

The Expected Albedo Change in the Year 2100 Due to the Reduced Arctic Sea Ice Extent

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<http://ccdatacenter.org/documents/FeedbackFromArcticSeaIceMelt.pdf>

Abstract

The reduced summer-time extent of the ice in the Arctic Ocean is decreasing the albedo of the Arctic region. A “back-of-the-envelope” calculation was done to estimate the magnitude of the both the current albedo change (about -0.001) and the expected change by the year 2100 (about -0.0033). Assuming a 70% cloud cover and a climate sensitivity of 3.1, the current albedo change will eventually add about 0.06° C to the Earth’s average temperature, and the albedo change by 2100 will increase the Earth’s temperature by about 0.20° C.

Note: An analysis published in the Proceedings of the National Academy of Sciences (see Page 13 below) estimated that the radiative heating from 1979 to 2011 for the Arctic is equivalent to 0.18 W/m² of radiative heating for the Earth – about 80% higher than this analysis estimates for the total change through 2014.

Time Period	Change in Radiative Forcing (W/m ²)	Equivalent Emissions (GTCO ₂ e)	Atmospheric CO ₂ e Change (PPM)	Temperature Increase for a Climate Sensitivity of 3.0
1870-2015	0.10	131	8.4	0.06
1870-2100	0.34	452	26.1	0.20
2011-2100	0.25	340	19.6	0.15
2015-2100	0.24	321	18.5	0.14
1870-3000	0.70*	979	56.4	0.42

* Agrees very closely with "A global radiative heating of 0.71 W/m² relative to the 1979 baseline state is expected from an ice-free Arctic Ocean." (20 June 2019 <https://doi.org/10.1029/2019GL082914>) (<https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL082914>)

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)

Background

The area of the Arctic Ocean covered by ice varies considerably from year to year and week to week (see Figure 1). By examining the available data for sea ice extent after 1900 (see Figure 1), a reasonable assumption is that the sea ice extent, while quite variable from year to year, shows very little overall change from 1900 to 1990, at which point the sea ice extent begins to decline. In addition, a data set of “every other day sea ice extent area” from 1979 to 2014⁴ enables the analysis of sea ice extent trends after 1979.

The annual sea-ice minimum, based on a five-day average, is seen as an important indicator of climate change. Overall, the Arctic has lost 40% of its sea-ice cover since 1980, and 75% of its volume. Most scientists believe the ocean at the north pole could be entirely ice-free in the summer by the middle of the century – if not sooner. (<http://www.theguardian.com/environment/2013/sep/20/arctic-sea-ice-decline-melting-summer>)

(The “Analysis” section starts on Page 6 below - after the figures.)

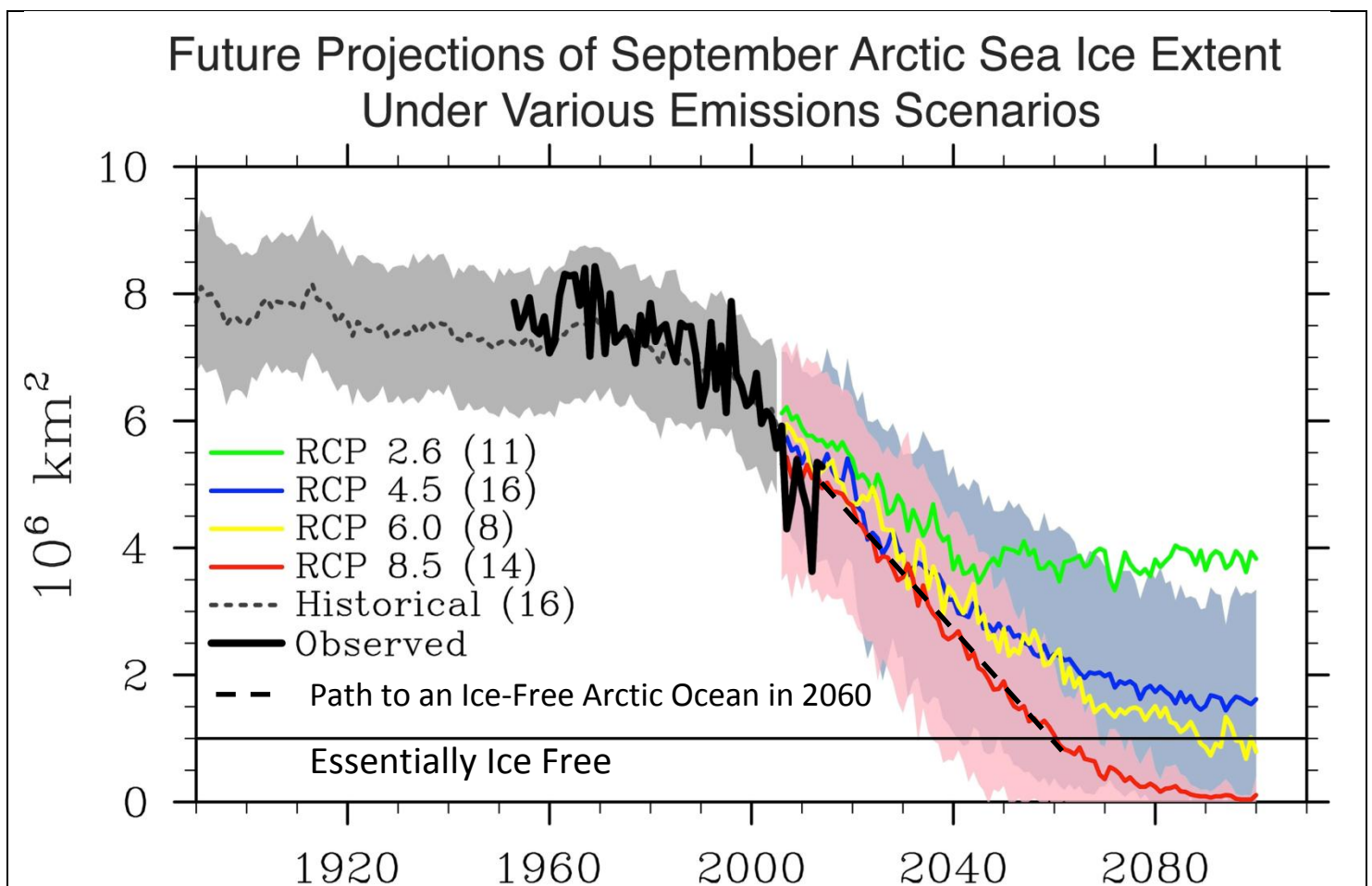


Figure 2.29. Model simulations of Arctic sea ice extent for September (1900-2100) based on observed concentrations of heat-trapping gases and particles (through 2005) and four scenarios. Colored lines for RCP scenarios are model averages (CMIP5) and lighter shades of the line colors denote ranges among 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. 2012¹³⁶).

