The Expected Albedo Change in the Year 2100 Due to the Reduced Northern Hemisphere Snow Cover Extent

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

Abstract

The reduced snow cover extent in the Northern Hemisphere 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 0.10° C to the Earth's current 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

The calculation was done in the following steps:

1. Adjust the weekly snow cover extent (SCE) data (for 1972-2015) to remove the area of permanent snow cover
2. Calculate rough weekly values for both the 1970 snow cover extent and for the average SCE loss from a linear fit of the adjusted snow cover extent and "smooth" these "rough" values to provide the data for the analysis
3. Calculate weekly decadal snow cover extents for 1970- and use the 1970 values as the "historical SCE" for the analysis
4. Estimate the land area per degree latitude in the Northern Hemisphere for 45° N to 70° N
5. 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
6. For each decade and each week, determine the "effective area" of the change in SCE by estimating the latitude where the change occurred and multiplying the corresponding "percent effective solar radiation" by the change in SCE
7. For each decade, sum the "effective areas" of the change in SCE and calculate the expected albedo change for the entire year.

Background

In the Northern Hemisphere winter, snow covers large parts of North America, Europe, Asia, and Greenland (see Figure 1). In addition, the snow cover extent (SCE) varies considerably during the year (see Figure 2). There is not a lot of data on the historical snow cover extent prior to 1968 but by examining the available data for SCE after 1920 (see Figure 3), a reasonable assumption is that the SCE, while quite variable from year to year, shows very little overall change from 1920 to 1970, at which point the SCE begins to decline. In addition, a weekly set of snow cover extent data from 1972 to 2015[4] enables the analysis of SCE trends after 1970: "[T]rend analysis results of the updated snowcover extent (SCE) series have been used to show that the NH spring snow cover has undergone significant reductions over the past 90 years and that the rate of decrease has accelerated over the past 40 years. In particular, the SCE has been reduced by 0.8 × 106 km2/decade (7% in March and 11% in April and very likely between 4.5 and 9.5% in March and between 8.5 and 13.5% in April) for the period 1970–2010 [(see Figure 4)]… Spring (March, April, and May) snow-covered areas have been declining at a rate that is even greater than predicted by the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model [(see Figure 5)]" [1].

(The "Analysis" section starts on Page 6 below - after the following five figures.)

