**Climate Sensitivity and Arctic Sea Ice Melt**

Bruce Parker (bruce@chesdata.com)

November 30, 2016
http://ccdatacenter.org/documents/ClimateSensitivityandArcticSeaIceMelt.pdf

The ice-albedo feedback has been included in climate models since the 1970s[1]. But what is hard to discern is the amount of the warming that is expected to come from the melting of Arctic sea ice, and hence what percent of climate sensitivity is due to Arctic sea ice melt. This is important because the Arctic sea ice is melting much faster than most climate models predict[2], and it would be very helpful to know how much more warming to expect. For example, the climate scenario RCP2.6, which was designed to show the temperature increase could be limited to 2°C, estimated that the Arctic Ocean would contain about 3.75 million square kilometers of ice in 2100[2]. Since this amount is equivalent to a radiative forcing of about .14 W/m-2[3], it would be responsible for about 5% of the radiative forcing increase of 2.6 W/m-2, or about .1°C[3,4]. Since climate scientists are projecting that the Arctic ocean will become ice free in September by 2060, the estimated temperature increase for models projecting a 2°C will need to be adjusted.

In order to determine the size of the adjustment it is necessary to predict the September Arctic sea ice extent for a 2°C temperature increase based on current knowledge. The Earth has warmed about 1°C and the September Arctic sea ice was about 3.5 million square kilometers in 2012. The extent increased in recent years but the record low value for the extent at the end of November, 2016 could indicate that the extent will reach that value again in the next few years. A reasonable assumption could then be that, if the Earth's temperature increase was 2°C for an extended period of time, then the radiative forcing would be about double what the models predict, or .28 W/m-2. If this is the case, then the additional radiative forcing for a 2°C temperature change, about .14 W/m-2, would require that either the IPCC's carbon budget be reduced by about 30 GTC (about 1/7 of the current IPCC budget[5]) or that $3.6-8.5 Trillion be spent on carbon dioxide removal[6].

Note: Climate scientists are projecting that the Arctic ocean will become ice free in September by 2060, which would correspond to a radiative forcing of about .4 W/m-2 in 2100. Since we are on temperature trajectory that will result in temperature increase of over 2°C in 2100, this is not inconsistent with the above analysis (i.e., if the temperature increase can be limited to 2°C in 2100 the Arctic Ocean might be ice-free for just "one day" in 2100).

**Footnotes**

| | |
|---|---|
| 1 | **Climate feedbacks** are processes that change as a result of a change in forcing, and cause additional climate change. An example of this is the "ice-albedo feedback." As the atmosphere warms, sea ice will melt. Ice is highly reflective, while the underlying ocean surface is far less reflective. The darker ocean will absorb more heat, getting warmer and making the Earth warmer overall. A feedback that increases an initial warming is called a "positive feedback." A feedback that reduces an initial warming is a "negative feedback." The ice-albedo feedback is a very strong positive feedback that has been included in climate models since the 1970s. http://ossfoundation.us/projects/environment/global-warming/feedbacks |

2

**Projected Arctic Sea Ice Decline**

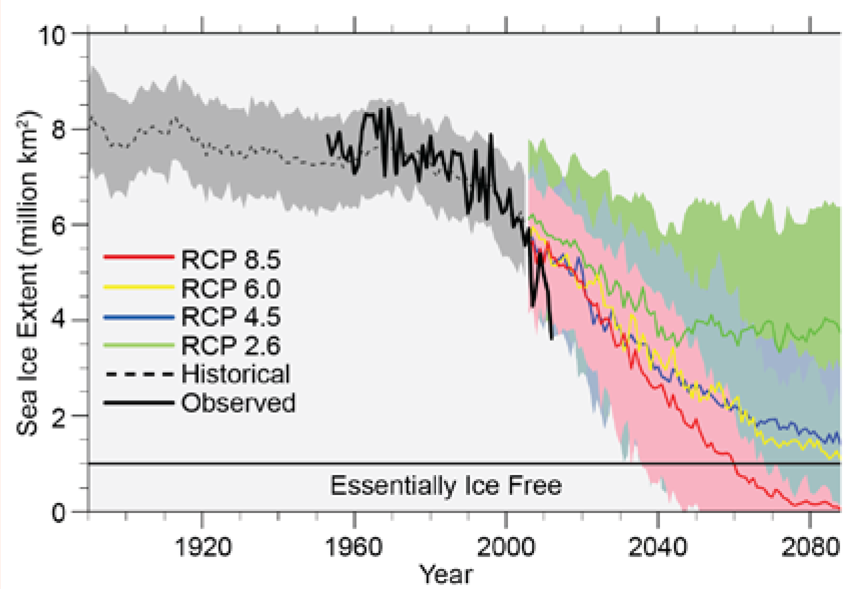


**Figure 2.29.** Model simulations of Arctic sea ice extent for September (1900-2100) based on observed concentrations of heat-trapping gases and particles (through 2005) and four scenarios. Colored lines for RCP scenarios are model averages (CMIP5) and lighter shades of the line colors denote ranges among models for each scenario. Dotted gray line and gray shading denotes average and range of the historical simulations through 2005. The thick black line shows observed data for 1953-2012. These newer model (CMIP5) simulations project more rapid sea ice loss compared to the previous generation of models (CMIP3) under similar forcing scenarios, although the simulated September ice losses under all scenarios still lag the observed loss of the past decade. Extrapolation of the present observed trend suggests an essentially ice-free Arctic in summer before mid-century.[139] The Arctic is considered essentially ice-free when the areal extent of ice is less than one million square kilometers. (Figure source: adapted from Stroeve et al. 2012[136]).