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

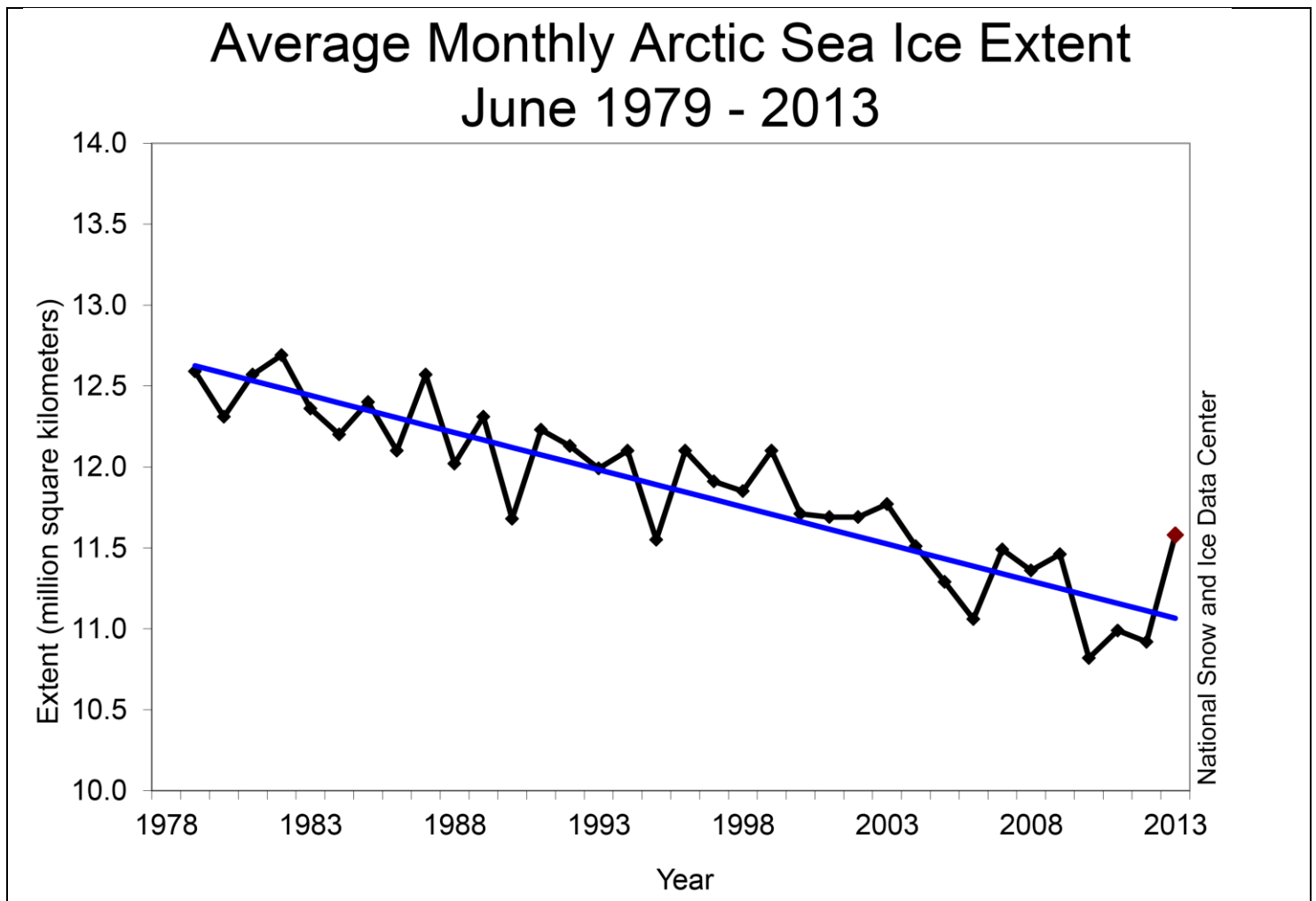


Figure 2 – Average Monthly Arctic Sea Ice Extent – June 1979-2013

What is most important for global warming is when the Arctic is ice-free in June, as this is when the sun is directly overhead and will cause the oceans to warm up the most. At the current rate it will take about 100 years for the Arctic to become ice free in June.

