

Radiative Forcing, Climate Sensitivity, and Global Warming

Bruce Parker (bruceparker@alum.mit.edu)

February 12, 2017

(<http://ccdatacenter.org/documents/RFandCS.pdf>)

Abstract

Based on physics, doubling atmospheric CO₂ will increase the Earth's average temperature by about 1.2°C. "Fast feedbacks" (water vapor, clouds, aerosols, and surface albedo changes) also contribute to the equilibrium temperature increase.

In climate models, on average, 6% of the total radiative forcing at the global tropopause was due to surface albedo changes¹

If the climate sensitivity is 3 (for a doubling of atmospheric CO₂) and the IPCC estimate of radiative forcing for 2011 was about 2.3 W m⁻², then the expected contribution from surface albedo changes should be about .14 W/m² (at temperature equilibrium)

Since the change in surface albedo from 1979-2008 was about 0.45 W m⁻², the IPCC estimate of the current radiative forcing should be increased by about 0.3 W m⁻² to about 2.6 W m⁻² in 2011 and 2.8 W m⁻² for 2016.

Since the equilibrium temperature increase is 2.0°C for a radiative forcing of 2.8 W m⁻², we are already "committed" to at least 2.0°C of warming

"Committed" warming is currently increasing at over twice the rate as "measured" warming (0.45°C per decade vs. 0.19°C per decade)³

Since the radiative forcing is apt to increase by about 1.7 W m⁻² by 2060⁴, the temperature increase "commitment" in 2060 will be about 3.9°C

Footnotes for Abstract

1	http://journals.ametsoc.org/doi/full/10.1175/JCLI3799.1
2	http://data.engin.umich.edu/faculty/flanner/content/ppr/FIS11.pdf
3	See "9. Rate of Global Warming" below
4	Change in radiative forcing for major global warming factors (W m ⁻²): CO ₂ - 0.27; Peat/soils - 0.11; Reservoirs - 0.08; Permafrost - 0.08; Afforestation/Soils - -0.1; Aerosols - 0.8; Surface Albedo Change - 0.45 (see section "7. Projected changes in Radiative Forcing in 40-50 Years" below)

1. Radiative Forcing

The Earth is constantly receiving energy from the sun, primarily in the form of visible light. An average of about 240 Watts per square meter ($W\ m^{-2}$) if energy is received daily over the entire surface of the Earth (see Figure 1). Greenhouse gases in the atmosphere trap some of the energy, making the Earth about 60°F warmer than it would otherwise be. Over the last few thousand years, when the atmospheric concentration of carbon dioxide (CO_2) was about 270 parts per million (PPM), the Earth's temperature varied slightly, with an average about 13.75° C (about 56.75° F).

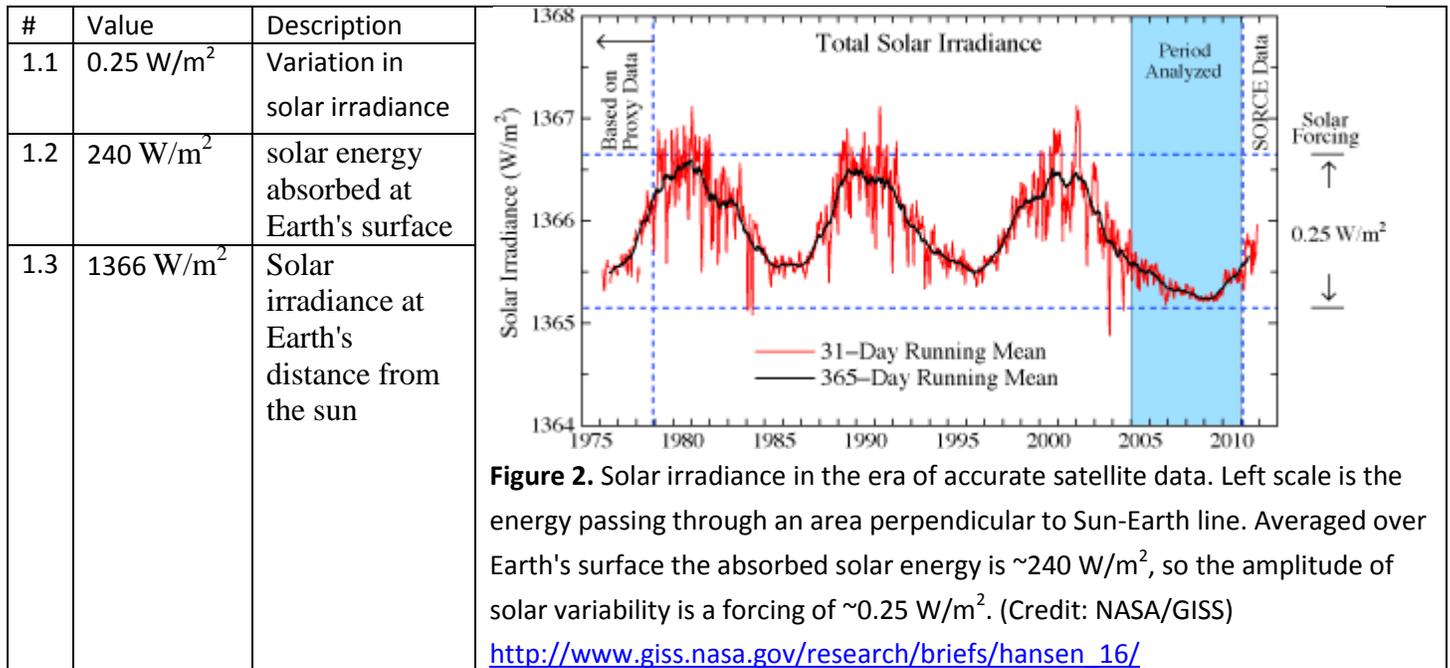


Figure 1 - Solar Irradiance

Global climate is determined by the radiation balance of the planet (see FAQ 1.1). There are three fundamental ways the Earth's radiation balance can change, thereby causing a climate change: (1) changing the incoming solar radiation (e.g., by changes in the Earth's orbit or in the Sun itself), (2) changing the fraction of solar radiation that is reflected (this fraction is called the albedo – it can be changed, for example, by changes in cloud cover, small particles called aerosols or land cover), and (3) altering the longwave energy radiated back to space (e.g., by changes in greenhouse gas concentrations). In addition, local climate also depends on how heat is distributed by winds and ocean currents. All of these factors have played a role in past climate changes.

<http://oceanservice.noaa.gov/education/pd/climate/factsheets/whatcause.pdf>

If any of these factors change significantly then more energy will be absorbed than is emitted (or vice versa) and the Earth temperature will increase (or decrease) until a new balance is achieved. Since the Sun's energy (or radiation) is the dominate force in determining the energy balance, climate scientists use the term "radiative forcing" to measure how much these three factors "force" the Earth's temperature to change, and the "forcing" is measured in Watts per square meter ($W\ m^{-2}$). Climate scientists then "convert" a change in atmospheric greenhouse gases (or albedo) to the equivalent change in radiation from the Sun. For example, if the atmosphere contains 400 PPM of CO_2 , then adding an additional 82 PPM of CO_2 is the equivalent to getting an additional $1\ Wm^{-2}$ of energy from the Sun (see Table 1 below). (And adding 130 PPM of CO_2 since preindustrial times has increased the radiative forcing by about $1.7\ W\ m^{-2}$). Likewise, a .01 change in albedo on the Earth's surface is equivalent to about $3.4\ W\ m^{-2}$ of radiative forcing, assuming there is no

cloud cover. (The Earth's albedo has a value from 0.0 to 1.0; the albedo of snow-covered ice is 0.85; and the albedo of an open ocean is 0.07.)

#	Value	Description
1.4	0.003	The decrease of the Earth's albedo that will case an increase of 1 Wm ⁻² of radiative forcing
1.5	0.85	The albedo of snow-covered ice
1.6	0.07	The albedo of an ice-free ocean

2. Radiative Forcing and CO2

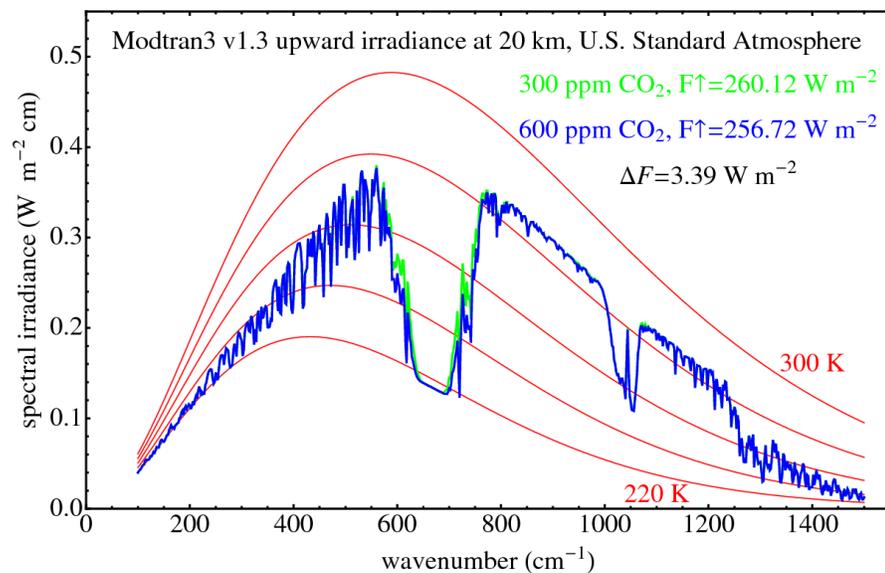
For a greenhouse gas, such as [carbon dioxide](#), radiative transfer codes that examine each spectral line for atmospheric conditions can be used to calculate the change ΔF as a function of changing gas concentration. These calculations can often be simplified into an algebraic formulation that is specific to that gas.

