Global Warming: East-West Connections

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Abstract. Air pollutants that damage human health and agricultural productivity, such as tropospheric ozone and black soot, also affect global climate. Multiple benefits of reducing these pollutants become more compelling as concern about global warming increases. Air pollution is especially harmful in developing countries that are now large emitters of carbon dioxide, providing incentive for developed and developing countries to cooperate in reducing both global air pollution and climate change.

The Earth's history provides a sobering perspective on prospects for climate change. The Earth's climate is sensitive to changes in climate forcings, human-made forcings now overwhelm natural climate forcings, and the climate system is dangerously close to tipping points that could have disastrous consequences. Atmospheric composition is now near the limits that must not be exceeded if we wish to maintain a planet resembling the one on which civilization developed, with the equable climate of the Holocene.

Yet quantitative examination of climate forcings reveals a potential path to climate stability with a bright future for life on the planet. Except for carbon dioxide, human-made forcings are increasing more slowly than in the scenarios of the Intergovernmental Panel on Climate Change (IPCC). A focused effort to achieve absolute reductions in non-CO_2 forcings, combined with a slowdown of CO_2 emissions and phase-out of coal use except at power plants that capture and store the gas, could keep additional global warming well below 1°C.

Attainment of this 'alternative scenario' for future climate requires overturning the common presumption of energy departments that all fossil fuels, including those that are remote or difficult to extract, must be exploited before the world turns to energy sources 'beyond fossil fuels' and begins placing much greater emphasis on energy efficiency and renewable energies. Cooperation between developed and developing countries is essential. Recognition of responsibilities for the present situation and the numerous mutual benefits of required actions make such cooperation plausible.

1. Introduction

A workshop on air pollution as a climate forcing was held at the East-West Center in Honolulu, Hawaii on April 4-6, 2005. Uncertainties about effective climate forcings by specific pollutants prevented attainment of a consensus at that time on the merits of including conventional health-damaging air pollutants in strategies for climate mitigation. Subsequent research has not only narrowed uncertainties about climate forcings, but also suggests that global warming has brought the Earth's climate close to dangerous tipping points.

A climate tipping point refers to a situation in which moderate additional climate forcing may produce large effects, such as loss of all Arctic sea ice and destabilization of the West Antarctic ice sheet. Large climate changes, overall, are inherently deleterious, as civilization developed during a period of climate stability and constructed extensive infrastructure based on current climate patterns and shorelines. Life on Earth will adapt to changing climate, but many species will be casualties if climate change is much more rapid than natural rates. Thus there is a need to quantify all climate forcings to help define strategies that minimize climate change.

Global climate change affects both developed and developing countries. Some regional air pollutants, such as mercury contamination of the ocean, now have near-global effects, and local air pollution is a major health hazard in developing countries. All countries will benefit from reduced air pollution and global climate forcings.

East-West cooperation in the research defining air pollution and climate problems will make it easier to agree upon actions needed to stabilize climate and provide clean air and water. Thus a summary of current understanding of air pollution as a climate forcing is timely and helps define further East-West dialogue.

We use the Earth's climate history to provide some insight about natural climate change and the significance of human-made forcings. Climate sensitivity on the time-scale of human-made atmospheric perturbations is greater than has commonly been supposed. However, recent trends of some global climate forcings are encouraging. We present evidence that feasible reductions of human-caused emissions of black soot, methane, carbon monoxide, other chemical precursors of tropospheric ozone, and several minor trace gases, combined with an aggressive but realistic and beneficial strategy for slowing fossil fuel CO_2 emissions, could keep human-made climate change within manageable bounds.

2. Perspective from the Earth's History

A reasonable person, but one not fully cognizant of current knowledge about climate change, may ask the question "Why should we bother to wrestle with human-made climate change? There have been huge climate changes during the Earth's history. It is arrogant to think that humans can control climate or that we know enough to say that today's climate is the best one for the planet."[1]

Yes, the Earth has experienced enormous climate variations. Indeed, the history of the Earth's climate provides an invaluable perspective for assessing the role of humans in shaping the planet's destiny.

Climate change during the entire 4.5 billion year history of the planet is of interest. However, the further back we look the murkier the climate and geologic records become. Also important factors influencing climate, such as the brightness of the sun and the size and location of continents, were significantly different in the distant past. Even the nature of life on Earth had dramatic consequences for climate on time scales of hundreds of millions of years (Berner 2004). For example, the large effect that trees have on chemical weathering of rocks, and thus on atmospheric composition, varied strongly as different plant types came into being, but these effects are not well quantified.

The Cenozoic Era, the past 65 million years, is a useful period to consider because it is recent enough to minimize these complicating factors. Yet it encompasses a large range of climates, including ice free conditions.

Solar luminosity is growing steadily on long time scales. Our sun is a well-behaved "main-sequence" star, i.e., it is still "burning" hydrogen, converting it to helium via nuclear fusion in the solar core. The sun's brightness is increasing at a rate such that solar luminosity in the early Cenozoic was ~0.5% less than today (Sackmann et al. 1993). Because the Earth

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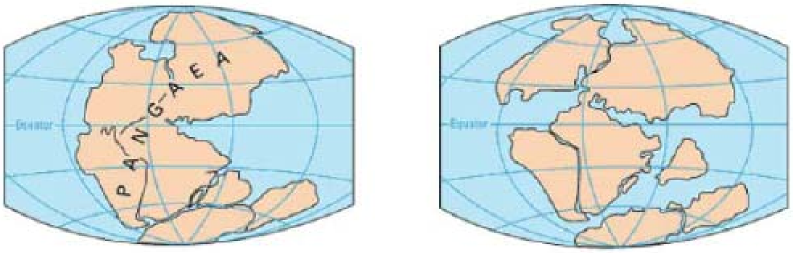
[1] This is a paraphrase of statements by NASA Administrator Michael Griffin on National Public Radio on 31 May 2007.

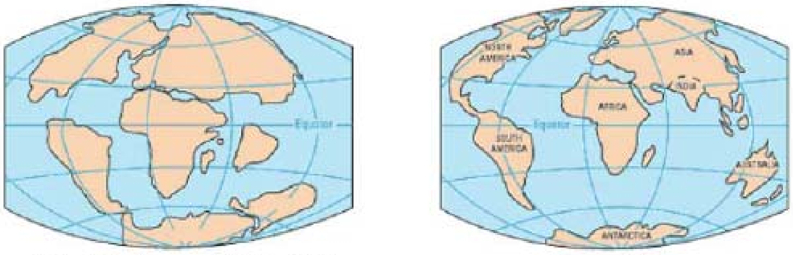
absorbs about 240 W/m^2 of solar energy, the climate forcing[2] due to reduced solar irradiance at the beginning of the Cenozoic was about -1 W/m^2 relative to today. The small growth of solar forcing through the Cenozoic era, as we will see, was a negligible factor in causing global climate change.[3]

Changing size and location of the continents is also an important climate forcing, as the "albedo" (literally the "whiteness" or reflectivity) of the Earth's surface depends on whether the surface is land or water and on the angle at which the sun's rays strike the surface. A quarter of a billion years ago the major continents were clumped together (Figure 1) in the super-continent Pangea centered on the equator (Keller and Pinter 1996). This configuration surely affected ocean and atmosphere circulations, as well as the amount of absorbed solar energy. However, by the early Cenozoic the continents were close to their present latitudes, albeit with the separation of the Americas from Europe-Africa being less than at present. Thus the direct (radiative) climate forcing due to movement of continents has been moderate during the Cenozoic.



End of Permian (250 My BP)

End of Jurassic (145 My BP)



End of Cretaceous (65 My BP)

Present Day

Fig. 1. Continental locations at various times (adapted from Keller and Pinter 1996).

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[2] A climate forcing is an imposed perturbation of the planet's energy balance, which tends to alter the planet's temperature. Thus a change of solar irradiance is a climate forcing, as is a change of the amount of long-lived greenhouse gases in the atmosphere, because these gases reduce emission of infrared (heat) radiation to space.

[3] Solar irradiance on the Earth also fluctuates on shorter time scales, primarily because fluctuating magnetic field strength near the sun's surface affects turbulence and heat storage, and thus the rate and directional distribution of solar energy emitted to space. Variations of solar irradiance at the Earth have been accurately measured since 1979, revealing that there is a significant variation of the solar forcing with the ~11 year sunspot cycle, solar maximum yielding about 0.1% (0.25 W/m^2) greater irradiance than solar minimum. There may be larger fluctuations of solar output on century time scales, as it is possible that the outer layers of the sun's atmosphere could store and release energy from the steadily "burning" solar interior. This is the basis for a suggestion that the period of the Maunder Minimum of solar activity (Eddy 1976), coinciding with the Little Ice Age, may have been due to a reduction of solar irradiance of as much as a few tenths of a percent. However, there is no observational confirmation of fluctuations of solar irradiance of that magnitude.

