenhouse gases. These amplifying feedbacks are responsible for practically the entire glacial-to-interglacial temperature change (e.g., Hansen et al., 2007a.; 2008; Köhler et al., 2010; Rohling et al., 2011)..

In these slow natural climate changes the amplifying feedbacks (ice area and $CO_2$ amount) acted as slaves to weak orbital forcings. But today $CO_2$, global temperature, and ice area are under the command of humanity: $CO_2$ has increased to levels not seen for at least 3 million years, global temperature is rising, and ice is melting rapidly all over the planet. Humans will not likely allow another ice age to occur. A single chlorofluorocarbon factory can produce gases with a climate forcing that exceeds the forcing due to Earth orbital perturbations.

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[16] This estimate of global mean temperature is obtained from ocean sediments at many locations around the world (Zachos et al., 2001; Hansen et al., 2008). The composition of the shells of deep-sea-dwelling microscopic animals (foraminifera), preserved in ocean sediments, carries a record of ocean temperature. Deep ocean temperature change is about two-thirds as large as global mean surface temperature change for the range of climates from the last ice age to the present interglacial period; that proportionality factor is included in Figure 2.

During the climate oscillations summarized in Figure 2, Earth's climate remained in near equilibrium with its changing boundary conditions, i.e., with changing ice sheet area and changing atmospheric $CO_2$. These natural boundary conditions changed slowly, over millennia, because the principal Earth orbital perturbations occur on time scales predominately in the range of 20,000 to 100,000 years.

Human-made changes of atmospheric composition are occurring much faster, on time scales of decades and centuries. The paleoclimate record does not tell us how rapidly the climate system will respond to the high-speed human-made change of climate forcings – our best guide will be observations of what is beginning to happen now. But the paleoclimate record does provide an indication of the eventual consequences of a given level of global warming.

The Eemian and Hosteinian interglacial periods, also known as marine isotope stages 5e and 11, respectively about 130,000 and 400,000 years ago, were warmer than the Holocene, but global temperature was probably less than 1°C warmer than peak Holocene temperature (Figure 2b). Yet it was warm enough for sea level to reach mean levels at least 4-6 meters higher than today (Hearty et al., 2007; Rohling et al., 2009; Kopp et al., 2009; Thomson et al., 2011).

Global mean temperature 2°C higher than peak Holocene temperature has not existed since at least the Pliocene, a few million years ago. Sea level at that time was estimated to have been 15-25 meters higher than today (Dowsett et al., 1999). Changes of regional climate during these warm periods were much greater than the global mean changes.

How does today's global temperature, given the warming of the past century, compare with prior peak Holocene temperature? Holocene climate has been highly variable on a regional basis (Mayewski et al., 2004). However, Hansen and Sato (2011) show from records at several places around the globe that mean temperature has been remarkably constant during the Holocene. They estimate that the warming between the 1800s and the period 1951-1980 (a warming of ~0.25°C in the Goddard Institute for Space Studies analysis, Hansen et al., 2010) brought global temperatures back to approximately the peak Holocene level.

If the 1951-1980 global mean temperature approximates peak Holocene temperature, this implies that global temperature in 2000 (5-year running mean) already exceeded the peak Holocene temperature. The uncertainty in the peak Holocene temperature is at least several tenths of a degree Celsius. However, strong empirical evidence that global temperature has already risen above the prior peak Holocene temperature is provided by the ongoing and accelerating mass loss of the Greenland and West Antarctic ice sheets, which began within the last few decades (VVelicogna et al, 2009; Rignot et al., 2011). Sea level was relatively stable for the past five to six thousand years, indicating that these ice sheets were in near mass balance. Now, however, both Greenland and West Antarctica are shedding ice at accelerating rates and sea level is rising at a rate of at least 3 mm/year (3 m/millennium). This is strong evidence that today's global temperature has reached a level higher than prior Holocene temperatures.

The conclusion is that global warming of 1°C relative to 1880-1920 mean temperature (i.e., 0.75°C above the 1951-1980 temperature or 0.3°C above the 5-year running mean temperature 2000) is already close to or into the 'dangerous' zone. The suggestion that 2°C global warming may be a 'safe' target is not well-founded. Global warming of that magnitude in a century would put Earth on a rapid journey toward Pliocene-like conditions. Species and ecosystems have no evolutionary experience with such an excursion. Consequences would include disruptions of society and ecosystems, with loss of ecosystem services that maintain human communities today. There are no credible arguments that such rapid change would not have catastrophic consequences for human well-being.

## Earth's Energy Imbalance

Earth's energy balance is a vital measure of the status of Earth's climate. In a period of climate stability, Earth radiates as much energy to space as it absorbs from incident sunlight. Today Earth is out of balance because of increasing atmospheric $CO_2$. Greenhouse gases such as $CO_2$ reduce Earth's heat radiation to space, causing a temporary energy imbalance, more energy coming in than going out. This imbalance causes Earth to warm until energy balance is restored.

The immediate planetary energy imbalance due to an increase of $CO_2$ can be calculated precisely. It does not require a climate model. The radiation physics is rigorously understood. However, the current planetary energy imbalance is complicated by the fact that increasing $CO_2$ is only one of the factors affecting Earth's energy balance, and Earth has already partly responded to the net climate forcing by warming 0.8°C in the past century.

Thus authoritative determination of the state of the climate system requires measuring the planet's current energy imbalance. This is a technical challenge, because the magnitude of the imbalance is expected to be only about 1 W/m$^2$ or less, so measurements must have an accuracy that approaches 0.1 W/m$^2$. The most promising approach to achieve this accuracy is to measure ongoing changes of the heat content of the ocean, atmosphere, land, and ice on the planet.

**Observed planetary energy imbalance.** The vast global ocean is the primary reservoir for changes of Earth's heat content. Because of the importance of this measurement, nations of the world launched a cooperative Argo float program, which has distributed more than 3000 floats around the world ocean (Roemmich and Gilson, 2009). Each float repeatedly sends an instrument package to a depth of two kilometers and back. Data are communicated via satellite to shore-based facilities.

The Argo program did not attain planned distribution of floats until late 2007, but coverage reached 90% by 2005, allowing good accuracy provided that systematic measurement errors are kept sufficiently small. Prior experience showed how difficult it is to eliminate all measurement biases, but the exposure of the difficulties over the past decade leads to expectation that the data for the 6-year period 2005-2010 are the most precise achieved so far.

Heat gain during 2005-2010 in the upper 2000 m of ocean sampled by Argo floats was 0.42 W/m$^2$ averaged over Earth's surface. Smaller contributions to planetary energy imbalance were provided by heat gain in the deeper ocean (+0.10 W/m$^2$), with the deep ocean estimates based on more spotty measurements over a decadal period, energy used in net melting of ice (+0.05 W/m$^2$), with loss of Arctic sea ice, the Greenland and Antarctic ice sheets, mountain glaciers and small ice caps all contributing to net heat uptake, and energy taken up by warming continents (+0.02 W/m$^2$). Data sources for these estimates and uncertainties are provided elsewhere (Hansen et al., 2011). The resulting net planetary energy imbalance for the six years 2005-2010 is +0.59 W/m$^2$ with estimated uncertainty 0.15 W/m$^2$.

