Projecting the Decline of Arctic Sea Ice

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

Abstract

The area of the Arctic Ocean covered by ice in the summer fluctuated in a fairly narrow range for most of the last 1400 years (see Figure 1) but after about 1990 began to decline rapidly. Since the reduced summer-time extent of the ice in the Arctic Ocean is decreasing the albedo of the Arctic region, it could have a modest effect on the expected temperature change both for the Arctic region and the Earth as a whole in this century. Using the "post 1978" Arctic Ocean ice extent data from NOAA, a "back-of-the-envelop" linear extrapolation of the sea ice extent was done both to estimate a plausible trajectory of the albedo change and to estimate the albedo change for various amounts of sea ice reduction. This data can then be used by other models to provide a better estimate of the expected temperature change this century.

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, about 20% higher than the linear extrapolation. Adjusting the linear extrapolation to meet Hudson's estimate, and assuming that the 3 W/m-2 change will occur in 2070, results in the following:

Assuming a 70% cloud cover the albedo change for the each decade would be as follow:

Year	Effective Area (m km2)	Number of Ice Free Weeks[1]	September Sea Ice Extent (m km2)	Yearly Albedo Change	Radiative Forcing (W/m-2)
1990	0.18	0	6496000	0.00028	0.03
2000	0.37	0	5672750	0.00056	0.07
2010	0.55	0	4849000	0.00084	0.10
2020	0.73	0	4025500	0.00112	0.13
2030	0.91	0	3202000	0.00140	0.17
2040	1.09	0	2378500	0.00167	0.20
2050	1.28	1	1572250	0.00195	0.23
2060	1.46	3	1108000	0.00223	0.27
2070	1.63	4	1000000	0.00249	0.30
2080	1.80	5	1000000	0.00275	0.33
2090	1.96	7	1000000	0.00299	0.36
2100	2.10	8	1000000	0.00322	0.39
3000	4.12	30	1000000	0.00630	0.76

Then the following time periods would have the indicated radiative forcing changes:

Time Period	Increase in Radiative Forcing
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

Radiative forcing based on number of ice free weeks

Ice Free Weeks[1]	RF
1	0.23
2	0.25
3	0.28
4	0.30
5	0.32
6	0.34
7	0.36
8	0.39

1. An "ice-free" Arctic Ocean is often defined as "having less than 1 million square kilometers of sea ice" (see Appendix A)

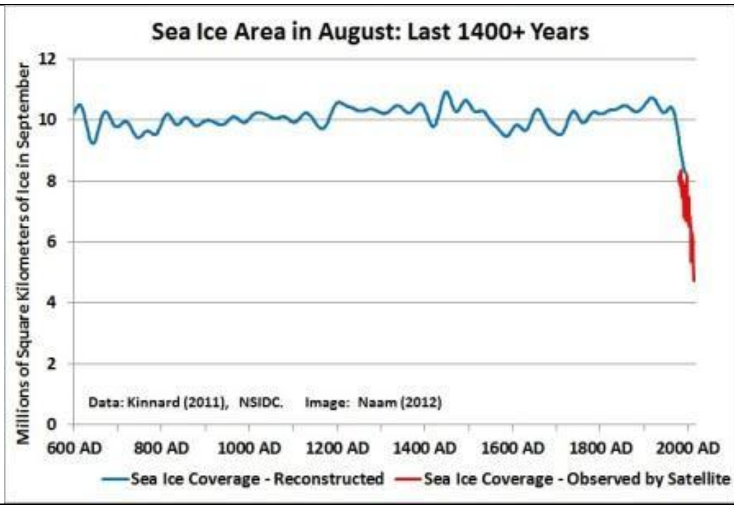	Arctic sea ice coverage, as reconstructed from 69 sites around the area, fluctuated in a fairly narrow range for more than 1400 years. In the last few decades, it has plunged abruptly.
http://blogs.scientificamerican.com/guest-blog/2012/09/21/arctic-sea-ice-what-why-and-what-next/	

Figure 1 – Arctic Sea Ice Area for last 1400 Years

(See http://ccdatacenter.org/documents/ReducedArcticSeaIceExtentBackground.pdf for additional background information.)