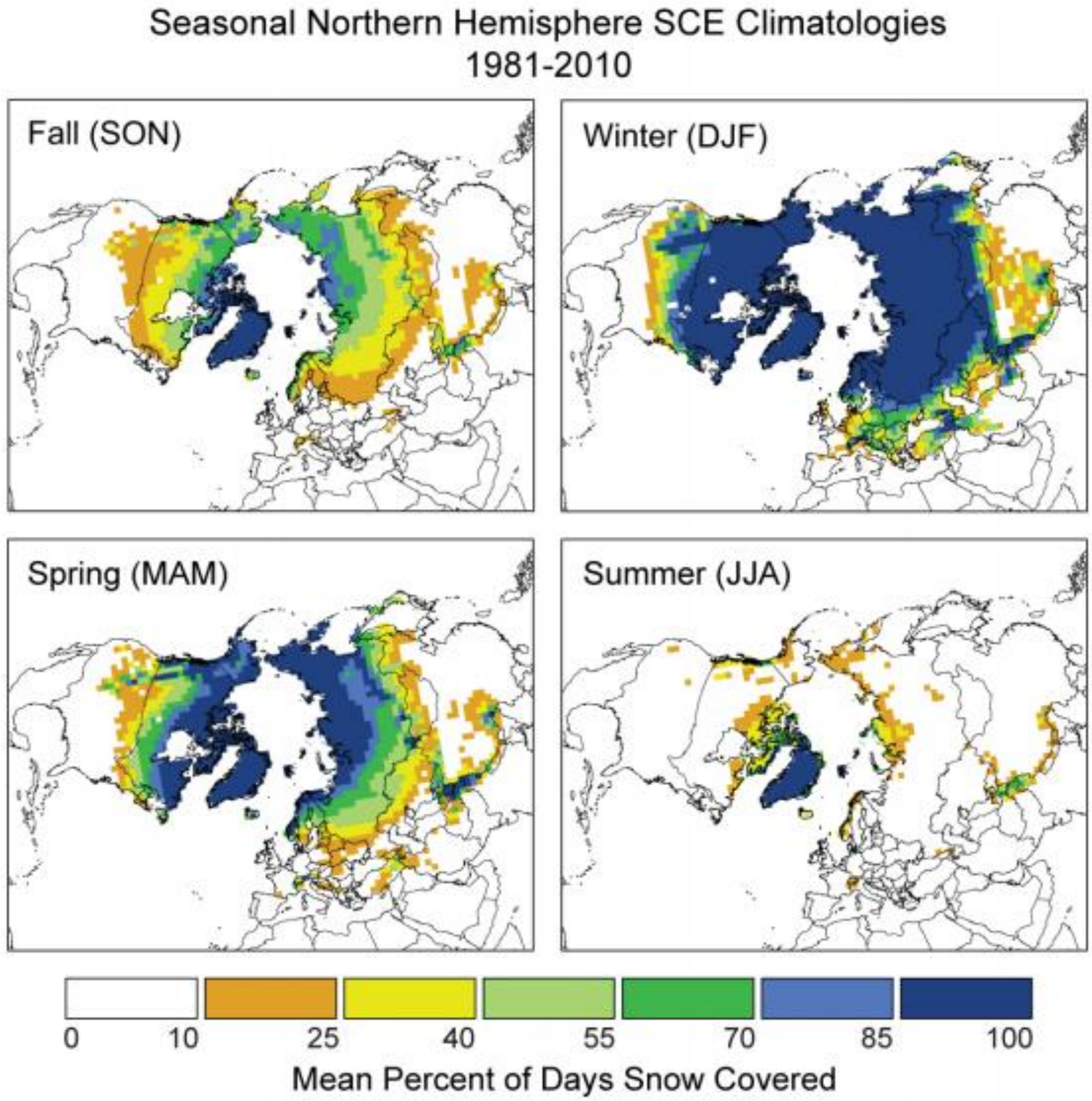
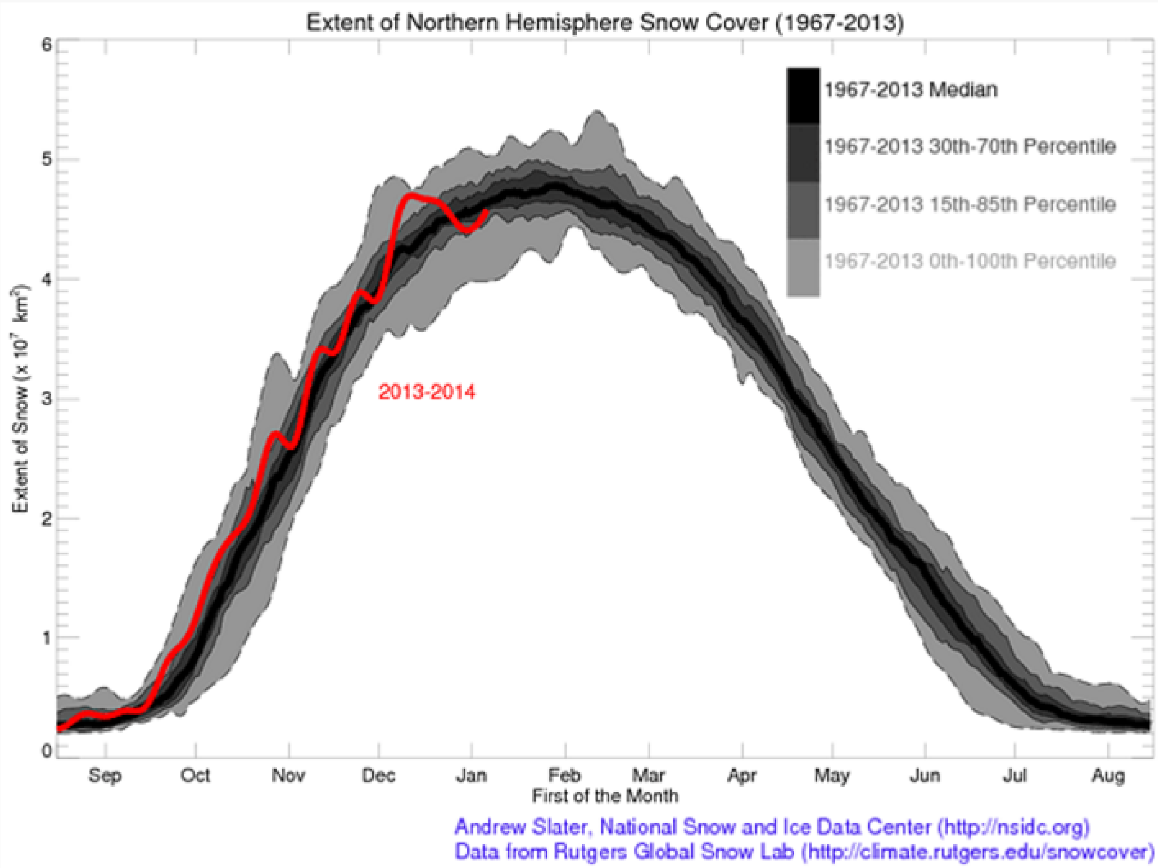


Figure 2. Mean spatial distribution of seasonal SCE over Northern Hemisphere lands. Each season is calculated using 3-month means. These maps illustrate seasonal variability, with maximum mean SCE occurring in winter. The data period used to calculate means spans the period from January 1981 to December 2010.

Figure 1 – Snow Cover Extent in the Northern Hemisphere[2]



Annual Cycle of Northern Hemisphere snow cover extent: This graph shows the annual cycle of snow cover, from September through August, for the years 1967-2013. Median extent appears in black. Greater ranges of extent variation appear in lighter shades of gray, with the entire range of extents appearing in the lightest shade. Snow cover extent for September 2013 through January 2014 appears as a red line. In the early 2013-2014 winter, Northern Hemisphere snow extent rose well above the 1967-2013 median before falling slightly below it, but did not fall outside the 1967-2013 range. Image by Andrew Slater, National Snow and Ice Data Center, University of Colorado, Boulder, based on data from the Rutgers Snow Lab.