The positive energy imbalance in 2005-2010 is particularly important, because that period has the lowest level of solar irradiance since accurate measurements of the sun began in the late 1970s (Frohlich and Lean, 1998). Solar variability is often hypothesized to be the one natural climate forcing with the potential to compete with human-made climate forcings. However, the large energy gain by Earth at the time of minimum solar irradiance confirms that the reduction of solar heating is overwhelmed by the warming effect of other climate forcings.

This result is not surprising, because the climate forcing by human-made greenhouse gases is known to be much larger than the forcing due to measured solar variability. The greenhouse gas forcing has been only partly expended in causing the observed 0.8°C global warming of the past century. The measured planetary energy imbalance is the net climate forcing that continues to act on our planet.

Earth's energy imbalance averaged over the 11-year cycle of solar variability is likely to be larger than the measured +0.59 W/m$^2$ at solar minimum. Hansen et al. (2011) suggest that the mean imbalance averaged over the solar cycle may be closer to +0.75 W/m$^2$, with uncertainty ±0.25 W/m$^2$. Precise quantification of Earth's energy imbalance will help us assess how much additional global warming is already 'in the pipeline'.

**Implications for atmospheric $CO_2$ target.** Accurate knowledge of Earth's energy imbalance will allow specification of how much $CO_2$ must be reduced to restore planetary energy balance and stabilize climate, if other factors remain unchanged. Earth's measured energy imbalance accounts for all natural and human-made climate forcings, including changes of the planet's surface reflectivity due to human activities and changes of atmospheric aerosols.

If Earth's mean energy imbalance is +0.5 W/m$^2$, $CO_2$ must be reduced from the current level of 390 ppm to about 360 ppm to increase Earth's heat radiation to space by 0.5 W/m$^2$ and restore energy balance, assuming that other forcings remain unchanged. If Earth's energy imbalance is 0.75 W/m$^2$, $CO_2$ must be reduced to about 345 ppm to restore energy balance.

Earth's measured energy imbalance thus affirms the conclusion that a good initial target level for atmospheric $CO_2$ to stabilize climate is "<350 ppm" (Hansen et al., 2008). The $CO_2$ target level must be refined as climate stability is approached. However, given the difficulty of reversing the growth of atmospheric $CO_2$, it is apparent that more precise knowledge of the ultimate target for $CO_2$ should be available by the time $CO_2$ has been restored to a concentration approaching 350 ppm.

Specification now of a $CO_2$ target more precise than "<350 ppm" seems inadvisable, as well as unnecessary, because of uncertainty about other human-made climate forcings such as changes of surface reflectivity, methane, other trace gases, reflecting aerosols, and black soot. These forcings are smaller than that by $CO_2$, but not negligible.

Future reductions of particulate air pollution may exacerbate global warming by reducing the cooling effect (negative climate forcing) of reflective aerosols. However, a concerted effort to reduce methane, tropospheric ozone, other trace gases and black soot may be sufficient to counteract the warming effect of a decline in reflective aerosols (Hansen et al., 2000). Our calculations of future global temperature below assume that reductions of these non-$CO_2$ forcings will be sufficient to offset changed forcing by reflective aerosols. To the degree that this goal is not achieved, future warming could exceed that which we calculate.

The important point is that $CO_2$ is the dominant climate forcing agent and it will be even more so in the future. The $CO_2$ injected into the climate system by burning fossil fuels will continue to affect our climate for millennia. We cannot burn all of the fossil fuels without producing a different planet, with changes occurring with a rapidity that will make Earth far less hospitable for young people, future generations, and most other species.

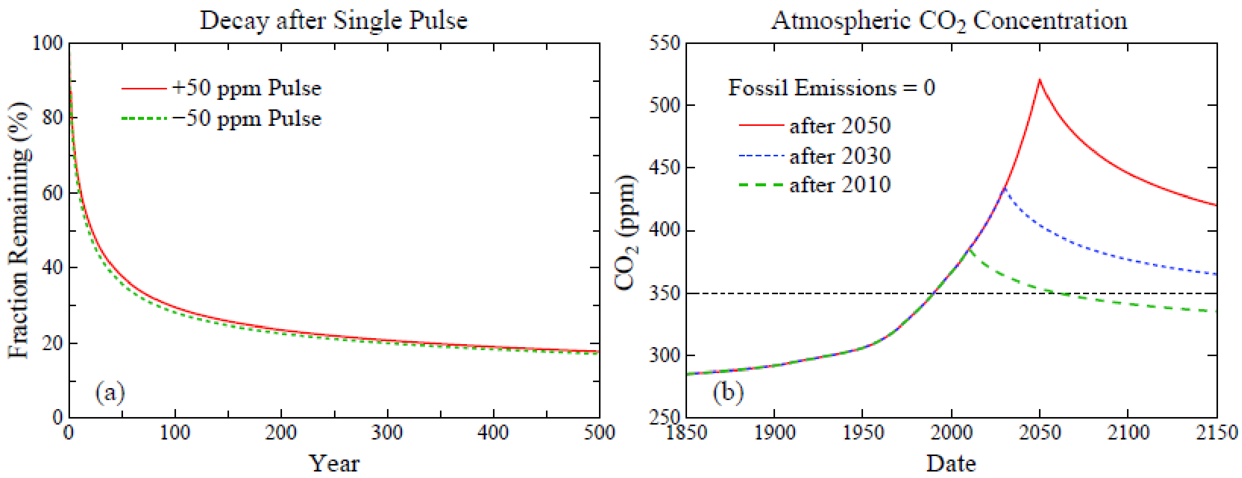

**Figure 3.** (a) Decay of instantaneous (pulse) injection and extraction of atmospheric $CO_2$, (b) $CO_2$ amount if fossil fuel emissions are suddenly terminated at the end of 2010, 2030, 2050.

## Carbon Cycle and Atmospheric $CO_2$

The 'carbon cycle' that defines the fate of fossil fuel carbon injected into the climate system is well understood (Archer, 2005; IPCC, 2007a). This knowledge allows accurate estimation of the amount of fossil fuels that can be burned consistent with restoring Earth's energy balance this century. Atmospheric $CO_2$ is already at about 390 ppm. However, it is still conceivable to get $CO_2$ back to a level near 350 ppm this century via a combination of rapid reduction of fossil fuel emissions and aggressive measures to increase $CO_2$ uptake by the soils and biosphere.

**Carbon cycle simulations.** $CO_2$ injected into the air by burning fossil fuels distributes itself over time among the surface carbon reservoirs: the atmosphere, ocean, soil, and biosphere. Here we use the well-tested Bern carbon cycle model to account for this redistribution and illustrate how rapidly atmospheric $CO_2$ could potentially decrease. Specifically, we use the dynamic-sink pulse-response function representation of the Bern model (Joos et al., 1996), as described by Kharecha and Hansen (2008) and Hansen et al. (2008).