Role of continental drift. Crustal dynamics and associated orogeny affect climate in several ways. The changing size and connections of ocean basins affect ocean circulation and heat transport. Even atmospheric circulation can be substantially altered by orogeny such as the rise of the Himalayas and the Tibetan Plateau (Raymo and Ruddiman 1992). However, the greatest impact of continental drift on global climate surely comes via its effect on atmospheric composition, especially its effect on the carbon cycle.

Figure 1 shows schematic sequences of continental locations, ranging from the supercontinent Pangea to the present configuration of land masses (more detailed maps based on computer modeling of global plate tectonics are available at http://www.scotese.com/earth.htm). A feature of note is the Tethys Ocean that separated the Eurasian plate from Africa and the Indian plate during the Jurassic period. The Tethys Ocean was largely closed off as the African and Indian plates moved north, but remnants still exist today as the Mediterranean, Black, Caspian and Aral seas. Much of the Tethys Ocean floor was subducted under Eurasia as Africa and India pushed north, while other portions of the ocean floor were pushed up forming the Alps and Himalayas, as revealed in fossils of sea creatures found high in those mountains today.

Geologic carbon cycle. Discussion of the carbon cycle in the industrial era and in recent glacial and interglacial cycles focuses on the division of carbon among the atmosphere, ocean, soil and biosphere pools, as well as on the distribution of anthropogenic emissions of fossil carbon among those pools. On the time scale of millions of years it is useful to lump these surface pools of carbon into one reservoir. Atmospheric CO_2 amount, PCO_2, is a small fraction, of the order of 10**(-2), i.e., of order 1%, of this total surface reservoir.

On geologic time scales, millions of years, CO_2 in the surface reservoir is removed primarily via (1) weathering with deposition as carbonate layers in the ocean, and (2) burial of organic matter. CO_2 returns to the surface reservoir via mantle degassing, which is primarily associated with subduction of carbonates at active plate boundaries. In the present industrial era, CO_2 is also being returned to the surface reservoir via humanity's burning of fossil fuels.

Edmund and Huh (2003) emphasize that there is no requirement of a steady state balance in exchanges between the surface reservoir and buried carbon, i.e., between weathering uptake and metamorphic regeneration of CO_2. Plate tectonics can alter uplift, weathering and carbon burial independently of the rate of subduction and regeneration of carbon in the surface reservoir. At present, for example, the major depocenters for carbonate are the Atlantic and Indian oceans, which are not presently sites of subduction and regeneration of atmospheric CO_2. Edmond and Huh (2003) note that substantial metamorphic regeneration of CO_2 is now restricted to trenches off Central and South America and the Southwest Pacific Ocean, where relatively young carbonate-rich sea floor is being subducted. Degassing of lesser degree is also occurring in association with continuing orogeny in Western Americas and the Alpine-Himalayan orogen.

Cenozoic climate change. Proxy measures of global temperature change and atmospheric CO_2 during the Cenozoic are consistent with the broad picture of the geologic carbon cycle painted by Edmond and Huh (2003) and with the importance of Himalayan orogeny suggested by Raymo and Ruddiman (1992). Figure 2 shows a global compilation[4] of benthic

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[4] Combination of isotopic records from many sites around the world into a single time series loses potentially valuable information on inter-ocean basin differences in temperature histories and can possibly confuse or misrepresent certain features of the climate record (Lear et al 2004). On the other hand, the composite record tends to minimize the effect of flaws and imprecision in individual records and provides a good overview of global climate change, which is our aim here.

foraminifera ^{18}O isotope records (Zachos et al. 2001). Benthic forams are microscopic shelled animals living in the deep ocean. In the absence of large ice sheets, as during the early Cenozoic, the proportion of heavy oxygen isotope, ^{18}O, in the forams provides a direct measure of deep ocean temperature where the forams lived. Thus ocean sediment cores yield a temperature record for the early Cenozoic, until about 35 My BP (million years before present), as geologic records indicate that there was little ice on the planet in that interval. ^{18}O evaporates less readily than the lighter isotope, and thus ice sheets, formed by condensation of water evaporated from the ocean, are deficient in ^{18}O. As a result, increases of ^{18}O in ocean cores after 35 My BP reflect both increasing ice sheet mass and decreasing ocean temperature.

Temperature change in the early Cenozoic reflects expected effects of continental drift on CO_2 outgassing and weathering. The Indian plate moved north rapidly (~15 cm/year) in the early Cenozoic, crashing into slowly retreating (~2 cm/year) Eurasia about 50 My BP. In the period 65-50 My BP just prior to collision of these plates, subduction of Tethys Ocean floor provided extensive CO_2 outgassing, which we presume was the cause of the global warming that peaked about 50 My BP. With the India-Eurasia collision, the rapid rise of the Himalayas and Tibetan Plateau caused greatly increased weathering and drawdown of atmospheric CO_2.

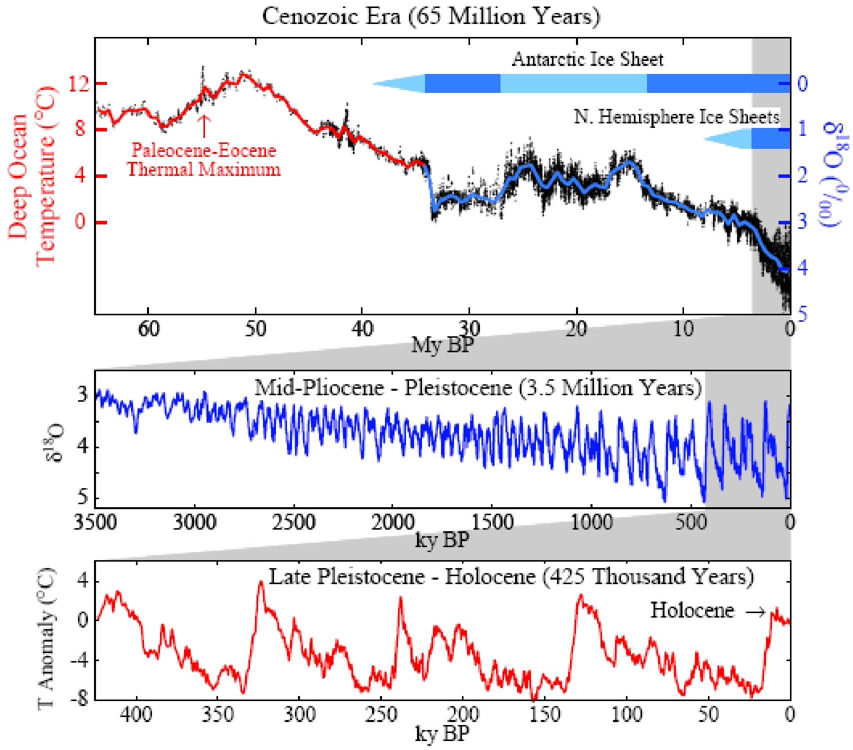

Figure 2. (a) Global compilation of deep-sea benthic foraminifera ^{18}O isotope records from Deep Sea Drilling Program and Ocean Drilling Program sites (Zachos et al 2001), temperatures applying only to ice-free conditions, thus to times earlier than ~35 My BP. The blue bar shows estimated times with ice present, dark blue being times when ice was equal or greater than at present. (b) Expansion of ^{18}O data for past 3.5 My. (Lisiecki and Raymo2005) (c) Temperature data based on Vostok ice core (Vimeux et al 2002).

Carbonates formed from weathering were deposited south of the subcontinent, in the new Indian Ocean, where they continue to accumulate today with, as yet, no return path to the atmosphere.

Proxy measures of CO_2, such as stomatal densities and indices in plants, provide only crude estimates. CO_2 amount at the thermal maximum 50 My BP was probably 600-1500 ppm, decreasing to about 400-600 ppm by 34 My BP (Pagani et al 2005; Royer 2006). Royer (2006) suggests a moderate recovery of CO_2 amount after 34 My BP, but then a further drawdown to 300-400 ppm by 23 My BP. Subsequent variations of CO_2 are too small to quantify with available proxy data (Pagani et al 2005; Royer 2006).

