**Global Warming Feedbacks**

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

The significance of the magnitudes of the positive feedbacks from global warming are not widely appreciated. This is most likely because (1) modeling their expected magnitudes through the end of the century is very difficult and likely understates the actual magnitudes[0]; (2) most analyses of the feedbacks look only at what has happened so far; and (3) the feedbacks are usually looked at individually. By doing some simple analyses of four of the primary feedbacks (albedo changes from melting Arctic sea ice and Northern Hemisphere snow cover; and greenhouse gas emissions from permafrost and peat) and estimating their magnitudes through 2100, a startling picture emerges:

1. The warming potential in 2100 from the four feedbacks are roughly equivalent to about ½ of current CO2 emissions
2. By 2100 this will result in a warming potential (99 PPM CO2e), about equivalent to that of all fossil fuel emissions since pre-industrial times, and capable of adding about 0.82° C to the Earth's average temperature.
3. The "CO2 emissions equivalent" of these feedbacks through 2100 is about twice the UNFCCC's carbon budget.

The results of the simple analysis are shown in Table 1.

| **Feedback** | Maximum Potential Radiative Forcing | RF Change Thru 2014 | Likely Change 2015 - 2100 | | | | Likely Change 1870 - 2100 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Albedo Changes | | | Rad. Forcing | Total Equiv. Emiss | Atmos. CO2e Change (PPM ) | Temp Incr. | Rad. Forcing | Total Equiv. Emiss | Atmos. CO2e Change (PPM ) | Temp Incr. |
| Arctic Ocean[1] | 0.76 | .10 | 0.29 | 340 | 19.6 | 0.15 | 0.39 | 452 | 26.1 | 0.20 |
| Retreating snowline[2] | 0.69 | .14 | 0.17 | 240 | 13.9 | 0.10 | 0.31 | 409 | 23.6 | 0.16 |
| Tundra greening[3] | | | | | . | | | | | |
| Land use changes[3] | | | | | | | | | | |
| Other?[3] | | | | | | | | | | |
| GHG Emissions | Carbon Store Size | Emiss. Thru 2014 | | | | | | | | |
| Permafrost[2a] | 6,230–6,780[4] 3,660[5] | N/A | 0.33 | 440 | 25.5* | 0.19 | .33 | 440* | 25.5 | 0.19 |
| Peatlands and Peat Bogs[6] | 2000[7,8] | 60 | .26 | 360 | 20.8* | 0.16 | .30 | 400* | 23.1 | 0.17 |
| Methane Hydrates[3] | 5000 to 36000[4] | | | | | | | | | |
| Reservoirs | | | | 60 | 3.5 | 0.10 | 0.05 | 60 | 3.5 | 0.10 |
| Other Soils[3] | | | | | | | | | | |
| Amazon[3] | 315 | | | | | | | | | |
| Temperate Forests[3] | | | | | | | | | | |
| Other?[3] | | | | | | | | | | |
| Total | | 0.24 | 1.02 | 1440 | 37.0 | 0.70 | 1.38 | 921 | 101.8 | 0.84* |

* Assumes a 45% airborne fraction

\# Temperature increases are not "additive", so the total temperature increase is based on the total radiative forcing

Table 1 – Feedback Estimates - Equivalent CO2 Emissions In GTCO2e; Radiative forcing in $W/m^2$; Temperature increase for a climate sensitivity of 3.0°C for a doubling of atmospheric CO2

Notes:

The analysis for the albedo changes are based on data from the National Snow and Ice Data Center (Arctic sea Ice extent) and from the “Snow Lab" at Rutgers University (Northern Hemisphere snow cover extent). The estimate for the permafrost is based on the “mean” estimate for total emissions from permafrost (120 GTC) reported by Kevin Schaefer of the National Snow and Ice Data Center. The estimate for peatlands and peat bogs assumes that the emissions will remain at the current rate (4 GTCO2/year) through 2100.