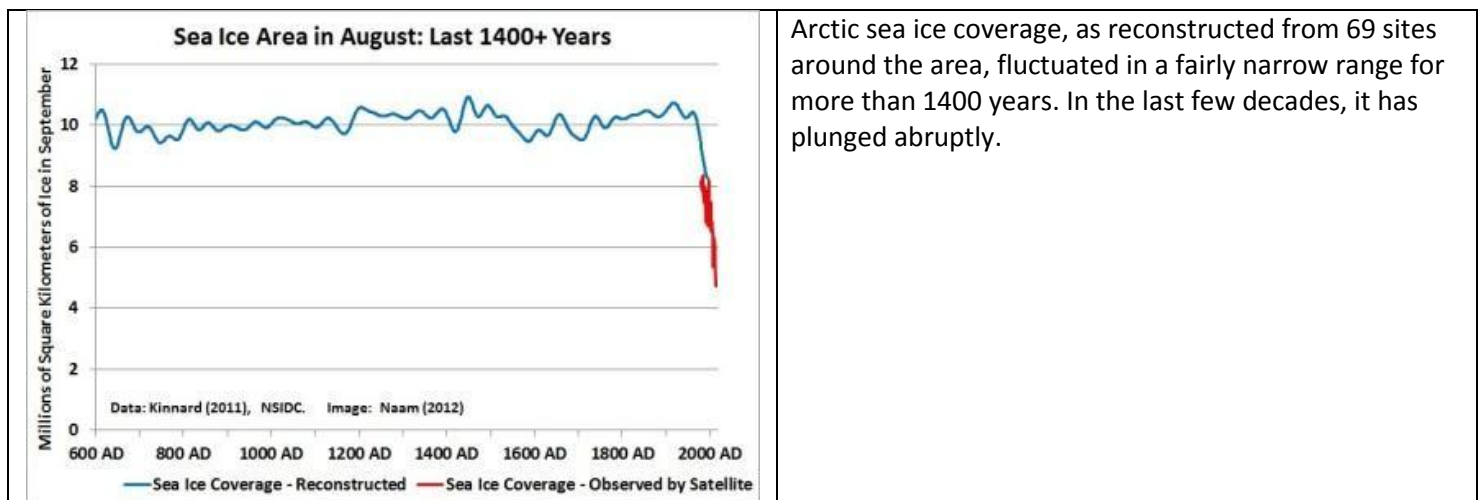


Figure 3 – Arctic Sea Ice Area for last 1400 Years

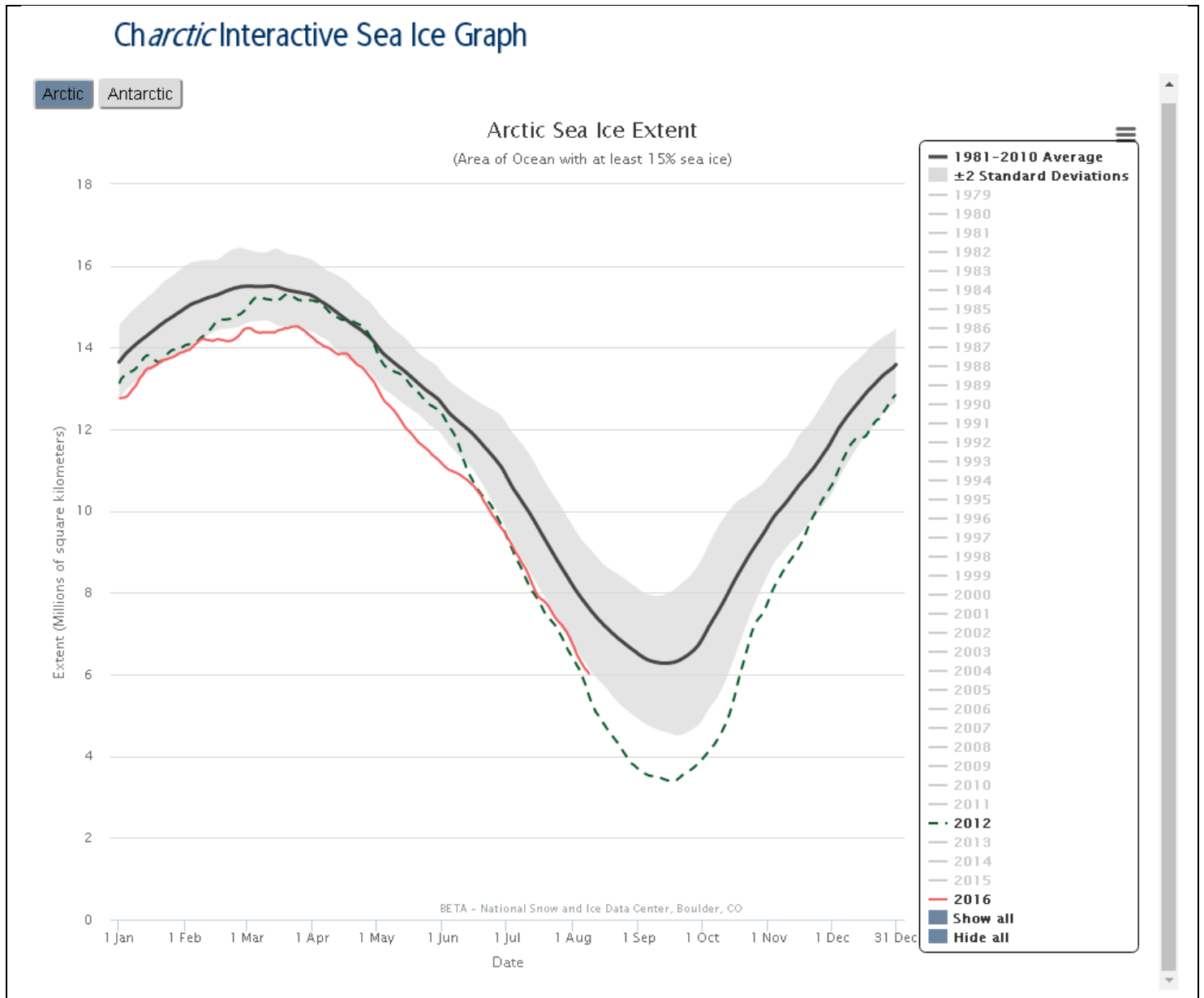


Figure 4 - Arctic Sea ice extent on 10 August 2016 (<http://nsidc.org/arcticseaicenews/charctic-interactive-sea-ice-graph/>)

<http://blogs.scientificamerican.com/guest-blog/2012/09/21/arctic-sea-ice-what-why-and-what-next/>

If the pace of the last decade were to continue on this recent pace – and didn't keep on accelerating – June ice would be gone by 2026...

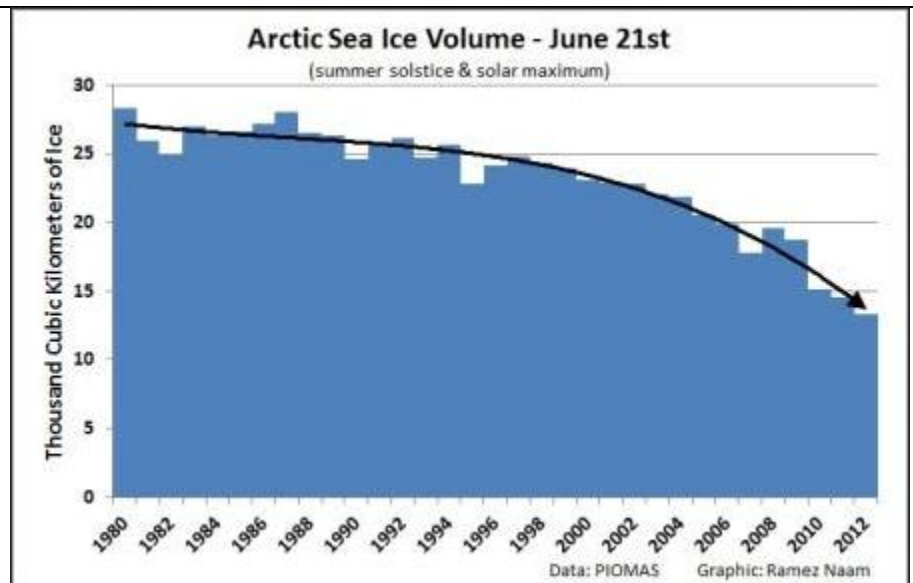
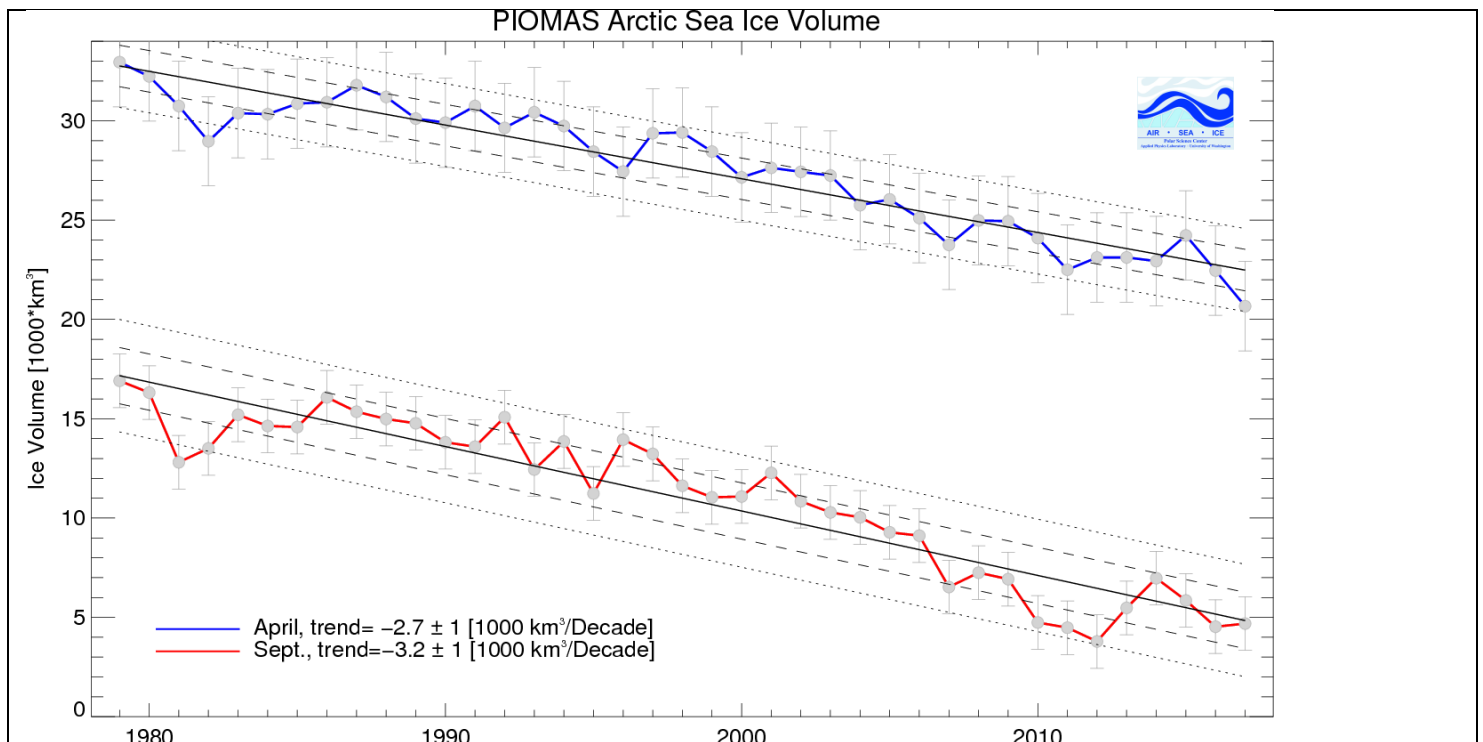