Figure 2 – Annual Cycle of Northern Hemisphere Snow Cover Extent[3]

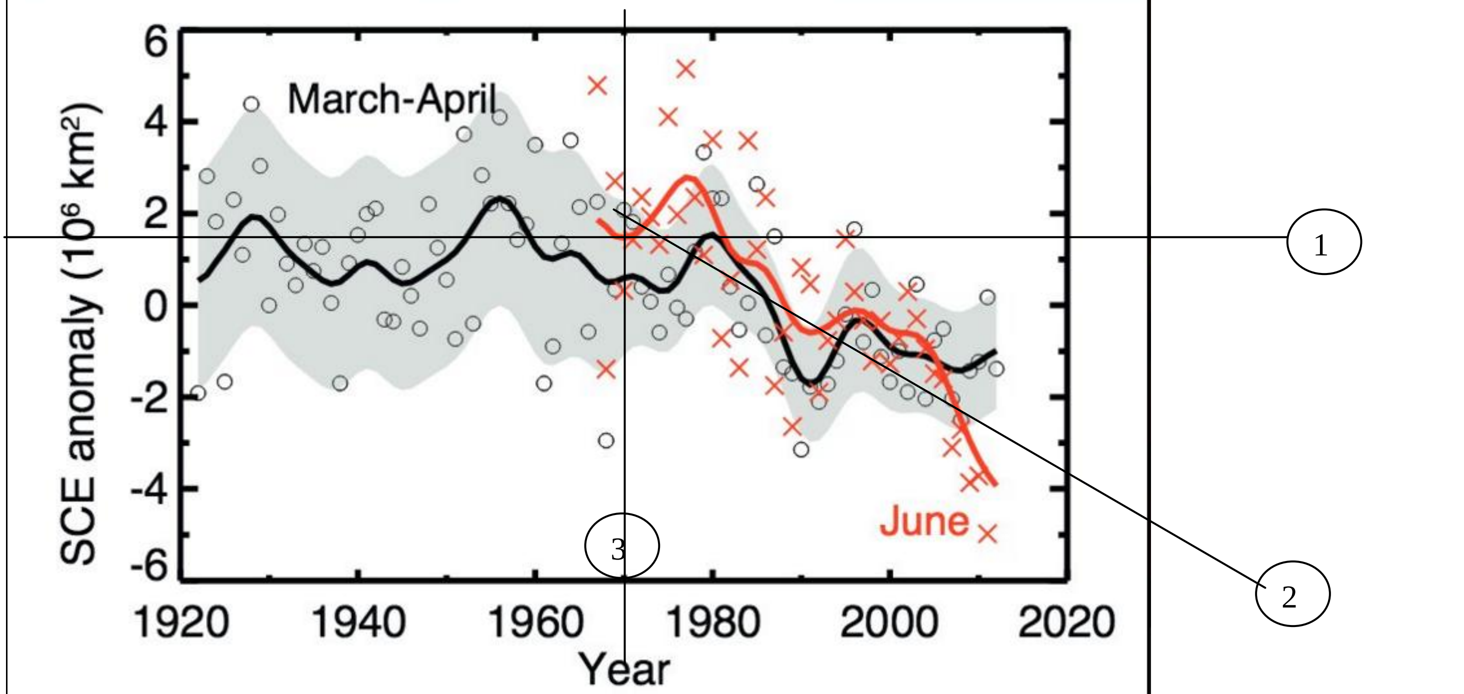


Figure 4.19 | March–April NH snow cover extent (SCE, circles) over the period of available data, filtered with a 13-term smoother and with shading indicating the 95% confidence interval; and June SCE (red crosses, from satellite data alone), also filtered with a 13-term smoother. The width of the smoothed 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 3 – Changes in the snow cover extent since 1920[4]

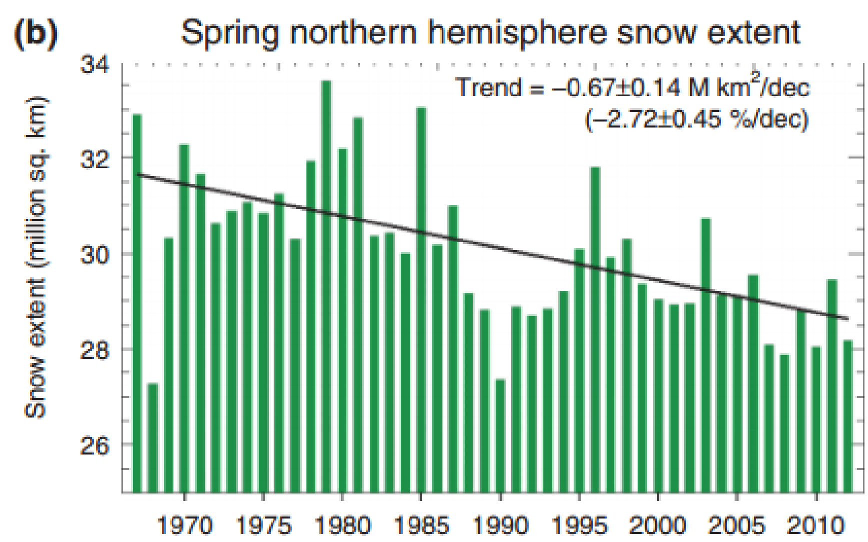


Figure 4 – Trends in NH Spring Snow Cover Extent[6]