For instance, the simplified first-order approximation expression for [carbon dioxide](#) is:

$$\Delta F = 5.35 \times \ln \frac{C}{C_0} \text{ W m}^{-2}$$

where C is the CO₂ concentration in parts per million by volume and C_0 is the reference concentration.^[6] The relationship between carbon dioxide and radiative forcing is [logarithmic](#)^[7] and thus increased concentrations have a progressively smaller warming effect.

A different formula applies for other greenhouse gases such as [methane](#) and [N₂O](#) (square-root dependence) or CFCs (linear), with coefficients that can be found e.g. in the [IPCC reports](#).^[8]



https://en.wikipedia.org/wiki/Radiative_forcing

The following table shows the change in radiative forcing since 1750 for various atmospheric quantities of CO₂e (based on the data in the IPCC's "CLIMATE CHANGE 2013 The Physical Science Basis" and above formula, with an initial concentration of CO₂ of 278 PPM so that, for the 2011 atmospheric concentration 390.5 PPM (Page 1402), the radiative forcing is 1.816 Wm⁻² (Page 1409)):

CO2 PPM	278	300	325	350	375	400	425	450	475	500	525	550	575	600
Radiative Forcing	0.00	0.41	0.84	1.23	1.60	1.95	2.27	2.58	2.87	3.14	3.40	3.65	3.89	4.12

Table 1

The formula for converting from radiative forcing to CO2 PPM is then: $C = C_0 \times e^{F/5.35}$, which gives the following values for increases in radiative forcing above 400 PPM:

CO2 PPM	0	8	15	23	31	39	47	56	65	73	82	91	101	110
Radiative Forcing	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3

Table 2

and the following values for increases in radiative forcing above 500 PPM:

CO2 PPM	0	9	19	29	39	49	59	70	81	92	103	114	126	138
Radiative Forcing	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3

Table 3

Assuming a 45% "airborne fraction" for CO2 emissions and atmospheric concentration of CO2 of 450 PPM, the following table provides values for increases in radiative forcing for increasing quantities of CO2 emissions (there are 2.12 GTC for 1 PPM of atmospheric CO2):

Emissions (GTC)	10	20	30	40	50	60	70	80	90	100	110	120	130	140
CO2 PPM	2.1	4.2	6.4	8.5	10.6	12.7	14.9	17.0	19.1	21.2	23.3	25.5	27.6	29.7
Radiative Forcing	0.03	0.05	0.08	0.10	0.12	0.15	0.17	0.20	0.22	0.25	0.27	0.29	0.32	0.34

Table 4

2A. Radiative Forcings of Greenhouse Gases (<https://www.esrl.noaa.gov/gmd/aggi/aggi.html>)

Radiative Forcing Calculations

To determine the total radiative forcing of the greenhouse gases, we have used IPCC [*Ramaswamy et al., 2001*] recommended expressions to convert greenhouse gas changes, relative to 1750, to instantaneous radiative forcing (see Table 1). These empirical expressions are derived from atmospheric radiative transfer models and generally have an uncertainty of about 10%. The uncertainties in the global average abundances of the long-lived greenhouse gases are much smaller (<1%).

Table 1. Expressions for Calculating Radiative Forcing*

Trace Gas	Simplified Expression Radiative Forcing, ΔF (Wm^{-2})	Constant
CO ₂	$\Delta F = \alpha \ln(C/C_o)$	$\alpha = 5.35$
CH ₄	$\Delta F = \beta(M^{1/2} - M_o^{1/2}) - [f(M, N_o) - f(M_o, N_o)]$	$\beta = 0.036$
N ₂ O	$\Delta F = \epsilon(N^{1/2} - N_o^{1/2}) - [f(M_o, N) - f(M_o, N_o)]$	$\epsilon = 0.12$
CFC-11	$\Delta F = \lambda(X - X_o)$	$\lambda = 0.25$
CFC-12	$\Delta F = \omega(X - X_o)$	$\omega = 0.32$

*IPCC (2001)

The subscript "o" denotes the unperturbed (1750) abundance

$$f(M, N) = 0.47 \ln[1 + 2.01 \times 10^{-5} (MN)^{0.75} + 5.31 \times 10^{-15} M(MN)^{1.52}]$$

C is CO₂ in ppm, M is CH₄ in ppb

N is N₂O in ppb, X is CFC in ppb

C_o = 278 ppm, M_o = 722 ppb, N_o = 270 ppb, X_o = 0

Because we seek an index that is accurate, only direct forcing from these gases has been included. Model-dependent feedbacks, for example, due to water vapor and ozone depletion, are not included. Other spatially heterogeneous, short-lived, climate forcing agents, such as aerosols and tropospheric ozone, have uncertain global magnitudes and also are not included here to maintain accuracy. Figure 3 shows the results for carbon dioxide global monthly averages for 1979-2015. An index based on the total of these contributions to radiative forcing would be similar to the Consumer Price Index, for example. It would include all the important components but not all the components of climate forcing. In contrast to climate model calculations, the results reported here are based mainly on measurements of long-lived, well mixed gases and have small uncertainties.

2015 Results

Figure 4 shows radiative forcing for the major gases and a set of 15 minor long-lived halogenated gases (CFC-113, CCl₄, CH₃CCl₃, HCFCs 22, 141b and 142b, HFCs 134a, 152a, 23, 143a, and 125, SF₆, and halons 1211, 1301 and 2402). Except for the HFCs and SF₆, which do not contain chlorine or bromine, these gases are also ozone-depleting gases and are regulated by the Montreal Protocol. As expected, CO₂ dominates the total forcing with methane and the CFCs becoming relatively smaller contributors to the total forcing over time. The five major greenhouse gases account for about 96% of

the direct radiative forcing by long-lived greenhouse gas increases since 1750. The remaining 4% is contributed by the 15 minor halogenated gases.

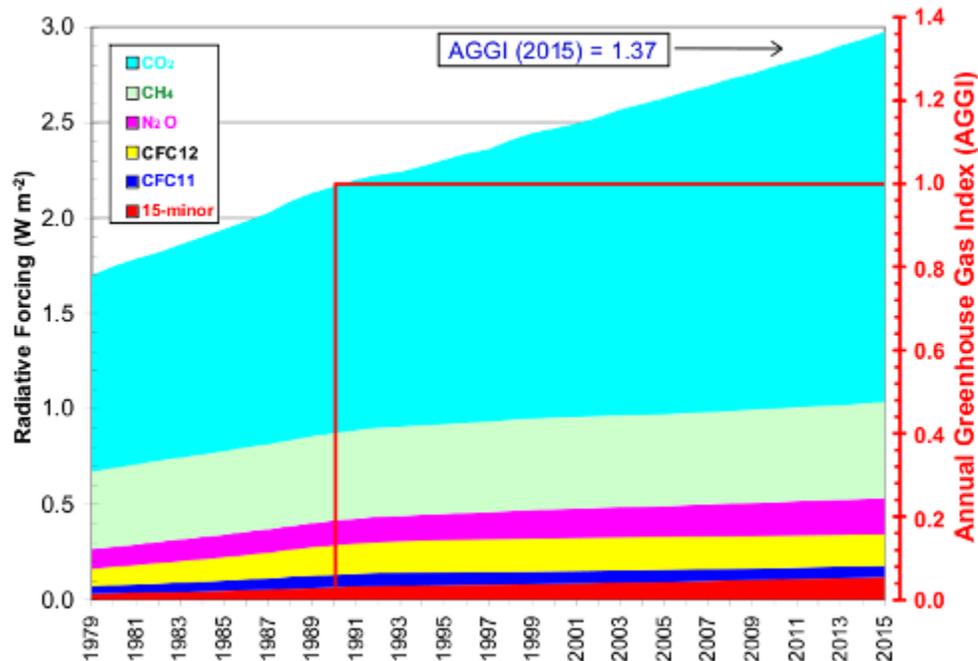


Figure 4. Radiative forcing, relative to 1750, of all the long-lived greenhouse gases. The NOAA Annual Greenhouse Gas Index (AGGI), which is indexed to 1 for the year 1990, is shown on the right axis.

Click on image to view full size figure.

