Global Warming Feedback Expectations
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September 19, 2018
http://ccdatacenter.org/documents/ GlobalWarmingFeedbackExpectations.pdf

- " The reaction of clouds to a warming atmosphere has been one of the major sources of uncertainty in estimating exactly how much the world will heat up from the accumulation of greenhouse gases"

Selected references

	Global warming is shifting Earth's clouds, study shows The reaction of clouds to a warming atmosphere has been one of the major sources of uncertainty in estimating exactly how much the world will heat up from the accumulation of greenhouse gases, as some changes would enhance warming, while others would counteract it. The study, detailed Monday in the journal Nature, overcomes problems with the satellite record and shows that observations support projections from climate models. But the work is only a first step in understanding the relationship between climate change and clouds, with many uncertainties still to untangle, scientists not involved with the research said. While clouds are a key component of the climate system, helping to regulate the planet's temperature, their small scale makes them difficult to accurately represent in climate models. https://www.theguardian.com/environment/2016/jul/12/global-warming-is-shifting-earths-clouds-study-shows
	Earth System Sensitivity [One] concept of climate sensitivity ..., sometimes called the "Charney Sensitivity", envisions the equilibrium sensitivity of Earth's climate to CO_2 forcing as the equilibrium response of the climate system to a doubling of CO_2 concentrations including all *fast feedbacks*—that includes changes in water vapor, clouds, sea ice, and perhaps even small ice caps and glaciers. The fast feedbacks do not, for example, include the slow retreat of the continental ice sheets or the slow response of the Earth's surface properties and vegetation as, e.g., boreal forests slowly expand poleward. Accounting for these *slow feedbacks* leads to the possibility that the equilibrium long-term response to anthropogenic greenhouse gas emissions is larger than the IPCC projections we have focused on up until now. This more general notion of climate sensitivity is typically referred to as *Earth System senstivity*. Studies using climate models that incorporate these slow feedbacks find that the *Earth System sensitivity* is indeed substantially greater than the nominal Charney sensitivity, roughly 50% higher. Thus, a stabilization of CO_2 levels at twice pre-industrial levels over the next century might lead to a warming of 3°C over the next 1-2 centuries, but an eventual warming closer to 4.5°C once the land surface and vegetation has equilibrated to the new climate and the ice sheets have melted back to their new equilibrium configuration for the higher CO_2 concentration—a process that could take a thousand years, but perhaps substantially less. https://www.e-education.psu.edu/meteo469/node/219
	Carbon Cycle Feedbacks [CO2] is being absorbed by various reservoirs that exist within the global carbon cycle.... [O]nly 55% of the emitted carbon has shown up in the atmosphere, while roughly 30-35% appears to be going into the oceans, and 15-20% into the terrestrial biosphere.

The problem is that this pattern of behavior may not continue. There is no guarantee that the ocean and terrestrial biosphere will continue to be able to absorb this same fraction of carbon emissions as time goes on

[T]he ocean's CO_2 solubility decreases as the ocean warms. When we look at the pattern of carbon uptake in the upper ocean, we see that one of the primary regions of uptake is the North Atlantic. This is, in part, due to the formation of carbon-burying deep water in the region...[T]he North Atlantic overturning circulation could weaken in the future (though as we have seen, there is quite a bit of uncertainty regarding the magnitude and time frame of this weakening). If that were to happen, it would eliminate one of the ocean's key carbon-burying mechanisms, and allow $CO_2$to accumulate faster in the atmosphere. On the other hand, the biological productivity of the upwelling zone of the cold tongue region of the eastern and central equatorial Pacific is a *net source* of carbon to the atmosphere, *from* the ocean. More El Niño-like conditions in the future could suppress this source of carbon, but more La Niña-like conditions could increase this source, further accelerating the buildup of CO_2 in the atmosphere. So uncertainties in the future course of oceanic uptake abound, but, on balance, it is likely that this uptake will decrease over time, yielding a *positive carbon cycle feedback*.