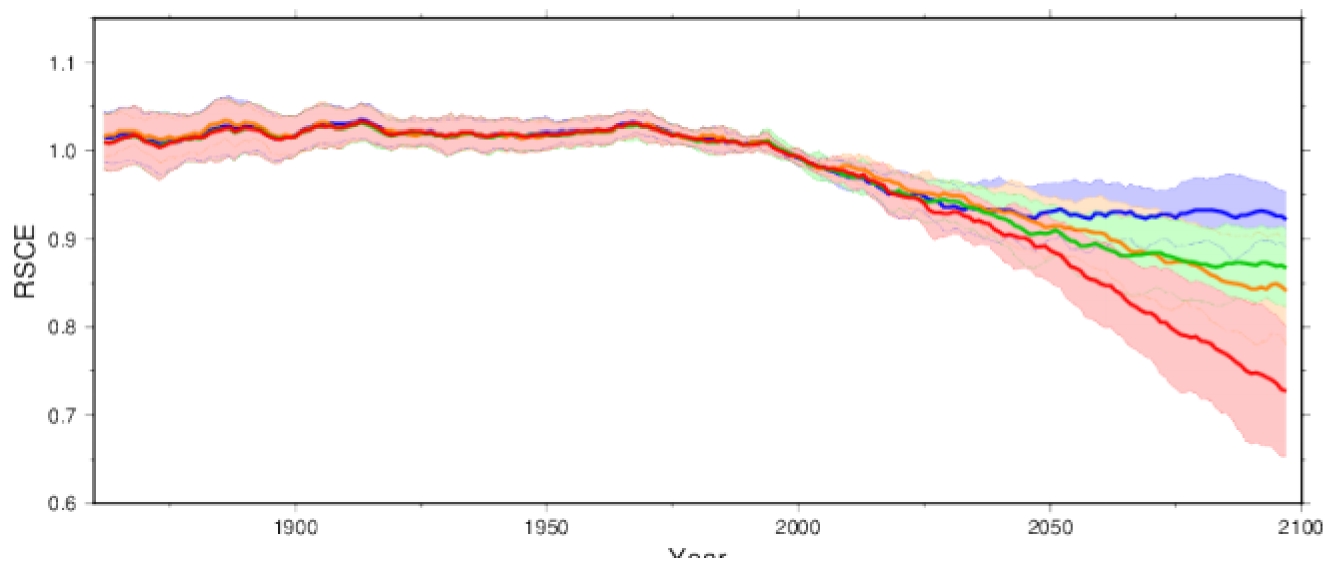


Fig. 7. Projected NH March–April average seasonal snow cover extent (RSCE, relative to the 1986–2005 reference period) for the different RCP scenarios (blue: RCP2.6; green: RCP4.5; yellow: RCP6.0; red: RCP8.5), multi-model average over all available models for each scenario. The 5-yr running average ensemble mean is taken for each individual model before the multi-model average is calculated. Intermodel spread is represented as plus or minus one standard deviation from the multi-model mean.

Figure 5 – CMIP5 – Projected NH March–April Average Snow Cover Extent[7]

Analysis

The following analysis uses the “post 1971” snow cover extent data[5] to develop a “back-of-the-envelop” calculation to estimate the magnitude of impact of the albedo change this century. The following assumptions were made when performing the analysis:

1. Any snow cover extent can be represented as occupying all of the land north of the latitude for which the land area matches snow cover extent
2. The “relative albedo” of a square kilometer of land 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 snow cover extent will be linear and will follow the same trajectory as it did from 1972 to 2015. (The actual decline is apt to be exponential, so this analysis probably underestimates the change for 2100.)

The data was analyzed as follows:

1. Adjust the weekly snow cover extent (SCE) data (for 1972-2015) to remove the area of permanent snow cover

The weekly snow cover extent is taken from the Rutgers University “Global Snow Lab” Web site[5]. Because of the glaciers in Greenland, Alaska, etc., there is a minimum amount of land that the snow will always cover. Greenland is about 2.166 m km^2 and the minimum snow cover extent since 1967 was about 2.027 m km^2 (for a week in August 1968). The most recent minimum snow cover extent was about 2.063 m km^2 (for a week in July 2012). So a reasonable minimum snow cover extent for the rest of the century is about 2.0 m km^2. (The advantages of adjusting the SCE are that the SCE decline can be measured as a percentage of the potential area that can become snow free and that the adjusted SCE will reach 0 for some months.)

Week#			1972	1973	1974	Week#			1972	1973	1974
14	Apr	1	36721023	36995784	34591752	14	Apr	1	34721023	34995784	32591752
15		8	32153818	34333488	31430048	15		8	30153818	32333488	29430048
16		15	27343230	31074989	30302116	16		15	25343230	29074989	28302116
17		23	25716885	23242354	27191135	17		23	23716885	21242354	25191135
18		29	24290300	23385872	26301453	18		29	22290300	21385872	24301453
19	May	6	21471274	22912852	27016525	19	May	6	19471274	20912852	25016525
20		13	15529896	22198314	22007073	20		13	13529896	20198314	20007073
21		20	17794150	19341261	20695474	21		20	15794150	17341261	18695474
22		27	16781787	13853751	17438058	22		27	14781787	11853751	15438058
23	June	3	13555127	12725527	13514928	23	June	3	11555127	10725527	11514928
24		10	10882870	13538212	14850954	24		10	8882870	11538212	12850954
25		17	7686018	10662906	8570264	25		17	5686018	8662906	6570264
Snow cover extent by year and week (km^2)[5]						Adjusted Snow cover extent by year and week (km^2)					

Table 1 - A Subset of the SCE Data Showing the Adjusted Values

2. Calculate rough weekly values for both the 1970 snow cover extent and for the average SCE loss from a linear fit of the adjusted snow cover extent

Since there is weekly SCE data from 1972 through 2015[5], that data can be used to estimate both the historical SCE (based on the expected values for 1970) and the average decline in the SCE since 1970 by determining the best "linear fit" for the weekly SCE from 1972 to 2015. Both values can then be "smoothed" to provide that data needed for the analysis (see Figures 5 and 6).