Of the five long-lived greenhouse gases that contribute 96% to radiative climate forcing, CO₂ and N₂O are the only ones that continue to increase at a regular rate; increases in radiative forcing from CH₄ vary substantially from year to year. Radiative forcing from CH₄ increased from 2007 to 2015 after remaining nearly constant from 1999 to 2006. While the radiative forcing of the long-lived, well-mixed greenhouse gases increased 37% from 1990 to 2015 (by ~0.81 watts m⁻²), CO₂ has accounted for nearly 80% of this increase (~0.65 watts m⁻²). Had the ozone-depleting gases not been regulated by the Montreal Protocol and its amendments, it is estimated that climate forcing would have been as much as 0.3 watt m⁻² greater in 2010 [Velders *et al.*, 2007], or more than half of the increase in radiative forcing due to CO₂ alone since 1990. Of the ozone-depleting gases and their substitutes, the largest contributors to direct warming in 2015 were CFC-12, followed by CFC-11, HCFC-22, CFC-113 and HCFC-134a. Although the concentration of HCFC-22 in the remote atmosphere surpassed that of CFC-11 by the end of 2015 (Figure 2), the radiative forcing arising from HCFC-22 is only 80% of that from CFC-11 because CFC-11 is more efficient at trapping infrared radiation on a per molecule basis.

An Annual Greenhouse Gas Index (AGGI) has been defined as the ratio of the total direct radiative forcing due to long-lived greenhouse gases for any year for which adequate global measurements exist to that which was present in 1990. 1990 was chosen because it is the baseline year for the Kyoto Protocol. This index, shown with the direct radiative forcing values in Table 2 and on the right-hand axis of Figure 4, is a measure of the interannual changes in conditions that affect carbon dioxide emission and uptake, methane and nitrous oxide sources and sinks, the decline in the atmospheric abundance of ozone-depleting chemicals related to the Montreal Protocol, and the increase in their substitutes (HCFCs and HFCs). Most of this increase is related to CO₂. For 2015, the AGGI was **1.37** (representing an increase in total direct radiative forcing of 37% since 1990). The increase in CO₂ forcing alone since 1990 was about 50% (see Fig. 3). The decline in the CFCs has tempered the increase in net radiative forcing considerably. The AGGI is updated each spring when air samples collected during the previous year from all over the globe have been obtained and analyzed.

Changes in radiative forcing before 1978 are derived from atmospheric measurements of CO₂, started by C.D. Keeling [Keeling *et al.*, 1958], and from measurements of CO₂ and other greenhouse gases in air trapped in snow and ice

in Antarctica and Greenland [Etheridge et al., 1996; Butler et al., 1999]. These results define atmospheric composition changes going back to 1750 and radiative forcing changes since preindustrial times (Figure 4). This longer-term view shows how increases in greenhouse gas concentrations over the past 60 years (since 1950) have accounted for three-fourths (75%) of the total increase in the AGGI over the past 260 years. Changes in radiative forcing before 1978 are derived from atmospheric measurements of CO₂, started by C.D. Keeling [Keeling et al., 1958], and from measurements of CO₂ and other greenhouse gases in air trapped in snow and ice in Antarctica and Greenland [Etheridge et al., 1996, 1998; Butler et al., 1999]. These results define atmospheric composition changes going back to 1750 and radiative forcing changes since preindustrial times (Figure 5). This longer-term view shows how increases in greenhouse gas concentrations over the past 60 years (since 1950) have accounted for three-fourths (75%) of the total increase in the AGGI over the past 260 years.

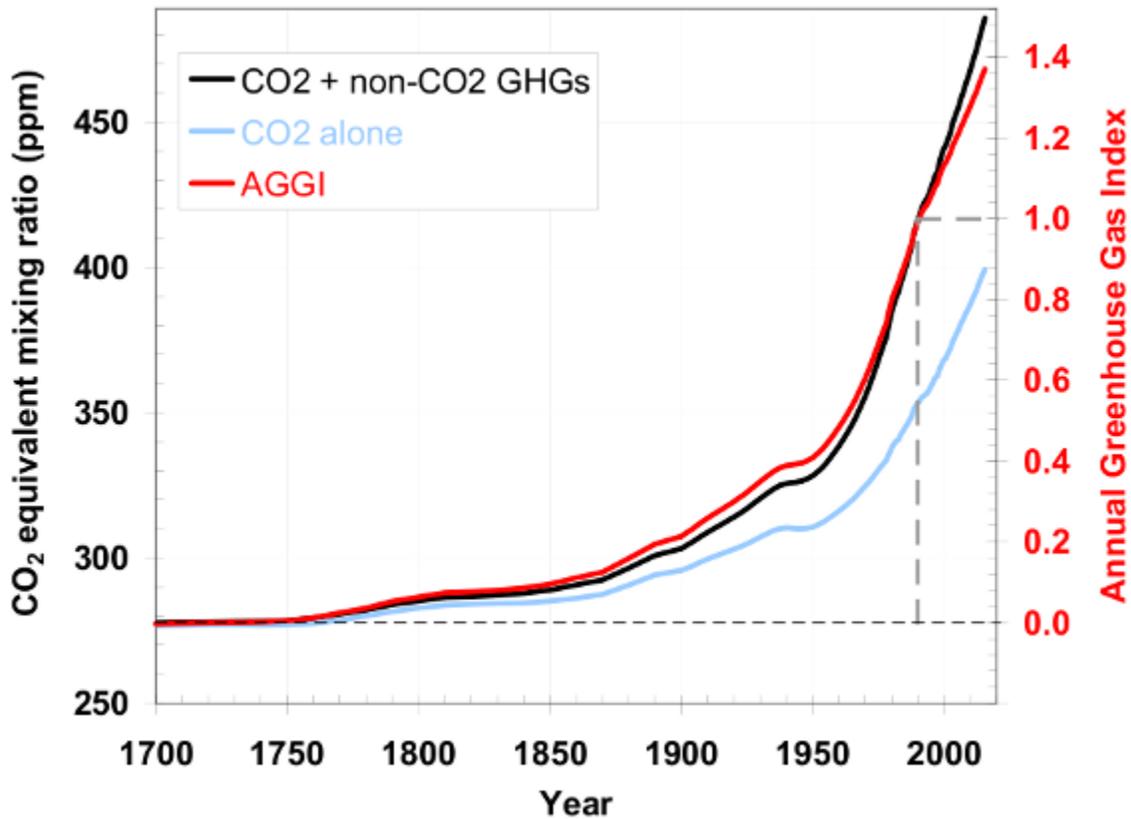


Figure 5. Pre-1978 changes in the CO₂-equivalent concentration and AGGI based on the ongoing measurements of all greenhouse gases reported here, measurements of CO₂ going back to the 1950s from C.D. Keeling [Keeling et al., 1958], and atmospheric changes derived from air trapped in ice and snow above glaciers [Machida et al., 1995, Battle et al., 1996, Etheridge, et al., 1996; Butler, et al., 1999]. Equivalent CO₂ atmospheric amounts (in ppm) are derived with the relationship (Table 1) between CO₂ concentrations and radiative forcing from all long-lived greenhouse gases.

3. Historical and Recent Radiative Forcing

Based on data from the IPCC, the net radiative forcing has been increasing at a rate of about 0.4 W m⁻² per decade since 1960 (see Figure 2).i