Analysis

The following analysis uses the "post 1978" Arctic Ocean ice extent data to develop a "back-of-the-envelop" calculation to estimate the magnitude of impact of the albedo change this century due to the change in the ice extent in the Arctic Ocean. The following assumptions were made when performing the analysis:

1. Any sea ice extent can be represented as occupying all of the Arctic Ocean north of the latitude for which the sea area matches sea ice cover extent
2. The "relative albedo" of a square kilometer of sea ice for a week at a specific latitude is the ratio of the "effective solar radiation" at that latitude to the "effective solar radiation" at the North Pole on the solstice
3. An annual average albedo change of .5 for 5.1k m-2 of surface area in the Arctic Circle would change the Earth's albedo by .005.
4. The reduction in sea ice extent will be linear and will follow the same trajectory as it did from 1979 to 2014. (The actual decline is apt to be exponential, so this analysis probably underestimates the change for 2100.)

This results in the following :

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2100	2.10	8	1000000	0.00322	0.33
3000	4.12	30	1000000	0.00630	0.64

Then the following time periods would have the indicated radiative forcing changes:

Time Period	Increase in Radiative Forcing
1990-2011	.09
1990-2016	.10
1990-2060	.23
1990-2100	.33
1990-3000	.64
2016-2060	.13
2016-2100	.23

Radiative forcing based on number of ice free weeks

Ice Free Weeks[1]	RF
1	0.20
2	0.22
3	0.23
4	0.25
5	0.27
6	0.29
7	0.31
8	0.33

1. An "ice-free" Arctic Ocean is often defined as "having less than 1 million square kilometers of sea ice" (see Appendix A)

Calculation Steps

The calculation was done in the following steps:

1. Compute the average weekly sea ice extent for each week and year
2. Compute the “linear fit” for each week for the sea ice extent.
3. Compute the average loss of sea ice extent for each week
4. Compute the sea ice extent for each week for each decade (1990-2120)
5. Estimate the ocean area per degree latitude in the Northern Hemisphere for 65° N to 90° N
6. Estimate the “percent effective solar radiation” for each degree of latitude for 30° N to 89° N for every seven days between 3/4/2015 and 9/23/2015
7. For each decade and each week, determine the “effective area” of the change in sea ice extent by estimating the latitude where the change occurred and multiplying the corresponding “percent effective solar radiation” by the change in sea ice extent
8. For each decade, sum the “effective areas” of the change in Sea ice extent and calculate the expected albedo change for the entire year.

(see http://ccdatacenter.org/documents/FeedbackFromArcticSeaIceMelt.xlsx for data and calculations)

1. Compute the average weekly sea ice extent for each week and year

The data for the Arctic Sea ice extent is in the file “NH_seaice_extent_final.csv”, which was obtained from the Web page ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/north/daily/data/. The file contains “every other day data” for the Arctic sea ice extent from 1979 to 2014