The conversion of radiative forcing ($W/m^2$) to the “equivalent CO2e PPM” involves an exponential function which uses the radiative forcing (*e* raised to the power of the radiative forcing, where *e* is about 2.178), so it takes more atmospheric CO2 to increase the radiative forcing a specific amount as the atmospheric CO2 increases. For example, the table below shows the radiative forcing and equivalent atmospheric CO2 PPM from a chart in Nature Climate Change (see http://ccdatacenter.org/documents/AlbedoCO2TempCalcs.pdf). Hence adding radiative forcing and the equivalent atmospheric concentration of CO2 for multiple components is problematic. In the above chart, the combined radiative forcing of the four components is about 1.28 $W/m^2$, which, by itself, would be equivalent to 113 PPM (or .82°C). But when the corresponding concentrations of CO2 increases for the individual components are added together, the result is 99 PPM (or .74°C). For example:

| RF | Equivalent Atmospheric CO2 PPM |
|---|---|
| 2.0 | 403 |
| 2.5 | 443 |
| 3.0 | 487 |
| 3.5 | 535 |
| 4.0 | 587 |

The current CO2 equivalents from the global warming feedbacks are sufficient to add about 0.22° C to the Earth’s average temperature (0.12° C from the snowline retreat, about 0.08° C from Arctic Ocean ice melt, and about 0.02° C from peat bogs).

There are multiple other feedbacks in the Arctic which could lead to much more warming than is calculated above – see “E. Arctic Amplification” below.

| Other Relevant Numbers | GTCO2e |
|---|---|
| IPCC Post 2011 Budget for CO2 (Table 2.2 of IPCC AR5 synthesis report) | 1000 |
| IPCC Post 2015 Budget for CO2 (38 GTCO2 emissions/year) | 850 |
| Atmosphere | 2670[4] |
| All living vegetation | 2380[4] |
| 2011 CO2 emissions from fossil fuels | 34.6[10] |
| Proven and economically recoverable fossil fuel reserves | 2800[9] |
| Fossil Fuels in the ground | 5500-18000[4] |