A pulse of $CO_2$ injected into the air decays by about half in 25 years (Fig. 3). However, nearly one-fifth of the $CO_2$ is still in the atmosphere after 500 years. Eventually, over millennia, weathering of rocks will deposit this excess $CO_2$ on the ocean floor as carbonate sediments.

A negative $CO_2$ pulse decays at about the same rate as a positive pulse (Fig. 3a), which is an important fact for policy considerations. If it is decided in the future that $CO_2$ must be sucked from the air and removed from the carbon cycle (e.g., by making carbonate bricks or storing the $CO_2$ in underground reservoirs), the magnitude of the $CO_2$ reduction will decline as the negative $CO_2$ increment becomes spread among the carbon reservoirs.

It is instructive to examine how fast atmospheric $CO_2$ would decline if fossil fuel use were instantly terminated. If emissions were halted in 2011, $CO_2$ would decline to 350 ppm at mid-century (Fig. 3b). With a 20 year delay in halting emissions, $CO_2$ returns to 350 ppm at about 2250. With a 40 year delay, $CO_2$ does not return to 350 ppm until after year 3000. These results suggest how difficult it will be to get back to 350 ppm $CO_2$ if fossil fuel emissions continue at a high level for even a few decades.

**Deforestation and reforestation effects.** The above results do not necessarily imply that it is implausible for atmospheric $CO_2$ to return to the 350 ppm level this century. We must also account for one other major factor in the carbon cycle: the effects of deforestation/reforestation.

Fossil fuel emissions account for about 80 percent of the increase of atmospheric $CO_2$ from 275 ppm in the preindustrial atmosphere to 390 ppm today. The other 20 percent is from net deforestation, where net deforestation accounts for forest regrowth. Net deforestation over the industrial era is estimated to be about 100 GtC (gigatons of carbon), with uncertainty about 50 percent (Stocker et al., 2011) Net deforestation of 100 GtC and historical fossil fuel use yield good agreement with historical growth of atmospheric $CO_2$ based on simulations with the Bern carbon cycle model (Figure S16 of Hansen et al., 2008).

Reforestation and improved forestry and agricultural practices potentially could help extract $CO_2$ from the atmosphere. Complete restoration of deforested areas is unrealistic, yet a total 100 GtC drawdown of $CO_2$ is conceivable for the following reasons: (1) the current human-enhanced atmospheric $CO_2$ level increases carbon uptake by vegetation and soils, (2) improved agricultural practices can convert agriculture from being a large $CO_2$ source into a carbon sink (Hillel and Rosenzweig, 2011), (3) biomass-burning power plants with $CO_2$ capture and storage could contribute to $CO_2$ drawdown.

Use of bioenergy to help draw down atmospheric $CO_2$ should employ feedstocks only from residues, wastes, and dedicated energy crops that do not compete with food crops, unlike most current-generation bioenergy sources, thus avoiding loss of natural ecosystems and cropland (Tilman et al., 2006; Fargione et al., 2008; Searchinger et al., 2008). Reforestation must compete with other land use, especially expansion of agriculture to feed a growing world population. Decreased use of animal products would reduce demand for agricultural land, as more than half of all crops are currently fed to livestock (Stehfest et al., 2009; UNEP, 2010).

Forest and soil storage of 100 GtC is a major task, yet it is possible and, as we will show, it is probably essential if atmospheric $CO_2$ is to be returned close to the 350 ppm level. This carbon storage has other major benefits. Present agricultural practices, based on plowing and chemical fertilizers, are dependent on fossil fuels and contribute to loss of carbon from soil via land degradation. World agriculture could sequester 0.4-1.2 GtC per year by adopting minimum tillage and biological nutrient recycling (Smith et al., 2008; Smith, 2011). That strategy can also increase water conservation in soils, build agricultural resilience to climate change, and increase productivity especially in smallholder rain-fed agriculture, thereby reducing expansion of agriculture into forested ecosystems (Rockstrom et al., 2009; Smith et al., 2010).

Consequently, we assume a 100 GtC drawdown (biospheric C uptake) in our reforestation scenarios, using a sinusoidal drawdown over the period 2031-2080. Alternative timings of this drawdown would have no qualitative effect on our conclusions about the potential for achieving a given $CO_2$ level such as 350 ppm.

**$CO_2$ emission reduction scenarios.** Reforestation of 100 GtC results in atmospheric $CO_2$ declining to 350 ppm by the end of this century, if fossil fuel emissions decline 5% per year beginning in 2013 (Fig. 4a). The effect of continued fossil fuel emissions at a business-as-usual (BAU) rate (2%/year) is shown in Fig. 4b.

Delaying initiation of emission cuts until 2020 causes $CO_2$ to remain above the 350 ppm level until 2300. If emissions reduction is delayed until 2030 or later, atmospheric $CO_2$ does not return to the 350 ppm level even by 2500. We conclude that a major reforestation program would permit the possibility of returning $CO_2$ to the 350 ppm level within this century, but only if rapid fossil fuel emission reductions begin promptly.

The modest overshoot of the 350 ppm goal for $CO_2$ in 2100 can be largely overcome by scenario adjustments such as to 6%/year emissions decrease, phasing out deforestation by 2020, and moving 100 GtC reforestation to 2020-2070. Such adjustments have little effect on the expected global temperature maximum, calculated in the next section. The dominant factor, by far, is the date at which fossil fuel emission phase-out begins.

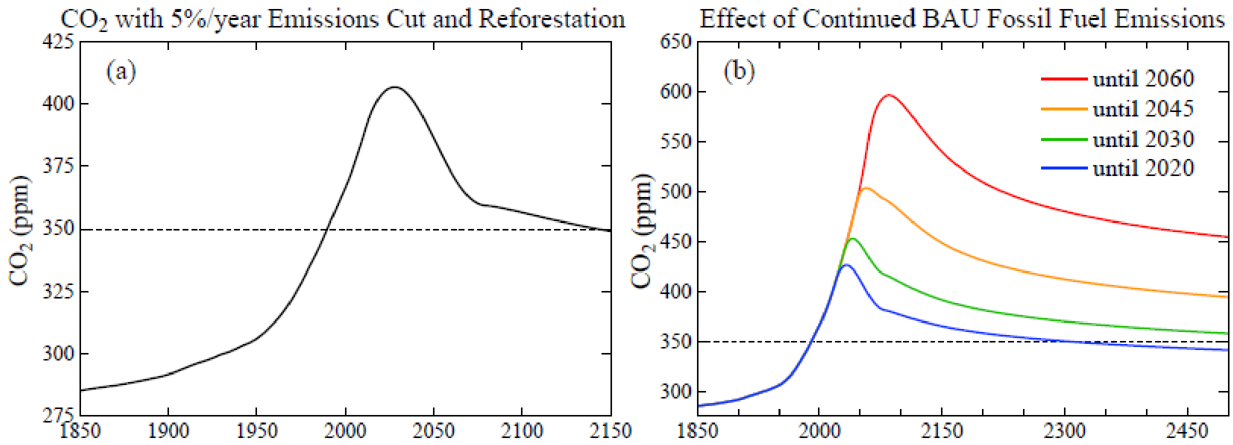

**Figure 4.** (a) Atmospheric $CO_2$ if fossil fuel emissions are cut 5%/year beginning in 2013 and 100 GtC reforestation drawdown occurs in 2031-2080, (b) effect of delaying onset of emissions reduction.