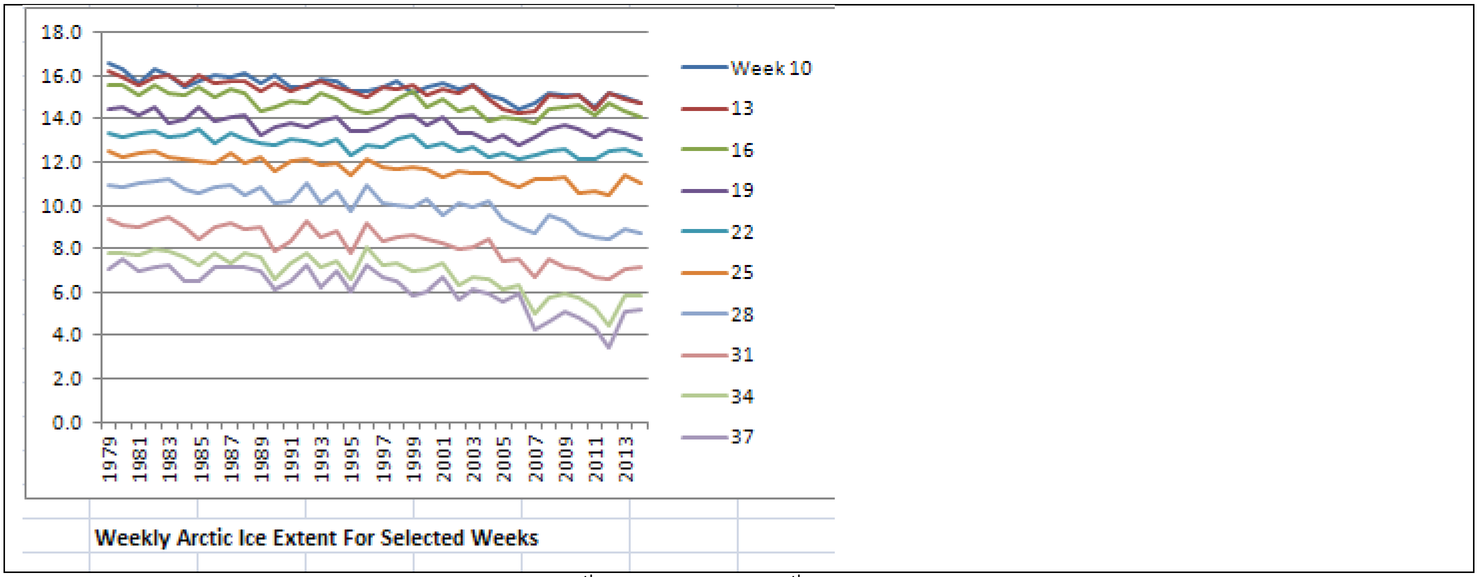


Figure __ - Weekly Sea ice extent from March 4th to September 9th for selected weeks

2. Compute the “linear fit” for each week for the sea ice extent.
This is the “trend” that will be used to project the sea ice extent for 2100

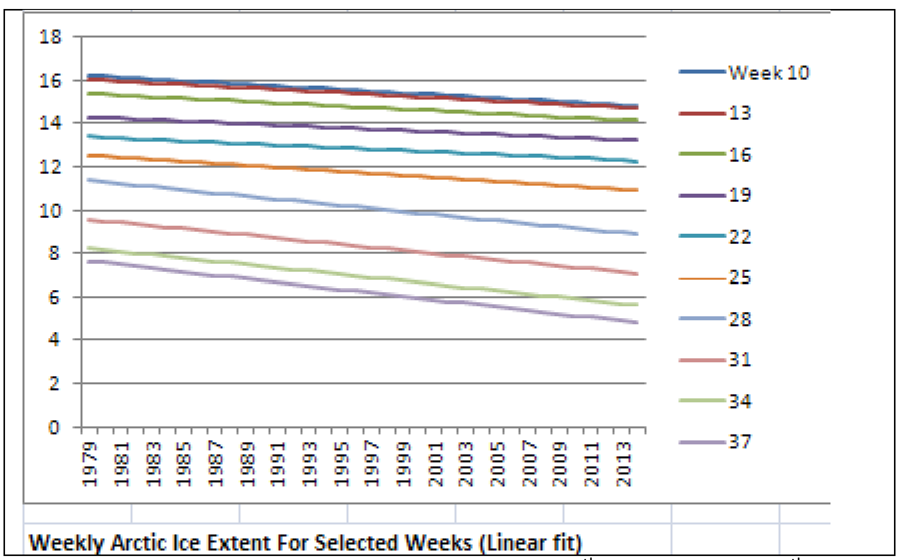


Figure __ - Weekly Sea ice extent from March 4th to September 9th (linear fit)

The result is also used to specify the “historical sea ice extent” for the starting year of 1979 (for “x = 0”) and the average decline per year. (This enables the sea ice extents through 2100 to be calculated as a linear extrapolation.)