There are a number of other carbon cycle feedbacks that apply to the *terrestrial biosphere*. They vary anywhere from a strong negative to a strong positive feedback. Among them are (a) warmer land increasing microbial activity in soils, which releases CO_2 (a small positive feedback), (b) increased plant productivity due to higher CO_2 levels (a strong negative feedback). Finally, there is the negative silicate rock weathering feedback which we know to be a very important regulator of atmospheric CO_2 levels on very long, geological timescales: a warmer climate, with its more vigorous hydrological cycle, leads to increased physical and chemical *weathering* (the process of taking CO_2 out of the atmosphere by reacting it with rocks), through the formation of carbonic acid, which dissolves silicate rocks, producing dissolved salts that run off through river systems, eventually reaching the oceans.

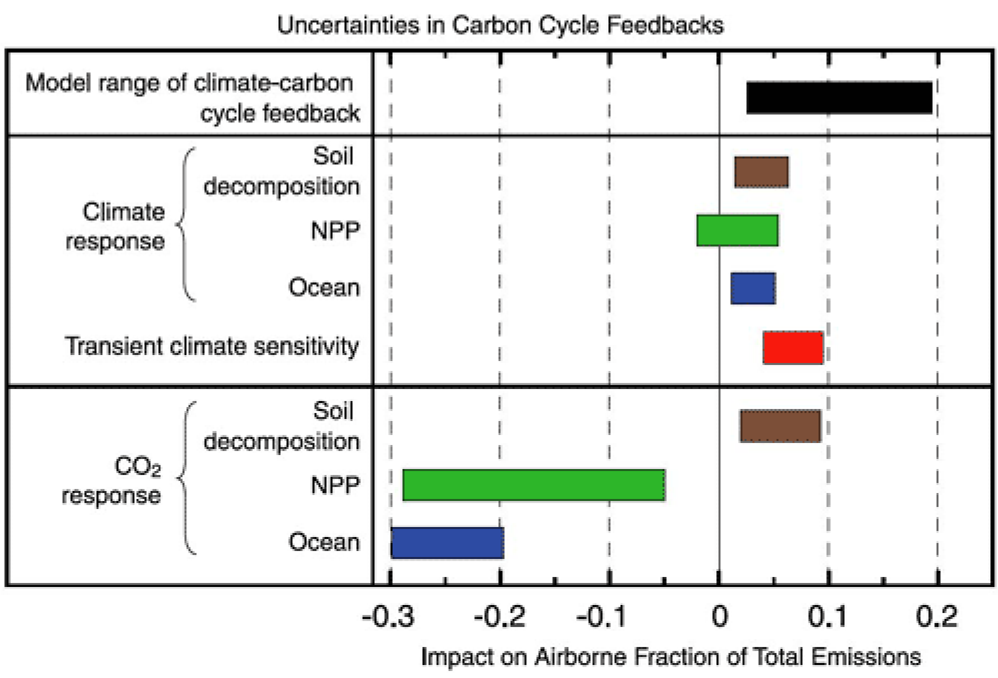


Figure 8.11: Estimated magnitudes (including uncertainty ranges) of various potential oceanic and terrestrial carbon cycle feedbacks, expressed in terms of positive or negative estimated change in the airborne fraction of CO_2 (based on average net increase by 2100 among the various climate models).
Credit: IPCC, 2007