**Geo-engineering atmospheric $CO_2$.** Perceived political difficulties of phasing out fossil fuel emissions have caused a surge of interest in possible 'geo-engineering' designed to minimize human-made climate change. Such efforts must remove atmospheric $CO_2$, if they are to avoid direct $CO_2$ effects such as ocean acidification.

At present there are no technologies capable of large-scale air capture of $CO_2$. Keith et al. (2006) suggest that, with strong research and development support and industrial scale pilot projects sustained over decades, costs as low as ~\$500/tC may be achievable. An assessment by the American Physical Society (http://www.aps.org/about/pressreleases/dac11.cfm) argues that the cost would be much greater (\$600/$tCO_2$ or \$2200/tC) and that required facilities are so great that their construction to deal with a climate emergency would be implausible.

The cost of removing 50 ppm of $CO_2$, at \$500/tC, is ~\$50 trillion (1 ppm $CO_2$ is ~2.12 GtC), but more than \$200 trillion for the price estimate of the American Physical Society study. Moreover, the resulting atmospheric $CO_2$ reduction is only ~15 ppm after 100 years, because most of the extraction leaks into other surface carbon reservoirs (Fig. 3a). The estimated cost of maintaining a 50 ppm reduction on the century time scale is thus ~\$150-600 trillion.

Below we discuss economic and social benefits of rapidly phasing over to clean energies and increased energy efficiency, as opposed to continued and expanded extraction of fossil fuels. At this point, we simply note that the present generation will be passing the $CO_2$ clean-up costs on to today's young people and future generations, if fossil fuel emissions are not phased out.

## Future Global Temperature Change

Future global temperature change depends mainly on atmospheric $CO_2$ amount. $CO_2$ accounts for more than 80 percent of the growth of greenhouse gas climate forcing in the past 15 years (Reference). Natural climate forcings, such as changes of solar irradiance and volcanic aerosols, contribute to global temperature variations, but their effect on the long-term global temperature trend is small compared with the effect of $CO_2$.

Global temperature change for a given $CO_2$ scenario can be simulated using a climate response function that accurately replicates results from sophisticated global climate models. We use the 'intermediate' response function (Fig. 9 of Hansen et al., 2011), which replicates well observed ocean heat uptake and observed global temperature change of the past century.

**Importance of slow climate feedbacks.** One caveat must be stressed. These calculations, as with most global climate models, incorporate only the effect of the so-called 'fast feedbacks' in

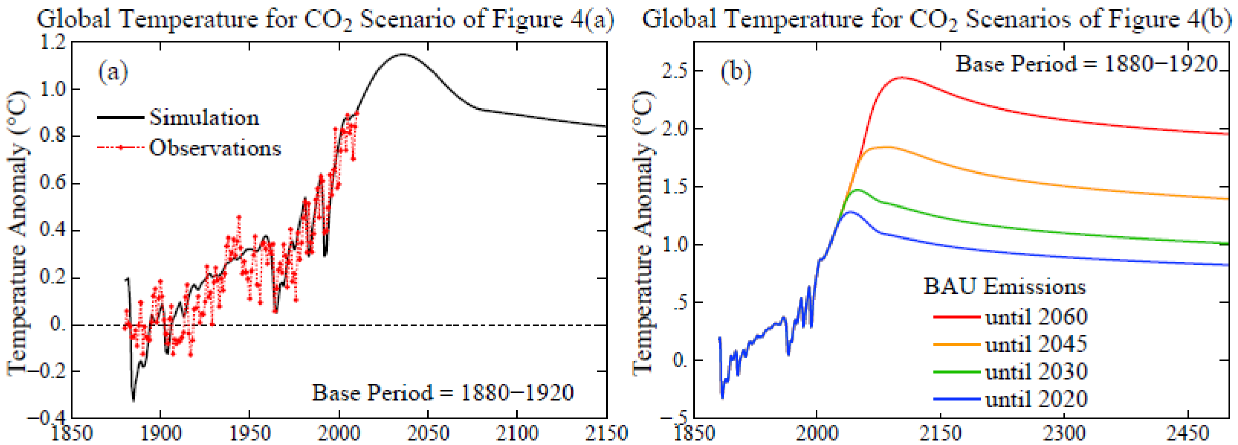

**Figure 5.** Simulated global temperature for $CO_2$ scenarios of Fig. 4. Observed temperature (Hansen et al., 2010) is relative to the 1880-1920 mean. Subtract 0.26°C to use 1951-1980 as zero-point. Subtract 0.70°C to use 5-year running mean in 2000 as zero point.

the climate system, such as water vapor, clouds, aerosols, and sea ice. Slow feedbacks, such as ice sheet disintegration and climate-induced changes of greenhouse gases, as may occur with the melting of tundra and warming of continental shelves, are not included.

Exclusion of slow feedbacks is appropriate for the past century, because the ice sheets were stable and our climate simulations employ observed greenhouse gas amounts. Observed greenhouse gas amounts include any changes caused by slow feedbacks. Exclusion of slow feedbacks in the 21st century is a dubious assumption, used in our computations here only because the rate at which slow feedbacks come into play is poorly understood. However, we must bear in mind the potential for slow feedbacks to fundamentally alter the nature of future climate change. Specifically, the principal slow feedbacks have an amplifying effect and they could create a situation with continuing climate change that is largely out of humanity's control.

Slow feedbacks help to crystallize the need to keep maximum warming from significantly exceeding 1°C. With current global warming evidence of slow feedbacks is beginning to appear, e.g., increasing loss of ice mass from Greenland and Antarctica (Velicogna, 2009; Rignot et al., 2011) and methane release by melting tundra (Walter et al., 2006) and warming of sea-bed gas hydrates (Westbrook et al., 2009). The fact that observed effects are small so far suggests that these feedbacks may not be a major factor if maximum global warming reaches only ~1°C and then recedes.

In contrast, if BAU $CO_2$ emissions continue for many decades there is little doubt that these slow feedbacks will come into play in major ways. $CO_2$ injected into the air stays in the surface carbon reservoirs for millennia, so the slow feedbacks will occur if $CO_2$ amount is elevated to a high level. It is only a question of how fast the slow feedbacks would occur, and thus which generations would suffer the greatest consequences.

There humanity faces a dichotomy. Either we achieve a scenario with declining $CO_2$ emissions, thus preserving a planetary climate resembling the Holocene or we pass tipping points that assure transition to a very different planet with foreseen and unforeseen consequences.