As Figure 2a indicates global cooling by 34 My BP was sufficient for a large ice sheet to form on Antarctica. We presume that the cooling was due in large part to the CO_2 drawdown, as calculations show (Hansen and Sato, in preparation) that the temperature and CO_2 changes are consistent with estimates of climate sensitivity. From 34 My BP until about 10 My BP, global temperature fluctuated, likely affected by the negative feedback due to reduced weathering in regions covered by ice (Lear et al 2004), as well as by variations of orogeny and subduction that occur with continental drift.[5]

In the last 10 My further global cooling has occurred. This additional cooling, as we show elsewhere (Hansen and Sato, in preparation), required only a small further drawdown of CO_2, because of the strong feedback caused by increasing ice cover. We suggest that the cooling in the past 10 My is due, at least in part, to rapid rise of the Andes (Garzione et al. 2006), which has both increased the rate of weathering and decreased outgassing by subduction in Central and South America. The increasing mass of the Andes is responsible for a ~30 percent slowdown of the Nazda plate (Iaffaldano et al 2007) and thus reduced subduction.

The middle section of Figure 2 expands the time scale for the most recent 3.5 My, showing a continuing cooling trend through the Plio-Pleistocene and the large glacial to interglacial climate cycles. The lower section further expands the past 425,000 years, for which ice cores provide a polar temperature history. The magnitude of glacial-interglacial global mean temperature variations are estimated to be about half as large as the changes at the poles, based on global climate reconstructions such as that for the last ice age.

Time scales. Absent humans, we suggest that it is likely that the Earth would have continued to cool off on the million year time scale. The Andes are continuing to grow, and thus subduction in Central and South America is likely to slow further. Weathering deposits due to continuing orogeny in the Himalayas and the Tibetan Plateau are at a high level (Figure 4F, Clift 2006). The rate of weathering is probably accelerated by the increasing areas subjected to glacial-interglacial grinding of the surface (Foster and Vance 2006). The major depocenters for carbonate formation, the Indian and Atlantic Oceans, are not presently contributing to subduction. The moderate continuing outgassing due to prior subductions, such as that in the Alps and Rocky Mountains presumably is continuing to dwindle on the million year time scale. Thus it seems likely that homo sapiens, with their industrial revolution and CO_2 emissions, saved the planet from a deeper freeze that would have occurred on the million year time scale.

This latter conjecture is no more than a curiosity, however, because of the huge difference in time scales between the natural and human-made effects. The magnitude of the flux of CO_2 to the atmosphere due to outgassing associated with subduction and the negative flux due to weathering are estimated by Edmond and Huh (2003) to be of the order of 2-4 x 10**12

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[5] It is noteworthy that the Antarctic ice largely disappeared in response to the partial CO_2 recovery. This behavior argues that formation of a large ice sheet is reversible, i.e., there is no hysteresis effect. Positive feedbacks allow an ice sheet to grow rapidly, but the feedbacks work in reverse when the forcing switches sign due to CO_2 recovery.

mol C/year; see also Staudigel et al. (1989). Even if the imbalance between outgassing and weathering were as large as say 2 x 10**12 mol C/year, this would change atmospheric CO_2 by only ~0.01 ppm per year. Moreover, any long-term imbalance between outgassing and weathering would be partitioned into the entire surface reservoir (two orders of magnitude larger than the atmospheric amount), so the hypothesized imbalance would contribute only of the order of 0.0001 ppm CO_2 per year to the atmosphere. Such an imbalance is important on million year time scales, amounting to 100 ppm atmospheric CO_2 in 1 My. However, it is negligible on the human time scale, given the enormous fluxes associated with burning of fossil fuels, as quantified below.

3. Climate Sensitivity

The earliest evidence of homo sapiens is at ~200,000 yr BP. The predecessor species, homo erectus, goes back to ~2 My BP. Thus humans have existed only during the cold period on the extreme right of Figure 2(a). Huge climate variations occurred before humans existed, and the large climate variations in the time of homo sapiens (Figure 2c) are clearly part of a long-term natural cycle. So what is the basis for saying that humans have become the dominant factor in long-term climate, and that continued growth of greenhouse gas emissions is dangerous?

The Earth's history provides our best assessment of how much climate will change in response to human-made climate forcings. A forcing is an imposed change of the planet's energy balance. For example, the increase of the sun's brightness over the past 65 My, as discussed above, has been a slow increase of climate forcing by about +1 W/m^2. This slow trend of incoming radiation over the several hundred thousand years of Figure 2c is ~0.01 W/m^2, which is negligible in comparison to the climate forcings due to changes on the Earth's surface and in the atmosphere. The changes on the surface and in the atmosphere are known well enough to permit accurate empirical evaluation of climate sensitivity.

Specifically, the amount of long-lived greenhouse gases in the atmosphere as a function of time is extracted from bubbles of air trapped as the ice sheets on Greenland and Antarctica built up from snowfall year-by-year. The primary change on the planet's surface[6] affecting the energy balance is the area of ice, which can be derived for the past 425,000 years from the sea level record. The climate forcings due to temporal change of atmospheric gases and surface albedo are shown in the middle part of Figure 3, after Hansen et al (2007a).

When these two forcings are added and multiplied by the factor ¾, as shown in the lower part of Figure 3, they yield remarkably good agreement with global temperature change inferred from paleoclimate records. The implied climate sensitivity, ¾°C per W/m^2 (equivalent to 3°C for doubled CO_2), is consistent with climate model estimates, but of greater precision. We can never be certain that climate models accurately include all relevant processes. But we know that the real world included all changes of clouds, water vapor, sea ice and any other such fast 'feedbacks' that exist.

It must be recognized that the specific climate sensitivity derived in this way includes only 'fast' feedbacks. We call this the Charney climate sensitivity, because it is essentially the case considered by Charney (1979), in which water vapor, clouds and sea ice were allowed to change in response to climate change, but GHG (greenhouse gas) amounts, ice sheet area, sea level and vegetation distributions were taken as specified boundary conditions. We would

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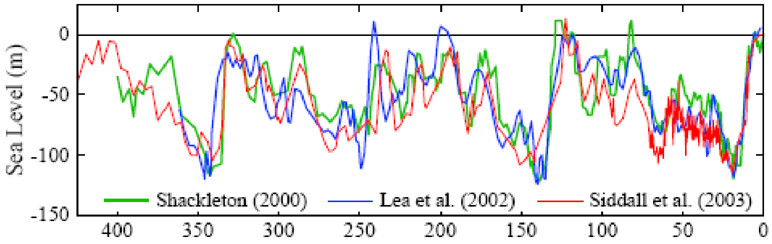
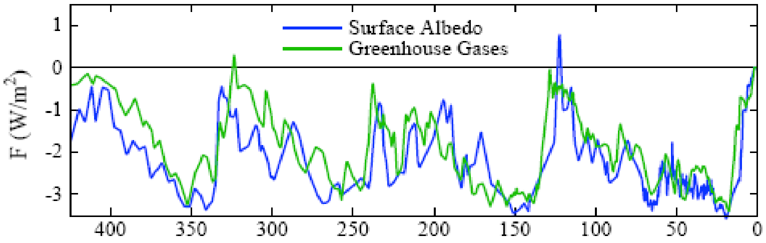
[6] The area of exposed continental shelf and the vegetation distribution are lesser factors that also change as sea level changes. These factors are included in the sensitivity ¾°C per W/m^2, which is obtained from climate simulations for conditions during the ice age 20 ky BP and the current interglacial period.

(a) Sea Level Records



(b) Climate Forcings



(c) Paleoclimate Temperature Change

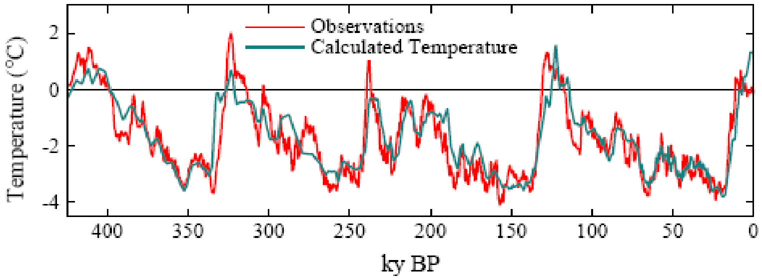


Figure 3. (a) Sea-level records of Shackleton (2000), Lea et al. (2002) and Siddall et al. (2003), (b) climate forcings due to greenhouse gases (CO_2, CH_4 and N_2O) and surface albedo, and (c) calculated and observed temperature change. Calculated temperature is the product of the climate forcing (b) and ¾°C per W/m^2. Observed temperature is Vostok temperature (Fig. 2c) divided by 2.

expect the Charney climate sensitivity to be most relevant on decadal time scales. On longer time scales as the quantities assumed to be fixed can change in response to climate change, thus becoming powerful climate feedback mechanisms.

