How Much Warming Can We Expect?

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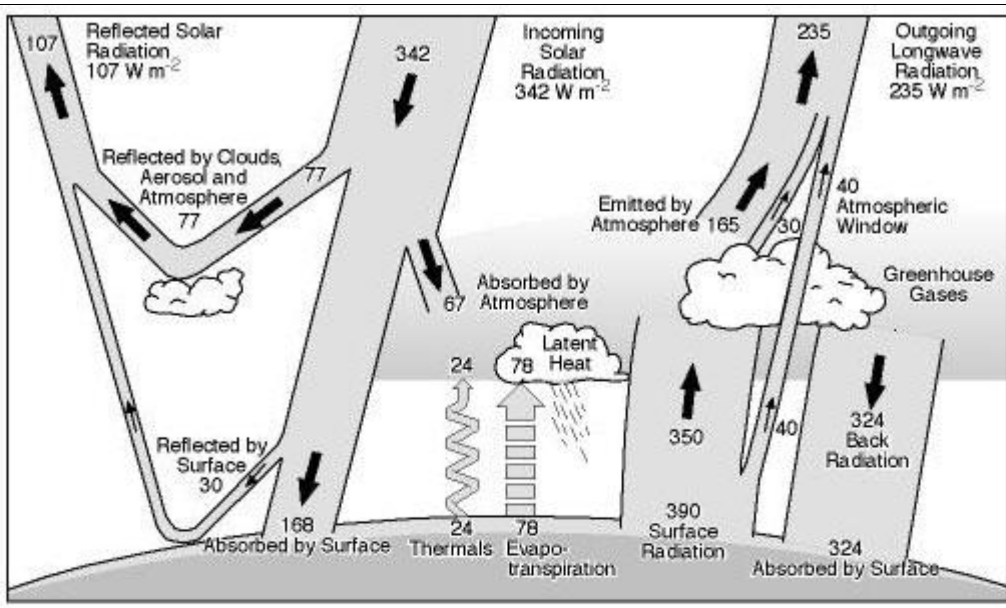
(http://ccdatacenter.org/documents/ HowMuchWarmingCanWeExpect.pdf)

The Earth has warmed about 1.1° C since the late 1800's, when the burning of coal started to drive a period of rapid industrialization. Given what we know about the climate system and a reasonable estimate of future greenhouse gas emission, how much total warming can we expect in the by the year 2100? The following is a step-by-step "top down" approach to making an estimate. It starts with what is known about the current climate, adds in expected greenhouse gas emissions from an *aggressive* emissions reduction scenario (which we will be lucky to meet), and factors in some of the *feedback*s that are expected from a warming world. This simple and straightforward approach makes it much easier for non-climate scientists to understand what to expect, and I would hope this could be used as template by climate scientists to explain how much warming they would expect by 2100.

Earth's Energy Balance

The energy that the Earth receives from the Sun (about 342 Watts/square meter[1]) is either reflected directly back into space or absorbed by the Earth's atmosphere and surface. Most of the absorbed energy is then re-radiated as thermal (heat) energy, and a significant portion of this energy eventually escapes from the top of the atmosphere (see Figure 1). Over long periods of time, the amount of energy that the Earth reflects and radiates must be the same as the energy the Earth receives, otherwise the Earth would either get warmer or cooler until a balance was reached. Due to the accumulation of greenhouse gases and changes in reflectivity, the Earth currently emits less energy than it receives, and it will warm until a new balance is achieved. The Earth has warmed about 1.1° C since the late 1800's and will warm an additional 0.5° C due to the current energy imbalance.

Over relatively short periods of time (hundreds of years), the energy from the Sun is fairly constant, so the atmosphere warms (or cools) to the point where the thermal energy emitted at the top of the atmosphere ("outgoing long wave radiation") matches the amount of energy that is absorbed by the atmosphere and surface of the Earth ("incoming solar radiation" minus "reflected solar radiation"). This leaves only two main factors that determine the Earth's equilibrium atmospheric temperature on a human timescale – the albedo, or reflectivity, of the Earth, and the quantity of heat trapping (greenhouse) gases in the Earth's atmosphere.



http://disc.sci.gsfc.nasa.gov/education-and-outreach/additional/science-focus/ocean-color/warming.shtml

Figure 1 – Earth's energy balance

Effective Radiative Forcing

In order to quantify the expected *temperature change* from the various components of the climate system, climatologists first estimate the impact of the individual components' equivalent change in solar radiation at the top of the atmosphere, using the term "effective radiative forcing" (ERF). For example, from pre-industrial times to 2011 the atmospheric concentration of CO2 increased by about 117 PPM (from about 275 PPM 392 PPM), for a change in radiative forcing of about 1.8 W/m^2 (see Figure 2).