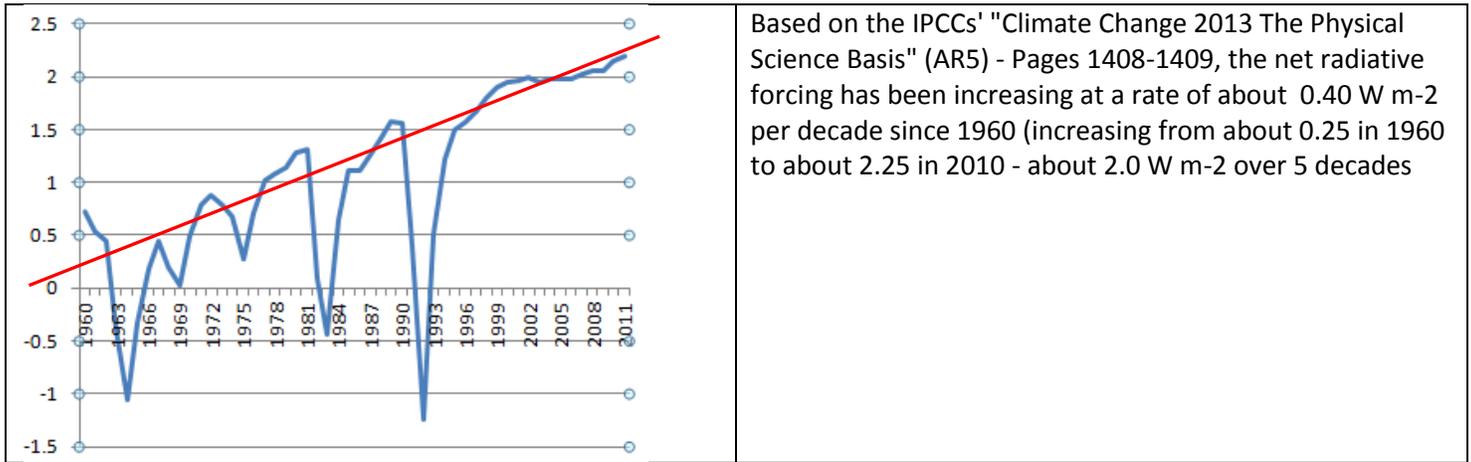


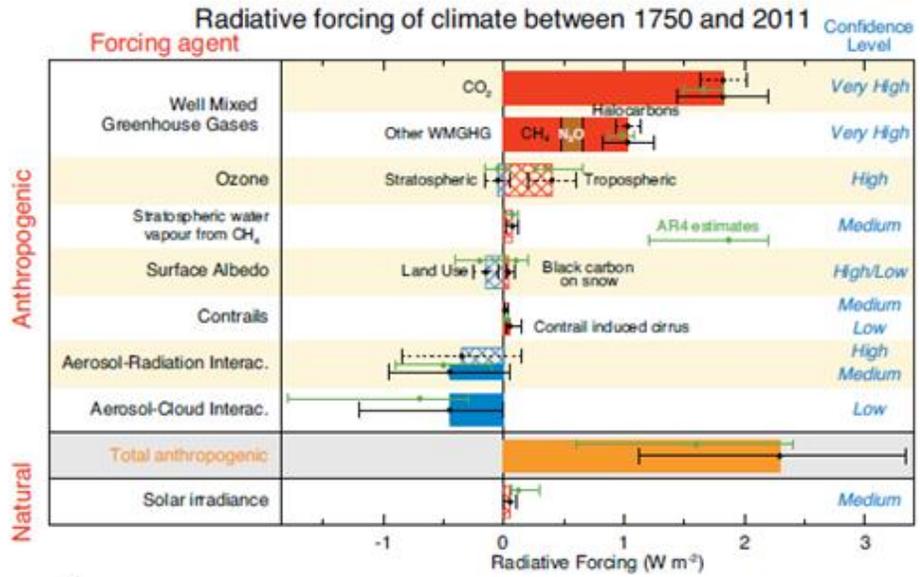
Figure 2 -Recent net forcing

3.1	0.4	The current increase per decade of net radiative forcing (primarily due to anthropogenic emissions and land use changes) (W m ⁻²)
3.2	2.3	Total radiative forcing in 2011 (W m ⁻²)
3.3	2.5	Total radiative forcing in 2016 (W m ⁻²)
3.4	2.0	Radiative forcing from greenhouse gases - 1987 (W m ⁻²)
3.5	3.0	Total radiative forcing from greenhouse gases - 2015 (W m ⁻²)
3.6	0.37	The current increase per decade of radiative forcing from greenhouse gases (W m ⁻²)

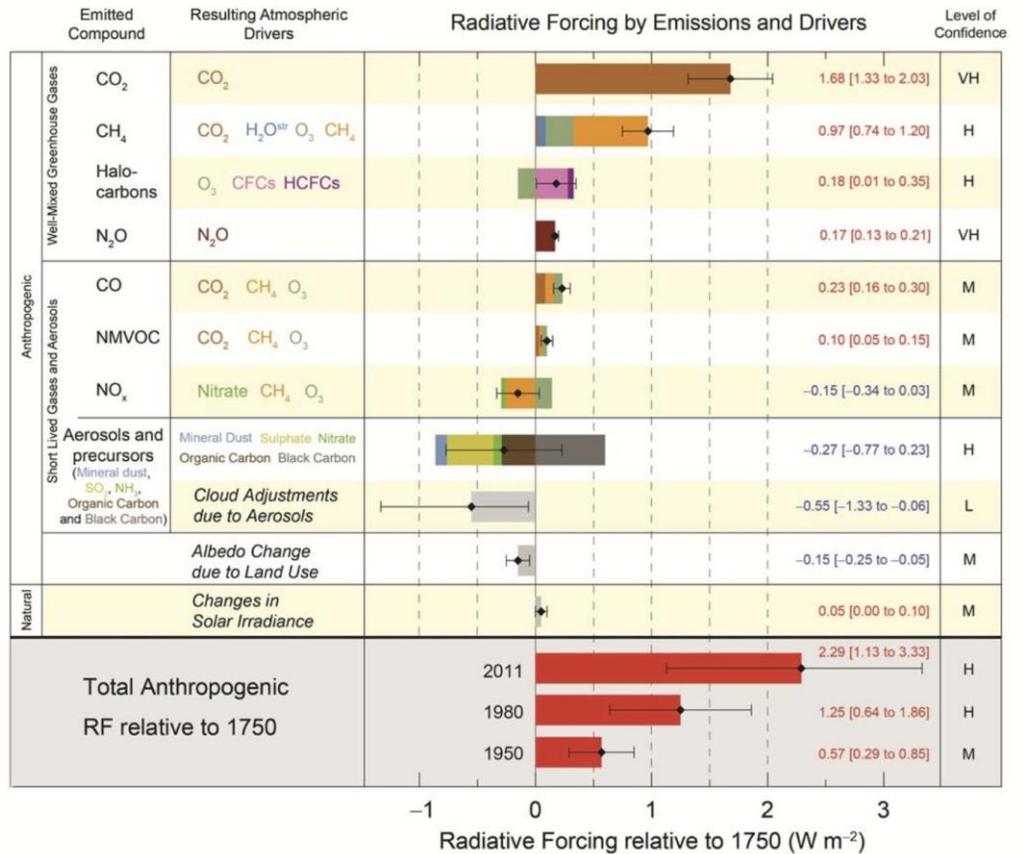
4. Radiative Forcing Factors and Components

Forcing agents are either chemicals that are emitted by anthropogenic and natural cases changes (e.g., CO₂, CH₄, O₃, etc.) or factors that affect the Earth's albedo (e.g., aerosols, the clearing of land, black carbon on snow, etc.). Figure 3A shows the most important forcing agents of our climate system. Since some of the forcing agents undergo chemical transformation in the atmosphere or cause other chemical to be formed, the IPCC also lists the actual *forcing components* that are responsible for either warming or cooling the atmosphere (e.g., chemical reactions with methane produce CO₂, H₂O, and O₃)(see Figure 3B).

#	Value	Description
4.1	2.3 W m ⁻²	Radiative Forcing in 2011



A. Radiative forcing by forcing agent (IPCC AR5 – Figure TS-6)



B. Radiative forcing by forcing component (IPCC AR5)

<http://www.realclimate.org/index.php/archives/2013/10/the-evolution-of-radiative-forcing-bar-charts/>

Figure 3 - Forcing Agents and Forcing Components

5. Radiative Forcing From Surface Albedo Changes

Brian J. Soden and Isaac M. Held ("An Assessment of Climate Feedbacks in Coupled Ocean–Atmosphere Models", 2006; <http://journals.ametsoc.org/doi/full/10.1175/JCLI3799.1>) estimated that the radiative forcing of the models they reviewed (roughly doubling in equivalent CO₂ between 2000 and 2100) was 4.3 W m⁻² and, "[o]n average, the strongest positive feedback is due to water vapor (1.8 W m⁻² K⁻¹), followed by clouds (0.68 W m⁻² K⁻¹), and surface albedo (0.26 W m⁻² K⁻¹), thus surface albedo changes (primarily Arctic sea ice and Northern Hemisphere snow cover extent) contribute about 6% of the total radiative forcing at the global tropopause.

In "Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008", Flanner, et. al., concluded that "cyrospheric cooling declined by 0.45 W m⁻² from 1979 to 2008, with nearly equal contributions from changes in land snow cover and sea ice. On the basis of these observations, we conclude that the albedo feedback from the Northern Hemisphere cryosphere falls between 0.3 and 1.1 W m⁻² K⁻¹, substantially larger than comparable estimates obtained from 18 climate models." <http://data.engin.umich.edu/faculty/flanner/content/ppr/FIS11.pdf>

#	Value	Description
5.1	6	In climate models, the % of the total radiative forcing at the global tropopause due to surface albedo changes (primarily Arctic sea ice and Northern Hemisphere snow cover extent)
5.2	0.45	Decline in cyrospheric cooling from 1979 to 2008 (W m ⁻²)
5.3	2.3	Radiative forcing 2011 (W m ⁻²)
5.4	.14	Radiative forcing for surface albedo change attributed by models (W m ⁻²) (2.3 * .06) (W m ⁻²)
5.5	.30	"Excess" Radiative forcing 2011 (W m ⁻²)
5.6	2.8	Adjusted Radiative forcing 2016 (W m ⁻²) (2.5 W m ⁻² + .30 W m ⁻²)
5.7	0.1	Decadal change in radiative forcing not attributable to models and hence not included in radiative forcing estimates (W m ⁻²)
5.8	0.5	The current increase of net radiative forcing due to anthropogenic emissions, land use changes, and surface albedo changes (0.4 (from #3.1 above) + 0.1) (W m ⁻²)