Week#	Raw	Smoothed
8	43001000	43818465
9	42001600	42457605
10	41229300	40907825
11	40086400	39189832
12	38052000	37324334
13	35723500	35332035
14	33742400	33233643
15	30955500	31049864
16	28626600	28801404
17	25796400	26508970
18	23606700	24193268
19	21552600	21875005
20	18755100	19574887
21	17501500	17313620
22	15559600	15111911
23	13735500	12990467
24	11470700	10969993
25	8796190	9071196
26	6751690	7314783
27	4874840	5721460
28	3640590	4311933
29	2792070	3106909
30	2348840	2127095
31	2321560	1393196
32	1840270	925919
33	1586050	745970
34	1518710	874057
35	1568820	1330885
36	1810570	2137160
37	2563740	3313590
38	3805070	4880880
39	6395770	6859738
40	9506240	9270869
41	11982900	12134979
42	16127300	15472776

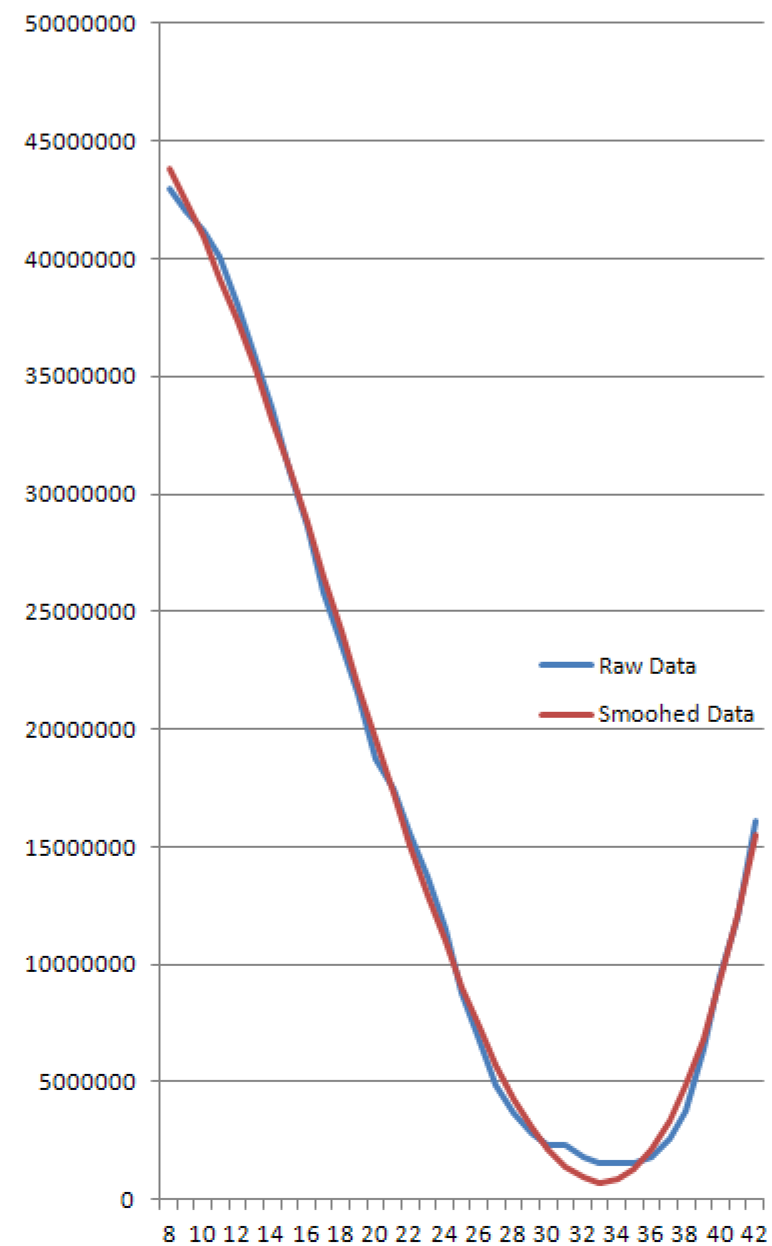


Figure 6 – Weekly Snow Cover Extents – the "Y" intercept for 1972, which is then used to specify the historical SCE

Week#	Raw	Smoothed
10	32312	39306
11	49697	39130
12	45039	40160
13	42861	42514
14	33601	46311
15	39739	51669
16	74214	58708
17	62467	67546
18	90599	78301
19	98097	91093
20	85074	106039
21	129359	123259
22	142953	142871
23	165821	164994
24	156476	147650
25	124679	126231
26	111085	107419
27	94841	90993
28	69077	76733
29	57223	64420
30	49140	53833
31	52474	44753
32	39063	36959
33	32410	30231
34	26286	24349
35	21240	19093
36	12389	14243
37	7075	9579
38	-1290	4881
39	5166	-71