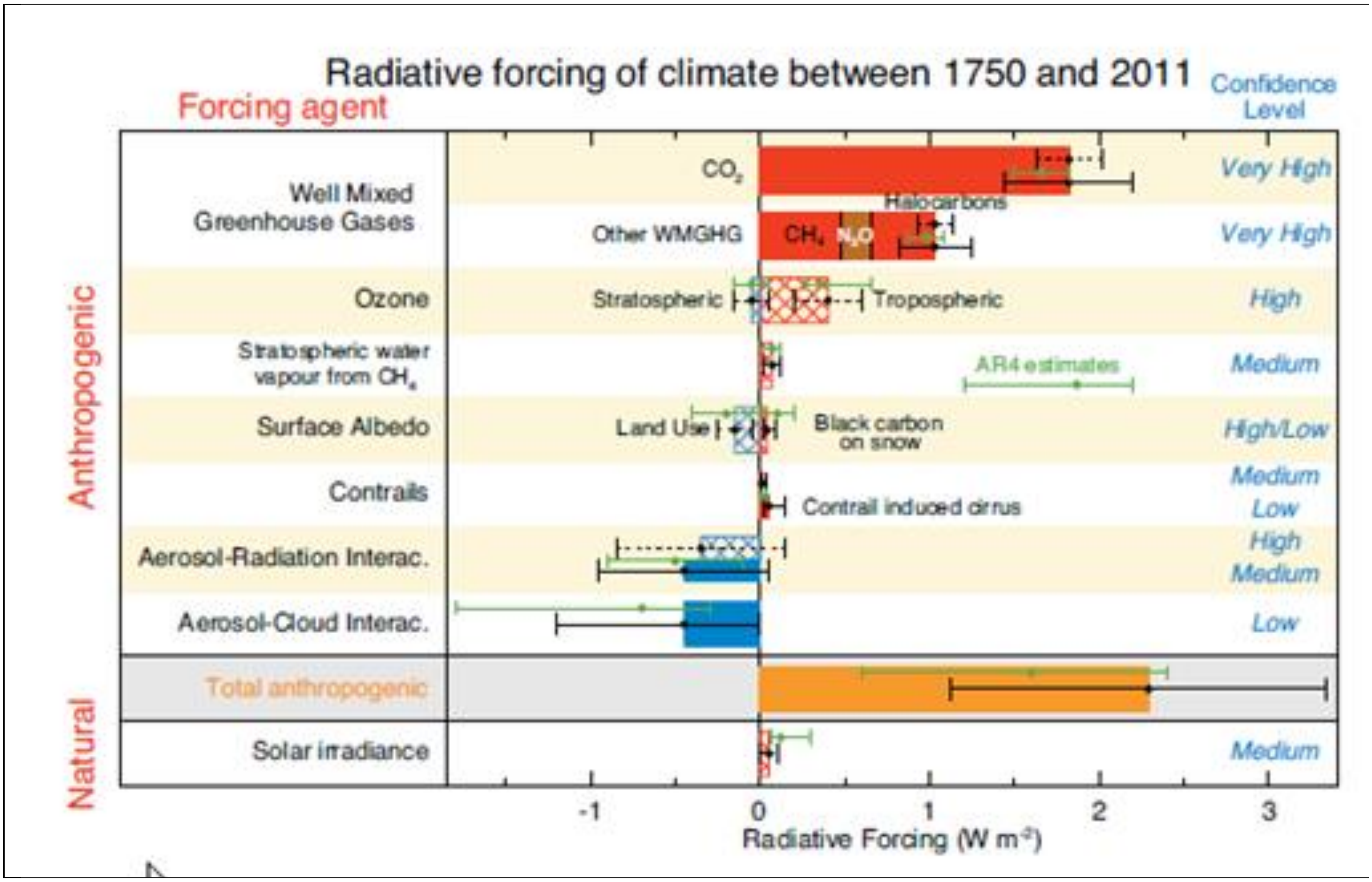


Figure 2 – Radiative forcing (IPCC AR5 – Figure TS-6)