6. Radiative Forcings in RCP 2.6

The RCP 2.6 pathway is supposed to demonstrate an emissions pathway that will result in a temperature increase of about 2°C by 2100. The following tables show some of the radiative forcing values from the IPCC's AR5 for both the . Table 6 shows the radiative forcing of some of the "climate factors" both 2011 and 2100, and Table 5 lists the radiative forcing at the end of each decade for RCP 2.6. Note that radiative forcing from all of the greenhouse gases does not change from 2011 to 2100, but just shifts significantly from methane and halocarbons to carbon dioxide. Note also that the IPCC data in "The Physical Science Basis" did not specifically list the aerosol radiative forcings after 2011. Since the majority of the aerosols come from the burning of fossil fuels, it's hard to see how the RCP 2.6 model "makes up" for the additional forcing that will come as fossil fuel use is reduced significantly (they could be assuming lots of CCS and BECCS and that these would both continue to emit aerosols). In addition, assuming the current growth rate in radiative forcing (0.43 W m⁻²) continues, the IPCC's 2030 value will be reached by 2023, and the 2040 value (which is just about the maximum value) will be reached in 2026. (Note: if surface albedo changes are taken into account then the IPCC's 2030 value will be reached by 2019, and the 2040 value will be reached in 2022.)

	2011	RCP2.6 (2100)	RCP 2.6		
CO2	1.816	2.220	Year	Radiative Forcing	Change Per Decade
CH4	0.425	0.270	2010	2.17	
N2O	0.195	0.230	2020	2.53	0.36
Halocarbons	0.395	0.142	2030	2.70	0.17
Greenhouse Gases	2.831	2.862	2040	2.84	0.14
Stratospheric	-0.050	-0.075	2050	2.85	0.01
Tropospheric	0.400	0.170	2060	2.77	-0.08
Ozone	0.350	0.140	2070	2.71	-0.06
Strato. H2O	0.073		2080	2.60	-0.11
Land Use	-0.150		2090	2.64	0.04
Black Carbon	0.040		From Page 1436 "Total anthropogenic plus natural ERF (W m ⁻²) from CMIP5 and CMIP3, including historical" (Adjusted by .2 W m ⁻² to bring in line with values for 2011 and 2020)		
Albedo	-0.110		Data based on the IPCCs' "Climate Change 2013: The Physical Science Basis" (AR5)		
Contrails	0.050				
Radiation Inter.	-0.450				
Cloud Inter	-0.450				
Aerosols	-0.900				
Total Anthropogenic	2.294				
Solar Radiance	0.030				
Total IPCC	2.324	2.600			

Table 5. Radiative Forcing Changes since 1750

Table 6. Radiative Forcing by Decade for RCP 2.6

7. Projected changes in Radiative Forcing in 40-50 Years

Assuming that a relatively aggressive greenhouse gas emissions reduction effort is undertaken without any "mechanical" sequestration, the radiative forcing in 40-50 years will increase by about 1.7 W m⁻², resulting in a total of about 4.0 W m⁻²:

	Global Warming Factor	Adjustments for 2060	RF Change	Description
Emissions		GTC	W m ⁻²	(100 GTC =0.4 W/m ⁻²)
1	CO2	110	0.27	2% increase in emissions through 2025 and then a two percent reduction per year (assumes a 45% airborne factor)
2	Peat/soils	45	0.11	"Drainage of peat soils results in carbon dioxide (CO2) and nitrous oxide (N2O) emissions of globally 2-3 Gt CO2-eq per year (Joosten & Couwenberg 2009)" http://www.wetlands.org/Portals/0/publications/Report/web_Methane_emissions_from_peat_soils.pdf
3	Reservoirs	30	0.08	http://www.climatecentral.org/news/greenhouse-gases-reservoirs-fuel-climate-change-20745 <i>Methane emissions from reservoirs contribute about .7GTC of CO2 equivalent per year, resulting in about 30 GTC through 2060 and 60 GTC through 2100.</i>

4	Permafrost	30	0.08	"It [(permafrost melt)] was first proposed in 2005. And the first estimates came out in 2011. Indeed, the problem is so new that it has not yet made its way into major climate projections, Schaefer says." ... "None of the climate projections in the last IPCC report account for permafrost," says Schaefer. "So all of them underestimate, or are biased low." ... "It's certainly not much of a stretch of the imagination to think that over the coming decades, we could lose a couple of gigatons per year from thawing permafrost," says Holmes.... But by 2100, the "mean" estimate for total emissions from permafrost right now is 120 gigatons, say Schaefer. " http://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet http://ccdatacenter.org/documents/FeedbackFromPermafrost.pdf
5	Afforestation/ Soils	-40	-0.10	Hansen estimates that up to 100 GTC could be sequestered with afforestation and soil management by 2100. Perhaps 40% of this amount could happen in the next 40-50 years ("Young People's Burden: Requirement of Negative CO2 Emissions" (October 4, 2016) http://www.earth-syst-dynam-discuss.net/esd-2016-42/
6	Other			
Radiative Forcing		W m-2	W m-2	
7	Greenhouse gases	0.0	0.0	Methane emissions have been increasing in recent years, but RCP 2.6 expects methane emissions to be 1/2 of 2010 emissions in 2100. So this analysis assumes that the RF from methane and other greenhouse gases will not be changed in 2060
8	Aerosols	0.8	0.8	Measured Earth energy imbalance, +0.58 W/m ² during 2005-2010, implies that the aerosol forcing is about -1.6 W/m ² , a greater negative forcing than employed in most IPCC models. (<i>One half of that value is used here</i>) http://www.giss.nasa.gov/research/briefs/hansen_16/
9	Surface Albedo Change	0.45	0.45	Using 4.5 decades of 0.1 W m-2 decadal change in radiative forcing not attributable to models (or included in climate sensitivity) and hence not included in radiative forcing estimates
10	Tundra Greening			
11	Other			
Total			1.7	

Table 7

8. Climate Sensitivity

Climate sensitivity is a metric used to characterise the response of the global **climate** system to a given forcing. It is broadly defined as the equilibrium global mean surface temperature change following a doubling of atmospheric CO₂ concentration

https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-6.html

"[E]stimates of climate sensitivity and of climate feedbacks differ among current models [due to] the role of key radiative feedback processes associated with water vapour and lapse rate, clouds, snow and sea ice in climate sensitivity," https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-6.html

The [IPCC Fourth Assessment Report](#) summarized climate sensitivity as *"likely to be in the range 2 to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values."*

If the climate sensitivity is 3°C for a doubling of CO₂, then the following table shows the expected equilibrium temperature for various amounts of atmospheric CO₂ and the corresponding radiative forcing (emissions are based on a 45% airborne fraction; note that the total for 550 PPM is 1281 GTC, which is actually close to the IPCC's 1,000 GTC budget; and significant CO₂ will be absorbed in the oceans (from the atmosphere) if anthropogenic CO₂ emissions can be eliminated)