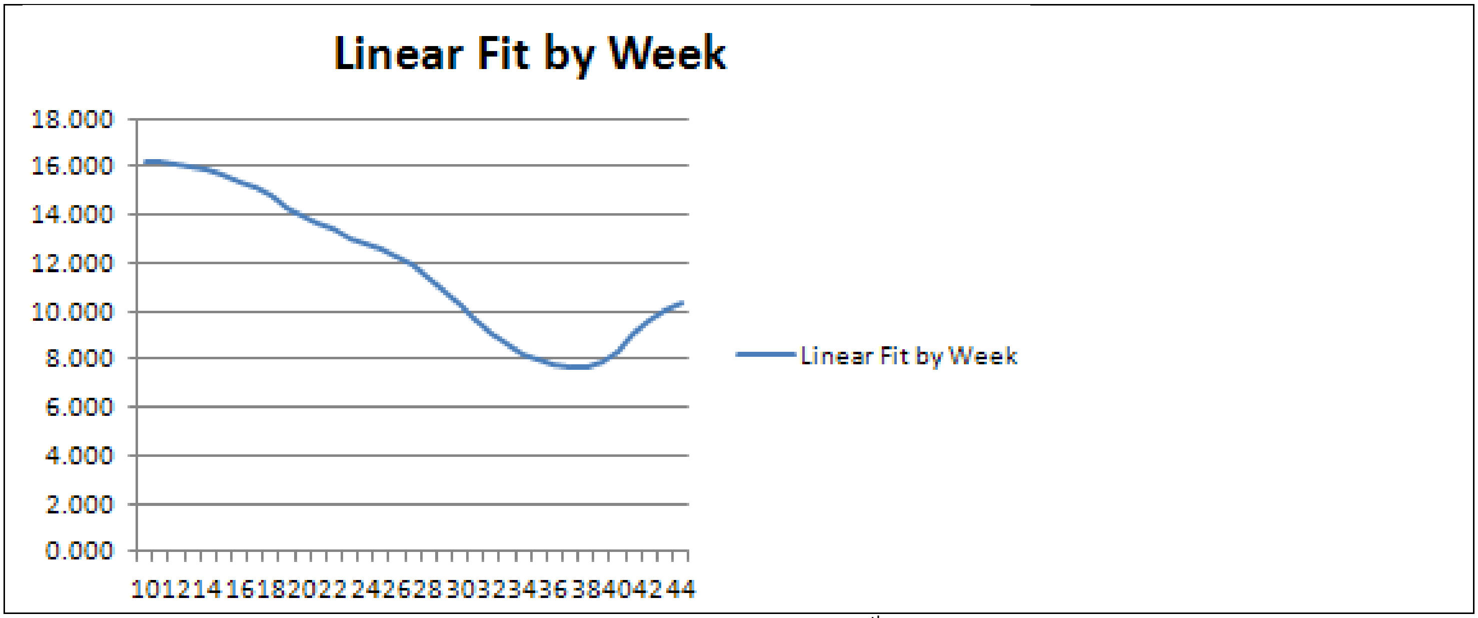
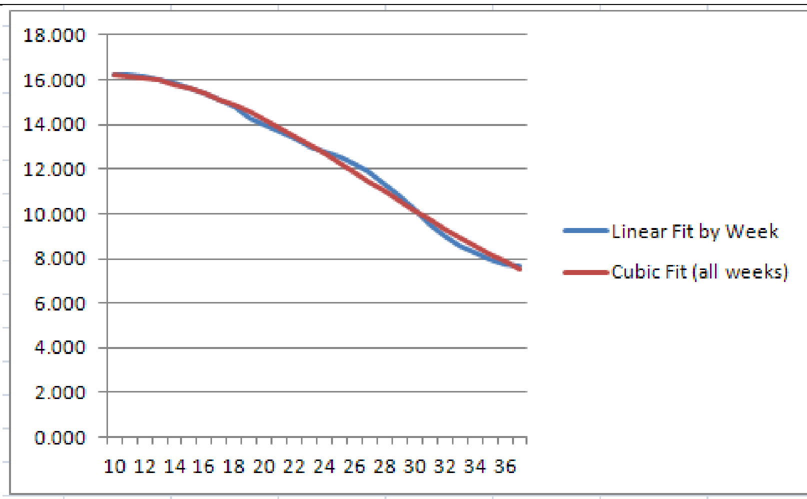


Figure __ - Historical Sea ice extent (for 1979) by week starting March 4th

The “linear fit” for the “historical” weekly extent was “smoothed” by computing a “cubic fit” (see Figure below). These are the numbers that are used for the initial values for the linear extrapolation from 1979 to 2100

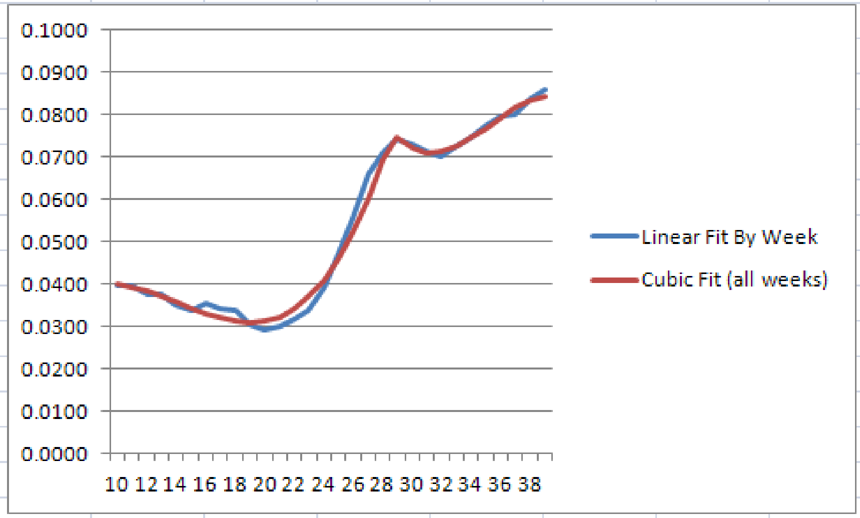
Week	Linear	Cubic
10	16.204	16.186
11	16.207	16.155
12	16.120	16.080
13	16.024	15.963
14	15.847	15.807
15	15.609	15.615
16	15.374	15.389
17	15.100	15.133
18	14.761	14.848
19	14.294	14.537
20	13.960	14.203
21	13.644	13.849
22	13.385	13.477
23	13.027	13.089
24	12.775	12.689
25	12.540	12.279
26	12.264	11.862
27	11.888	11.440
28	11.360	11.016
29	10.821	10.593
30	10.184	10.172
31	9.569	9.758
32	9.010	9.352
33	8.585	8.957
34	8.241	8.576
35	7.990	8.211
36	7.774	7.865
37	7.640	7.540
38	7.699	7.240