Important insight emerges from close examination of the temperature and forcing curves: the temperature change leads the forcings by several hundred years. Thus the greenhouse gas and ice sheet changes, although they are the principal direct mechanisms for the climate change, are changing as feedbacks. The pacemaker and instigator of the changes is cyclic variation of the Earth's orbit (Hays et al. 1976), which alters the seasonal and geographical distribution of solar radiation. Insolation changes by a significant amount over several thousand years.

Variations of atmospheric CO_2 occurring as a climate feedback on the time scale of the ice ages (Figure 3) can be ~100 ppm in 5000 years, or 0.02 ppm/year. This atmospheric change is due to a shifting of carbon among the atmosphere, ocean, soil and biosphere compartments within the surface carbon pool, a warmer climate driving more CO_2 into the air. This natural glacial-interglacial variation of atmospheric CO_2 is quite rapid in comparison with the geologic

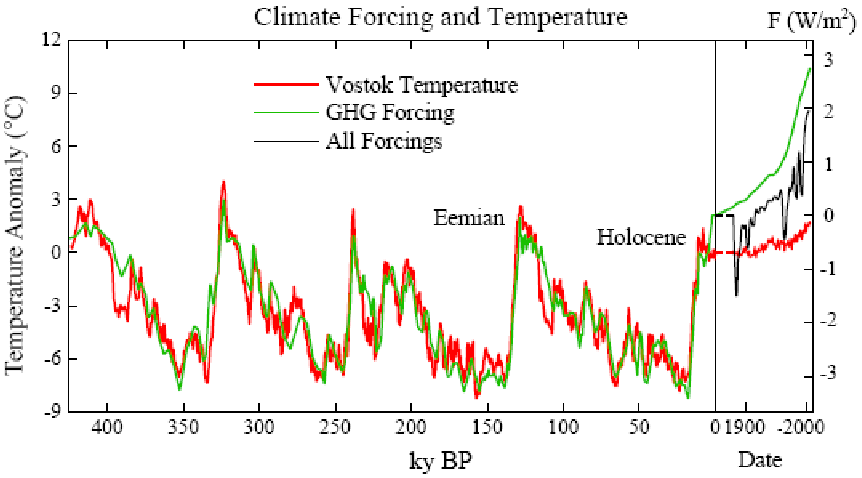


Figure 4. Greenhouse gas forcing (right scale) and Antarctic temperature change (left scale) based on Vostok ice core (Vimeux et al. 2002). Forcing zero point is for 1850 climate forcings specified by Hansen et al. (2007b). Temperature zero point is 'present' value from the Vostok ice core (Vimeux et al. 2002). Ratio of temperature and forcing scales (3.02°C per W/m^2) is chosen such that the standard deviations of temperature and forcing are equal. In the 1850-present expanded time scale on the right, the temperature change is the global mean times two, for consistency with the Antarctic temperature change on the left. Two forcing curves are shown for 1850-present, one for long-lived GHGs and one for the net of all 10 radiative forcings of Hansen et al. (2007b), which include a substantial negative forcing by tropospheric aerosols.

cycling of carbon between the Earth's crust and the surface carbon pool, which amounts to ~ 10**(-4) ppm/year of CO_2, as discussed above.

These natural rates of atmospheric CO_2 change must be compared with the human-caused growth of atmospheric CO_2, which is now ~ 2 ppm/year (see below). Humans, indeed, are now in control of long-lived atmospheric GHGs. As a result it is important to investigate climate sensitivity for the case in which GHGs are specified as the forcing. The Charney climate sensitivity applies to this case under the assumption that slow feedbacks such as ice sheet area, vegetation distribution, and climate-induced GHG changes are not allowed to operate.

As a complement to the Charney climate sensitivity, let us derive the climate sensitivity that applies if these slow feedbacks are allowed to operate: we call this the 'long-term' climate sensitivity. We can obtain this 'long-term' climate sensitivity from paleoclimate data by finding the scale factor that causes the GHG forcing to match the paleoclimate temperature change as accurately as possible. Figure 4 shows that multiplying the climate forcing due to long-lived GHGs ($CO_2 + CH_4 + N_2O$) by 3.02°C per W/m^2 yields remarkably good agreement with Antarctic temperature. Given that glacial-interglacial global temperature change is about half of Antarctic temperature change, this implies a 'long-term' climate sensitivity of ~1.5 W/m^2 or about 6°C for doubled CO_2.

Which climate sensitivity is more relevant to humanity: the Charney 3°C for doubled CO_2 or the 'long-term' 6°C for doubled CO_2? Both. The net human-made climate forcing, including negative forcing by tropospheric aerosols, has been substantially positive only for the past three decades. On that time scale the Charney sensitivity is a good approximation, as little contribution from slow feedbacks would be expected. Thus climate models with 3°C sensitivity for doubled CO_2, incorporating only the fast feedbacks, are able to achieve good agreement with observed warming of the past century. We suggest, however, that these models provide only a lower limit on the expected warming on century time scales due to the assumed forcings. The real world will be aiming on the longer run at a warming corresponding to the higher climate sensitivity.

Note that the 6°C sensitivity for doubled CO_2 applies to the Pleistocene. About half of that sensitivity is from the ice sheet albedo feedback. At earlier times in the Cenozoic, between 65 and 35 My BP when there was little ice on the planet, the sensitivity should have been closer to the Charney 3°C sensitivity.

Elsewhere (Hansen et al. 2007a) we have described evidence that slower feedbacks, such as poleward expansion of forests, darkening and shrinking of ice sheets, and release of methane from melting tundra, are likely to be significant on decade-century time scales. This realization increases the urgency of estimating the level of climate change that would have dangerous consequences for humanity and other creatures on the planet, and the urgency of defining a realistic path that could avoid these dangerous consequences.

4. Dangerous Climate Change

Almost all nations, including the United States, have signed the Framework Convention on Climate Change (United Nations 1992), which has the specified objective of stabilizing atmospheric composition at a level avoiding "dangerous atmospheric interference" with climate. However, the Convention does not define the level of climate change constituting 'danger'.

We have suggested (Hansen 2006; Hansen et al. 2007b) that principal criteria defining 'dangerous' should include sea level rise and extermination of species, because these effects could not be reversed, on time scales relevant to humanity, by later reduction of the human-made climate forcing. We also suggest that the Earth's history provides our most reliable guidance.

Civilization developed during a period of relative climate stability, the Holocene (Figure 2c). It is probably not a coincidence that the first congregations of people in cities with state-governed societies beyond the scope of Neolithic agricultural villages developed shortly after sea level (Figure 3a) stabilized 6-8 thousand years ago (Kennett and Kennett 2006; Day et al. 2007). Stable sea level was needed for high coastal ocean biological productivity, and eventually stable shorelines aided establishment of ship-based commerce. Large infrastructure has been built on world coastlines. More than one billion people lived within 25 meter elevation of sea level in 2000, about 400,000,000 were within 7 meters of sea level, and those numbers continue to increase. Sea level rise of even 2-3 meters would have devastating consequences for humanity.

Maintaining a reasonably stable sea level almost surely requires keeping global temperature within the range of the warmest interglacial periods of the past several hundred thousand years. Sea level was probably a few meters higher during some of these interglacial periods, but it might be argued that, if warming is such that sea level is only aiming for an equilibrium rise of a few meters, it may require many centuries or millennia for that to occur.

In contrast, global warming ~2°C above the temperature in 2000, comparable to the warmth of the middle Pliocene, would imply a system aiming for an eventual sea level rise of tens of meters. With polar magnification of such warming, both West Antarctica and Greenland would have much heavier summer melt for longer melt seasons. In such a case, that is with continued business-as-usual growth of annual GHG emissions, it is likely that sea level rise this century would be measured in meters (Hansen 2007a). Furthermore, such a course would set in

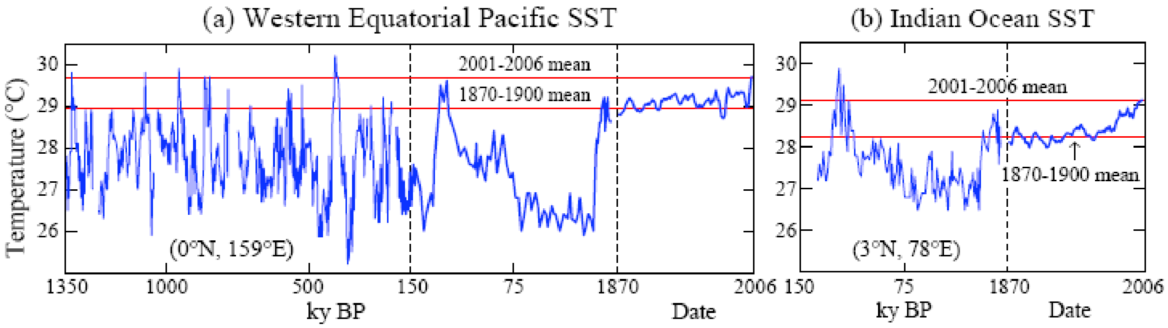


Figure 5. Modern sea surface temperatures compared with paleoclimate proxy data for the Western Equatorial Pacific and Indian Oceans, updated from Hansen et al (2006).

motion further ice sheet disintegration on longer time scales, a process that would be exceedingly difficult to stop.