	NPP = Net Primary Production (e.g., biosphere) *CO2 Response =current CO2 being absorbed by oceans and plants* Other potential positive carbon cycle feedbacks that are even more uncertain, but could be quite sizeable in magnitude, are methane feedbacks, related to the possible release of frozen methane currently trapped in thawing Arctic permafrost, and so-called "clathrate"—a crystalline form of methane that is found in abundance along the continental shelves of the oceans, which could be destablized by modest ocean warming. Since methane is a very potent greenhouse gas, such releases of potentially large amounts of methane into the atmosphere could further amplify greenhouse warming and associated climate changes. The key potential implication of a net positive carbon cycle feedback is that current projections of future warming ... may actually underestimate the degree of warming expected from a particular carbon emissions pathway. This is because the assumed relationship between *carbon emissions and* CO_2 *concentrations* would underestimate the actual resulting CO_2concentrations because they assume a fixed airborne fraction of emitted CO_2, when, in fact, that fraction would instead be increasing over time. While the magnitude of this effect is uncertain, the best estimates suggest an additional 20-30 ppm of CO_2 per degree C warming, leading to an additional warming of anywhere from 0.1°C to 1.5°C relative to the nominal temperature projections shown in earlier lessons. https://www.e-education.psu.edu/meteo469/node/160
	Aerosols We know that the production of sulphate and other aerosols has played an important role, cooling substantial regions of the Northern Hemisphere continents, in particular, during the past century. The best estimate of the impact of this anthropogenc forcing, while quite uncertain, is roughly -0.8 W/m^2 of forcing, which is equivalent—in this context—to the contribution of *negative* 60 ppm of CO_2. https://www.e-education.psu.edu/meteo469/node/146
	Radiative Forcing from Clouds Much of this uncertainty comes from the previously discussed uncertainty in cloud radiative feedbacks. On average, as we know from our previous lesson, cloud radiative feedbacks are estimated to be negative. The uncertainty, however, is huge. Among the 20+ models used in the IPCC assessment, the cloud radiative feedback for CO_2 doubling varies anywhere from around $-2W/m^2$(offsetting roughly half of the direct radiative forcing by the CO_2 increase) to nearly $+2W/m^2$ (adding nearly half of the radiative forcing due to the CO_2 increase alone).

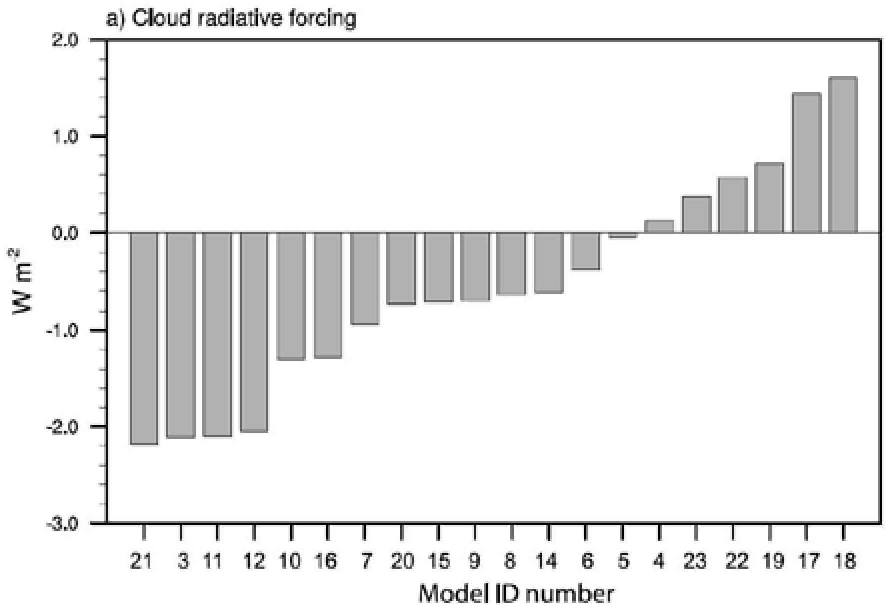


Figure 7.2: Cloud Radiative Forcing for Various IPCC Models.
Credit: IPCC, 2007

Collectively, the various scenarios and their physical uncertainty ranges span a very large spread of projected warming for the next century. In the most optimistic of scenarios—indeed, an arguably unrealistic scenario—where we could manage to keep CO_2 fixed at the year 2000 concentration (this would require immediate cession of all activities—including fossil fuel burning, deforestation, etc.—contributing to anthropogenic CO_2 emissions), warming nonetheless persists for decades owing to the "commitment to warming" we investigated in the previous lesson in our EdGCM experiments. This is warming already in the pipeline but not yet realized because of the delayed response of ocean warming to greenhouse gas concentration increases that have already taken place. The additional warming by 2100 might be anywhere between 0.2 and 0.6°C depending on the precise sensitivity of the climate, with most likely warming of 0.4°C. At the upper end of the scenarios is the A1FI scenario, which yields anywhere from 2.5 to 6.5°C additional warming (with the most likely warming of about 4°C) depending, again, on the sensitivity of the climate. Interestingly, we find that the *scenario uncertainty* and *physical uncertainty* are, in a sense, of nearly the same magnitude. While the most likely warming (i.e., the central estimates for each scenario) ranges from 0.4 to 4°C, i.e., just under a range of 4°C, the range for any one scenario (i.e., A1FI, which ranges from 2.5 to 6.5°C warming) also corresponds roughly to a maximum 4°C range. In this sense, roughly half the spread shown in the various projections of future warming is under our control, i.e., it depends on choices *we* make about future emissions.