3. Compute the average loss of sea ice extent for each week

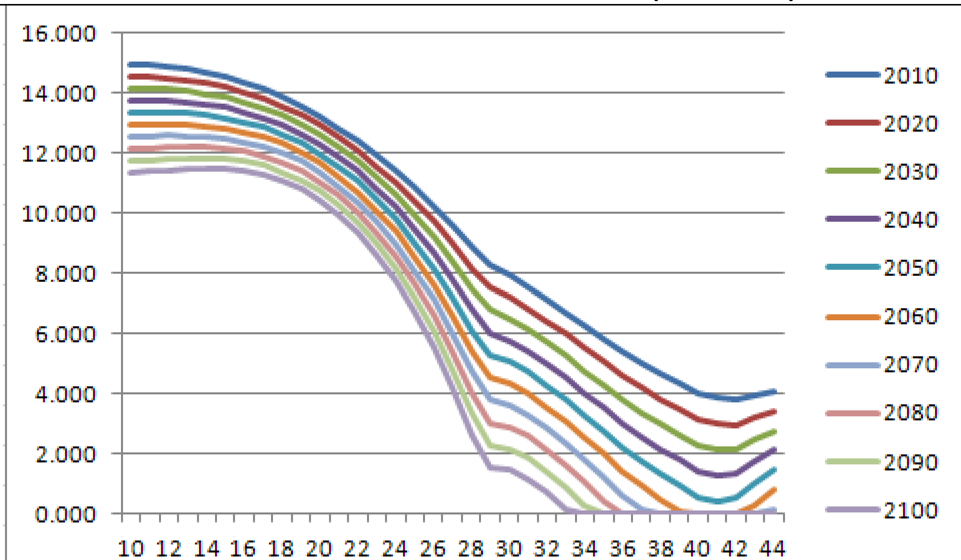
"Smoothed" the annual change for each week by computing two "cubic fits" (see figure below)

Week	Linear	Cubic	Week	Linear	Cubic
10	0.0397	0.0400	24	0.0390	0.0408
11	0.0395	0.0394	25	0.0471	0.0459
12	0.0375	0.0384	26	0.0556	0.0522
13	0.0376	0.0371	27	0.0660	0.0599
14	0.0351	0.0357	28	0.0710	0.0692
15	0.0337	0.0343	29	0.0744	0.0748
16	0.0355	0.0330	30	0.0729	0.0721
17	0.0341	0.0320	31	0.0713	0.0711
18	0.0339	0.0312	32	0.0702	0.0713
19	0.0306	0.0310	33	0.0725	0.0726
20	0.0293	0.0313	34	0.0747	0.0746
21	0.0299	0.0323	35	0.0778	0.0770
22	0.0318	0.0342	36	0.0798	0.0794
23	0.0339	0.0370	37	0.0803	0.0817
			38	0.0839	0.0834



Annual Sce Ice Extent Loss By Week

4. Compute the sea ice extent for each week for each decade (1990-2120)



Yearly Sea ice extent By Week (2010-2100) (millions of sqiare kilometers)

5. Estimate the ocean area per degree latitude in the Northern Hemisphere for 65° N to 90° N

To a very rough approximation, the land area (not including Greenland) inside the Arctic Circle is little larger than the area between the Arctic Circle (66°34′) and 70° (see below). South of the Arctic Circle to about 45°N, the land comprises about 2/3 of the surface area. Based on this the "land area" per degree and total land area north of each degree of latitude can be computed (see below)