http://s3.amazonaws.com/nca2014/low/NCA3_Full_Report_02_Our_Changing_Climate_LowRes.pdf

(footnote 139: Overland, J. E., and M. Wang, 2013: When will the summer Arctic be nearly sea ice free? Geophysical Research Letters, 40, 2097-2101, doi:10.1002/grl.50316. [Available online at http://onlinelibrary. wiley.com/doi/10.1002/grl.50316/pdf])

3 Hudson, et all ("Estimating the Global Radiative Impact of the Sea-Ice-Albedo Feedback in the Arctic", JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D16102, DOI:10.1029/2011JD015804, 2011) estimated a .3 W/m-2 change in forcing if the Arctic Ocean is ice-free for a month. Assuming (1) a 0.3 W/m-2 change in forcing if the Arctic Ocean in 2070; (2) an "essential ice-free" Arctic Ocean in 2060 (just for "one day" - see #2 above), and (3) a linear extrapolation of radiative forcing and sea ice extent changes, the radiative forcing for various sea ice extents can be calculated (see Table 3.1 below). By estimating the September sea ice extent from #2 above, both the radiative forcing contribution of the Arctic sea ice melt and the percent of the RCPs radiative forcing due to Arctic sea ice melt can be calculated (see Table 3.2 below). From these calculation it appears that the Arctic sea ice melt contributes about 5% of the total radiative forcing.

*(Note that the minimum sea ice extent is about 1,000,000 km-2 due to the difficultly of melting the sea ice in the Canadian Arctic Archipelago -https://en.wikipedia.org/wiki/Arctic_sea_ice_decline)*

| Year | Radiative Forcing (W/m-2) | September Sea Ice Extent (km-2) |
|---|---|---|
| 1990 | 0.00 | 7,000,000 |
| 2000 | 0.04 | 6,142,857 |
| 2010 | 0.08 | 5,285,714 |
| 2020 | 0.11 | 4,428,571 |
| 2030 | 0.15 | 3,571,429 |
| 2040 | 0.19 | 2,714,286 |
| 2050 | 0.23 | 1,857,143 |
| 2060 | 0.26 | 1,000,000 |
| 2070 | 0.30 | 1,000,000 |
| 2080 | 0.33 | 1,000,000 |
| 2090 | 0.36 | 1,000,000 |
| 2100 | 0.39 | 1,000,000 |

Table 3.1

| RCP Scenario | September Sea Ice Extent (km-2) | Radiative Forcing (W/m-2) | Percent of RCP Radiative Forcing |
|---|---|---|---|
| 2.6 | 3,750,000 | 0.14 | 5.4 |
| 4.5 | 1,500,000 | 0.24 | 5.3 |
| 6.0 | 1,250,000 | 0.25 | 4.2 |
| 8.5 | 0 | 0.40 | 4.7 |

Table 3.2

http://ccdatacenter.org/documents/ProjectingTheDeclineOfArcticSeaIce.pdf

4 If the Arctic sea ice component of the temperature increase for RCP 2.6 were 1/2 that of an one-month ice free summer, then the warming from the melting of the Arctic sea ice would be about 0.1°C, or 5% of the total temperature increase:

"A 2011 study, for example, found that if the Arctic were ice-free for one month a year plus associated ice-extent decreases in other months then, without taking cloud changes into account, the global impact would be about 0.2ºC of warming. If there were no ice at all during the months of sunlight, the impact would close to 0.5ºC of global warming (2)."

http://www.climatecodered.org/2014/06/carbon-budgets-climate-sensitivity-and.html

(2): Hudson S. (2011) “Estimating the global radiative impact of the sea ice–albedo feedback in the Arctic”, JGRA, 16 August 2011; For a more detailed discussion, see: http://www.climatecodered.org/2012/10/after-arctic-big-melt-1-hotter-planet.html\

<table>
<tr><td>5</td><td>According to Climate Central (https://docs.google.com/spreadsheets/d/1odltJu_rxabdVXv_pACMBNIRiFSkc_HqJn-V8z0av2w/edit#gid=731498129), the remaining carbon budget for a 66% chance of limiting warming to 2°C is about 220 GTC.</td></tr>
<tr><td>6</td><td>These calculations are based on the following table:
<table>
<tr><td></td><td>Units</td><td colspan="2">Temperature Increase Sensitivity (°C)</td><td colspan="3">Negative Emissions to reach 350 PPM in 2100<br>(Assumes 100 GTC of forest and soil carbon sequestration)</td></tr>
<tr><td>Sensitivity to:</td><td></td><td>2060</td><td>2100</td><td>GTC</td><td>Min Cost ($B)</td><td>Max Cost ($B)</td></tr>
<tr><td>Increase in Radiative Forcing</td><td>1.0 W/m-2</td><td>.45</td><td>.51</td><td></td><td></td><td></td></tr>
<tr><td>Net increase in $CO_2$ emissions</td><td>100 GTC</td><td>.18</td><td>.16</td><td>90</td><td>13,500</td><td>31,500</td></tr>
</table>
(See http://ccdatacenter.org/documents/TemperatureSensitivitytoChangesinRadiativeForcingsandCO2Emissions.pdf)</td></tr>
</table>