There is so much focus on climate projections through 2100 that it is easy to lose sight of the fact that the climate does not magically stop changing at 2100 in the emissions scenarios we have been exploring—indeed, there is, in many cases, significant additional warming and associated changes in climate for several more centuries.

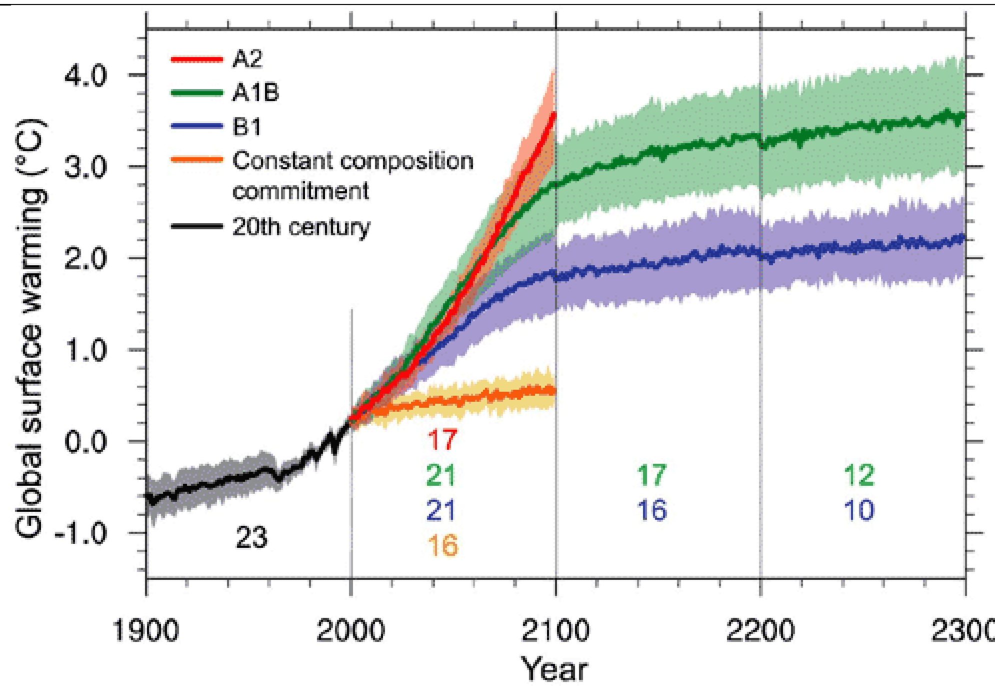
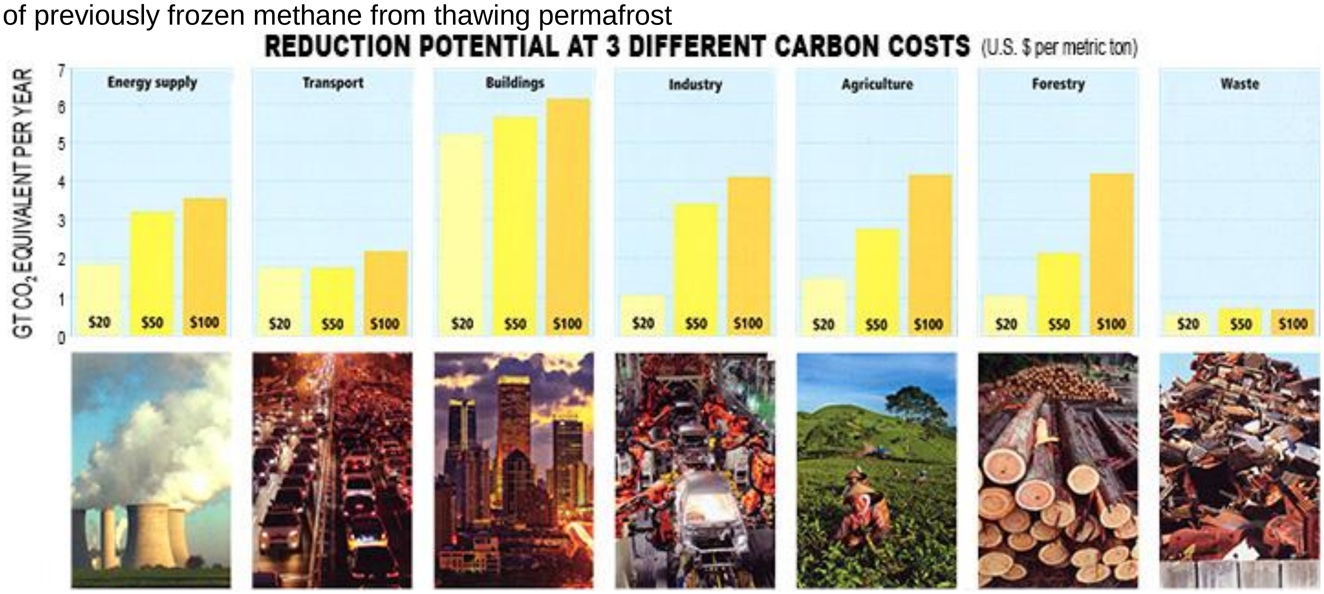