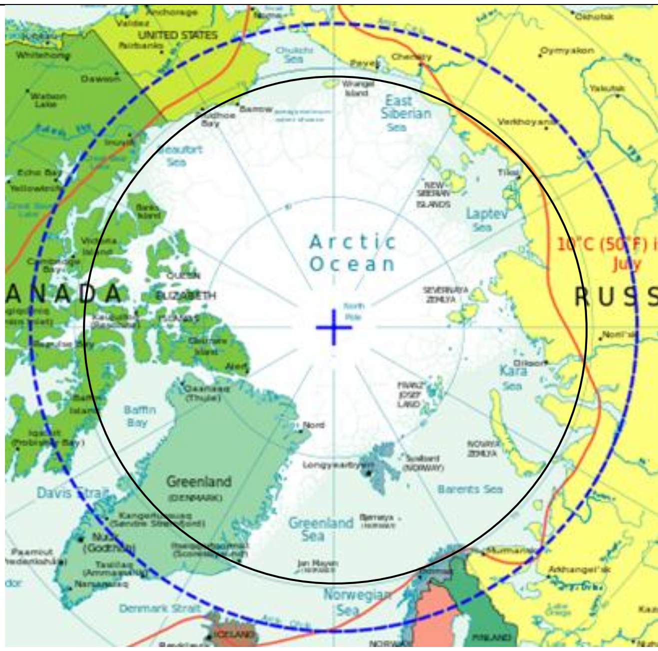


Figure 9 – Map of the Arctic Region Showing the Arctic Circle (dashed line) and 70° N (solid black line)

Latitude	Circle Length	Two Thirds of Circle Length+	Sea Area Per Degree	Sea Area North Of Latitude
65	16936	11291	1,218,641	16,696,961
66	16300	10866	1,171,787	15,478,320
67	15658	10439	1,124,575	14,306,533
68	15012	10008	1,077,021	13,181,958
69	14361	9574	1,029,139	12,104,937
70	13706	9137	980,944	11,075,797
71	13047	8698	932,450	10,094,853
72	12384	8256	883,671	9,162,404
73	11717	7811	834,624	8,278,733
74	11046	7364	785,322	7,444,109
75	10372	6915	735,781	6,658,787
76	9695	6463	686,016	5,923,006
77	9015	6010	636,042	5,236,990

Latitude	Circle Length	Two Thirds of Circle Length+	Sea Area Per Degree	Sea Area North Of Latitude
78	8332	5555	585,874	4,600,948
79	7647	5098	535,528	4,015,074
80	6959	4639	485,018	3,479,547
81	6269	4179	536,611	2,994,528
82	5577	5577	575,358	2,457,918
83	4884	4884	498,998	1,882,560
84	4189	4189	422,487	1,383,562
85	3493	3493	345,847	961,075
86	2795	2795	269,101	615,229
87	2097	2097	192,274	346,128
88	1399	1399	115,388	153,854
89	699	699	38,466	38,466
90	0		0	0

+ Area above 81 Degrees does not contain any land

Table – Total ocean area north of each degree of latitude

6. Estimate the "percent effective solar radiation" for each degree of latitude for 30° N to 89° N for every seven days between 3/4/2015 and 9/23/2015

The daily solar radiation for 30-89 Degrees North for every seven days between 3/4/2015 and 9/23/2015 was computed using the vba code in the spreadsheet "solrad.xls"[8]. The "percent effective solar radiation" was then determined by calculating the ratio of each day's solar radiation to the maximum solar radiation (493).

For example, the following calculations are for 50°N to 60°N for the month of April 2015

Degrees N	5/20	27	6/3	10	17
75	390	412	429	440	445
76	396	419	435	446	451
77	402	425	441	452	457
78	408	431	447	457	463
79	414	436	452	462	467
80	419	441	457	467	472
81	424	446	461	471	476
82	428	450	465	475	480
83	432	453	468	478	483
84	435	456	471	481	485
85	438	459	473	483	488

Daily solar radiation

Degrees N	5/20	27	6/3	10	17
75	79	84	87	89	90
76	80	85	88	90	91
77	82	86	89	92	93
78	83	87	91	93	94
79	84	88	92	94	95
80	85	89	93	95	96
81	86	90	94	96	97
82	87	91	94	96	97
83	88	92	95	97	98
84	88	92	96	98	98
85	89	93	96	98	99

Percent effective solar radiation

Table 4 – Solar Radiation for 50°N to 60°N

7. For each decade and each week, determine the "effective area" of the change in sea ice extent by estimating the latitude where the change occurred and multiplying the corresponding "percent effective solar radiation" by the change in sea ice extent

The first step is to determine the southern-most latitude that includes the historical sea ice extent. Based on the change in area of sea ice extent, the latitude to the south of the change is then determined. The fraction of the area within each latitude "band" is determined to calculate the area in the latitude band that is now snow-free. This area is multiplied by the effective solar radiation percent to compute the "effective area" for the week (where the "effective area" is the area at the North Pole that would have the same total solar radiation). For example, data for the week of June 3, 2030 is as follows:

Year	Week #	Month	Day	sea ice extent Historical	sea ice extent	sea ice extent Change	Latitude	Snow Free Area	Fraction	Effective Solar Radiation	Effective Area
2030	23	June	3	13055000	11362000	1693000	68	950063	0.882	78	741049
2030	23	June	3	13055000	11362000	1693000	69	742937	0.722	79	586920
										Total:	**1327969**

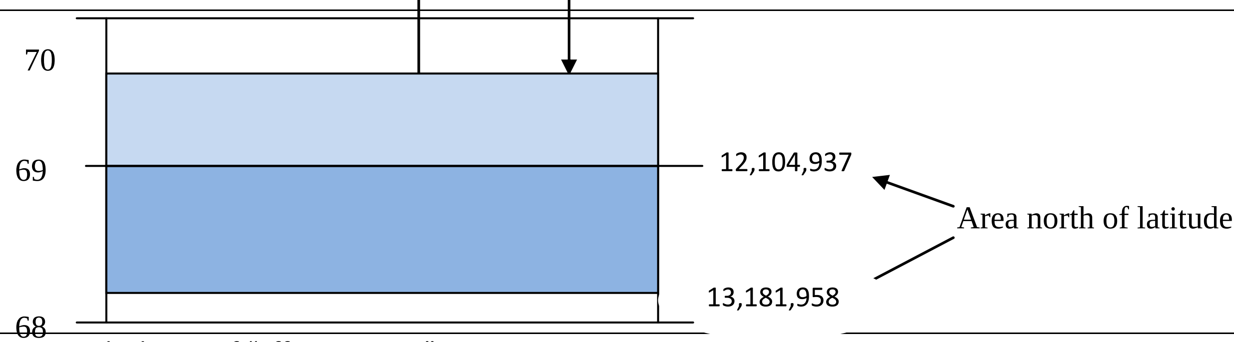


Figure 10 – Calculation of "Effective Area"

8. For each decade, sum the “effective areas” of the change in Sea ice extent and calculate the expected albedo change for the entire year.

Given these parameters:

0.85	Albedo of snow-covered ice
0.65	Albedo of melting ice
0.07	Albedo of open ocean
0.78	Change in albedo (snow-covered ice to open ocean)
3.4	W/m-2 / .01 albedo change
510	million km^2 surface area for the Earth
17.3429333	Gigatons of CO2 emissions per PPM of atmospheric CO2 (airborne fraction = 45%)

The following computations can be made:

	Effective Radiative Forcing (W/m-2)				Equiv. CO2e PPM		Equiv CO2 Emiss. (GTCO2)		Temp. Increase (70% Cloud Cover)	
			Cloud Cover %		Cloud Cover %		Cloud Cover %		Clim. Sensitivity	
Year	Effective Area (m km2)	Yearly Albedo Change	70	80	70	80	70	80	2.6	3.0
1990	0.183203	0.00028	0.03	0.02	1.8	1.1	31	18	0.01	0.01
2000	0.366177	0.00056	0.06	0.04	3.9	2.5	68	43	0.03	0.03
2010	0.548719	0.00084	0.09	0.06	6.1	3.9	106	68	0.04	0.05
2020	0.730971	0.00112	0.11	0.08	8.2	5.4	143	93	0.05	0.06
2030	0.912718	0.00140	0.14	0.09	10.4	6.8	181	118	0.07	0.08
2040	1.094448	0.00167	0.17	0.11	12.6	8.2	218	143	0.08	0.10
2050	1.275903	0.00195	0.20	0.13	14.8	9.7	256	168	0.10	0.11
2060	1.456982	0.00223	0.23	0.15	17.0	11.1	295	193	0.11	0.13
2070	1.637810	0.00250	0.26	0.17	19.2	12.6	333	218	0.12	0.15
2080	1.815560	0.00278	0.28	0.19	21.4	14.0	371	243	0.14	0.17
2090	1.987493	0.00304	0.31	0.21	23.5	15.4	407	267	0.15	0.18
2100	2.151678	0.00329	0.34	0.22	25.5	16.7	442	290	0.17	0.20
3000	4.496773	0.00688	0.70	0.47	55.6	36.1	965	627	0.36	0.43