**Dangerous level of warming.** What level of global warming would necessarily push Earth past such tipping points? We cannot be precise, due to poor understanding of slow feedbacks. But consider the case with BAU emissions until 2030 (Fig. 5b). Even though $CO_2$ emissions are phased out rapidly (5%/year reductions) after 2030 and 100 GtC reforestation occurs in 2031-2080, the global temperature rise reaches 1.5°C and stays above 1°C until after 2400. It is highly unlikely that the ice sheets would be stable at their present size with such long-lasting warmth. If BAU continues only until 2020, the temperature rise exceeds 1°C for about 100 years.

The scenario with 5%/year reduction of $CO_2$ emissions beginning in 2013 (Fig. 5a) yields a maximum global temperature just exceeding 1°C, remaining above that level for just a few decades. This scenario provides the prospect that humanity and other life on the planet still have a chance of residing in a world similar to the one in which civilization developed.

Precise consequences of continuing BAU emissions for several decades are difficult to define, because Earth has never experienced such a large rapid increase of climate forcings as would occur with burning of most fossil fuels this century. The closest analogy in Earth's history is probably the PETM (Paleocene-Eocene Thermal Maximum) in which rapid global warming of at least 5°C occurred (Zachos et al., 2001). The PETM warming spike occurred in conjunction with injection of 3000-5000 GtC of carbon into the surface climate system during two 1-2 thousand year intervals separated by several thousand years (Zeebe et al., 2009). It is often assumed that the carbon originated from melting of methane hydrates, because of the absence of other known sources of that magnitude. PETM occurred during a 10-million year period of slow global warming, and thus methane release might have been a feedback magnifying that warming.

The PETM witnessed extinction of about half small shelled deep ocean animals that serve as a biological indicator for ocean life in general, but, unlike several other large warming events in Earth's history, there was little extinction of land plants and animals. An important point is that the magnitude of the PETM carbon injection and warming is comparable to what will occur if humanity burns most of the fossil fuels, but the human-made warming is occurring 10-100 times faster. The ability of life on Earth today to sustain a climate shock comparable to the PETM but occurring 10-100 times faster is highly problematic. Climate zones would be shifting much faster than species have ever faced. Thus if humanity burns most of the fossil fuels, Earth, and all species residing on it, will be pushed into uncharted climate change territory.

## Likely Impacts of Global Warming

Despite the absence of a good paleoclimate analog, we can use a variety of sources to gain insight about likely effects of human-made warming. Paleoclimate data provide an indication of likely long-term responses to changed boundary conditions. Global observations of ongoing climate change help to reveal the rate at which changes may occur. Climate models allow us to simulate the global response to alternative climate forcings. But we must bear in mind that some important processes, such as ice sheet disintegration and species extermination, are difficult to simulate and have the potential to be highly non-linear. That means changes can be slow until a tipping point is reached (Lenton et al., 2008) and more rapid change occurs.

**Sea level.** The most recent prior interglacial period, the Eemian, was at most about 1°C warmer than the Holocene (Fig. 2). Sea level reached heights several meters above today's level with instances of sea level change by 1-2 meters per century (Rohling et al., 2008; Muhs et al., 2011). Geologic shoreline evidence has been interpreted as indicating a rapid sea level rise to a peak 6-9 meters above present late in the Eemian followed by a precipitous sea level fall (Hearty and Neumann, 2001; Hearty et al., 2007), although there remains debate within the research community about this specific history. The important point is that the high Eemian sea level excursions imply rapid partial melting of Antarctic and/or Greenland ice when the world was little warmer than today. During the Pliocene, when Earth may have been only 1-2°C warmer than the Holocene (Figure 2), sea level was probably 15-25 meters higher than today (Dowsett et al., 1999, 2009; Naish et al., 2009).

Expected human-caused sea level rise is controversial partly because the discussion and predictions of IPCC (2001, 2007) have focused on sea level rise at a specific date, 2100. Recent estimates of likely sea level rise by 2100 are of the order of 1 m (Vermeer and Rahmstorf, 2009; Grinsted et al., 2010). Ice-dynamics studies estimate that rates of sea-level rise of 0.8 to 2 m per century are feasible (Pfeffer et al., 2008) and Antarctica alone could contribute up to 1.5 m per century (Turner et al., 2009). Hansen (2005, 2007) has argued that BAU $CO_2$ emissions produce a climate forcing so much larger than any experienced in prior interglacial periods that a non-linear ice sheet response with multi-meter sea level rise may occur this century.

Accurate measurements of ice sheet mass loss may provide the best means to detect nonlinear ice sheet loss. The GRACE satellite, measuring Earth's gravitational field since 2003, reveals that the Greenland ice sheet is losing mass at an accelerating rate, now more than 200 cubic kilometers per year, and Antarctica is losing more than 100 cubic kilometers per year (Sorensen and Forsberg, 2010; Rignot et al., 2011). However, the present rate of sea level rise, 3 cm per decade, is moderate, and the ice sheet mass balance record is too short to determine whether we have entered a period of continually accelerating ice loss.

Satellite observations of Greenland show that the surface area with summer melting has increased over the period of record, which extends back to the late 1970s (Steffen et al., 2004; Tedesco et al., 2011). Yet the destabilizing mechanism of greatest concern is melting of ice shelves, tongues of ice that extend from the ice sheets into the oceans and buttress the ice sheets, limiting the rate of discharge of ice to the ocean. Ocean warming is causing shrinkage of ice shelves around Greenland and Antarctica (Rignot and Jacobs, 2002).

Loss of ice shelves can open a pathway to the ocean for portions of the ice sheets that rest on bedrock below sea level. Most of the West Antarctic ice sheet, which alone could raise sea level by 3-5 meters, rests on bedrock below sea level, so it is the ice sheet most vulnerable to rapid change. However, parts of the larger East Antarctic ice sheet are also vulnerable. Indeed, satellite gravity and radar altimetry reveal that the Totten Glacier of East Antarctica, fronting a large ice mass grounded below sea level, is already beginning to lose mass (Rignot et al., 2008)

The important point is that uncertainties about sea level rise mainly concern the timing of large sea level rise if BAU emissions continue, not whether it will occur. If all or most fossil fuels are burned, the carbon will be in the climate system for many centuries, in which case multi-meter sea level rise is practically certain (e.g., Rohling et al., 2009). Such a sea level rise would create millions of global warming refugees from highly-populated low-lying areas, who must migrate from the coastline, throwing existing global demographics into chaos.

**Shifting climate zones.** Theory and climate models indicate that subtropical regions expand poleward with global warming (Held and Soden, 2006; IPCC, 2007). Observations already reveal a 4-degree latitude average poleward expansion of the subtropics (Seidel and Randel, 2006), yielding increased aridity in the southern United States (Barnett et al., 2008; Levi, 2008), the Mediterranean region, and Australia. Increased aridity and temperatures contribute to increased forest fires that burn hotter and are more destructive (Westerling et al., 2006).