It is similarly difficult to define a precise level of global warming that places excessive stress on animal and plant species. The warming of 0.8°C in the past century is already contributing to stress on some polar and alpine species (Hansen 2008). If migration of isotherms continues for another century as in the past 30 years, when global warming has been 0.2°C per decade, or if warming accelerates as in business-as-usual GHG scenarios, such warming would require large migrations for many species if they are to stay within habitable climatic zones. Prior warmings of several degrees are known to have caused mass extinctions of species, even though the warmings were slower than in the present human-caused event. Again, our best estimate of an upper limit for global warming, a target for the purpose of avoiding highly undesirable increased stress on species, would be to keep global temperature within the range of interglacial climates of the past million years.

Accurate measures of global mean surface temperature are not available for such paleoclimate time scales, but measurements are available at specific relevant places. Hansen et al. (2006) argue that the most relevant places to look are (1) the Pacific Warm Pool, which is of special importance as the prime source region for transport of heat to high latitudes in both the ocean and atmosphere, and (2) the Indian Ocean, which is the place with highest correlation with global mean temperature. Figure 5 shows that, with the warming of the past three decades, these places are now both within one degree Celsius of the warmest of the recent interglacial periods.

This estimate for the additional global warming that would constitute danger is supported in an approximate but important way by the data in Figure 2. The curve in Figure 2 is based on globally distributed ocean cores, and it provides a constraint on deep ocean temperature change. Between 35 My BP, when the planet was nearly ice free and sea level was about 75 meters higher, and the present, the ocean temperature cooled only about 4°C. Thus an ocean warming of even 2°C would take ocean temperature half way back to a level of warming at which there was little if any ice on the planet.

Of course it requires time for the ocean to warm, and it requires time for ice sheets to disintegrate. The inertia of the system is helpful in one sense: it means that, even if we pass the dangerous level of GHGs, it may be possible to decrease the climate forcings in time to avoid the equilibrium response of the climate system. But in another sense the inertia is harmful: because of the inertia we have seen only a fraction of the eventual change expected for gases already in the air, and the resulting 'small' climate effects to date have provided a misleading indication of what the 'dangerous' level of GHGs is.

The Cenozoic temperature curve, Figure 2a, in combination with information on atmospheric GHG amounts for the same period, provides a sobering perspective on the 'dangerous' level of change. Proxy measures of CO_2 amount (Pagani et al 2005; Royer 2006) and climate simulations (Hansen and Sato, in preparation) consistent with empirical data on climate sensitivity both indicate that atmospheric CO_2 amount when an ice sheet first formed on Antarctica (34-35 My BP) was probably only 400-600 ppm. This information raises the possibility that today's CO_2 amount, ~383 ppm, may be, indeed, likely is, already in the dangerous range.

5. Global Climate Forcings

Fortunately, CO_2 is not the only climate forcing, or the only human-made forcing, and the inertia of the climate system does allow the possibility of a reversal of the growth of human-made climate forcings before the full effects of those forcings have been realized. A strategy to deal with overshoot of the dangerous level will need to take account of (1) the unusual response function of the ocean surface temperature (Figure 7b in Hansen et al. 2007a), about half of the response occurring within two decades, while the other half requires several centuries, and (2) the exceedingly long tail of the airborne CO_2 curve (Figure 6a in Hansen et al. 2007a), about half of human-made CO_2 being taken up in two decades, another quarter in the first century, and most of the last quarter staying in the air for millennia.

The first requirement in developing a strategy to avert disastrous climate change is recognition that CO_2 is only one of the important global climate forcings. Figure 6 summarizes the estimated change of global climate forcings in the industrial era, between 1750 and 2000. These are "effective" climate forcings as defined by Hansen et al. (2005a), i.e., account has been taken of that fact that some forcing mechanisms have a greater or lesser efficacy for causing global temperature change than does an equal forcing (with the simplest definition of radiative forcing) by CO_2.

In addition, known indirect forcings are grouped with the primary forcing in Figure 6. Thus the total forcing due to methane (CH_4) includes the effect of methane on tropospheric

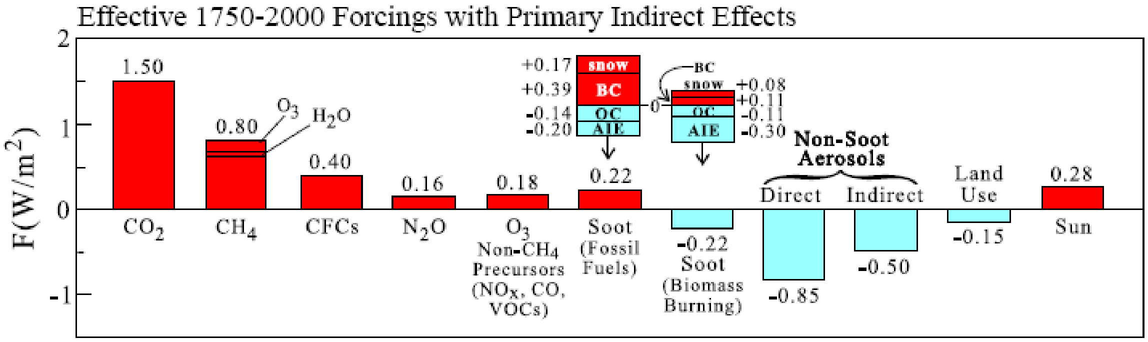


Figure 6. Estimated effective climate forcings for the industrial era, 1750-2000, with primary indirect effects grouped with the sources of direct forcing (Hansen et al. 2005). BC, black carbon; OC, organic carbon; AIE, aerosol indirect effect; CFCs, chlorofluorocarbons; VOCs, volatile organic compounds.

ozone amount and stratospheric water vapor. It is apparent that CH_4, N_2O, tropospheric O_3, and soot (defined as the black carbon and organic carbon that is produced in incomplete combustion of fossil fuels and biomass) together cause a forcing at least comparable to that by CO_2.

CO_2 is increasing more rapidly than the non-CO_2 forcings, so CO_2 must be the principal focus of efforts to stabilize climate. At the same time, however, it is essential to pay greater attention to the non-CO_2 forcings. The net human-made climate forcing is nearing, if it has not already past, the level that will have dangerous effects as the climate system has more time to respond. It is only by addressing both CO_2 and non-CO_2 forcings that will be possible to avoid disastrous climate effects. Before looking at the status of climate forcing trends, however, it is worth looking specifically at climate change in the Arctic and implications thereof.

6. Air Pollutants and Tipping Points

For the last decade or longer, as it appeared that climate change may be underway in the Arctic, the question was repeatedly asked: "is the change in the Arctic a result of human-made climate forcings?" The scientific response was, if we might paraphrase, "we are not sure, we are not sure, we are not sure…yup, there is climate change due to humans, and it is too late to prevent loss of all sea ice." If this is the best that we can do as a scientific community, perhaps we should be farming or doing something else.

Fortunately, the conclusion that it is too late for the Arctic or for global climate is premature. However, before discussing strategies for solutions, it is worth pointing out that the Arctic is an instructive example for a more important problem.

Arctic climate change in response to a growing human-made climate forcing illustrates the nature of 'tipping points'. When warming climate reaches the point that Arctic sea ice cover begins to recede substantially, that is a critical point. Loss of sea ice causes a positive feedback, as the darker ocean absorbs more sunlight, magnifying the warming. It is not a run-away feedback, but the positive feedback means that response to a forcing is larger than it would be without the feedback. Combined with the inertia of the climate system, it also may imply that little if any additional forcing is needed to cause loss of all Arctic sea ice.