Table 2 – Other Relevant Numbers

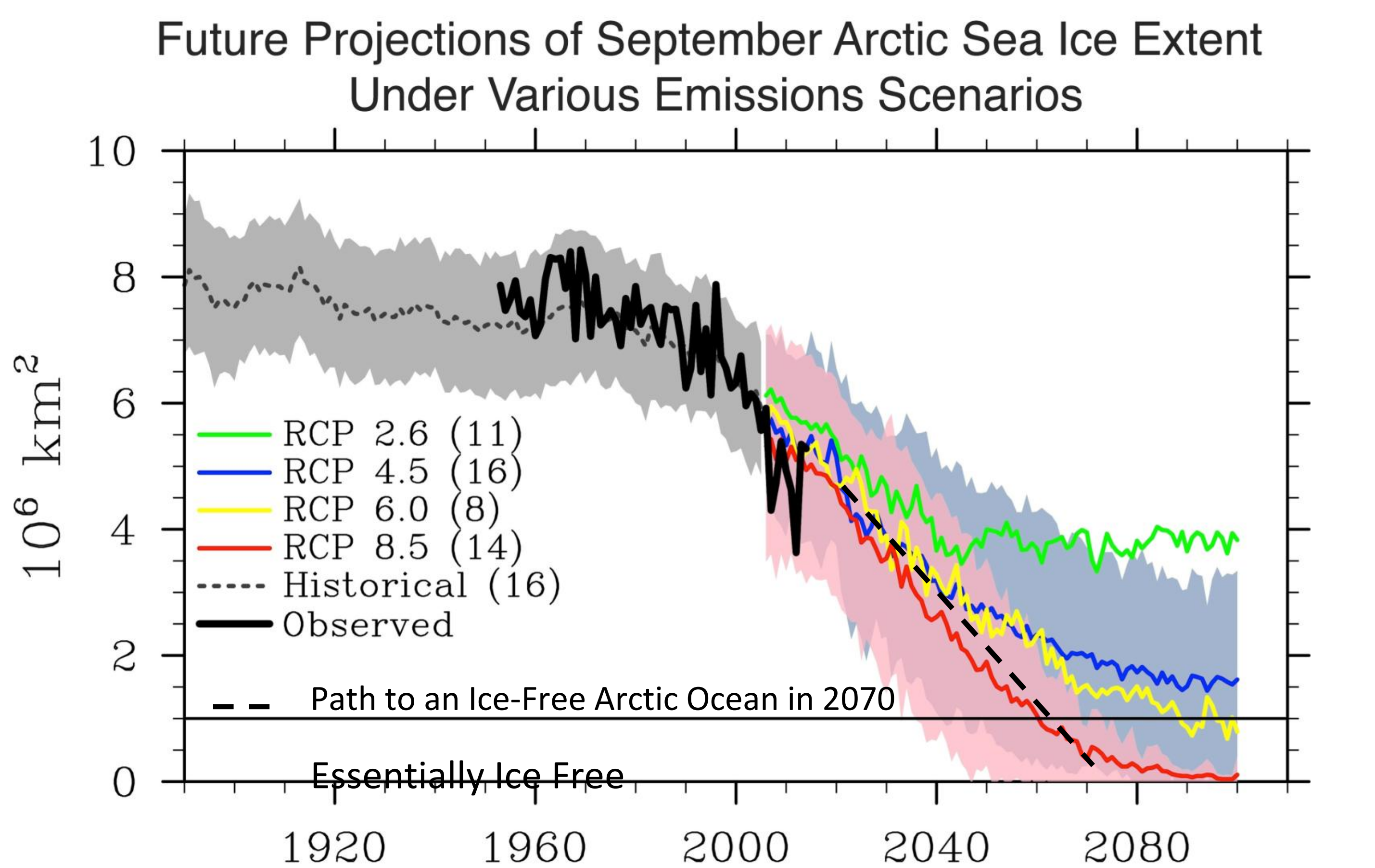
**Footnotes**

| | |
|---|---|
| 0 | **Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008**<br><br>We find 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.<br><br>http://www.nature.com/ngeo/journal/v4/n3/pdf/ngeo1062.pdf |
| 1 | See "A. Arctic Ocean Albedo Change" below<br>Details: http://ccdatacenter.org/documents/FeedbackFromArcticSeaIceMelt.pdf<br>Data: http://ccdatacenter.org/documents/FeedbackFromArcticSeaIceMelt.xlsx |
| 2 | See "B. Snowline Retreat" below<br>Details: http://ccdatacenter.org/documents/FeedbackNHSnowCover.pdf<br>Data: http://ccdatacenter.org/documents/FeedbackNHSnowCover.xlsx |
| 2a | See "C. Permafrost" below<br>Details: http://ccdatacenter.org/documents/Feedback Permafrost.pdf |
| 3 | No data available – included for completeness)<br>Temperate Forests - US forests will change from a sink to a source later this century |
| 4 | http://www.nap.edu/read/18373/chapter/4#82<br>Abrupt Impacts of Climate Change: Anticipating Surprises (2013) |
| 5 | https://www.washingtonpost.com/news/energy-environment/wp/2015/04/01/the-arctic-climate-threat-that-nobodys-even-talking-about-yet/ |
| 6 | See "D. Peatlands and Peat Bogs" below |
| 7 | http://www.imcg.net/media/download_gallery/climate/couwenberg_2009b.pdf |
| 8 | http://www.wetlands.org/Whatarewetlands/Peatlands/Carbonemissionsfrompeatlands/tabid/2738/Default.aspx |
| 9 | http://www.climatecentral.org/news/ipcc-climate-change-report-contains-grave-carbon-budget-message-16569 |
| 10 | http://cdiac.ornl.gov/ftp/ndp030/global.1751_2011.ems (Global $CO_2$ emissions 1751-2011) |

### A. Arctic Ocean Albedo Change

The models used by the IPCC have underestimated the speed with which the summer-time ice in the Arctic Ocean has been melting (See Figure 1), so the resulting temperature forecasts for 2100 and likely low. To get a better idea of what to expect, a simple approach can be used to estimate the albedo change from 2015 to 2100: linearly extrapolate the 1979-2014 weekly sea ice extent to 2100, determine the decrease of sea ice extent for each week from 2015 to 2100, estimate the albedo change for each week, then factor in the cloud cover. For any given week, the albedo change for that week can be approximated by estimating both the average latitude of the southern edge of the sea ice extent on that date and then estimating the average solar radiation for that latitude and date. The results for 2100 are a change in albedo of about 0.0032, which would result in a temperature increase of about 0.20°C. *(Note that an exponential decrease in sea ice is more likely, which would result in a greater temperature increase.)* Based in the linear extrapolation the following time periods would have the indicated radiative forcing changes:

| Time Period | Increase in Radiative Forcing (W/m-2) |
|---|---|
| 1990-2011 | 0.10 |
| 1990-2016 | 0.12 |
| 1990-2060 | 0.27 |
| 1990-2100 | 0.39 |
| 1990-3000 | 0.76 |
| 2016-2060 | 0.15 |
| 2016-2100 | 0.27 |




*Note: The IPCC has really underestimated when the summer-time Arctic ocean will likely become ice free, so it's temperature estimates are likely low*