Total Effective Radiative Forcing and Temperature Change

The next step is to estimate how much the Earth's temperature will increase for a change in total radiative forcing since preindustrial times. Since the relationship between radiative forcing is logarithmic – and not linear- it is necessary to sum all of the radiative forcings to determine the temperature change rather than adding up the expected temperature change based on the radiative forcing of each component[3]. Since there is a quantifiable relationship between radiative forcing and atmospheric CO2 concentrations, it is straightforward to convert from one to the other[3]. And to estimate the expected warming from a change atmospheric CO2, climate scientists use the term "climate sensitivity", which refers to the expected temperature change for a doubling of CO2. Using a "consensus" value for climate sensitivity of 3° C for CO2 alone[4], mathematical formulas can be used to derive the expected equilibrium temperature for various increases in radiative forcing since preindustrial times:

Effective Radiative Forcing (W/m-2)	Equiv. CO2e PPM	Temp Increase (°C)	Effective Radiative Forcing (W/m-2)	Equiv. CO2e PPM	Temp Increase (°C)	Effective Radiative Forcing (W/m-2)	Equiv. CO2e PPM	Temp Increase (°C)
2.0	404	1.4	3.0	487	2.3	4.0	587	3.3
2.1	412	1.4	3.1	496	2.4	4.1	598	3.5
2.2	419	1.5	3.2	506	2.5	4.2	609	3.6
2.3	427	1.6	3.3	515	2.6	4.3	621	3.7
2.4	435	1.7	3.4	525	2.7	4.4	633	3.8
2.5	444	1.8	3.5	535	2.8	4.5	645	4.0
2.6	452	1.9	3.6	545	2.9	4.6	657	4.1
2.7	460	2.0	3.7	555	3.0	4.7	669	4.2
2.8	469	2.1	3.8	566	3.1	4.8	682	4.4
2.9	478	2.2	3.9	576	3.2	4.9	695	4.5

Table 1 – Expected temperature increase for a given change in radiative forcing[3]

The last step is to add up the expected changes in radiative forcing between preindustrial times and 2100 and use the above table to calculate the expected equilibrium temperature for 2100 (note that these calculations assume that no CO2 will be sequestered by either carbon capture and storage (CCS) or carbon dioxide removal (CDR)):

#	ERF (W/m2)	Description
	Anthropogenic Changes	
1	2.33	ERF in 2011 (IPCC)
3	0.50	Half of the ERF due to aerosols (the burning of coal is one of the primary sources of aerosols; when coal burning is stopped there will be significantly fewer aerosols). The estimated cooling effect from the aerosols from the burning of coal is about 0.5°C[5] (also, see Figure 2)
4	0.88	From the CO2 emissions from aggressive emission reduction scenario (emissions peak in 2025 and go to zero in 2055)[6,7]. No emissions after 2055 are included, but they could be significant if goals are not met.
5	-0.37	Due to the change of atmospheric concentrations of CH4, N2O and halocarbons in 2100 (IPCC RCP 2.6)
	Additions from Natural Feedbacks[8]	
6	0.34	Arctic Ocean
7	0.31	Retreating snowline
8	0.33	Permafrost
9	0.30	Peatlands and Peat Bogs
	4.62	Total Change in ERF from preindustrial times to 2100