This 'tipping point' concept is important because of the difficulties it poses for strategies to avert undesirable climate change, especially with regard to the time pressure that it demands for convincing the public and policy-makers that actions are needed. The Arctic sea ice tipping point provides a useful lesson of what could happen in the more important case of potential instability of the West Antarctic (and Greenland) ice sheets. The ice sheet problem is more important not only because the effect of rising sea level is potentially more devastating (for humans), but because ice sheet changes are not as easily reversed as sea ice changes. If climate forcings are reversed (decreased), so that the planet begins to cool, sea ice will come back quickly, but it requires thousands of years to build an ice sheet.

Rather than address the difficult question of how much additional sea ice can we expect to lose given the additional global warming that is already "in the pipeline", let us address the more important questions: how much do we need to reduce the human-made forcing to stabilize climate, Arctic sea ice, and perhaps even ice sheet mass. And is such a reduction feasible?

The basic requirement to stop further climate change, at least to a good approximation and first estimate, is to restore planetary energy balance. Because of the inertia of the climate system, together with the recent trend of increasing GHGs, the planet is now out of energy balance, absorbing between 0.5 and 1.0 W/m^2 more energy from the sun than it emits to space as heat radiation (Hansen et al. 1997, 2005b, 2007b).

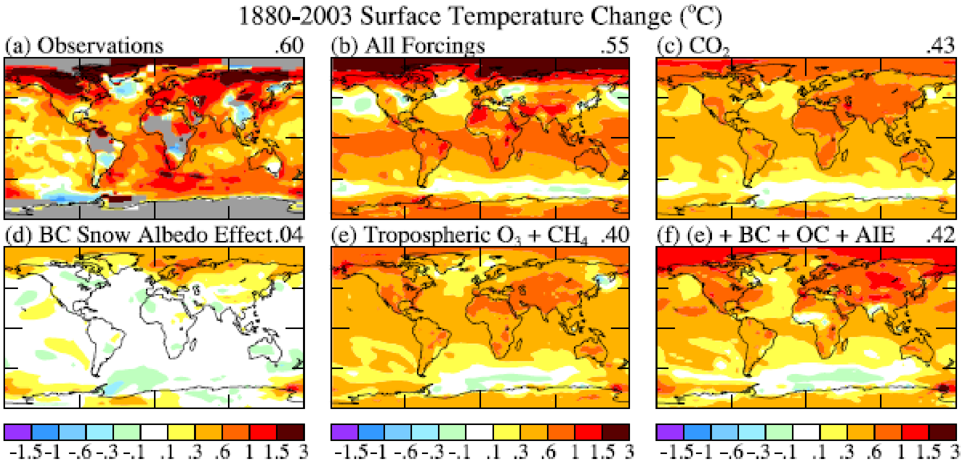


Figure 7. Surface temperature change based on local linear trends for (a) observations, and (b-f) simulations employing various indicated combinations of transient 1880-2003 forcings. BC snow albedo effect has 1880-2003 Fa ~ 0.05 W/m^2. Results in (f) include forcings of (e) plus direct effects of BC, OC, AIE and the snow albedo effect.

Is there a potential to reduce the net climate forcing by 0.5-1 W/m^2? The practicality of restoring energy balance certainly depends upon whether the imbalance is closer to 0.5 or 1 W/m^2. However, Figure 6 shows that the methane, ozone, chlorofluorocarbon and fossil fuel soot forcings total more than 1 W/m^2, so, at least in principal can be achieved, but, in addition to reducing the human-made portion of non-CO_2 forcings, it would be necessary to keep additional CO_2 forcing very small.

Before addressing current trends of non-CO_2 forcings, we point out that some of the non-CO_2 forcings are particularly effective in the Arctic. Figure 7, adapted from Hansen et al. (2007a), shows that the results of climate simulations with all known forcings (Figure 7b) do a reasonably good job of reproducing the magnitude of global and Arctic warming in the period 1880-2003. When the modeling results are broken down via simulations that incorporate only subsets of the forcings, it is found that air pollutants (tropospheric ozone, its precursor methane, and soot, including effects on snow albedo and clouds) have at least as large a warming effect in the Arctic as does CO_2.

There are other good reasons, in addition to climate change, to reduce these pollutant forcings. We argue below that a concerted effort to reduce these pollutants, in combination with a stabilization of CO_2 amount, as agreed by the United States and practically all other countries in the Framework Convention on Climate Change, could avoid the loss of all Arctic sea ice and stabilize climate.

7. Current Trends of Air Pollutants and Climate Forcings

Figure 8 uptakes the growth of all significant long-lived GHGs through 2006. The most important of these is CO_2, which is dealt with in all three graphs on the left hand side. Fossil fuel use, Figure 8a, is following close to the upper end of the range of IPCC scenarios. The annual growth of CO_2 in the air, Figure 8b, has large year-to-year fluctuations, but from the 5-year mean it is clear that growth of CO_2 in the air is near the upper end of the IPCC range, and much higher than the ‘alternative scenario’ of Hansen et al. (2000). The alternative scenario was designed to

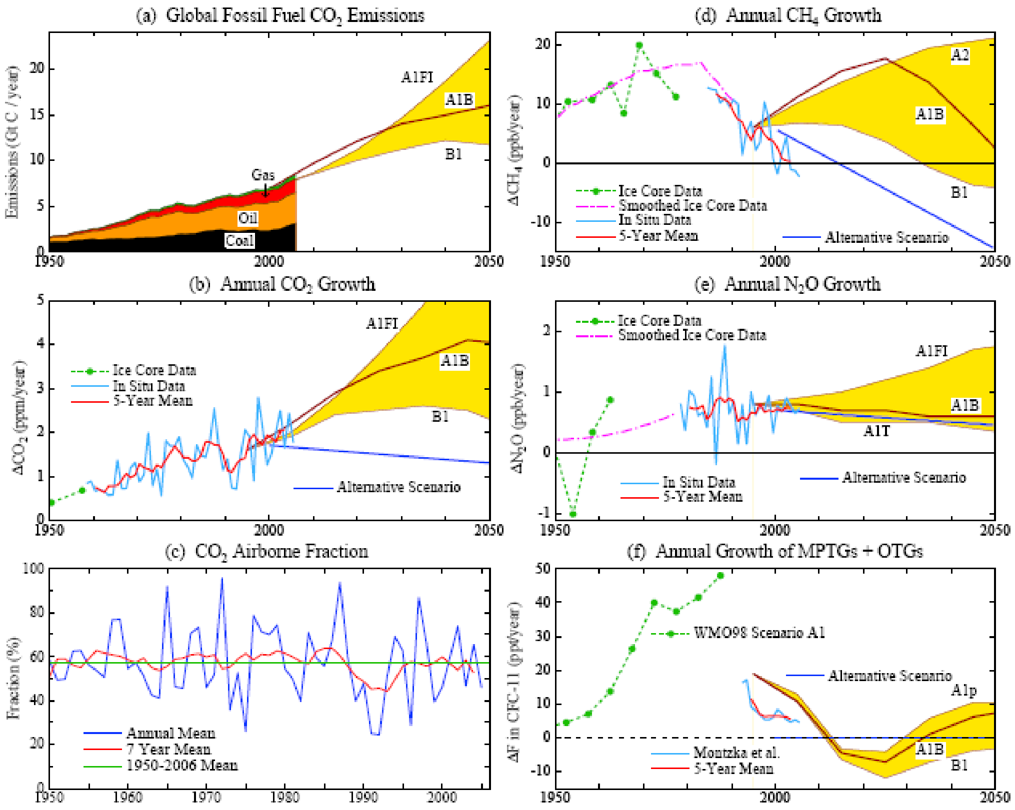


Figure 8. (a) fossil fuel CO_2 emissions by fuel type and IPCC total emission scenarios, (b) annual atmospheric CO_2 growth rates, (c) ratio of annual atmospheric CO_2 increase to annual fossil fuel emissions, (d,e,f) annual growth of atmospheric CH_4, N_2O, and the sum of MPTGs (Montreal Protocol Trace Gases) and OTGs (Other Trace Gases). The 'alternative scenario' is the scenario defined by Hansen et al. (2000) aimed at keeping global warming beyond 2000 less than 1°C.

keep added GHG forcing about 1 W/m^2 in the first half of the 21st century, ½ W/m^2 in the second half of the century, and thus to keep global warming relative to 2000 less than 1°C, assuming that equilibrium climate sensitivity is ~ 3°C for doubled CO_2.

One piece of good news about CO_2 growth is that the airborne fraction of fossil fuel CO_2 emissions, i.e., the ratio of atmospheric CO_2 increase divided by fossil fuel CO_2 emissions, continues to show no sign of increasing. Indeed, the average for the full half century of data has fallen to ~57%. Most carbon cycle models predict that the airborne fraction should increase, especially as global warming increases. However, possible changes in rates of deforestation and forest regrowth make it difficult to draw implications about the magnitude of CO_2 sinks from the airborne CO_2 fraction.