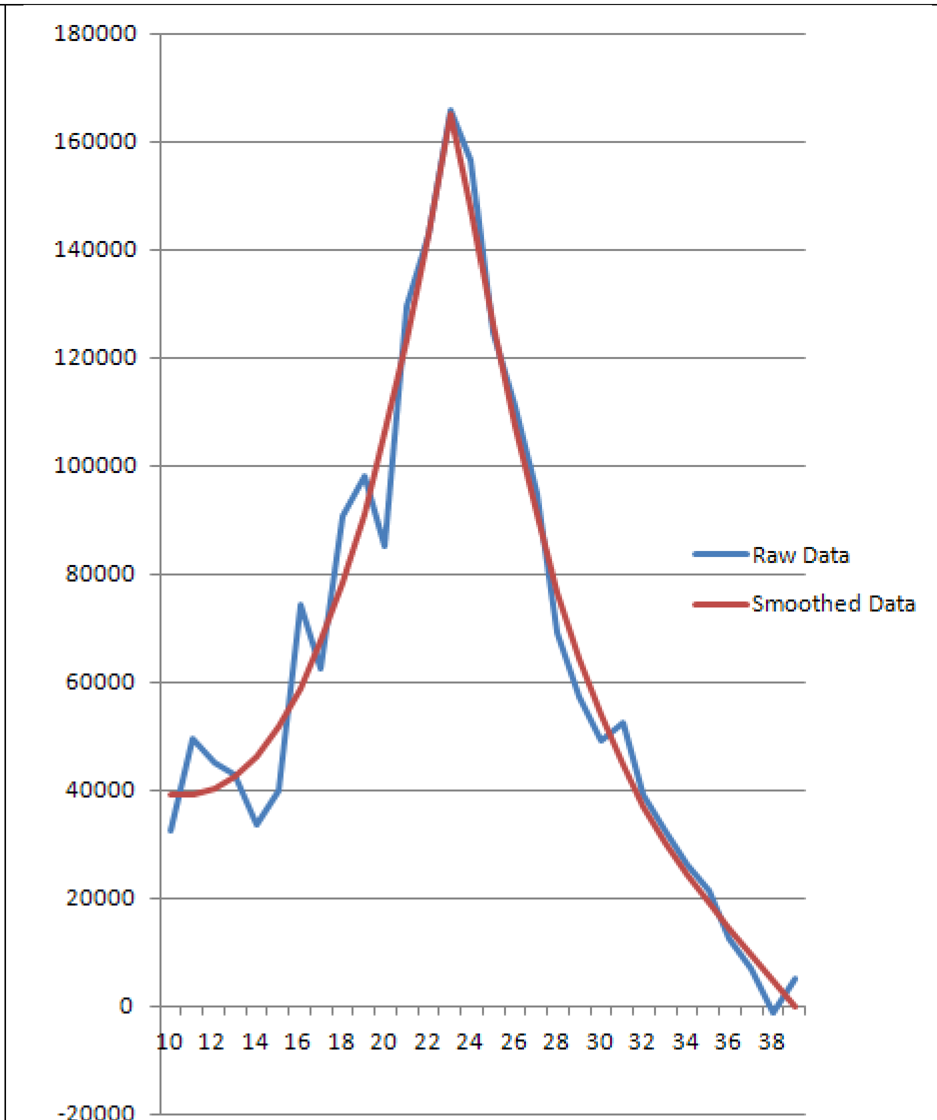
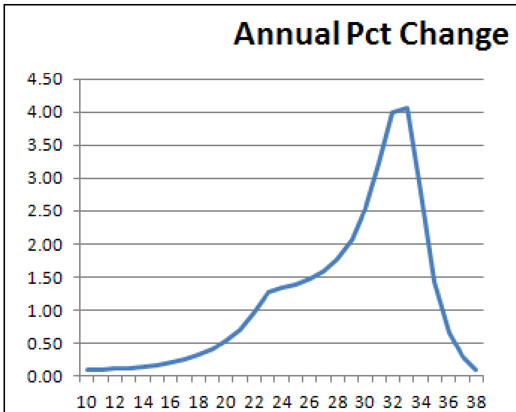


Figure 7 – Weekly Snow Cover Loss – the “slope” for each week, which is then used to specify the snow loss per year for each week



Note: the “bump” at week 23 occurs because the peak week of SCE change (week 23) does not coincide with the week of minimum SCE (week 33)

Figure 8 – Annual Percent Change in the Snow Cover Extent

3. Calculate weekly decadal snow cover extents for 1970-2100

Based on the "smoothed" values derived in Step 2 above, calculate the SCE for 1970 ("Historical") through 2100 (assume a linear decline of the value from Figure 7 from the starting value in Figure 6, with the calculated value never going below zero).

Wk			1970	1980	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
10	Mar	4	40.9	40.5	40.1	39.7	39.3	38.9	38.5	38.2	37.8	37.4	37.0	36.6	36.2	35.8
11		11	39.2	38.8	38.4	38.0	37.6	37.2	36.8	36.5	36.1	35.7	35.3	34.9	34.5	34.1
12		18	37.3	36.9	36.5	36.1	35.7	35.3	34.9	34.5	34.1	33.7	33.3	32.9	32.5	32.1
13		25	35.3	34.9	34.5	34.1	33.6	33.2	32.8	32.4	31.9	31.5	31.1	30.7	30.2	29.8
14	Apr	1	33.2	32.8	32.3	31.8	31.4	30.9	30.5	30.0	29.5	29.1	28.6	28.1	27.7	27.2
15		8	31.0	30.5	30.0	29.5	29.0	28.5	27.9	27.4	26.9	26.4	25.9	25.4	24.8	24.3
16		15	28.8	28.2	27.6	27.0	26.5	25.9	25.3	24.7	24.1	23.5	22.9	22.3	21.8	21.2
17		23	26.5	25.8	25.2	24.5	23.8	23.1	22.5	21.8	21.1	20.4	19.8	19.1	18.4	17.7
18		29	24.2	23.4	22.6	21.8	21.1	20.3	19.5	18.7	17.9	17.1	16.4	15.6	14.8	14.0
19	May	6	21.9	21.0	20.1	19.1	18.2	17.3	16.4	15.5	14.6	13.7	12.8	11.9	10.9	10.0
20		13	19.6	18.5	17.5	16.4	15.3	14.3	13.2	12.2	11.1	10.0	9.0	7.9	6.9	5.8
21		20	17.3	16.1	14.8	13.6	12.4	11.2	9.9	8.7	7.5	6.2	5.0	3.8	2.5	1.3
22		27	15.1	13.7	12.3	10.8	9.4	8.0	6.5	5.1	3.7	2.3	0.8	0.0	0.0	0.0
23	June	3	13.0	11.3	9.7	8.0	6.4	4.7	3.1	1.4	0.0	0.0	0.0	0.0	0.0	0.0
24		10	11.0	9.5	8.0	6.5	5.1	3.6	2.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0
25		17	9.1	7.8	6.5	5.3	4.0	2.8	1.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0
26		24	7.3	6.2	5.2	4.1	3.0	1.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	Jul	1	5.7	4.8	3.9	3.0	2.1	1.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28		8	4.3	3.5	2.8	2.0	1.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29		15	3.1	2.5	1.8	1.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30		23	2.1	1.6	1.1	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31		29	1.4	0.9	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	Aug	5	0.9	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33		12	0.7	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34		19	0.9	0.6	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35		26	1.3	1.1	0.9	0.8	0.6	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	Sept	2	2.1	2.0	1.9	1.7	1.6	1.4	1.3	1.1	1.0	0.9	0.7	0.6	0.4	0.3
37		9	3.3	3.2	3.1	3.0	2.9	2.8	2.7	2.6	2.5	2.5	2.4	2.3	2.2	2.1
38		16	4.9	4.8	4.8	4.7	4.7	4.6	4.6	4.5	4.5	4.4	4.4	4.3	4.3	4.2
39		23	6.9	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.7	6.7	6.7