Table 2 – Total ERF calculations

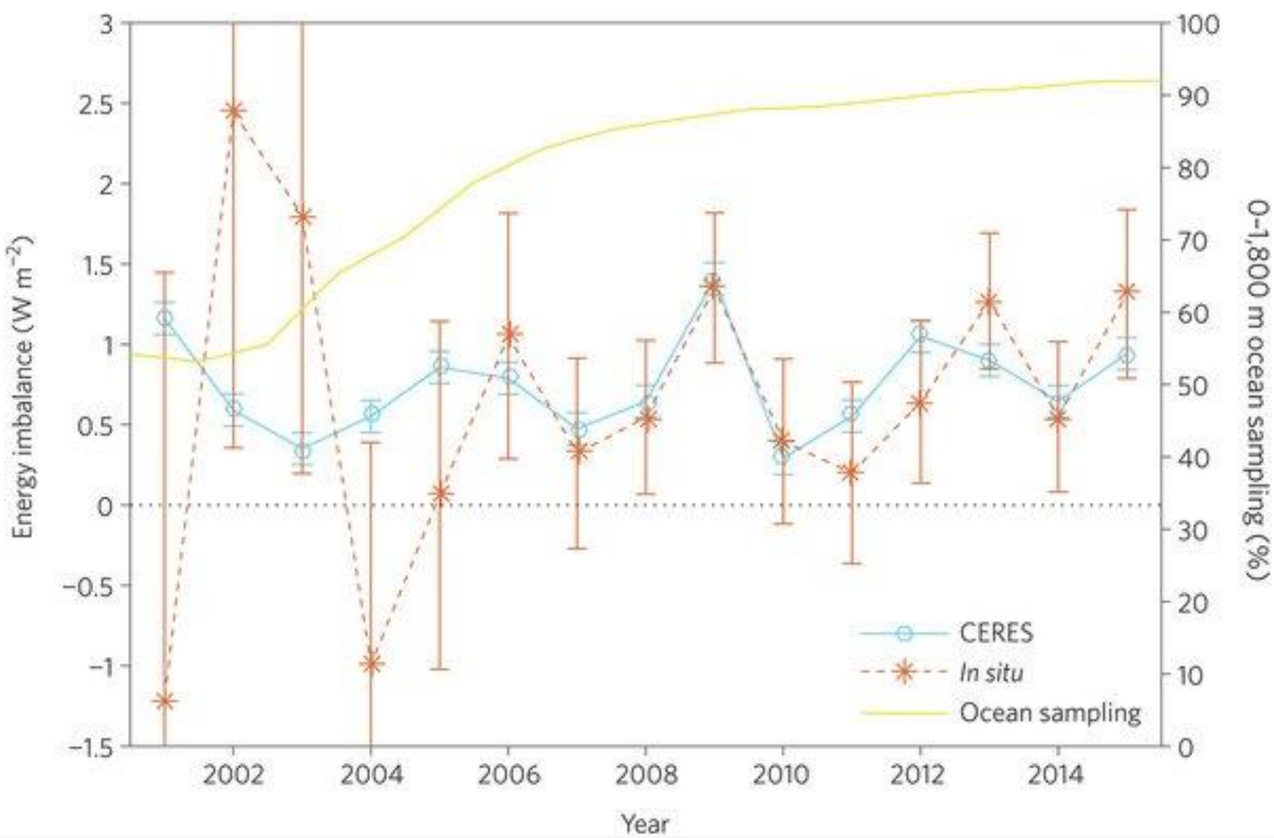
The expected equilibrium temperature increase in 2100 is then about 4.1° C. Note that this result varies considerably from most peoples' expectations for the likely temperature increase from an aggressive greenhouse gas reduction program. One of the major reasons for this might be that that the assumptions behind the UNFCCC's "1000 GTCO2 budget" are very difficult to determine – we are simply given an emissions budget and have no way to determine how it was derived other than through very complex climate models. Since the results have never been quantified as in Table 2 above, the average person has no way to know if a particular emissions scenario is realistic and will result in the stated temperature increase.

Conclusion

Climate scientists believe that a 1.5° C rise in global temperature is enough to start permafrost thaw in Siberia[9]. Since by mid century the global temperature will almost certainly be over 2° C, significant amounts of the permafrost will be thawing annually, releasing even more greenhouse gases in a “feedback loop”. If 50% of the carbon in the permafrost (3,000 GTCO2) is released, the expected temperature increase will be about 1.3°C. Thus the feedbacks from Arctic sea ice melt, Northern Hemisphere snow line retreat, permafrost thaw, and peat drying will be enough to eventually raise the Earth’s temperature to well over 4.0° C. And it is possible that the release of methane from the destabilization of sea-floor methane hydrates could greatly exacerbate global warming[10]. Because of the unacceptable costs associated with removing CO2 from atmosphere in the quantities needed to offset both the feedbacks and future emissions, nothing besides albedo modification can possibly stop catastrophic climate change.

Footnotes

<table>
<tr><td>1</td><td>Incoming solar radiation at the top of the atmosphere, averaged around the entire Earth, is about 342 W/m^2 day and night. The amount of energy received in space at the distance of the Earth from the Sun is about 1370 W/m^2.</td></tr>
<tr><td>2</td><td>The current enargy imbalance is about 0.7 W/m^2, equivalent to about 0.42° C of warming.