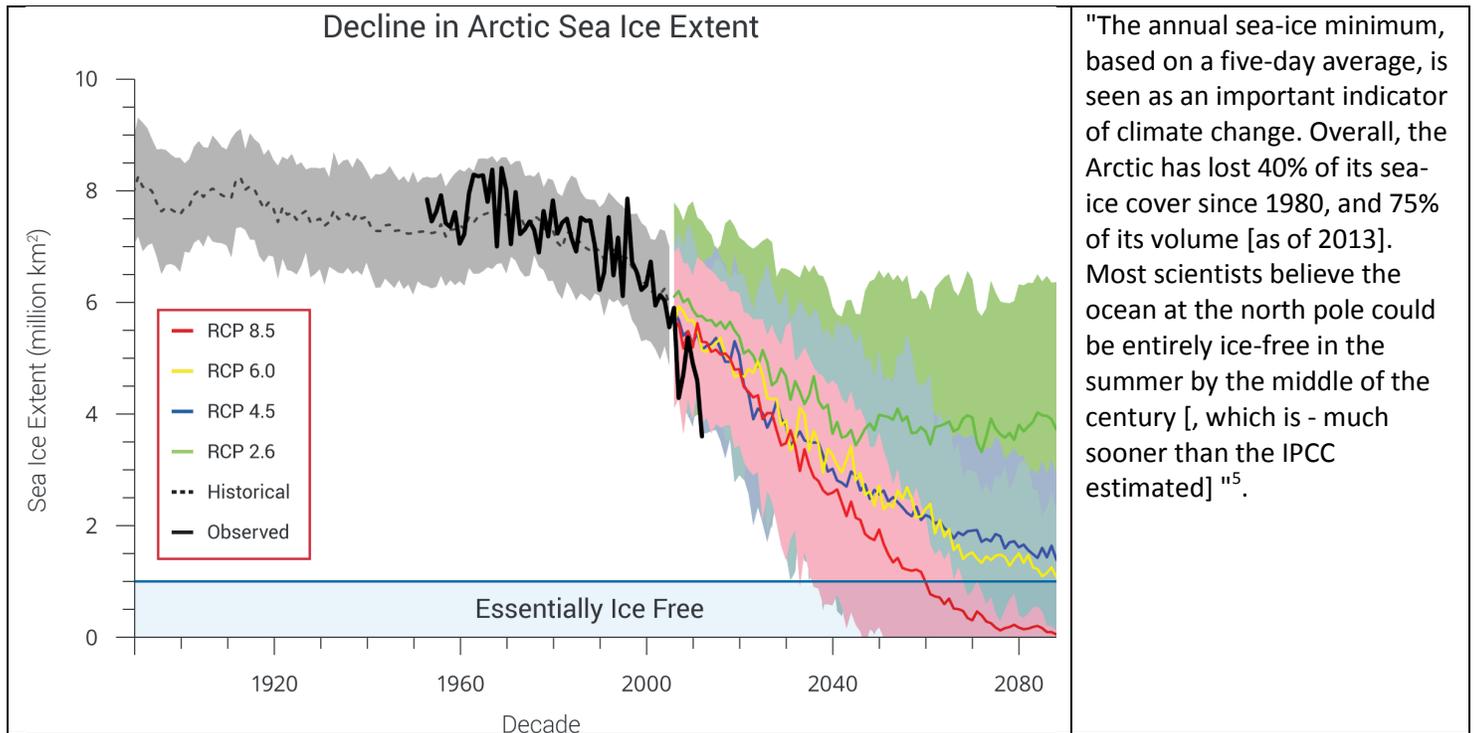
CO2 PPM	278	300	325	350	375	400	425	450	475	500	525	550	575	600
Equilibrium Temp.	0.00	0.24	0.51	0.78	1.05	1.32	1.59	1.86	2.13	2.40	2.67	2.94	3.21	3.47
Radiative Forcing	0.00	0.41	0.84	1.23	1.60	1.95	2.27	2.58	2.87	3.14	3.40	3.65	3.89	4.12
Emissions (GTC)	0	104	221	339	457	575	693	810	928	1046	1164	1281	1399	1517

Table 8

The following calculations can then be made

#	Value	Description
6.1	2.8	Adjusted Radiative forcing 2016 (W m ⁻²) (2.5 W m ⁻² + .30 W m ⁻²)
6.2	2.0	Equilibrium temperature change for radiative forcing in 2016 (°C)
6.3	4.50	Radiative forcing in 40-50 years (2.8 + 1.7)
6.4	3.9	Equilibrium temperature change for radiative forcing in 2060 (°C)

As the sea ice in the Arctic Ocean melts and as the Northern Hemisphere snow cover extent is reduced, the Earth's albedo will be reduced and the Earth will warm. Surface albedo is included as one of the fast feedbacks when determining a value for climate sensitivity, but it is likely that the climate models (and climate sensitivity) underestimate the rate of change^{3,4}. We need to know, for a typical 2°C scenario, the amount of radiative forcing that was estimated for the change in surface albedo.



"The annual sea-ice minimum, based on a five-day average, is seen as an important indicator of climate change. Overall, the Arctic has lost 40% of its sea-ice cover since 1980, and 75% of its volume [as of 2013]. Most scientists believe the ocean at the north pole could be entirely ice-free in the summer by the middle of the century [which is - much sooner than the IPCC estimated]"⁵.

9. Rate of Global Warming

The temperature has increased at about 0.19°C per decade since 1960 (Figure 4). By looking at these trends over the last 50 years (and extrapolating this to 2020) and assuming a climate sensitivity of 3°C for a doubling of atmospheric CO₂ (see Table 8) it appears that the increasing energy imbalance is not causing the global temperature to increase more rapidly, and, as a result, the equilibrium temperature is increasing at over twice the rate as that of the global temperature (i.e., the global temperature increasing at about .19°C per decade but we are committing ourselves to a temperature increase of about .45°C per decade when all of the factors are considered).

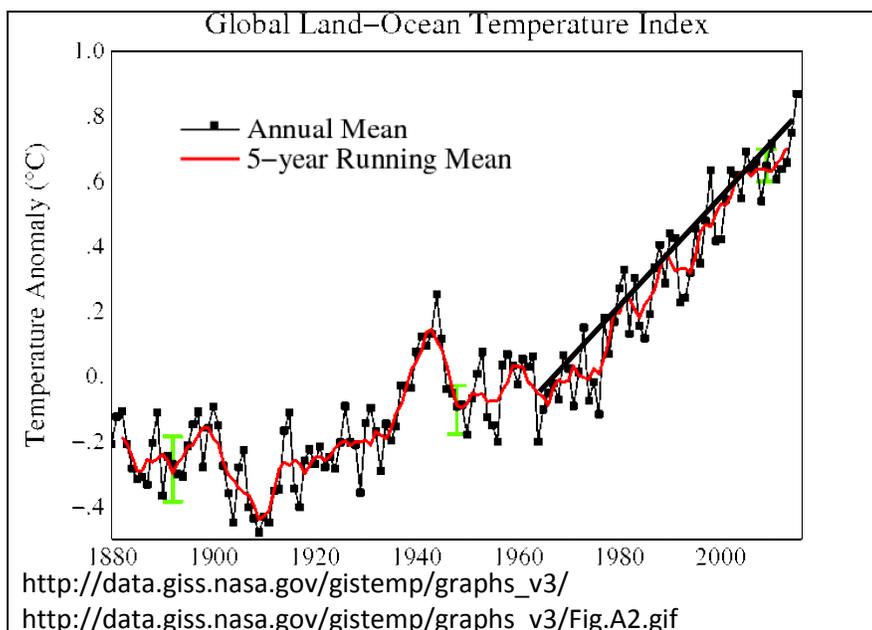


Figure 4 - Historical temperature increase

#	Value	Description
7.1	0.19	The temperature as increased per decade since 1960 (°C)
7.2	0.36	Committed warming per decade from 0.4 W m ⁻² of radiative forcing per decade from mostly anthropogenic factors (when atmospheric CO ₂ is at 450 PPM) (°C)
7.3	0.45	Committed warming per decade from 0.5 W m ⁻² of radiative forcing per decade from all factors (when atmospheric CO ₂ is at 450 PPM) (°C)
7.4	82 PPM	The increase of atmospheric CO ₂ above 400 PPM that will cause an increase of 1 Wm ⁻² of radiative forcing
7.5	102 PPM	The increase of atmospheric CO ₂ above 500 PPM that will cause an increase of 1 Wm ⁻² of radiative forcing
7.6	10 PPM	The increase of atmospheric CO ₂ above 450 PPM that will cause an equilibrium temperature increase of 0.1 °C
7.7	0.1 W m ⁻²	The amount of radiative forcing that will cause an equilibrium temperature increase of 0.1 °C
7.8	44 GTC	The quantity of CO ₂ emissions that, if emitted, will cause an equilibrium temperature increase of 0.1 °C
7.9	10 GTC	The quantity of CO ₂ emissions that, if emitted, will cause an equilibrium temperature increase of 0.022° C
7.10	48 GTC	The quantity of CO ₂ emissions that need to be sequestered to reduce the radiative forcing by 0.1 W m ⁻²
7.11	480 GTC	The quantity of CO ₂ emissions that need to be sequestered to reduce the radiative forcing by 1.0 W m ⁻²

9. Target Values for Radiative Forcing for 2100

Possible values for the long-range target value for radiative forcing include:

#	W/m ⁻²	Description
1	1.3	James Hansen - there are "slow feedbacks" (glacier ice melt, sea level rise, etc.) which will likely "kick in" (and be out of our control) if the temperature stays much above that of the Holocene (a 0.25° C to 0.75° C increase over preindustrial times) for an extended period of time (decades to a century), so the total radiative forcing must be kept below this value ("Young People's Burden: Requirement of Negative CO ₂ Emissions" (October 4, 2016) (http://www.earth-syst-dynam-discuss.net/esd-2016-42/))
2	1.6	The radiative forcing for the 1°C temperature increase through 2150. Radiative forcings from surface albedo in the Arctic are already contributing 0.25-.50 W m ⁻² to the total, and natural emissions from soils, permafrost, and reservoirs are contributing additional greenhouse gas emissions. The combination of all of these is probably sufficient to lead to "runaway global warming" (8-10°C, not like Venus) as the additional warming causes additional greenhouse gases to be released in the Arctic region in a feedback loop.
3	2.2	The "lower bound" of the Paris agreement
4	2.7	The "upper bound" of the Paris agreement

10. Target Radiative Forcing for 2060

Based on RCP 2.6, which shows a 0.2 W m^{-2} decline in radiative forcing after the peak value is reached and net CO₂ emissions approach zero, the following table shows the amount of CO₂ that would need to be sequestered in order to meet the various radiative forcing targets for 2100 assuming that we are on a trajectory for about 4.5 W m^{-2} by 2060

2100 Target Temperature (°C)	0.8	1.0	1.5	2.0
2100 Target RF	1.3	1.6	2.2	2.7
2060 Target RF (0.2 more than 2100)	1.5	1.8	2.4	2.9
RF of sequestered CO ₂ to meet the target	3.0	2.7	3.1	1.6
GTC to be sequestered to meet the target	1440	1296	1488	768
Minimal Cost - Trillions of Dollars (\$150/ton C)	216	194	223	115

1. Give the significant radiative forcings from natural causes, we could already be on an un-stoppable path to "run away" global warming (not like Venus, but perhaps enough to raise global temperatures by $8-10^\circ \text{C}$). If we are not already on an "un-stoppable path", what combination of temperature increase and radiative forcing will likely put us on such a path?
2. If surface albedo changes are taken into account, the current radiative forcing is about the same as the maximum radiative forcing in RCP 2.6, which occurs about 2040.