Table 2 - Projected Snow Cover Extent (millions of square kilometers –used here so that all of the data can be displayed)

4. Estimate the land area per degree latitude in the Northern Hemisphere for 45° N to 70° 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)

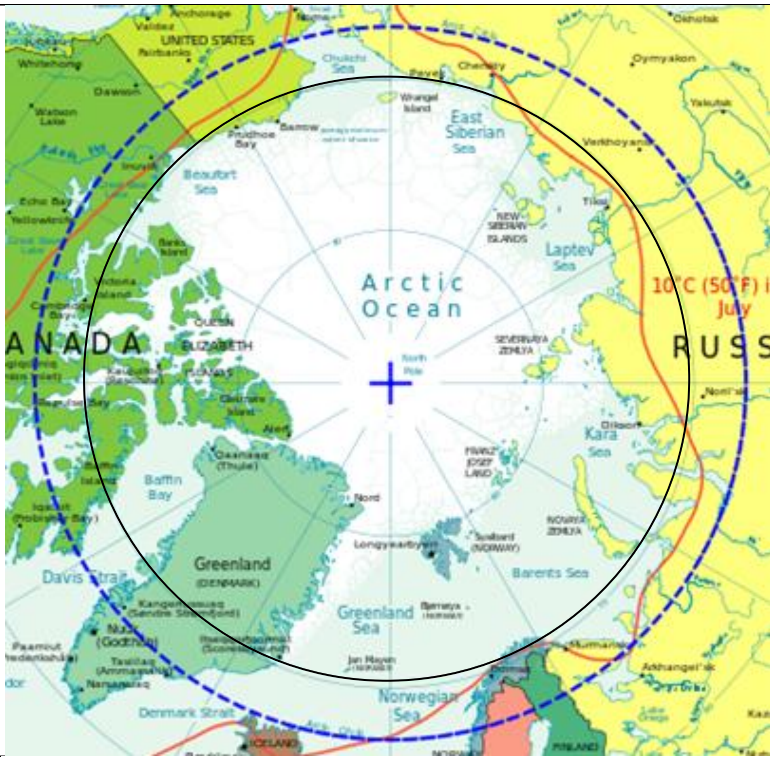


Figure 9 – Map of the Arctic Region Showing the Arctic Circle (dashed line) and 70° N (solid black line)

Latitude	Circle Length	Two Thirds of Circle Length*	Land Area Per Degree	Land Area North Of Latitude
45	28337	18891	2,096,915	42,328,186
46	27838	18559	2,059,999	40,231,272
47	27330	18220	2,022,456	38,171,273
48	26815	17877	1,984,297	36,148,817
49	26291	17527	1,945,533	34,164,520
50	25759	17173	1,906,177	32,218,987
51	25219	16813	1,866,240	30,312,810
52	24672	16448	1,825,735	28,446,569
53	24117	16078	1,784,673	26,620,835
54	23555	15703	1,743,068	24,836,161
55	22986	15324	1,700,932	23,093,093
56	22409	14939	1,658,278	21,392,160
57	21826	14551	1,615,119	19,733,882

Latitude	Circle Length	Two Thirds of Circle Length*	Land Area Per Degree	Land Area North Of Latitude
58	21236	14157	1,571,468	18,118,763
59	20640	13760	1,527,338	16,547,296
60	20037	13358	1,482,743	15,019,958
61	19428	12952	1,437,696	13,537,215
62	18814	12542	1,392,211	12,099,520
63	18193	12129	1,346,302	10,707,309
64	17567	11712	1,299,983	9,361,007
65	16936	11291	1,253,268	8,061,024
66	16300	16300	1,809,257	6,807,756
67	15658	15658	1,738,061	4,998,499
68	15012	15012	1,666,335	3,260,438
69	14361	14361	1,594,102	1,594,102
70	13706	13706	0	0

*Not used for area calcs for 66 degrees to 70 degrees

Table 3 - Total land area north of each degree of latitude

5. 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

Daily solar radiation

Degrees N	4/1	8	15	22	29
50	263	278	291	303	315
51	261	276	290	302	314
52	259	274	288	301	314
53	256	272	286	300	313
54	253	269	285	299	312
55	250	267	283	298	312
56	247	265	281	297	311
57	244	262	279	295	310
58	241	260	277	294	309
59	238	257	275	292	308
60	235	254	273	291	307