Figure 1 – September Arctic Sea Ice Extent 1953-2012 - with data added for 2013-2015

Details: http://ccdatacenter.org/documents/ProjectingTheDeclineOfArcticSeaIce.pdf
Data: http://ccdatacenter.org/documents/ FeedbackFromArcticSeaIceMelt.xlsx
See also: http://ccdatacenter.org/documents/ReducedArcticSeaIceExtentBackground.pdf

### B. Snowline retreat

The Northern Hemisphere snow cover extent has been declining since about 1979 (see Figure 2), and this is decreasing the springtime albedo of the Arctic region. A "back-of-the-envelop" calculation was done to estimate the magnitude of the both the current albedo change (about -0.0014) and the expected change by the year 2100 (about -0.003). Assuming a 70% cloud cover and a climate sensitivity of 3.1, the current albedo change will eventually add about 0.09° C to the Earth's average temperature, and the albedo change by 2100 will increase the Earth's temperature by about 0.18° C.

| Time Period | Change in Radiative Forcing ($W/m^2$) | Equivalent Emissions (GTCO2e) | Atmospheric CO2e Change (PPM ) | Temperature Increase for a Climate Sensitivity of 3.0 |
|---|---|---|---|---|
| 1870-2100 | 0.31 | 409 | 23.6 | 0.18 |
| 2011-2100 | 0.18 | 240 | 13.9 | 0.10 |
| 2015-2100 | 0.16 | 220 | 12.7 | 0.10 |
| 1870-3000 | 0.69 | 946 | 54.6 | 0.41 |

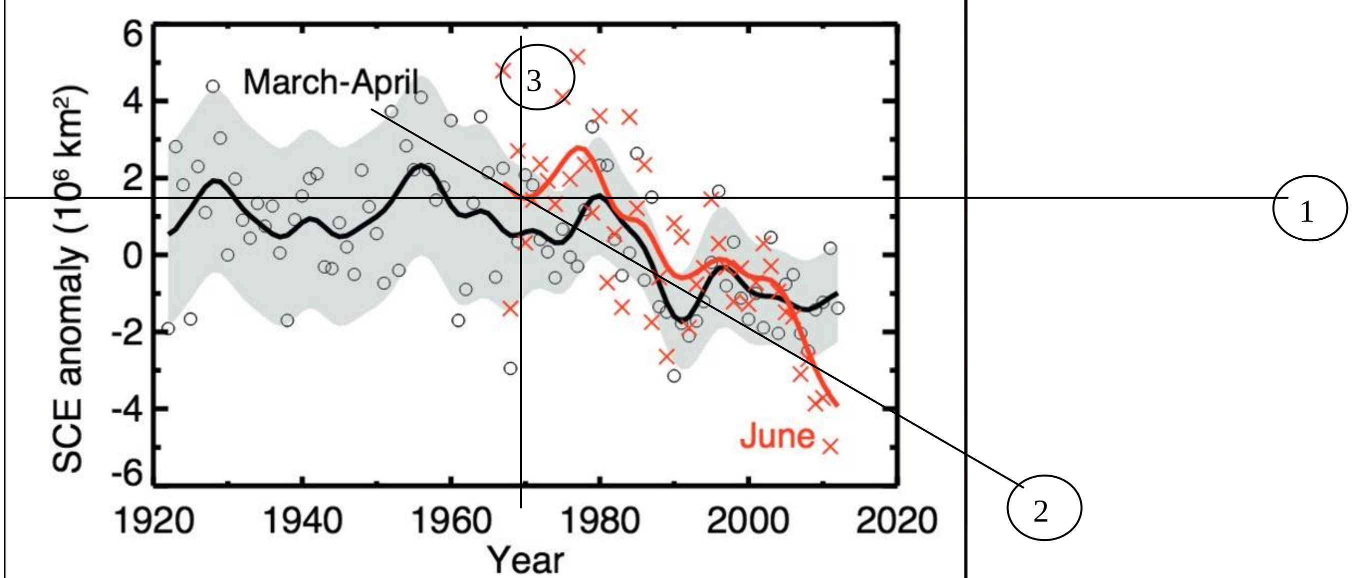



**Figure 4.19 |** March–April NH snow cover extent (SCE, circles) over the period of available data, filtered with a 13-term smoother and with shading indicating the 95% confidence interval; and June SCE (red crosses, from satellite data alone), also filtered with a 13-term smoother. The width of the smoothed 95% confidence interval is influenced by the interannual variability in SCE. Updated from Brown and Robinson (2011). For both time series the anomalies are calculated relative to the 1971–2000 mean.