Figure 5 – Arctic Sea Ice volume on June 21st for 1980-2012

The volume of Arctic ice has been declining steadily since 1990, and the Arctic is expected to be ice-free in the summer sometime in the next 20-30 years. An ice-free Arctic will absorb a substantial amount of heat from the sun – equivalent to the warming caused by the CO₂ which has been emitted since 1870. This will likely increase the rate at which the Earth warms.



Analysis

The following analysis uses the “post 1978” Arctic Ocean ice extent data to develop a “back-of-the-envelope” 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 m² 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.)

The data was analyzed as follows:

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

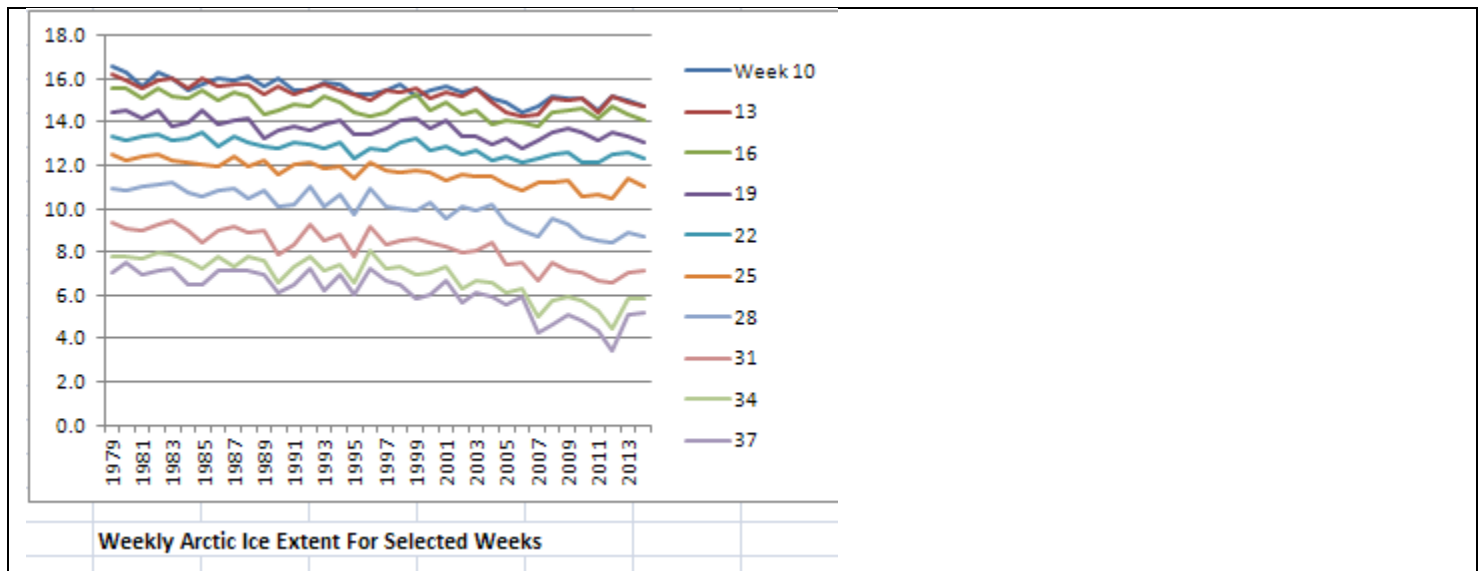


Figure __ - Weekly Sea ice extent from March 4th to September 9th for selected weeks

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

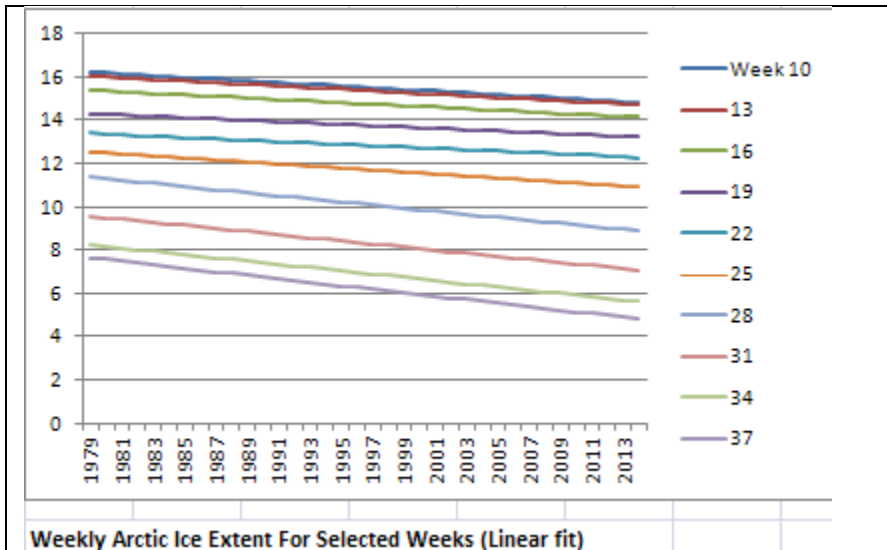


Figure __ - Weekly Sea ice extent from March 4th to September 9th (linear fit)

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.)