Percent effective solar radiation

Degrees N	4/1	8	15	22	29
50	53	56	59	61	64
51	53	56	59	61	64
52	53	56	58	61	64
53	52	55	58	61	63
54	51	55	58	61	63
55	51	54	57	60	63
56	50	54	57	60	63
57	49	53	57	60	63
58	49	53	56	60	63
59	48	52	56	59	62
60	48	52	55	59	62

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

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

The first step is to determine the southern-most latitude that includes the historical SCE. Based on the change in area of SCE, 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 April 15, 1980 is as follows:

Year	Week #	Month	Day	SCE Historical	SCE	SCE Change	Latitude	Snow Free Area	Fraction	Effective Solar Radiation	Effective Area
1980	16	Apr	15	28801404	28214324	587080	51	354835	0.19	59	209353
1980	16	Apr	15	28801404	28214324	587080	52	232245	0.127	58	134702
										Total:	**344055**

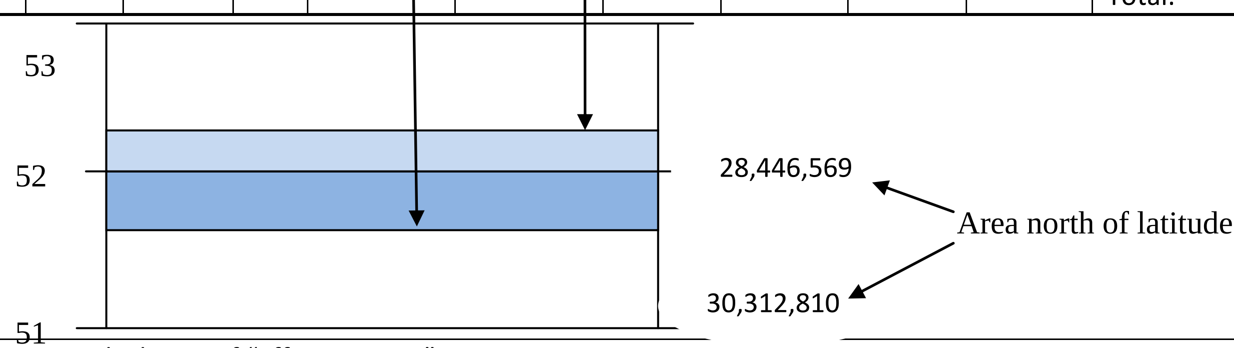


Figure 10 – Calculation of "Effective Area"

7. For each decade, sum the “effective areas” of the change in SCE and calculate the expected albedo change for the entire year.

Given these parameters:

0.9	Albedo of snow
0.25	Albedo of "Tundra"
0.65	Change in albedo
3.4	W/m-2 / .01 albedo change
510	million km^2 surface area for the Earth
17.3429	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 Em. (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	3.1
1980	0.26	0.25689	0.03	0.02	2.2	1.3	38	23	0.01	0.02
1990	0.52	0.51476	0.07	0.05	4.7	3.0	82	52	0.03	0.04
2000	0.78	0.76938	0.10	0.07	7.3	4.7	126	82	0.05	0.06
2010	1.02	1.01409	0.13	0.09	9.7	6.3	168	110	0.06	0.08
2020	1.26	1.24905	0.16	0.11	12.1	7.9	209	137	0.08	0.09
2030	1.49	1.47248	0.19	0.13	14.3	9.4	249	163	0.09	0.11
2040	1.69	1.67635	0.22	0.15	16.4	10.8	285	186	0.11	0.13
2050	1.85	1.82930	0.24	0.16	18.0	11.8	312	204	0.12	0.14
2060	1.97	1.94732	0.26	0.17	19.2	12.6	333	218	0.12	0.15
2070	2.09	2.06529	0.27	0.18	20.4	13.4	354	232	0.13	0.16
2080	2.20	2.17436	0.29	0.19	21.5	14.1	374	245	0.14	0.17
2090	2.29	2.27181	0.30	0.20	22.5	14.8	391	256	0.15	0.17
2100	2.39	2.36934	0.31	0.21	23.6	15.4	409	268	0.15	0.18
3000	5.30	5.24771	0.69	0.46	54.6	35.5	946	615	0.35	0.42

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)

Footnotes

1	WIREs Clim Change 2014, 5:389–409. doi: 10.1002/wcc.277
2	http://www.earth-syst-sci-data.net/7/137/2015/essd-7-137-2015.pdf
3	https://nsidc.org/cryosphere/sotc/snow_extent.html
4	https://twitter.com/MichaelEMann/status/704345939331440642/photo/1
5	http://climate.rutgers.edu/snowcover/table_area.php?ui_set=0&ui_sort=0 Robinson, David A., Estilow, Thomas W., and NOAA CDR Program (2012):NOAA Climate Date Record (CDR) of Northern Hemisphere (NH) Snow Cover Extent (SCE), Version 1. [Weekly data]. NOAA National Climatic Data Center. doi:10.7289/V5N014G9 [3/1/2016].
6	http://onlinelibrary.wiley.com/doi/10.1002/wcc.277/pdf WIREs Clim Change 2014, 5:389–409. doi: 10.1002/wcc.277
7	http://www.the-cryosphere.net/7/67/2013/tc-7-67-2013.pdf
8	http://rredc.nrel.gov/solar/codesandalgorithms/links.html Solar position using VBA translation of NOAA's functions. Solar radiation from Bird and Hulstrom's model. by Greg Pelletier Department of Ecology Olympia WA e-mail: gpel461@ecy.wa.gov Bird model direct radiation normal to the beam at the earth surface (W/m2)