Figure 7.3: Extended Model Projections of Future Warming Under Two IPCC Emissions Scenarios.
Credit: IPCC, 2007

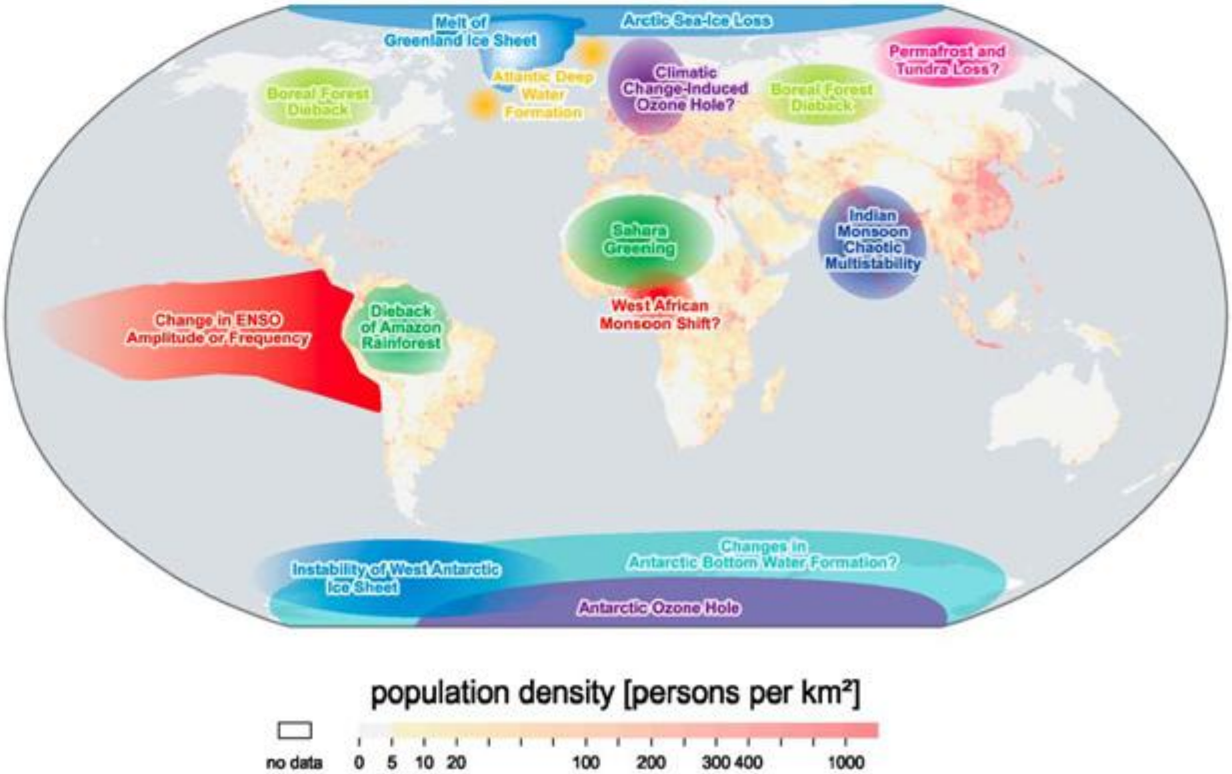
https://www.e-education.psu.edu/meteo469/node/150