The best news is that the methane growth rate (Figure 8d) is falling well below all IPCC scenarios, and even lower than in the alternative scenario. Indeed, in the past year atmospheric CH_4 amount decreased slightly and the 5-year mean rate is now zero change. The N_2O growth rate is near the lower end of the IPCC range, and falls approximately on the alternative scenario. The annual growth of climate forcing by MPTGs (Montreal Protocol trace gases) and OTGs

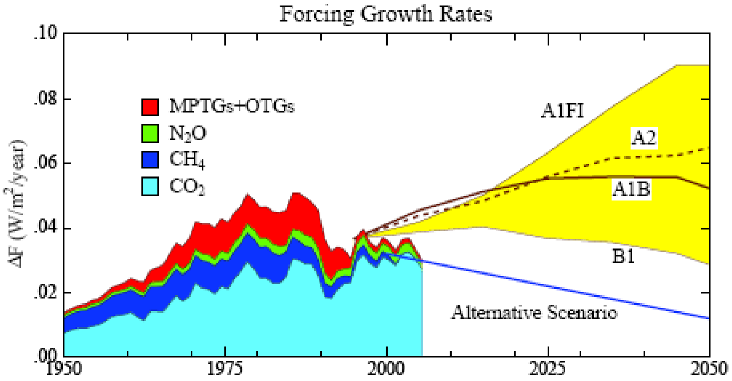


Figure 9. Climate forcing annual growth rate due to changing amounts of long-lived greenhouse gases. Forcing is 5-year running mean through 2004, 3-year mean in 2005, and the single year mean for 2006. Future forcings are shown for the IPCC scenarios and the 'alternative scenario' of Hansen et al. (2000).

(other trace gases) is continuing to fall; it is well below IPCC scenarios and getting close to the alternative scenario, which assumes zero net growth of forcing by MTPGs plus OTGs after 2000.

Figure 9 summarizes the 5-year running mean of the sum of all long-lived GHGs. One word of caution: the graph leaves the impression that the real world growth rates have fallen to the level of the alternative scenario. The graph is misleading in that regard, as the final point is a 1-year (2006) mean and the penultimate point (for 2005) is a 3-year (2004-2006) mean. These latter two points are held down by the fact that the highly variable annual increase of CO_2 was small in 2006 (Figure 8b), with an airborne fraction of only 45% (Figure 8c). If one looks only at true 5-year means, i.e., through 2004, it is apparent that the GHG forcing for the real world is falling about half way between the lowest IPCC scenario (B1) and the alternative scenario.

The decrease of the growth rate for the sum of all GHGs, which is below the rates of the 1970s and 1980s, is entirely due to slowdown of the growth rate of non-CO_2 GHGs. Also note that the present growth rate for all long-lived GHGs of ~0.03 W/m^2, if continued for a century would yield an additional greenhouse forcing of 3 W/m^2, double the amount allowed for in the 'alternative scenario' and enough to cause warming more than 1°C. Moreover, if annual CO_2 emissions continue to increase ~2% per year, as in the past decade, the GHG climate forcing increase this century will be more than 3 W/m^2.

These data help define actions needed to keep additional global warming less than 1°C, as discussed in section 9 below. We emphasize, however, that the 1°C limit on additional warming (above year 2000, thus 1.7°C above "pre-industrial" global temperature) is only a first estimate for the level of global warming constituting "dangerous" climate change. Paleoclimate data discussed above and by Hansen et al. (2007a) strongly suggest that even stricter limits will be needed. Precise definition of the dangerous level of atmospheric GHGs requires more research and empirical evidence, but enough is known to say that prior suggestions that warming of 2-3°C may be acceptable are ill-advised. Although more needs to be learned, the remaining range of uncertainty has little impact on the practical steps that need to be taken to get the global climate forcings onto a path that can stabilize climate.

8. Responsibilities for Climate and Pollution Trends

Responsibility for fossil fuel CO_2 emissions can be assigned with reasonable accuracy via available data for fossil fuel use. For fossil fuel CO_2 emissions through 2004 we use the Carbon Dioxide Information Analysis Center (CDIAC) data set of Marland et al. (2007) supplemented with data for 2005-2006 from British Petroleum (BP) (2007). The data are imperfect; but adjustments of the CDIAC data (through 2004) in 2007 increased emissions from China and are believed to have largely corrected a problem of under-reporting in China, especially in the late 1990s (Sinton 2001). We include estimates for CO_2 from gas flaring (0.3% of CO_2 emissions) and cement production (3.8% of emissions in 2005). We normalize British Petroleum (2007) data for each fossil fuel such that it coincides with the final year of Marland et al. (2007) data (2004 in present analysis).

Cumulative CO_2 emissions, shown by the pie chart in Fig. 10b, largely determine the contribution to climate change, as shown by Figure 10 of Hansen et al. (2007b). Current (2005) fossil fuel emissions from China and the United States are approximately equal, but the cumulative emissions (Fig. 10b) by the United States are more than three times those of any other country.

Figure 10b shows that Europe and the United States plus Canada and Australia, which have per capita emissions comparable to the United States (Fig. 10 of Hansen et al. 2007b), each contribute more than 30 percent to cumulative emissions and global warming. Much of the ship and air emissions also originate from these sources and some of the emissions within developing countries originate from companies that are owned by developed countries. Thus, despite ascendancy of developing country in current emissions, the developed countries will remain primarily responsible for global warming for at least the next few decades. This fact has given rise to the concept that developed and developing countries must share a common but differentiated responsibility to address global warming.

Responsibility for non-CO_2 emissions is not as well quantified as for CO_2. It is likely that developing countries are responsible for a larger portion of the non-CO_2 emissions, given the

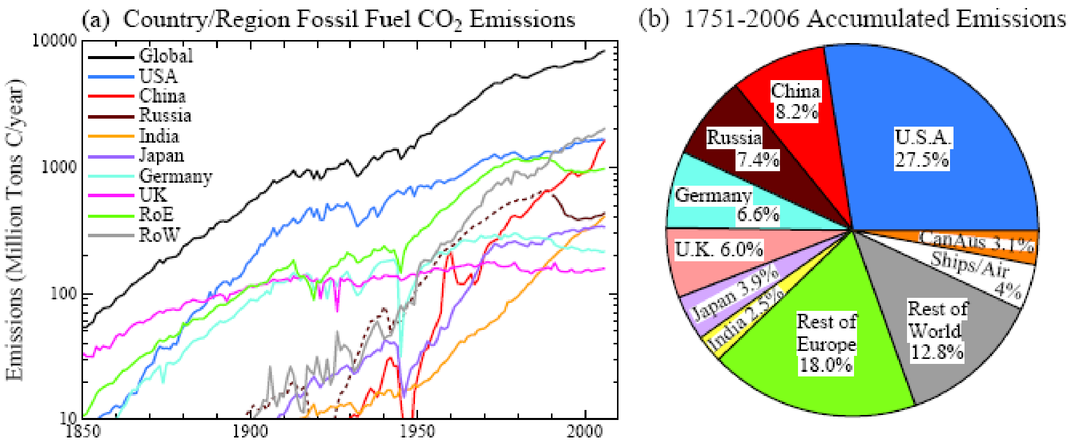


Figure 10. Fossil fuel CO_2 emissions (a) by source country as a function of time, and (b) cumulative 1750-2006 emissions. Original data through 2004 from Marland et al. (2007) with updates through 2006 from British Petroleum (2007).

greater efforts to control local pollutants in developed countries. Long-lived non-CO_2 GHGs are not increasing much now (Figure 9). Also, it seems likely that the growth of short-lived pollutants such as soot and ozone, now occurring in developing countries, will at least level off soon as pollution there is becoming increasingly intolerable.

However, the fact that future growth of human-made climate forcing will probably be mainly from CO_2 does not reduce the importance of addressing the non-CO_2 forcings. On the contrary, as Figure 6 illustrates, if the (human-made portion of[7]) non-CO_2 forcings were reduced it would be possible to negate some further increase of CO_2 forcing, or even roll back the net forcing if CO_2 is stabilized.

9. Summary

Lessons from the Cenozoic. Huge climate changes have occurred on long time scales with no role of humans. Over the Cenozoic era (past 65 My) the climate forcing due to changing CO_2 amount dwarfs other known global forcings such as changing solar irradiance or changing planetary albedo due to continental drift.