Michael E. Mann @MichaelEMann · Feb 29
Far less Northern Hemisphere winter snowcover now than in previous decades due to global warming, via #IPCC #AR5:
63 21

1. Rough estimate of historical SCE

2. Rough estimate of SCE decline
3. Rough estimate of when the SCE decline started (also indicates that 1970 is a reasonable "historical" year)

Figure 2 – Changes in the snow cover extent since 1920[4]

Details: http://ccdatacenter.org/documents/FeedbackNHSnowCover.pdf
Data: http://ccdatacenter.org/documents/FeedbackNHSnowCover.xlxs

### C. Permafrost Thawing

The permafrost alone contains almost twice as much carbon as that atmosphere, so even if only a small percentage (even a few tenths of one percent) of the carbon is released each year the quantities could dwarf the anthropogenic emission reduction efforts.

Carbon released from permafrost soils will likely have a very significant impact on future temperatures (perhaps 0.13 to 0.3 degrees C by 2100, and certainly more by 2200). "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

| Time Period | Change in Radiative Forcing ($W/m^2$) | Equivalent Emissions (GTCO2e) | Atmospheric CO2e Change (PPM ) | Temperature Increase for a Climate Sensitivity of 3.0 |
|---|---|---|---|---|
| 1870-2100 | .33 | 440 | 25.5 | 0.19 |
| 2011-2100 | .33 | 440 | 25.5 | 0.19 |
| 2015-2100 | .33 | 440 | 25.5 | 0.19 |
| 1870-3000 | 0.69 | 6100 | 54.6 | 0.41 |

(Although there are current greenhouse gas emissions from permafrost thawing, no source could be found which estimated the current annual or historical amounts)

Details: http://ccdatacenter.org/documents/FeedbackFromPermafrost.pdf

**D. Peatlands and Peat Bogs**

Since I could not find any estimates for future emissions from peatlands and peat bogs, I assumed that the current annual emissions of about 4GTCO2e would continue until 2100. To see if this is in the right "ballpark", if carbon from 40% of shallow peat and 86% of deep bogs will be emitted over several centuries, perhaps 70% of the carbon will be emitted over four centuries, which would be about 3.6 GTCO2e/year.

| |
|---|
| "Our modeling suggests that higher temperatures could cause water tables to drop substantially, causing more peat to dry and decompose," says Paul R. Moorcroft, professor of organismic and evolutionary biology in Harvard's Faculty of Arts and Sciences. "Over several centuries, some 40 percent of carbon could be lost from shallow peat bogs, while the losses could total as much as 86 percent in deep bogs."<br><br>Typically found at northerly latitudes, peat bogs are swampy areas whose cold, wet environment preserves organic matter, preventing it from decaying. This new work shows how peat bogs' stability could be upset by the warming of the Earth, which has disproportionately affected the higher latitudes where the bogs are generally found.<br><br>Each square meter of a peat bog contains anywhere from a few to many hundreds of kilograms of undecomposed organic matter, for a total of 200 billion to 450 billion metric tons of carbon sequestered in peat bogs worldwide. This figure is equivalent to up to 65 years' worth of the world's current carbon emissions from fossil-fuel burning. |
| http://news.harvard.edu/gazette/story/2008/11/global-warming-predicted-to-hasten-carbon-release-from-peat-bogs/ |

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| **Peatlands are a major storage of carbon in the world. They account for 550 Gt carbon worldwide.**<br><br>Peat fires, such as those take place in Southeast Asia every year and also in Russia, release huge amounts of $CO_2$ as well. Altogether global $CO_2$ emissions amount to at least 2,000 million tonnes annually, equivalent to 5% of the global fossil fuel emissions. |
| http://www.wetlands.org/Whatarewetlands/Peatlands/Carbonemissionsfrompeatlands/tabid/2738/Default.aspx |

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| 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 |

### E. Reservoirs

Methane emissions from reservoirs contribute about .7GTC of $CO_2$ equivalent per year, resulting in about 30 GTC through 2060 and 60 GTC through 2100.

http://www.climatecentral.org/news/greenhouse-gases-reservoirs-fuel-climate-change-20745
" Globally, reservoirs are responsible for about 1.3 percent of the world's man-made greenhouse gas emissions each year"