Other Interesting Information

Historical net forcing and Temperature Change

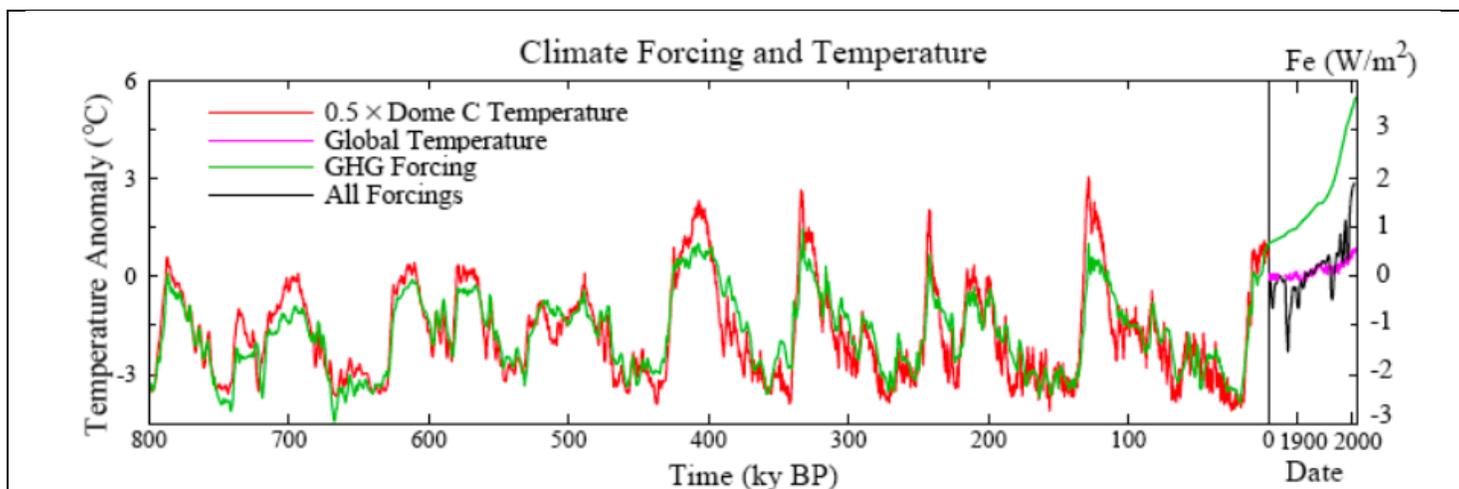
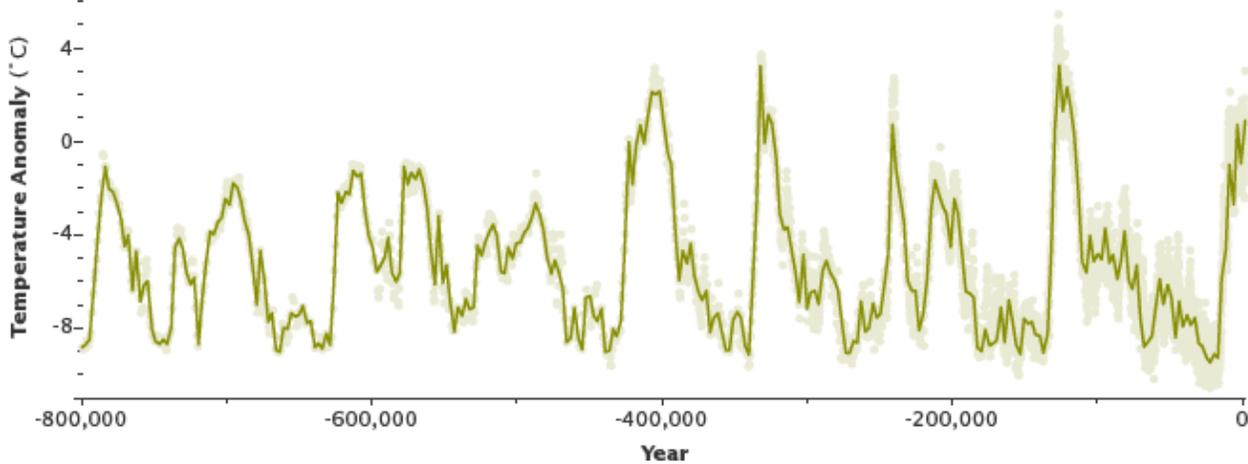


Fig. S18. Global temperature (left scale) and GHG forcing (right scale) due to CO₂, CH₄ and N₂O from Vostok ice core (11, 15). Ratio of temperature and forcing scales is 1.5°C per W/m^2 . Time scale is expanded in the extension to recent years. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance (5). GHG forcing zero point is the mean for 10-8 ky before present. Net climate forcing and modern temperature zero points are at 1850. The implicit presumption that the positive GHG forcing at 1850 is largely offset by negative human-made forcings (6) is supported by the lack of rapid climate change at that time.

<http://ossfoundation.us/projects/environment/global-warming/milankovitch-cycles>

The earth warmed by about 8°C over 10,000 years (18,000 – 8,000 years ago)



<http://earthobservatory.nasa.gov/Features/GlobalWarming/page3.php>

	3.0 W m ⁻²	Increase in radiative forcing coming out of the last ice age
	8° C	Increase in temperature coming out of the last ice age (18,000 – 8,000 years ago)

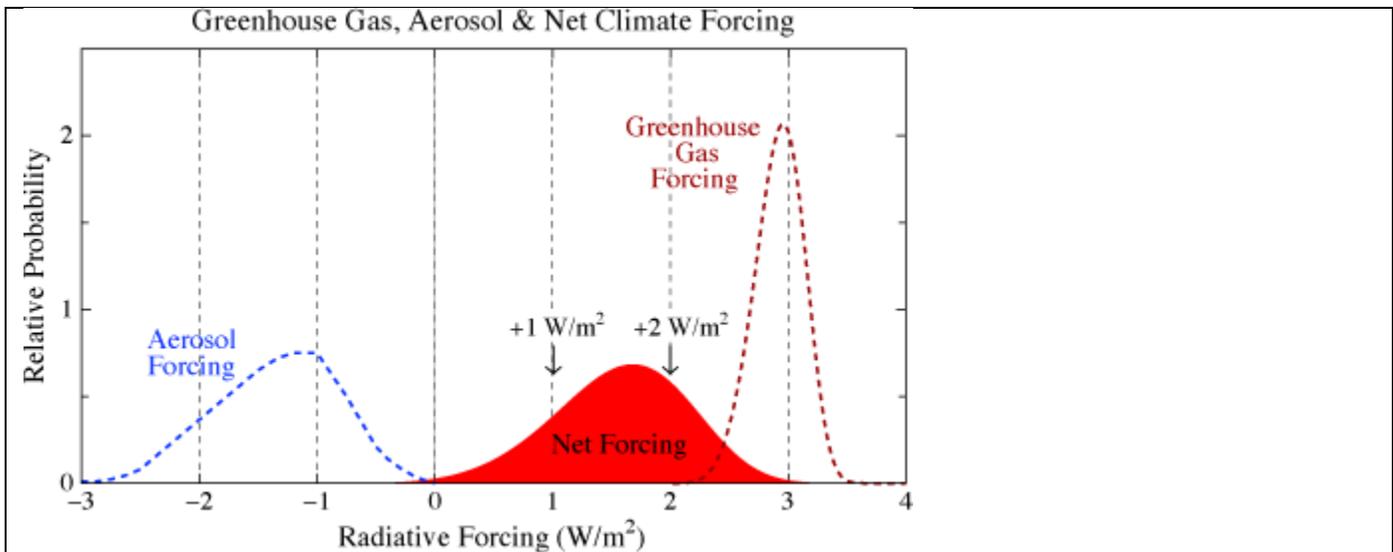


Figure 3. Schematic diagram of human-made climate forcings by greenhouse gases, aerosols, and their net effect. (Credit: NASA/GISS)

The net human-made aerosol forcing is negative (cooling), but its magnitude is uncertain within a broad range (Fig. 3). The aerosol forcing is complex because there are several aerosol types, with some aerosols, such as black soot, partially absorbing incident sunlight, thus heating the atmosphere. Also aerosols serve as condensation nuclei for water vapor, thus causing additional aerosol climate forcing by altering cloud properties. As a result, sophisticated global measurements are needed to define the aerosol climate forcing...