Despite large year-to-year variability of seasonal temperature, decadal averages reveal that isotherms (lines of a given average temperature) having been moving poleward at a rate of about 100 km per decade during the past three decades (Hansen et al., 2006). This rapid shifting of climatic zones far exceeds natural rates of change. The direction of movement (poleward) has been monotonic since about 1975. Wild species have responded to this climatic shift, with at least 52 percent of species having shifted their ranges poleward (and upward) by as much as 600 km in terrestrial systems and 1000 km in marine systems (Parmesan and Yohe, 2003; Hoegh-Guldberg and Bruno, 2010). This trend will continue as long as the planet is as far out of energy balance as at present, a conclusion based on comparison of the observed trend with interdecadal variability in climate simulations (Hansen et al., 2007).

Humans may be to adapt to shifting of climate zones better than many other species. However, political borders can interfere with migration, and indigenous ways of life have already been adversely affected. Impacts are apparent in the Arctic, with melting tundra, reduced sea ice, and increased shoreline erosion. Effects of shifting climate zones may also be important for indigenous Americans who possess specific designated land areas, as well as other cultures with long-standing traditions in South America, Africa, Asia and Australia.

**Loss of Species.** Explosion of the human population across the landscape is having a profound influence on the well being of all other species. As recently as two decades ago biologists were more concerned with effects on biodiversity other than climate change, such as land use changes, nitrogen fertilization, and the direct effects of increased atmospheric $CO_2$ on plant ecophysiology (Parmesan, 2006). However, easily discernible impacts on animals, plants, and insects of the nearly monotonic global warming during the past three decades (Fig. 1) have sharply altered perceptions of the greatest threats.

A dramatic awakening was provided by sudden widespread decline of frogs, with extinction of entire mountain-restricted species attributed to global warming (Pounds et al., 1999, 2006). Although there are somewhat different interpretations of the detailed processes involved in global amphibian declines and extinctions (Alford et al., 2007; Fagotti and Pascolini, 2007), there is agreement that global warming is a main contributor to a global amphibian crisis: "The losses portend a planetary-scale mass extinction in the making. Unless humanity takes immediate action to stabilize the climate, while also fighting biodiversity's other threats, a multitude of species is likely to vanish" (Pounds et al., 2007).

Mountain-restricted species are particularly vulnerable to global warming. As isotherms move up the mountainside, so does the climate zone in which a given species can survive. If global warming continues unabated,many mountain-dwelling species will be driven to extinction as these species literally run out of mountain habitat.

Polar-restricted species face similar problems. There are documented reductions in the population and health of Arctic species living in the southern parts of the Arctic and Antarctic species in the more northern parts of the Antarctic. A critical factor for survival of some Arctic species will be retention of all-year sea ice. Continued BAU fossil fuel use will result in loss of all Arctic summer sea ice within the next several decades. In contrast, the scenario in Fig.5a, with global warming peaking just over 1°C and then declining slowly, should allow some summer sea ice to survive and then gradually increase to levels representative of recent decades.

The threat to species survival is not limited to mountain and polar species. Plant and animal distributions are a reflection of the regional climates to which they are adapted. Although species attempt to migrate in response to climate change, their paths may be blocked by human-constructed obstacles or natural barriers such as coast lines. As the shift of climate zones becomes comparable to the range of some species, the less mobile species will be driven to extinction. Because of extensive species interdependencies, this can lead to mass extinctions.

IPCC Working Group II (IPCC, 2007b) reviews studies relevant to estimating eventual extinctions as a function of global warming. If global warming relative to the pre-industrial level exceeds 1.6°C, they estimate that 9-31 percent of species will be committed to extinction. With global warming of 2.9°C, an estimated 21-52 percent of species will be committed to extinction.

Mass extinctions have occurred in conjunction with rapid climate change during Earth's long history, and new species evolved over hundreds of thousands and millions of years. But such time scales are almost beyond human comprehension. If we drive many species to extinction we will leave a more desolate planet for our children, grandchildren, and as many generations as we can imagine.

**Coral reef ecosystems.** Coral reefs, often described as the rainforests of the ocean, are the most biologically diverse marine ecosystem. An estimated 1-9 million species, most not yet described (Reaka-Kudla, 1997), populate coral reef ecosystems generating crucial ecosystem services for at least 500 million people in tropical coastal areas. These ecosystems are vulnerable to the effects of ocean acidification and warming.

Acidification arises as the ocean absorbs $CO_2$, producing carbonic acid. The palaeontological record shows that ocean pH is already outside its range of the past several million years (Raven et al., 2005; Pelejero et al., 2010). Warming causes coral bleaching, as overheated coral expel symbiotic algae and die. Coral bleaching and slowing of coral calcification already are causing mass mortalities, increased coral disease, and reduced reef carbonate accretion, thus disrupting coral reef ecosystem health (Hoegh-Guldberg et al., 2007; De'Ath et al., 2009).

Local human-made stresses add to the global warming and acidification effects, together driving a rapid contraction, 1-2% per year, in the extent of coral reefs (Bruno and Selig, 2007). Loss of the three-dimensional framework that typifies coral reefs has consequences for the millions of species that depend on the reefs for their existence. Loss of these frameworks also has consequences for the important roles that coral reefs play in supporting fisheries and protecting coastlines from wave stress. Consequences of lost coral reefs can be economically devastating for many nations, especially in combination with other impacts such as sea level rise.

The situation with coral reefs has been aptly summarized (Schuttenberg and Hoegh-Guldberg, 2007): "Although the current greenhouse trajectory is disastrous for coral reefs and the millions of people who depend on them for survival, we should not be lulled into accepting a world without corals. Only by imagining a world with corals will we build the resolve to solve the challenges ahead. We must avoid the 'game over' syndrome and marshal the financial, political, and technical resources to stabilize the climate and implement effective reef management with unprecedented urgency."

**Hydrologic extremes and storms.** Extremes of the hydrologic cycle are intensified as Earth becomes warmer. A warmer atmosphere holds more moisture, so heavy rains become more intense and increase flooding. Higher temperatures, on the other hand, cause an intensification of droughts, as does expansion of the subtropics with global warming.

The IPCC (2007) report confirms existence of expected trends, e.g., precipitation has generally increased over land poleward of the subtropics and decreased at lower latitudes. Tropospheric water vapor has increased. Heavy precipitation events have increased substantially. Droughts are more common, especially in the tropics and subtropics.

**Mountain glaciers.** Glaciers are in near-global retreat (IPCC, 2007). After a one-time added flush of fresh water, glacier demise will frequently yield summer and autumn drying of rivers originating in the Himalayas, Andes, and Rocky Mountains that now supply water to hundreds of millions of people (Barnett et al., 2008). Present glacier retreat and global warming in the pipeline indicate that 390 ppm of $CO_2$ is already a threat for future fresh water security.

**Human health.** Children are especially vulnerable to the health impacts of climate change. Principal effects are summarized in Table 1 under the headings: (1) heat waves, (2) asthma and allergies, (3) infectious disease spread, (4) pests and disease spread across taxa: forests, crops and marine life, (5) winter weather anomalies, (6) drought, (7) food insecurity. Climate change poses a threat to health through many pathways, especially by placing additional stress on the availability of food, clean air, clean water, and potentially by expanding the burden of disease from vector-borne diseases (Bernstein and Myers, 2011).