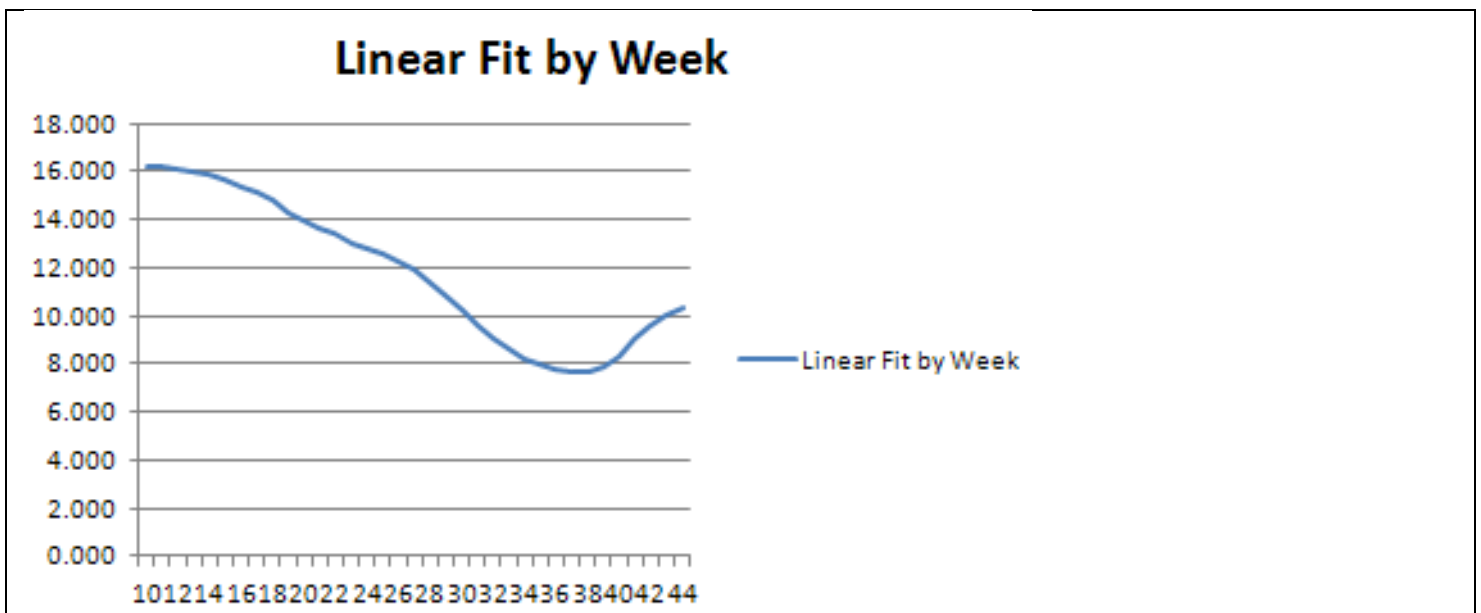
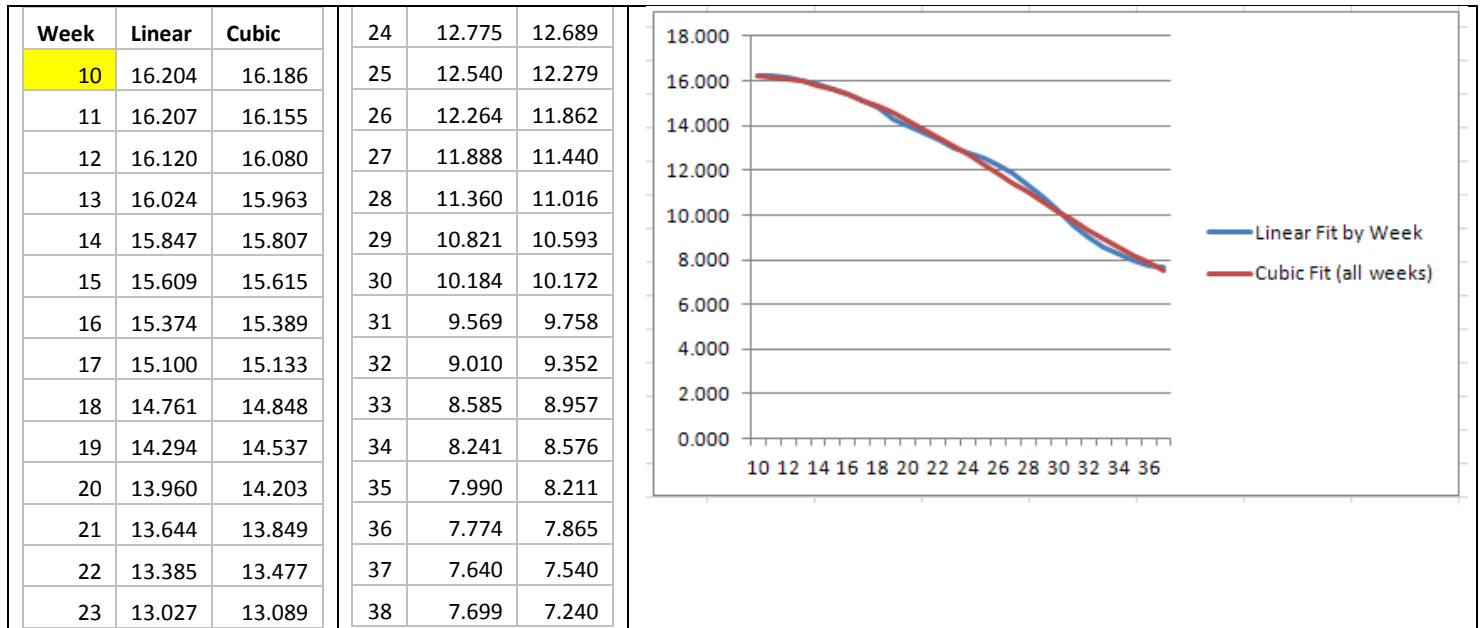