[A]erosols remain airborne only several days...

Measured Earth energy imbalance, +0.58 W/m² during 2005-2010, implies that the aerosol forcing is about -1.6 W/m², a greater negative forcing than employed in most IPCC models.

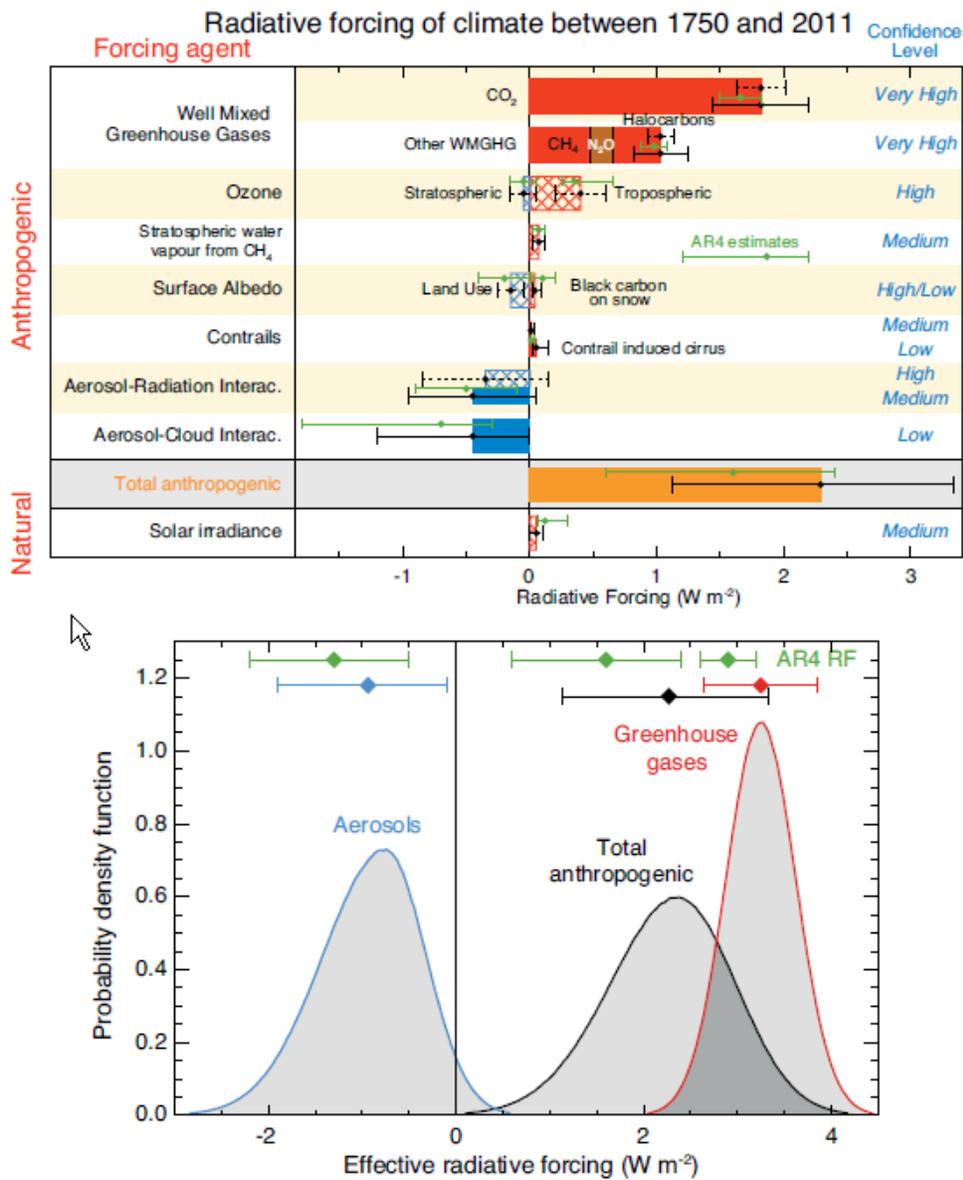


Figure TS.6 | Radiative forcing (RF) and Effective radiative forcing (ERF) of climate change during the Industrial Era. (Top) Forcing by concentration change between 1750 and 2011 with associated uncertainty range (solid bars are ERF, hatched bars are RF, green diamonds and associated uncertainties are for RF assessed in AR4). (Bottom) Probability density functions (PDFs) for the ERF, for the aerosol, greenhouse gas (GHG) and total. The green lines show the AR4 RF 90% confidence intervals and can be compared with the red, blue and black lines which show the AR5 ERF 90% confidence intervals (although RF and ERF differ, especially for aerosols). The ERF from surface albedo changes and combined contrails and contrail-induced cirrus is included in the total anthropogenic forcing, but not shown as a separate PDF. For some forcing mechanisms (ozone, land use, solar) the RF is assumed to be representative of the ERF but an additional uncertainty of 17% is added in quadrature to the RF uncertainty. (Figures 8.15, 8.16)

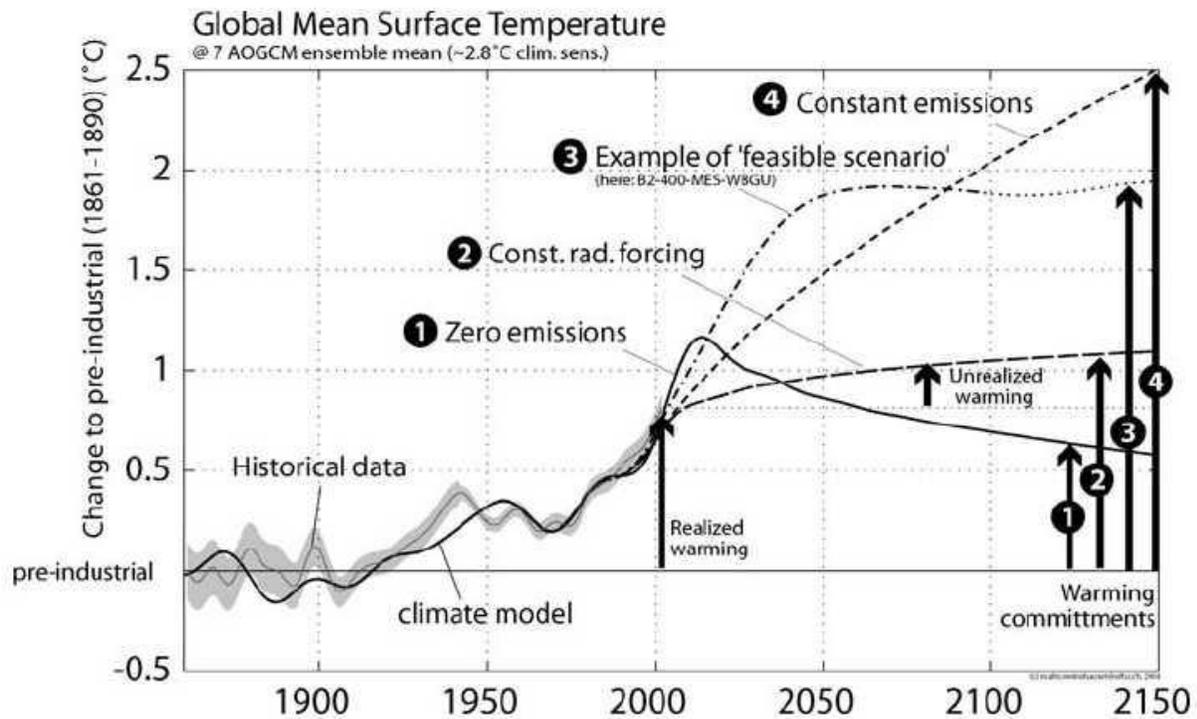


Figure 1. Four different types of warming commitments. (1) The 'geophysical' warming commitment in case that emissions are abruptly reduced to zero after 2005 ('Zero Emissions'); Note that emissions initially rise due to ceased cooling by aerosols. (2) The 'present forcing' warming commitment corresponds to constant radiative forcing at present (2005) levels and comprises the 'realized' and 'unrealized' warming; (3) the 'feasible scenario' warming commitment is the temperature rise that corresponds to the lowest emission scenario judged feasible. Note that the mitigation scenario B2-400-MES-WBGU is shown for illustrative purposes only (dash-dotted line: original scenario up to 2100; dotted part: the extended scenario as described in text). Lastly, (4) the 'constant emissions' warming commitment that corresponds to highest warming levels in the long term. The historical temperature record and its uncertainty (grey shaded area) is taken from Folland et al. (2001).

Climatic Change

March 2006, Volume 75, [Issue 1](#), pp 111–149

Hare, B. & Meinshausen, M.

How Much Warming are We Committed to and How Much can be Avoided

http://www.pik-potsdam.de/~mmalte/simcap/publications/Hare_Meinshausen_2004_WarmingCommitment_PIK-Report.pdf