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Trajectory Analysis of Black Carbon in the Arctic Region

By

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Abstract

Black carbon (BC) is a troubling particulate. Commonly known as soot, BC forms through the incomplete combustion of fossil fuels, biofuels, and biomass. It has a very low albedo compared to natural particulates making it a very efficient absorber of solar radiation. As BC is deposited on snow and ice, albedo is decreased - enhancing solar heating and increasing meltwater production. With rising air temperatures, melting rates of polar ice are increasing and are being enhanced by BC, leading to accelerated global sea level rise.

This study aimed to document sources and deposition areas of BC in the Arctic. Utilizing HySplit, an air trajectory model, patterns of BC trajectories are assessed. Spatial patterns of deposition are estimated from known sources and source regions predicted from known deposition locations through the use of backward trajectory. Atmospheric circulation transports BC from temperate regions into the Arctic. The strength and location of the polar front in relation to the North Atlantic Oscillation is a dominant controlling factor.

Preliminary results show reoccurring potential sources located in the Northeastern United States, Nova Scotia, Northern United Kingdom, and the Scandinavian Peninsula with large deposition events occurring within the first six months of the year.

Keywords: Arctic, Greenland, Black Carbon, BC, Albedo, Ice, Snow, Climate Change, Global Warming

Introduction

Global ice coverage has been steadily decreasing over the past 40 years (Vinnikov et al. 1999). Many observational and climate modeling studies have shown a trend towards decreasing ice in the Arctic due to warmer conditions. Rothrock et al. (1999) demonstrated that the perennial sea ice in the Arctic Ocean was 1 m thinner in the 1990's than it had been in two to four decades. Volume was calculated to be down by ~ 40% when compared to previous years. In his words, "The thinning is remarkable in that it has occurred in a major portion of the perennially ice-covered Arctic Ocean" (Rothrock et al. 1999).

While atmospheric CO_2 concentration is named the largest factor in global climate warming, black carbon (BC) also plays an important role in regions predominantly covered by snow and ice. BC is a particulate created by incomplete combustion of fossil fuels, biofuels and biomass (Jiao et al., 2014). Particle size can range from ~0.1 to 1 micron. Dependent on the size, the particulate can be transported long distance (~1000 km) and be deposited on snow and ice. Residence time of BC particles (< 1 um) in the atmosphere is up to two weeks while larger particles are deposited within a matter of days or until they encounter precipitation (Mahowald et al. 2011).

BC can create regional issues, such as localized warming of regional glaciers, when the particles are large, or global issues, such as polar warming, when the particle released is small enough to be transported long-range. BC transport into the Arctic is affected by the strength and location of the polar front in relation to the North Atlantic Oscillation (Wallace & Thompson, 2002; Koch & Hansen 2005). Aerosol transport into the Arctic is greatest during late winter and early spring. These large transport events are collectively known as Arctic haze (Barrie et al. 1986).

Once deposited on snow and ice, BC is very effective at increasing the absorption of solar radiation of the surrounding ice and snow particles. According to Hadley and Kirchstetter (2012), radiation transfer calculations for 10-100 ppb of BC in the cryosphere decreased albedo by 1-5%. Globally BC reduces albedo and creates a positive radiative climate forcing (Hadley & Kirchstetter 2012). Positive radiative climate forcing occurs when more solar radiation is incoming to a climate system, warming the system overall. Smaller particles are more effective at absorbing solar radiation. Radiation transfer calculations indicated that minute amounts of BC from 10–100 ppb decrease snow albedo by 1–5% (Hadley and Kirchsetter 2012). Natural sediment, dust, and other particulates are also present in snow

and ice. However, these other particulates are less effective in decreasing albedo than BC. BC is effective in absorbing solar energy across the entire light spectrum, where as other particulates are only effective at absorbing specific ranges within the solar radiation spectrum (Yang et al. 2009). BC's effectiveness in decreasing albedo makes it a larger concern to Arctic ice and snow.

Snow grain size is an important factor when calculating radiation transfer from BC to snow. As snow becomes older and begins to melt, the decrease in albedo caused by BC is amplified (Wiscombe and Warren, 1980). Snow grains characterized by effective optical radii, a simplified sphere used to calculate the optical properties of snow grains by radius size, (Reff) of 55, 65 and 110 µm were tested and demonstrated an increase in affinity for solar radiation by BC, lowering the albedo of the snow particles the BC was deposited on, as the grains increased in size (Figure 1). In Figure 1, snow grain radii increases from 1A to 1C. As the snow grain radii increases, the ability of BC to significantly lower the albedo of the snow particles also increases (Figure 1C). This means, as snow melts and begins to aggregate, or clump together, the ability of BC to lower the albedo of the snow increases, causing further and faster melting rates (Hadley and Kirchsetter 2012).