Causes of atmospheric CO_2 change, CO_2 drawdown from weathering of rocks and burial of organic matter, and CO_2 increase from outgassing associated with subduction and metamorphism, need not be in balance at any given time as the rates depend on continental locations and motions, the resulting orogeny, and the availability of carbon-rich crust at the places of subduction. Over the past 50 My CO_2 has been in general decline, as regions of subduction have been limited, while strong orogeny has occurred at the Himalayan-Tibetan orogen and recently in the Andes.

A large ice sheet did not form on Antarctica until CO_2 had declined to about 400-600 ppm about 34 My ago. When CO_2 rebounded, by perhaps ~200 ppm (Pagani et al. 2005), the ice sheet largely disappeared, indicating that ice sheet growth is reversible if forcing increases.

Natural rates of change of CO_2 due to these geologic processes are typically of the order 10**(-4) ppm/year of atmospheric CO_2. This is substantial on geologic time scales, the order of magnitude being 100 ppm/My, but negligible in comparison to human emissions from fossil fuel burning, which now exceed +3 ppm/yr with ~+2 ppm/yr remaining in the air. Humans are now in control of the carbon cycle, and, as a result, in control of climate.

Lessons from the Plio-Pleistocene. More detailed information is available for the most recent portion of the Cenozoic, the Plio-Pleistocene. The temperature declined during the past few million years with increasingly large glacial-interglacial oscillations (middle portion of Figure 2), as ice sheet size increased with falling temperature. The most detailed data exist for the past ~700,000 yr, including accurate ice core records of atmospheric composition.

We lumped the atmosphere, ocean, soil and biosphere pools of carbon into one reservoir in discussing the geologic carbon cycle of the Cenozoic. The partitioning of carbon among these surface pools varies faster than the exchanges between the surface reservoir and the lithosphere. The atmospheric contains only 1-2% of the carbon in the surface reservoir, but the atmospheric component increases with global temperature, with a lag of several hundred years. GHGs and surface albedo are both strong positive feedbacks amplifying weak orbital-insolation forcings.

The most important practical lesson from the Plio-Pleistocene is that the changes of ice sheet volume occur in consonance with the weak orbital forcings with little if any discernible lag

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[7] It is only the human-made portion that is used in calculating the forcings. Thus to reduce the CH_4 forcing by the full amount in Figure 6 does not require reducing atmospheric CH_4 to zero, rather to the 1750 abundance of CH_4. The alternative scenario assumes that the human-made portion of CH_4 would be reduced about 45%.

(Hansen et al. 2007a). Sea level changes of a few meters per century are common in the Plio-Pleistocene record, even though the forcings are weak, much weaker than the present human-made climate forcing. The Plio-Pleistocene record dismisses the misconception that ice sheets are large blocks of ice that can disintegrate only on millennial time scales.

Dangerous Global Warming. The notion that the dangerous level of global warming may be of the order of 3°C above recent global temperature, as suggested by the "burning embers" diagram and probabilistic approach of IPCC (2001) and Schneider and Mastrandrea (2005) is itself exceedingly dangerous. Global warming of an additional 3°C would be a guarantee of ineffable disasters for humanity and other creatures of the planet. It is inconceivable that the West Antarctic and Greenland ice sheets could survive 3°C additional global warming, with expected warming 2-3 times larger at the location of the ice sheets.

A more realistic assessment is that global temperature should be kept approximately within the range of prior interglacial periods of the past million years, which implies that additional global warming (above the temperature in 2000) should be less than 1°C. If recent evidence of instability of the West Antarctic and Greenland ice sheets continues to increase, it may be that even 1°C additional global warming is dangerous for humanity.

Dangerous CO_2. A global warming limit of 1°C above the temperature in 2000 implies a CO_2 limit of the order of 450 ppm. However, the CO_2 limit is a function of the course of non-CO_2 climate forcings (Hansen and Sato 2004).

Non-CO_2 Climate Forcings. Long-lived GHGs have been increasing much more slowly than in IPCC scenarios, despite the absence of strong efforts to achieve reductions. Serious efforts to reduce the emissions of these gases could provide substantial negative forcings, in the case of methane and trace gases, and a lesser growth rate than usually assumed for N_2O. Rather than lumping these gases with CO_2, it would be more effective to have programs for each of the specific gases. Methane deserves special attention, because it is a powerful greenhouse gas and is also responsible for about half of the global human-made increase of tropospheric ozone, itself a strong greenhouse gas. Black soot from fossil fuel burning has a substantial net positive forcing, with a global warming potential for a sustained emission cut of about 500 relative to CO_2 for the 100 year time horizon (Hansen et al. 2007a).

Positive Trends. Despite pell-mell global construction of coal-fired power plants, growth of total GHG forcing is well below all IPCC scenarios. Despite continued 2%/year growth rate of fossil fuel CO_2 emissions for more than three decades, and despite seemingly rampant deforestation, the CO_2 'airborne fraction' is not increasing, staying at about 57%.

Potential for Positive Feedbacks. Hansen (2007b) describes the two fundamental requirements for the world to move onto a downward spiral of CO_2 emissions: (1) a moratorium on construction of new coal-fired power plants until the technology is available and used for actual capture and sequestration of emitted CO_2, and (2) a moderate but increasing price on carbon emissions. Experts in building technologies and renewable energies agree that there is plenty of potential in energy efficiency and CO_2-free energy sources to handle near-term energy needs (Romm et al., 1998; Pacala and Socolow, 2004; NCEP, 2004).

Given the preponderance of coal as the prime source of human-made CO_2 (Hansen et al. 2007b), in the past and all the more so in the future, and given even generous estimates of oil and gas resources (Kharecha and Hansen 2007), annual CO_2 emissions should begin to decline once phase-out of old-technology coal-fired power plants begins. With such a trend in emissions, the airborne fraction of CO_2 would also be expected to decline, reducing the CO_2 growth rate even further. Moreover, there is considerable potential in improved agricultural practices for more storage of carbon in soils (McCarl et al 2007), and there is potential for reduction of deforestation rates.

Dangerous Defeatism and Dichotomy of Paths. Despite the good news about trends of climate forcings, and despite the great potential for reductions in emissions, there are scientists who argue that disastrous climate change is inevitable. This defeatism discourages the actions that are needed to get onto a sustainable path.

Defeatism is a serious issue, because we face a dichotomy of possible futures. If we do not begin to reduce emissions, the airborne fraction of CO_2 is likely to increase, as carbon cycle models predict. Other positive feedbacks are likely in that scenario, as paleoclimate data shows that GHGs increase in response to a warming world, a particular concern being possible release of methane from melting tundra.

Yet an alternative path is feasible. Figure 9 is a good summary of those parts of the problem that are well quantified, including CO_2. The world has not been doing so badly, despite the lack of a concerted effort to reduce emissions.

The most difficult part of the problem is CO_2, but there is a basis for optimism even there. Despite rapidly accelerating coal use, and lack of progress in land use and deforestation, the portion of fossil fuel CO_2 emissions appearing in the air remains about 57% (45% in 2006). By getting CO_2 emissions onto a downward trend, it is possible to achieve even a smaller airborne fraction.

One must be careful to remember that a substantial fraction of fossil fuel CO_2 emissions stays in the air for “an eternity”, more than 500 years. But we must also remember that the system does have the capacity to soak up an enormous amount of carbon. If the bulk of coal resources are removed from the equation, via use only at power plants with carbon capture and sequestration, it is readily possible to keep future CO_2 well below 450 ppm (Kharecha and Hansen 2007).

Common Sense and Cooperation. The global warming crisis differs fundamentally from the planetary crisis of the past century, the nuclear standoff between the Soviet Union and the United States, in which disaster depended upon at least one party taking action. In contrast, the present threat to the planet and civilization, with the United States and China the principal players (although Europe has a large responsibility, as shown in Figure 10), requires only inaction in the face of clear scientific evidence of danger.

Common sense does not support inaction, even if all parties place highest priority on economic well being. Fossil fuel inventories are limited and national and global pictures when energy has moved “beyond fossil fuels” are highly attractive. Cooperation among nations would make sense for all parties, and this can occur on many levels, even without major international treaties.

Indeed, it is a mistake to think that progress and turning the corner toward decreasing emissions is dependent upon hammering out a grandiose international agreement, which would almost surely take more time than is available. The primary need is insightful leadership. There is great economic advantage in getting to that cleaner future sooner. Once this is comprehended, by either of the principal players, progress could become rapid.

The roadblock to the needed actions is not national economic well-being. It is the special interests who give primacy to their own short-term profits. Unfortunately, these special interests have undue sway in many national governments. For this reason, we believe that solution of global warming requires the public to pay attention to this issue in the electoral process, and we have suggested use of a specific Declaration of Stewardship (Hansen 2007c).

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