Gavin Schmidt @ClimateOfGavin Jun 23
New estimate of Earth’s energy imbalance ~0.7 W/m2 (2005-15)
http://www.nature.com/nclimate/journal/v6/n7/full/nclimate3043.html … NB predicted before observed
https://twitter.com/ClimateOfGavin/status/765237770839269378 8/15/16

http://www.nature.com/nclimate/journal/v6/n7/full/nclimate3043.html</td></tr>
<tr><td>3</td><td>http://ccdatacenter.org/documents/AlbedoCO2TempCalcs.pdf</td></tr>
</table>

4	"Climate sensitivity" usually includes "fast feedbacks", such as change to sea ice. But I have not been able to determine how big a reduction of sea ice (and the corresponding albedo change) is expected for a doubling of CO2 - it could be anywhere from 10% to 100%. But, in the final analysis, it does not really make a difference how much the summer-time Arctic sea ice was expected to be reduced for a climate sensitivity of 3, as all of the natural feedbacks are expected to be the equivalent of almost 100 PPM of atmospheric CO2 by 2100, equivalent to about one half of current emissions for the next 85 years and over which we have no control. "Climate sensitivity" describes the amount of global warming you get from a specified forcing once all climate feedbacks are taken into account. A forcing is something that changes the Earth's energy budget: the difference between the amount of energy entering the Earth system and the amount leaving it. If the energy budget is in balance, the Earth's temperature is stable. A forcing creates an energy imbalance, causing global temperature change until the system gets back in balance. Forcings can be quantified in watts per square metre (W/m^2), and causes can include variation in sunlight or the Earth's orbit, surface reflectivity ("albedo"), and the greenhouse effect. Climate sensitivity is usually expressed in degrees per doubling of atmospheric carbon dioxide (CO_2), a forcing of about 4 W/m^2. A recently published paper by Hansen and Sato (2011), *Paleoclimate Implications for Human-Made Climate Change*, examines evidence from past climates about the various feedbacks that affect climate sensitivity. A feedback is a mechanism that either amplifies (positive feedback) or dampens (negative) the initial effect. Interest is a feedback on a loan. If there were no feedbacks in the Earth's climate system, physics tells us climate sensitivity would be 1.2°C for a doubling of CO_2. In reality, a complex array of interacting positive and negative feedbacks come into play. Climate models include "fast feedbacks" like water vapor, clouds, sea ice, and aerosols (reflective particles that hang in the atmosphere), but exclude longer-term "slow feedbacks" like ice sheets (an icy surface reflects more heat than a dark surface) and greenhouse gases (warming releases gases from the oceans, melting permafrost, etc)." There is a broad consensus that fast-feedback sensitivity is 3°C for doubled CO_2. In other words, fast feedbacks multiply the 1.2°C direct warming by two-and-a-half. http://www.skepticalscience.com/climate-sensitivity-feedbacks-anyone.html See also: http://www.realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/ http://www.skepticalscience.com/climate-sensitivity-advanced.htm http://www.bitsofscience.org/real-global-temperature-trend-climate-sensitivity-leading-climate-experts-7106
5	http://ccdatacenter.org/documents/BurningCoalCoolsPlanet.pdf
6	2010 emissions were about 34 GTCO2; if they increase annually by 2% until 2025 and then decline by 1.5 GTCO2 annually, there will be net zero emissions after 2055 and the total emissions will be about 1240 GTCO2. There are about 17.3 gigatons of CO2 per PPM of atmospheric CO2 (assuming 45% of CO2 emissions remain in the atmosphere). Emissions of 1240 GTCO2 will then result in an additional 71 PPM of CO2 in the atmosphere, which is equivalent to a forcing of about .88
7	The IPCC 2.6 pathway assumes that net CO2 emissions will become negative due to carbon capture and storage, resulting in additional CO2 being sequestered by the ocean as net CO2 emissions cease However, it is unlikely that significant money will be spent on carbon capture, and even if net anthropogenic CO2 emissions become negative, significant natural emissions of CO2 will likely mean that there will always be net total CO2 emissions.
8	http://ccdatacenter.org/documents/GlobalWarmingFeedbacks.pdf
9	https://www.theguardian.com/environment/2013/feb/21/temperature-rise-permafrost-melt
10	http://worldoceanreview.com/en/wor-1/ocean-chemistry/climate-change-and-methane-hydrates/