Tipping Points

We have already seen some examples of potential climate tipping points—e.g., in the potential response of the cryosphere or patterns of ocean circulation to ongoing warming. There are many other potential tipping points in the system, however. These include the possibility that the ENSO phenomenon might transition rather suddenly into a very different mode of behavior, or that the Indian monsoon system—whose role is so critical to fresh water availability in large parts of South Asia—might suddenly collapse. Other possibilities include one of the possible carbon cycle feedbacks alluded to previously in this lesson; that a sudden release of previously frozen methane from thawing permafrost



suddenly enters into the atmosphere. It is, of course, possible that other tipping points exist that we are not even aware of yet!



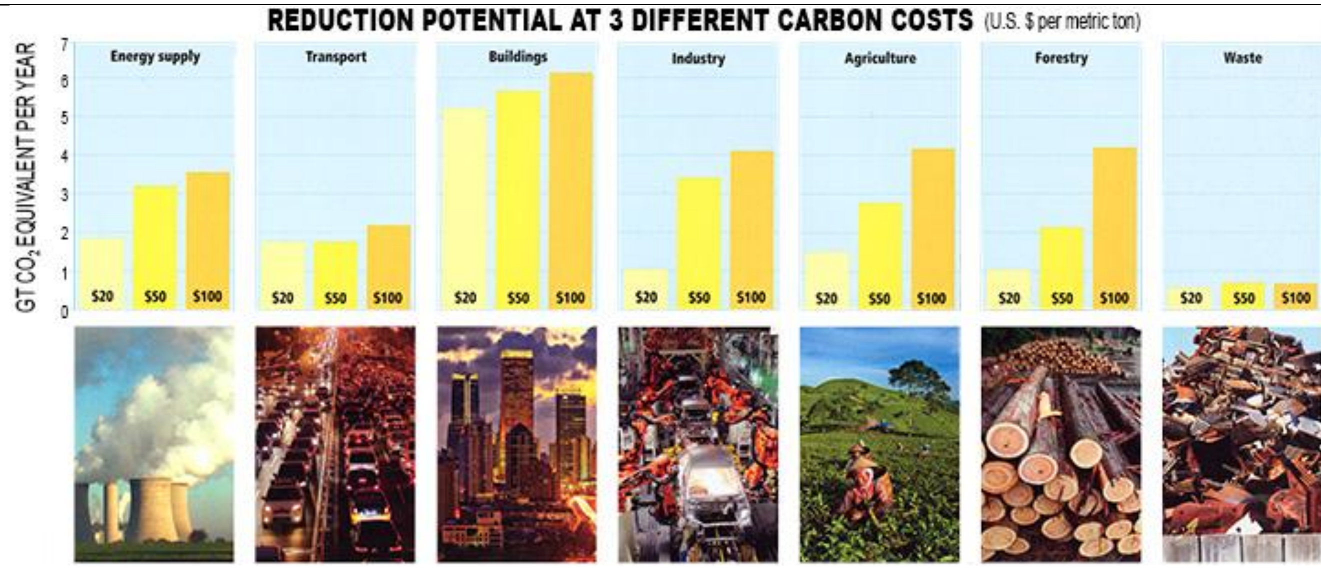
Tipping Points:

- **Change in ENSO Amplitude or Frequency**
- **Boreal Forest Dieback**
- **Dieback of Amazon Rainforest**
- **Instability of West Antarctic Ice Sheet**
- **Melt of Greenland Ice Sheet**
- **Atlantic Deep Water Formation**
- **Antarctic Ozone Hole**
- **Changes in Antarctic Bottom Water Formation?**
- **Arctic Sea-Ice Loss**
- **Sahara Greening**
- **West African Monsson Shift?**
- **Climatic Change-Induced Ozone Hole?**
- **Permafrost and Tundra Loss?**
- **Indian Monsoon Chaotic Multistability**

Credit: The Copenhagen Diagnosis

https://www.e-education.psu.edu/meteo469/node/217

	Carbon Tax - CO2 Reduction Potential



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Stabilize below 450 ppm

CO_2 levels must be brought to a peak within the next decade, and ramped down to 80% below 1990 levels by mid-century. Emissions in 1990 were about 6.5 gigatons carbon per year.

So, doing the calculations, 80% below 1990 levels yields about 5 gigatons [C] of CO_2 equivalent per year, about 40% of the 13 gigatons we estimated would result from an SCC of $100/ton. So, let us estimate that reducing emissions to 5 gigatons CO_2 equivalent would require a SCC on the order of $180/ton[, which approaches a total of $1 Trillion].

So, the bottom line is that if you place a large enough cost on emitting carbon, it is possible to achieve the necessary reductions to stabilize CO_2 concentrations at non-dangerous levels. Stabilizing CO_2concentrations at 450 ppm would appear to require an SCC roughly in the range of $180/ton carbon emitted, which, in turn, would amount to a roughly 4% per year improvement in carbon efficiency.

https://www.e-education.psu.edu/meteo469/node/225

Warmer soil is 'supercharging' bacteria and fungi to release more carbon and worsen climate change
By ASSOCIATED PRESS 1 August 2018

- As temperatures warm bacteria and fungi in the soil are becoming more active
- The 'turbo-charged' microbes are feeding on dead leaves and plants
- This releases more heat-trapping carbon dioxide into the air

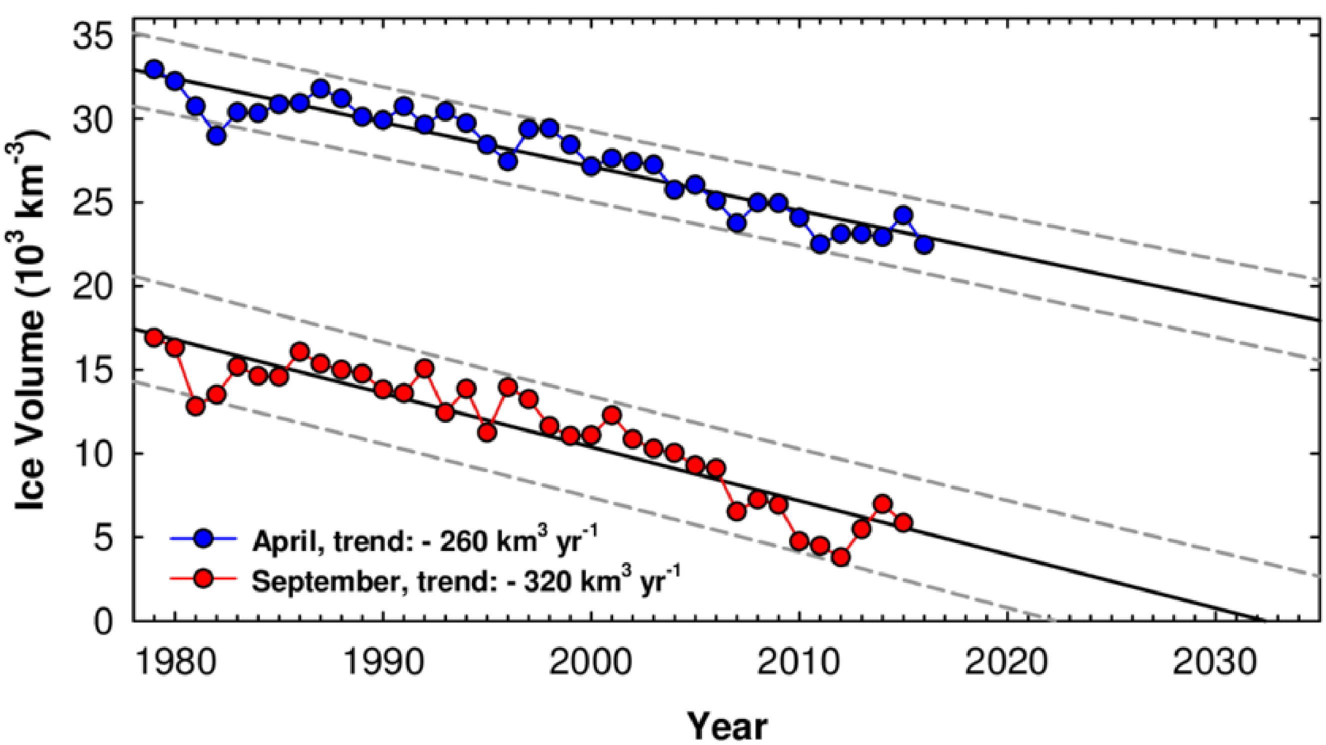
Researchers found a significant increase in the amount of carbon since the 1990s coming out of microbes when compared to other releases of carbon.