World health experts have concluded with "very high confidence" that climate change already contributes to the global burden of disease and premature death (IPCC, 2007b). Effects so far are small, but they are projected to progressively increase in all countries and regions. IPCC (2007b) describes evidence that climate change has already altered the distribution of some infectious disease vectors, altered the seasonal distribution of some allergenic pollen species, and increased heat-related deaths.

If BAU $CO_2$ emissions continue and global warming increases IPCC (2007b) projects the following trends, where we include only those that are assigned either high confidence or very high confidence: (1) increased malnutrition and consequent disorders, including those related to child growth and development, (2) increased death, disease and injuries from heat waves, floods, storms, fires and droughts, (3) increased cardio-respiratory morbidity and mortality associated with ground-level ozone, (4) some benefits to health, including fewer deaths from cold, although it is expected that these would be outweighed by the negative effects.

## Table 1. Climate Change Impacts on Human Health

| | |
|---|---|
| **Heatwaves.** | Heatwaves are not only increasing in frequency, intensity and duration, but their nature is changing. Warmer nighttime temps [double the increase of average temperature since 1970 (Karl et al., 1993)] and higher humidity (7% more for each 1ºC warming) make heat-waves all the more lethal. |
| **Asthma and allergies.** | Asthma prevalence has more than doubled in the U.S. since 1980, with several of the exacerbating factors stemming from fossil fuel burning.<br>Increased $CO_2$ and warming boost pollen production from fast growing trees in the spring and ragweed in the fall (allergenic proteins also increase). Particulates help deliver pollen and mold spores deep into the lung sacs. Ground-level ozone, which increases in heat-waves, primes the allergic response. Climate change has extended the allergy and asthma season two-four weeks in the Northern Hemisphere (depending on latitude) since 1970.<br>Increased $CO_2$ stimulates growth of poison ivy and a chemical in it (uruschiol) that causes contact dermatitis. |
| **Infectious disease spread.** | The spread of infectious diseases is influenced by climate change in two ways: warming expands geographic and temporal conditions conducive to transmission of vector-borne diseases (VBDs), while floods can leave "clusters" of mosquito-, water – and rodent-borne diseases (and spread toxins). The warming atmosphere, holding more water vapor, has increased rainfall intensity in the U.S. since 1970 -- 7% overall, 14% for 2"/day rain, 20% for 4"/day, 27% for 6"/day (Groisman et al., 2005), with many implications for health, crops and nutrition.<br>Tick-borne Lyme disease (LD) is the most important VBD in the U.S. LD reports rose 8-fold in New Hampshire in the past decade and 10-fold in Maine (now in all of its 16 counties). Warmer winters and disproportionate warming toward the poles mean that the changes in range are occurring faster than models based on changes in average temperatures project. Biological responses of vectors (and plants) to warming have generally been underestimated, and may be leading indicators of warming due to the disproportionate increase of winter minimum and high latitude temperatures. |
| **Pests and disease spread across taxa: forests, crops and marine life.** | Pests and diseases of forests, crops and marine life are favored in a warming world. Bark beetles are overwintering (absent sustained killing frosts) and expanding their range, and getting in more generations, while droughts in the West dry the resin that drowns the beetles as they try to drive through the bark. (Warming emboldens the pests while extremes weaken the hosts.) Forest health is also threatened in the Northeast U.S. (Asian Long-horned beetle and wooly adelgid of hemlock trees), setting the stage for increased wildfires with injury, death and air pollution, loss of carbon stores, and damage to oxygen and water supplies. In sum, forest pests threaten basic life support systems that underlie human health.<br>Crop pests and diseases are also encouraged by warming and extremes. Warming increases their potential range, while floods foster fungal growth and droughts favor whiteflies, aphids and locust. Higher $CO_2$ also stimulates growth of agricultural weeds. More pesticides, herbicides and fungicides (where available) pose other threats to human health. Crop pests take up to 40% of yield annually, totaling ~$300 billion in losses (Pimentel).<br>Marine diseases (e.g., coral, sea urchin die-offs, and others), harmful algal blooms (from excess nutrients, loss of filtering wetlands, warmer seas and extreme weather events that trigger HABs by flushing nutrients into estuaries and coastal waters), plus the over 350 "dead zones" globally affect fisheries, thus nutrition and health. |
| **Winter weather anomalies.** | Increasing winter weather anomalies is a trend to be monitored. More winter precipitation is falling as rain rather than snow in the Northern Hemisphere, increasing the chances for ice storms, while greater atmospheric moisture increases the chances of heavy snowfalls. Both affect ambulatory health (orthopedics), motor vehicle accidents, cardiac disease and power outages with accompanying health effects. |
| **Drought.** | Droughts are increasing in frequency, intensity, duration, and geographic extent. Drought and water stress are major killers in developing nations, bringing disease outbreaks including water-borne cholera and mosquito-borne dengue fever (mosquitoes breed in stored water containers). Drought and higher $CO_2$ increase the cyanide content of cassava, a staple food in Africa, leading to neurological disabilities and death. |
| **Food insecurity.** | Food insecurity is a major problem worldwide. Demand for meat, fuel prices, displacement of food crops with biofuel crops all contribute. Extreme weather events today are an acute driver. Russia's extensive 2010 summer heat-wave (several standard deviations above the norm, killing over 50,000 people) reduced wheat production ~40%; unusually extensive worldwide floods and droughts in 2010 caused grain shortages and raised prices in many nations. Food riots occurred in Uganda and Burkino Faso; resulting desperation from food and fuel price hikes probably contributed to uprisings in North Africa and the Middle East. Food shortages and price hikes contribute to malnutrition that underlies much of poor health and vulnerability to infectious diseases. Food insecurity also leads to political instability, conflict and war. |

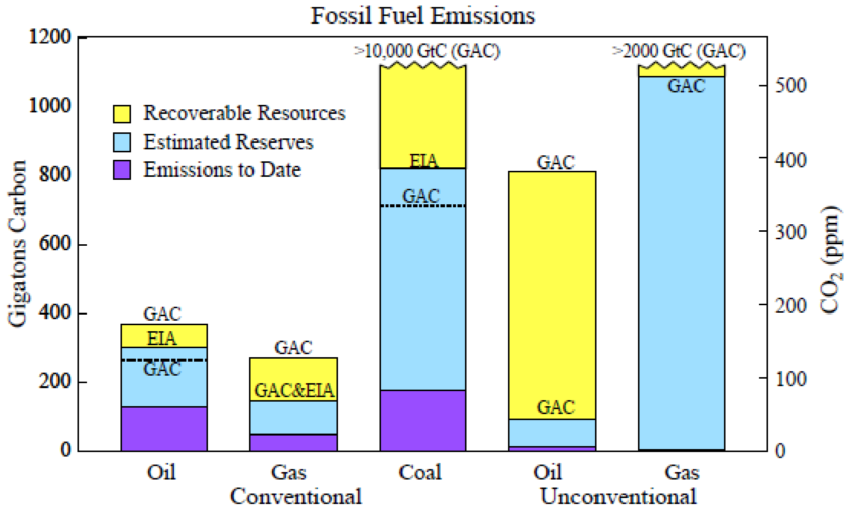

**Figure 6.** $CO_2$ emissions by fossil fuels (1 ppm $CO_2$ ~ 2.12 GtC). Estimated reserves and potentially recoverable resources are from EIA (2011) and GAC (2011).