Table 5 – Results by Decade

- The year 3000 is used to specify a completely snow free NH after March 1
- The “Effective Area” is the sum of the weekly “effective areas” / 52 (to get the average “effective area” for the entire year)
- The “Yearly Albedo Change” is the computed by multiplying the “Change in albedo” by the ratio of the “Effective Area” to the Earth’s surface area
- The “Effective Radiative Forcing” **(**ERF) for a cloud cover percent is computed using the formula
  “Yearly Aledo Change”*((100-cloud cover pct)/100)*(3.4 W/m-2 / .01 albedo change)
- The “Equivalent CO2 PPM” = 275 * POWER(2.718,(ERF+2)/5.35) – 400 (the ERF for 400PPM is 2 W/m-2 so this formula computes the change in ERF above the current value of 2)
- The “Equiv CO2 Emissions” = “Equivalent CO2 PPM” * 7.80432 GTCO2 per PPM/ (“Airborne Fraction of emitted CO2 which stay in the atmosphere” = 0.45)

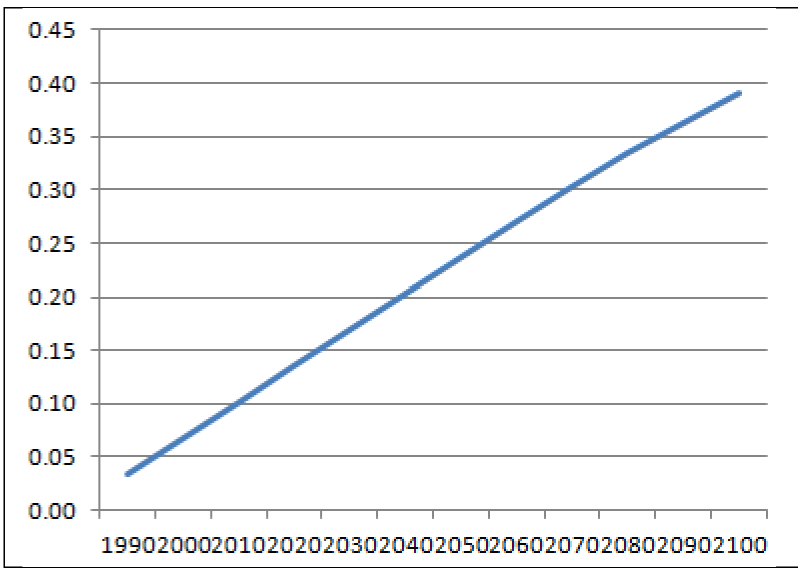
Appendix A - "Ice-free" Arctic Ocean

An "ice-free" Arctic Ocean is often defined as "having less than 1 million square kilometers of sea ice", because it is very difficult to melt the thick ice around the Canadian Arctic Archipelago.[10][11][12] The IPCC AR5 defines "nearly ice-free conditions" as sea ice extent less than 10^6 km^2 for at least five consecutive years.[3]

Many scientists have attempted to estimate when the Arctic will be "ice-free". They have noted that climate model predictions have tended to be overly conservative regarding sea ice decline.[2][13] A 2013 paper suggested that models commonly underestimate the solar radiation absorption characteristics of wildfire soot.[14] A 2006 paper predicted "near ice-free September conditions by 2040".[15] Overland & Wang (2009) predicted that there would be an ice-free Arctic in the summer by 2037.[16] The same year Boé et al. found that the Arctic will probably be ice-free in September before the end of the 21st century.[17] A follow-up study concluded with the possibility of major sea ice loss within a decade or two.[18] The IPCC AR5 (for at least one scenario) estimates an ice-free summer might occur around 2050.[3] The Third U.S. National Climate Assessment (NCA), released May 6, 2014, reports that the Arctic Ocean is expected to be ice free in summer before mid-century. Models that best match historical trends project a nearly ice-free Arctic in the summer by the 2030s.[19] However, these models do tend to underestimate the rate of sea ice loss since 2007. A 2010 study suggested that the Arctic Ocean will be ice-free sooner than global climate models predict. They chart the summer of 2016 as ice-free, but show a possible date range out to 2020.[20] This assessment was reported in the press as "US Navy predicts summer ice free Arctic by 2016" [21] In a study from 2016, the prediction uncertainty of an ice-free Arctic was quantified to be at around two decades, based on model simulations [22]

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

Appendix B . Radiative Forcing For the Expected Albedo Change



Radiative Forcing For the Expected Albedo Change from 1990 for a Linear Decrease in Arctic Ice extent

Based on .3 W/m-2 for 4 weeks of an ice-free Arctic Ocean in 2070

Figure X. Radiative Forcing For the Expected Albedo Change