http://www.dailymail.co.uk/sciencetech/article-6016171/Warmer-soil-releasing-carbon-worsening-climate-change.html

Quantifying global soil carbon losses in response to warming
The majority of the Earth's terrestrial carbon is stored in the soil. If anthropogenic warming stimulates the loss of this carbon to the atmosphere, it could drive further planetary warming1–4. Despite evidence that warming enhances carbon fluxes to and from the soil5,6, the net global balance between these responses remains uncertain. Here we present a comprehensive analysis of warming-induced changes in soil carbon stocks by assembling data from 49 field experiments located across North America, Europe and Asia. We find that the effects of warming are contingent on the size of the initial soil carbon stock, with considerable losses occurring in high-latitude areas. By extrapolating this empirical relationship to the global scale, we provide estimates of soil

carbon sensitivity to warming that may help to constrain Earth system model projections. Our empirical relationship suggests that global soil carbon stocks in the upper soil horizons will fall by 30 ± 30 ・ petagrams of carbon to 203 ± 161 ・ petagrams of carbon under one degree of warming, depending on the rate at which the effects of warming are realized. Under the conservative assumption that the response of soil carbon to warming occurs within a year, a business-as-usual climate scenario would drive the loss of 55 ± 50 ・ petagrams of carbon from the upper soil horizons by 2050. This value is around 12–17 per cent of the expected anthropogenic emissions over this period7,8. Despite the considerable uncertainty in our estimates, the direction of the global soil carbon response is consistent across all scenarios. This provides strong empirical support for the idea that rising temperatures will stimulate the net loss of soil carbon to the atmosphere, driving a positive land carbon–climate feedback that could accelerate climate change.The exchange of carbon (C) between the soil and atmosphere represent a prominent control on atmospheric C concentrations and the climate1,6,9. These processes are driven by the organisms (plants, microbes and animals) that live in the soil, the activity of which could be accelerated by anthropogenic warming10. If warming stimulates the loss of C into the atmosphere, it could drive a land C–climate feed-back that could accelerate climate change. Yet despite considerable scientific attention in recent decades, there remains no consensus on the direction or magnitude of warming-induced changes in soil C11,12. There is growing confidence that warming generally enhances fluxes to and from the soil8,12, but the net global balance between these responses remains uncertain and direct estimates of soil C stocks are limited to single-site experiments that generally reveal no detectable effects5,13–15.Given the paucity of direct measurements of the responses of soil C stocks to warming, Earth system models (ESMs) must rely heavily on the short-term temperature responses of soil respiration (Q10) to infer long-term changes in global C stocks. Without empirical obser-vations that capture longer-term C dynamics, we are limited in our ability to evaluate model performance or to constrain the uncertainty in model projections16. As such, the land C–climate feedback remains one of the largest sources of uncertainty in current ESMs12,14,17, restrict-ing our capacity to develop C emissions targets that are compatible with specific climate change scenarios. Direct field measurements

https://www.nature.com/articles/nature20150.epdf



https://www.researchgate.net/figure/Monthly-average-Arctic-sea-ice-volume-for-April-and-September-Linear-

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