## Implications for Humanity

Burning all fossil fuels would create a different planet than the one that humanity knows. It is clear from paleoclimate data and ongoing climate change that the climate system would be pushed beyond tipping points, setting in motion irreversible changes, including ice sheet disintegration with a continually adjusting shoreline, extermination of a substantial fraction of species on the planet, and increasingly devastating regional climate extremes.

Fossil fuel emissions so far are a small fraction of known reserves and potentially recoverable resources (Fig. 6). There are uncertainties in estimated reserves and resources, especially coal (Reference), some of which may not be economically recoverable with current technologies and energy prices. But there is already more than enough fossil fuel reserve to transform the planet, and fossil fuel subsidies and technological advances will make more and more of the resources available.

We have shown that phase out of fossil fuel emissions is urgent. $CO_2$ from fossil fuel use stays in the surface climate system for millennia. Failure to phase out emissions rapidly will leave young people and future generations an enormous clean-up job. The task of extracting $CO_2$ from the air is so great that success would be dubious, raising the likelihood of a spiral into climate catastrophes and efforts to "geo-engineer" restoration of planetary energy balance.

Most proposed schemes to artificially restore Earth's energy balance aim to reduce solar heating, e.g., by maintaining a haze of stratospheric particles that reflect sunlight to space. Such attempts to mask one pollutant with another pollutant almost inevitably will have unintended consequences. Moreover, schemes that do not remove $CO_2$ will not avert ocean acidification. The pragmatic path is for the world to move expeditiously to carbon-free energies and increased energy efficiency, leaving most remaining fossil fuels in the ground.

Transition to a post-fossil fuel world of clean energies will not occur as long as fossil fuels are the cheapest energy. However, fossil fuels are not actually least cost – they seem cheap only because they are subsidized directly and indirectly, and because they do not pay their costs to society – the costs of air and water pollution and costs of present and future climate change.

Thus the essential underlying policy, albeit not sufficient, is a price on carbon emissions. The price should rise over decades such that people and businesses can efficiently adjust their lifestyles and investments to minimize costs. The right price for carbon and the best mechanism for carbon pricing are more matters of practicality than of economic theory.

Economic analyses suggest that a carbon price fully incorporating environmental and climate damage, though uncertain, would be high (Stern, 2007). Ackerman and Stanton (2011) conclude that the cost of climate damage is uncertain by at least a factor of 10, but could be as high as ~\$1000/tCO$_2$. Such high prices are outside the realm of short-term political feasibility, but prices that high are not necessary to engender a change in emissions trajectory.

An economic analysis indicates that a tax of \$15/tCO$_2$, rising \$10/tCO$_2$ per year, could reduce emissions in the United States by 25-30% after 10 years (Reference). Such a reduction of carbon emissions is more than 10 times greater than the carbon content of tar sands oil that would be carried by the proposed Keystone XL pipeline (Reference).

The relative merits of a carbon tax versus cap-and-trade continue to be discussed (Hsu, 2011; other references; also see our Supplementary Material). Cap-and-trade has had some success in Europe, but failed in the crucial arena of U.S. policy, as opponents decisively won the rhetorical battle by describing it as a devious new tax. The merits of an alternative, a gradually rising fee on carbon emissions collected from fossil fuel companies with proceeds distributed to the public, have been summarized by DiPeso (2010), Policy Director of Republicans for Environmental Protection, as: "Transparent. Market-based. Does not enlarge government. Leaves energy decisions to individual choices… Sounds like a conservative climate plan."

A rising carbon price is the *sine qua non* for fossil fuel phase out, but it is not sufficient. Other needs include investment in energy R&D and testing of new technologies such as improved low-loss smart electric grids, electrical vehicles interacting effectively with the power grid, energy storage for intermittent renewable energy, new nuclear power plant designs, and carbon capture and storage. Governments need to support energy planning for housing and transportation, energy and carbon efficiency requirements for buildings, vehicles and other manufactured products, global monitoring systems, and climate mitigation and adaptation in undeveloped countries.

Rhetoric of political leaders, including phrases such as "a planet in peril", leaves the impression that they fully grasp the planetary crisis caused by rising atmospheric CO$_2$. However, closer examination reveals that much of this rhetoric is aptly described as "greenwash", as even nations considered to be among the "greenest" are supporting expanded fossil fuel extraction including the most carbon-intensive fuels such as tar sands (Hansen, 2009). The reality is that most governments, rather than taking actions to rapidly phase out fossil fuels, are allowing and partially subsidizing continued fossil fuel extraction, including expansion of oil drilling to increasing ocean depths, into the Arctic, and onto environmentally fragile public lands; squeezing of oil from tar sands and tar shale; hydro-fracking to expand extraction of natural gas; and increased mining of coal via mechanized longwall mining and mountain-top removal.

How is it possible that a specter of large human-driven climate change has unfolded virtually unimpeded, despite scientific understanding of likely consequences? Would not governments – presumably instituted for the protection of all citizens – have stepped in to safeguard the future of young people? A strong case can be made that the absence of effective leadership in most nations is related to the undue sway of special financial interests on government policies and effective public relations efforts by people who profit from the public's fossil fuel addiction and wish to perpetuate that dependence (Oreskes and Conway, 2010).

Such a situation, with the science clear enough to demand action but with public understanding of the situation, and thus political response, hampered by the enormous financial power of special interests, suggests the possibility of an important role for the judiciary system. Indeed, in some nations the judicial branch of government may be able to require the executive branch to present realistic plans to protect the rights of the young (Wood, 2009). Plans for emission reductions should be consistent with what the science shows is required to stabilize climate.

Judicial recognition of the exigency and the rights of young people may be helpful in drawing attention to the need for a rapid change of direction. However, fundamental change is unlikely without public support. Obtaining public support probably requires widespread recognition that a prompt orderly transition to the post fossil fuel world, via a gradually rising price on carbon emissions, makes sense and is economically beneficial

The most basic matter, however, is not one of economics. It is a matter of morality – a matter of intergenerational justice. The blame, if we fail to stand up and demand a change of course, will fall on us, the current generation of adults. Our parents did not know that their actions could harm future generations. We, the current generation, can only pretend that we did not know. And that is unforgiveable.

[This last section, i.e., after the science has been made clear, would seem to be where we should try to bring in the moral aspect more strongly – it would be extremely powerful if brought with the moral authority of the Dalai Lama and Desmond Tutu.]

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