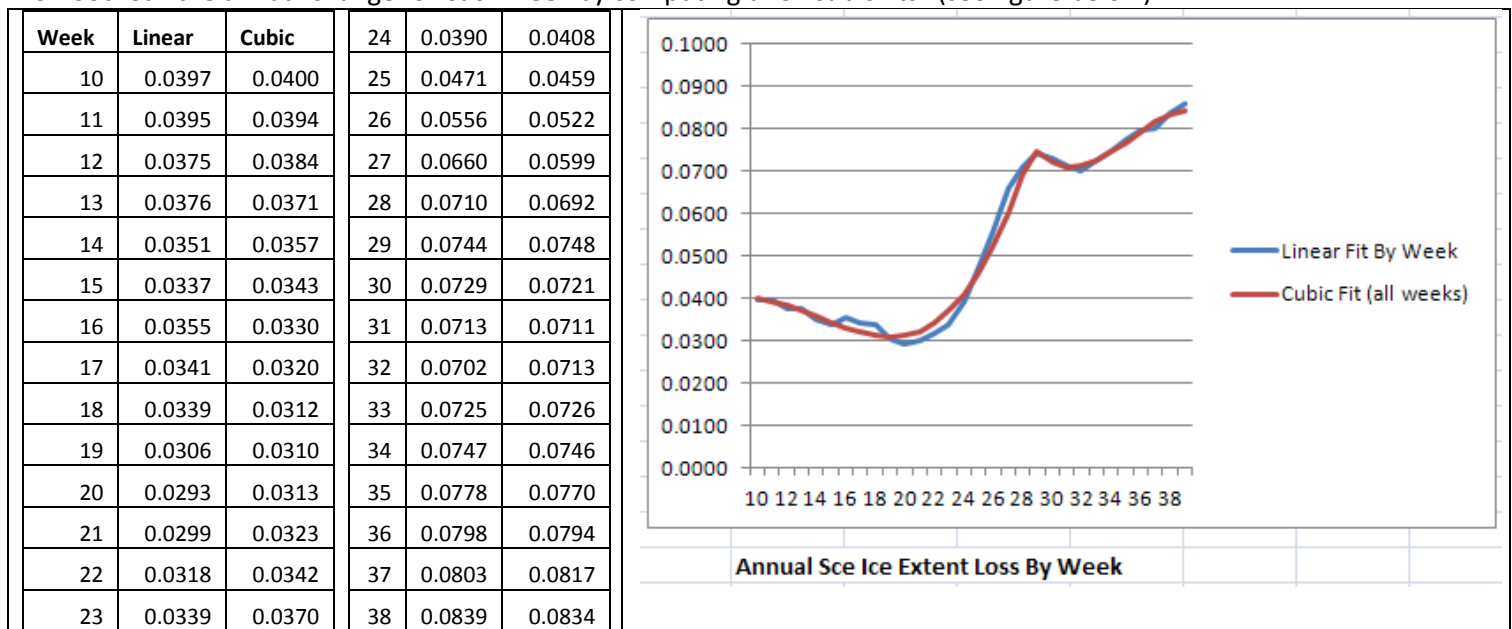
Figure __ - Historical Sea ice extent (for 1979) by week starting March 4th

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

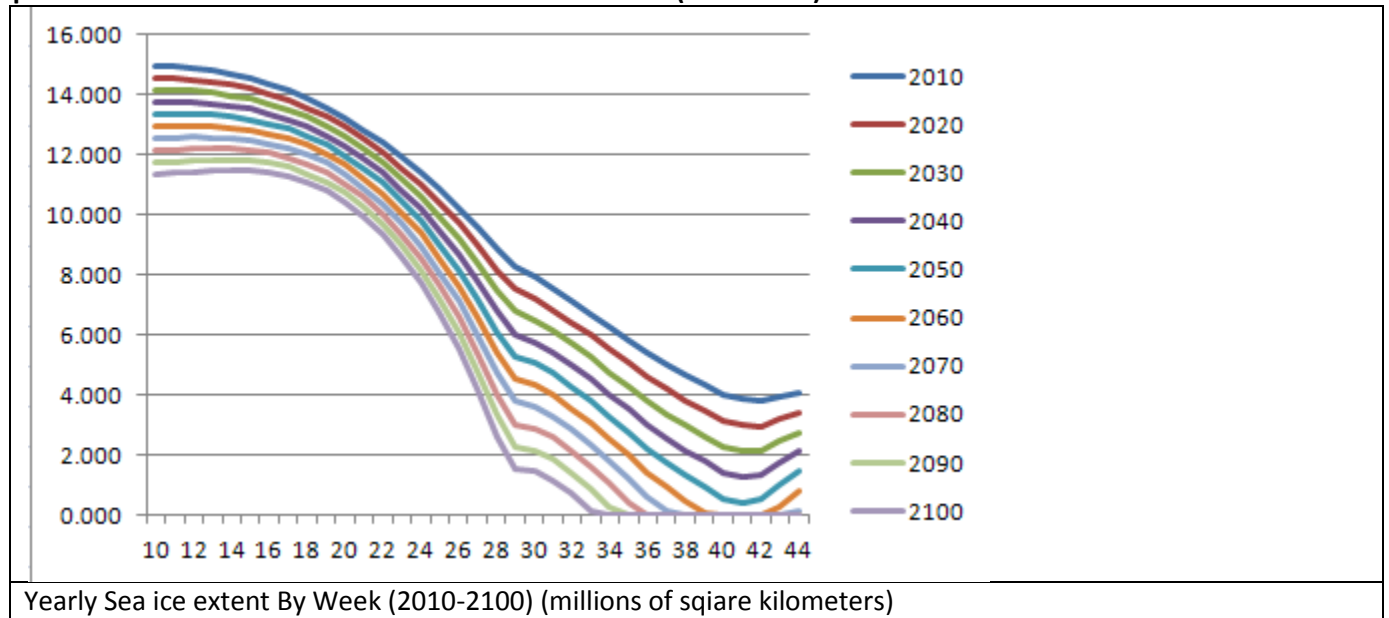


3. Compute the average loss of sea ice extent for each week

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



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

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:

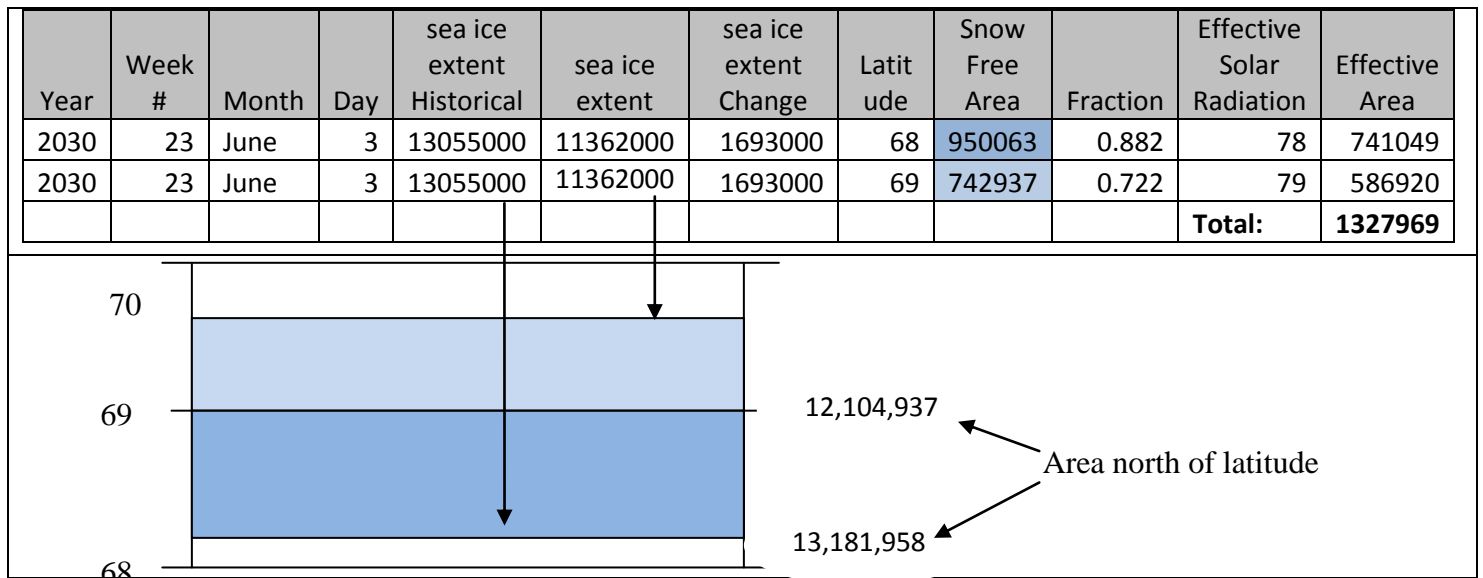


Figure 10 – Calculation of “Effective Area”

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 km² 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 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 Albedo Change”*((100-cloud cover pct)/100)*(3.4 W/m-2 / .01 albedo change)
- The “Equivalent CO2 PPM” = $275 * \text{POWER}(2.718, (\text{ERF}+2)/5.35) - 400$ (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)

Additional Background Information

Other estimates of albedo/radiative forcing changes

One estimate of the radiative forcing from a summer-time ice-free Arctic Ocean is about 0.3 W/m^2 .

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
Stephen R. Hudson Norwegian Polar Institute, Tromsø, Norway Submitted 11 February 2011; revised 18 April 2011; accepted 10 May 2011; published 16 August 2011
Abstract. A simple method for estimating the global radiative forcing caused by the sea-ice-albedo feedback in the Arctic is presented. It is based on observations of cloud cover, sea-ice concentration, and top-of-atmosphere broadband albedo. The method does not rely on any sort of climate model, making the assumptions and approximations clearly visible and understandable, and allowing them to be easily changed. Results show that the globally and annually averaged radiative forcing caused by the observed loss of sea ice in the Arctic between 1979 and 2007 is approximately 0.1 W m^{-2} ; a complete removal of Arctic sea ice results in a forcing of about 0.7 W m^{-2} , while a more realistic ice-free-summer scenario (no ice for one month, decreased ice at all other times of the year) results in a forcing of about 0.3 W m^{-2} , similar to present-day anthropogenic forcing caused by halocarbons. The potential for changes in cloud cover as a result of the changes in sea ice makes the evaluation of the actual forcing that may be realized quite uncertain, since such changes could overwhelm the forcing caused by the sea-ice loss itself, if the cloudiness increases in the summertime.
http://www.npolar.no/npcms/export/sites/np/en/people/stephen.hudson/Hudson11_AlbedoFeedback.pdf

However, recent observations determined that the change in radiative forcing from 1979-2011 (6.4 W/m^2) was about 0.18 W/m^2 for the Earth as a whole, and the ice melt in that time frame represents only a small fraction of the ice that is expected to have melted by 2100.

Arctic Albedo Observational determination of albedo decrease caused by vanishing Arctic sea ice Sept 2013 http://www.pnas.org/content/111/9/3322.full Significance
The Arctic sea ice retreat has been one of the most dramatic climate changes in recent decades. Nearly 50 y ago it was predicted that a darkening of the Arctic associated with disappearing ice would be a consequence of global warming. Using satellite measurements, this analysis directly quantifies how much the Arctic as viewed from space has darkened in response to the recent sea ice retreat. We find that this decline has caused $6.4 \pm 0.9 \text{ W/m}^2$ of radiative heating since 1979, considerably larger than expectations from models and recent less direct estimates. Averaged globally, this albedo change is equivalent to 25% of the direct forcing from CO_2 during the past 30 y.
<i>Note: The albedo from Arctic ice extent change 1979-2011 is the equivalent of about 14 PPM CO_2e. ($=278 * \text{POWER}(2.718, ((6.4 * 14 / 510) + 1.99) / 5.35) - 403$), which is equivalent to emissions of about 240 GTCO₂</i>

And another recent study shows that the increase in absorbed radiation from 2000 to 2014 was about 0.27 W/m^2 , or about the same as Hudson and projected for the year 2100.

NASA Satellites Measure Increase of Sun's Energy Absorbed in the Arctic (Dec. 17, 2014)
Since the year 2000, the rate of absorbed solar radiation in the Arctic in June, July and August has increased by five percent... When averaged over the entire Arctic Ocean, the increase in the rate of absorbed solar radiation is about 10 Watts per square meter (<i>about .27 Watts per square meter globally</i>).

<http://www.nasa.gov/press/goddard/2014/december/nasa-satellites-measure-increase-of-sun-s-energy-absorbed-in-the-arctic/#.VOdX7ubF9bl>

And another calculation shows results almost identical to this analysis – an ice-free Arctic Ocean in the summer time would “have an additional heating effect just as large as the heating effect of all human CO₂ and other greenhouse gasses to date” (but that does not include the effects of cloud cover). Given that the current radiative forcing is about 2.3 W/m² and that cloud cover is 60% in the summer, the radiative forcing would be about .92 W/m², almost the same radiative forcing projected by this analysis - .93 W/m²

Arctic Sea Ice: What, Why, and What Next

By Ramez Naam on September 21, 2012

Scientific American blog

The sunniest time of year in the northern hemisphere is the summer solstice, in late June, and the weeks preceding and following it. For several weeks the sun’s rays are at their most intense and the Arctic receives 24/7 sunlight, giving it a double whammy of heating. In fact, in June, July, and the latter half of May, the Arctic receives *more total solar energy per day* than regions at the equator do at any time of year.

Thus, every patch of dark ocean water revealed by melting ice in June, or May, or July, has a warming effect much larger – as much as five or six times larger – than the same change in ice coverage in September, when the ice hits its minimum today. The loss of ice in September is one thing. Loss of ice in June would have a far bigger impact on the region and the planet.

If the pace of the last decade were to continue on this recent pace – and didn’t keep on accelerating – June ice would be gone by 2026, exposing the dark waters of the Arctic Ocean to the year’s most intense influx of solar energy, which would then be captured as heat.

Peter Wadhams of the Global Oceans Physics Program at Cambridge calculates that the loss of the Arctic ice throughout the summer would have a warming effect roughly equivalent to all human activity to date. That is to say, with the ice gone in summer, the planet would have an additional heating effect just as large as the heating effect of all human CO₂ and other greenhouse gasses to date.

In other words, the complete meltdown of the Arctic could roughly double the rate of warming of the planet as a whole.

There are important caveats and uncertainties to that analysis. First, Wadhams doesn’t take into account the effect of clouds. Darker waters absorb more energy from sunlight only if the sunlight reaches them. Cloud cover in the Arctic – something which may increase as rising temperatures enable Arctic air to carry more moisture – may reflect sunlight back into space before it ever touches the water, thus reducing the warming effect of ice melt.

<http://blogs.scientificamerican.com/guest-blog/arctic-sea-ice-what-why-and-what-next/>

The central role of diminishing sea ice in recent Arctic temperature amplification

James A. Screen & Ian Simmonds

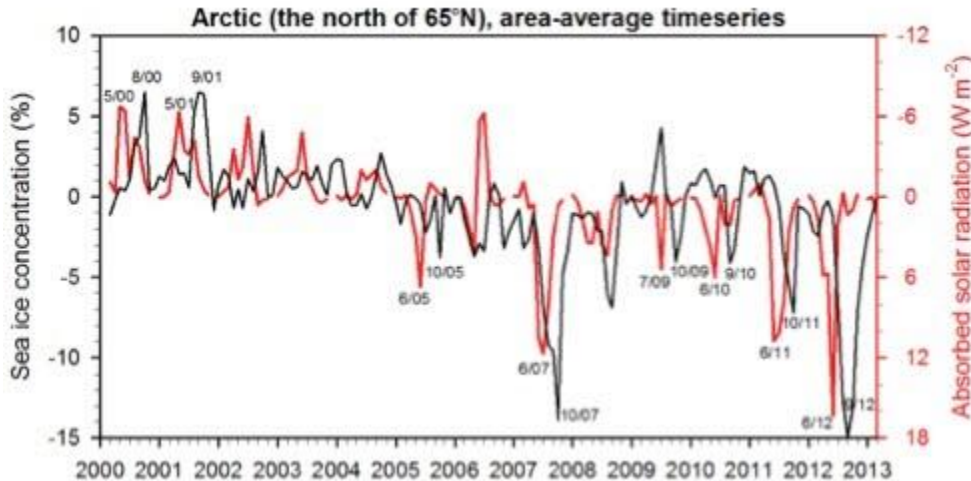
Nature. 2010 Apr 29 (<http://www.nature.com/nature/journal/v464/n7293/full/nature09051.html>)

Abstract

The rise in Arctic near-surface air temperatures has been almost twice as large as the global average in recent decades—a feature known as 'Arctic amplification'. Increased concentrations of atmospheric greenhouse gases have driven Arctic and global average warming; however, the underlying causes of Arctic amplification remain uncertain. The roles of reductions in snow and sea ice cover and changes in atmospheric and oceanic circulation, cloud cover and water vapour

are still matters of debate. A better understanding of the processes responsible for the recent amplified warming is essential for assessing the likelihood, and impacts, of future rapid Arctic warming and sea ice loss. Here we show that the Arctic warming is strongest at the surface during most of the year and is primarily consistent with reductions in sea ice cover. Changes in cloud cover, in contrast, have not contributed strongly to recent warming. Increases in atmospheric water vapour content, partly in response to reduced sea ice cover, may have enhanced warming in the lower part of the atmosphere during summer and early autumn. We conclude that diminishing sea ice has had a leading role in recent Arctic temperature amplification. The findings reinforce suggestions that strong **positive ice-temperature feedbacks have emerged** in the Arctic, increasing the chances of further rapid warming and sea ice loss, and will probably affect polar ecosystems, ice-sheet mass balance and human activities in the Arctic.

(Uses data for 1989-2008)



Absorbed solar radiation at the top of the atmosphere (red) versus sea ice concentration (black) for the Arctic region between 2000 and 2013. Courtesy: Climate System Laboratory, Seoul, Korea

The record low in Arctic sea ice recorded in September 2012 when the sea ice extent dropped to just 3.41 million square kilometers was related to anomalously low cloud cover over the Arctic region in the early summer, according to new research.

Researchers have found that the low amounts of cloud in the early summer lead to low concentrations of sea ice in the late summer. This relationship between cloud cover and sea ice is so strong that it can explain up to 80 per cent of the variation in sea ice over as much as 60 per cent of the sea ice area.

Furthermore, computer climate models fail to capture the role of clouds in mediating the relationship between solar radiation absorbed at the top of the atmosphere in the early summer and Arctic sea ice concentrations in the late summer, according to the research published in the *Journal of Geophysical Research Atmospheres*.

<http://www.reportingclimatescience.com/news-stories/article/high-cloud-levels-drive-low-arctic-sea-ice.html>

Low cloud cover in winter can lead to more summer ice

This process is known as the cloud radiative effect, or cloud forcing. It is because of this effect, Key said, that clouds warm the Earth's surface at night, and, likewise, "if you don't have clouds, most of that longwave radiation just escapes to space and the surface of the Earth cools."

Liu and Key were not dealing with a small change in cloud cover, but up to 20 percent less cloud cover than average.

"That's a big difference, especially in the coldest part of the winter," said Key. "That turns into a lot of cooling, and more ice growth."

The scientists estimated that in an area of 20 percent less cloud cover, ice could grow 45 centimeters more in two

months. - See more at: <http://www.ssec.wisc.edu/news/articles/6621#sthash.hxZOykeg.dpuf>

<http://www.ssec.wisc.edu/news/articles/6621>

<http://www.carbonbrief.org/blog/2015/02/aerosols-dampen-pace-of-arctic-warming-for-now-say-scientists/>

Aerosols dampen pace of Arctic warming for now, say scientists

As the Earth warms under increasing greenhouse gas emissions, temperatures have risen more quickly in the Arctic than the rest of the world. But particles emitted as fossil fuels are burned mask a lot of that warming. Without them, the temperature rise in the Arctic would be more than double what we've seen in the past century, a new study finds.