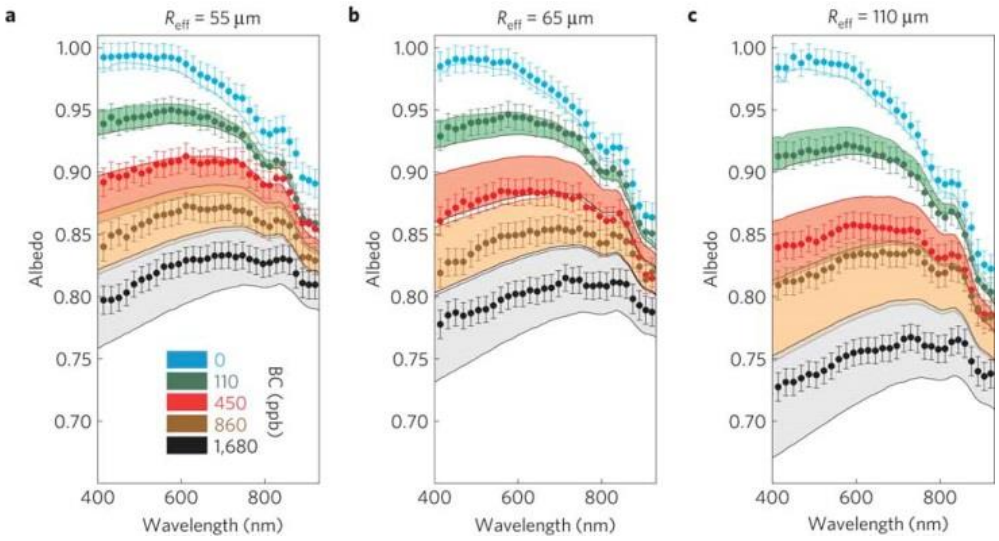

Figure 1 Effect of black carbon on different sizes of snow grains characterized by optical effective radii (Reff) of 55, 65 and 110. Hadley, Odelle and Kirchstetter, Thomas (2012)

The Russian Arctic has the highest levels of BC, largely due to biomass burning. Industrial sources play a role, but the Arctic as a whole has become cleaner since 1999 (Hegg et al. 2010). While there has been a reduction in emissions related to air pollution policies in

many nations worldwide (Novakov et al. 2003), the effect of emissions on snow and ice is being compounded by the rising temperatures due to other climate warming. Although industrial emissions from China have grown within the past 20 years, they have been shown to have a stronger local effect on snow and ice rather than long distance effects in the Arctic (Koch and Hansen 2005). Greenland has the lowest amount of BC in the Arctic with an average of 2 ppb on the ice sheet. However, during the summer season, BC levels increase to 20 to 30 ppb as the snow and ice begin to melt (Hadley and Kirchsetter 2012). These higher levels of BC enhance melt rates and lead to a larger reduction in snow and ice. Even though snow and ice can still appear to be clean to the human eye at 100 ppb, the increase in absorption of solar radiation is significant.

Previous studies using a variety of modeling systems have been performed to attempt to identify source areas of BC in the Arctic cryosphere. The 2014 AeroCom assessment of black carbon in the Arctic cryosphere was performed using the Community Earth System Model. A 2005 study by Koch and Hansen used the Goddard Institute for Space Studies ModelE to determine the distant origins of BC in the Arctic snow, sea ice and glacial coverage (Figure 2). Industrial BC emissions were centered in the temperate regions in the heavily populated post- and current-industrial regions (Figure 2). Biomass BC emissions were focused in the Southern hemisphere in developing regions of South America and the African continent (Figure 2).

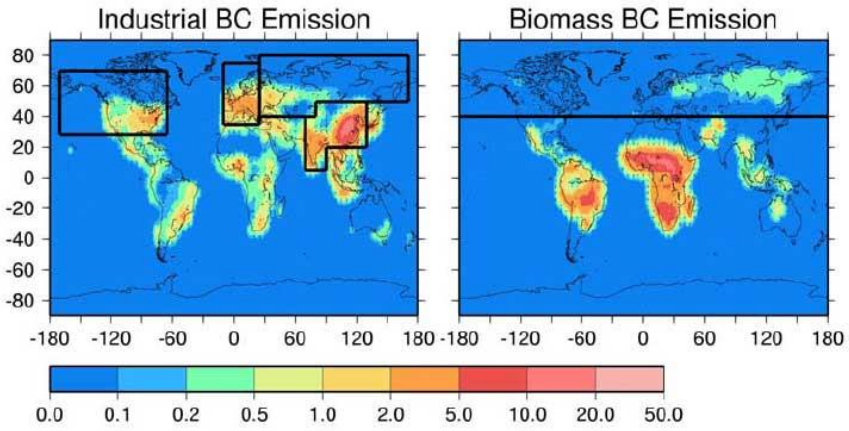

Figure 2 Black Carbon Emissions: Industrial and biomass black carbon emissions with boxed areas showing regions assumed in the model experiments. Credit: NASA/GISS

My work utilized the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HySplit), a computer model created by the National Oceanic and Atmospheric

Administration's (NOAA) Air Resources Lab (ARL) (Draxler & Rolph). HySplit calculates air parcel trajectories, dispersion, and deposition of atmospheric pollutants. In this study, I have utilized only the trajectory function of the HySplit model. The model was used to perform a backward trajectory of black carbon from one set location within the Arctic that has measurements of BC. By performing a backward trajectory from this point, one can identify areas of possible sources of BC. Meteorological data from the Global Data Assimilation System (GDAS) includes historical precipitation and wind data from which past trajectories can be calculated.

The location of BC measurements was 72.58 N, 38.48 W on the Greenland Ice Sheet. Greenland Summit Station was established by the National Science Foundation and the Danish Commission for Scientific Research. This station is part of the Earth System Laboratory (ESRL) Global Monitoring Division of NOAA which provides meteorological and observational data from the Summit Station online for use by the scientific community. This location was chosen for the amount of corresponding in situ data available for these areas.

Methodology

Datasets collected by previous studies were utilized for the meta-analysis. In situ measurements collected by Warren and Doherty (2008) were used to identify times of large deposition events on the Greenland Ice Sheet. Data collected centered around the Greenland Summit Station and nearby areas. Meteorological data from Greenland Summit Station was used to back-calculate the snowfall that occurred in the years 2006, 2007 and 2008. Snowfall records were matched with sampling from the vertical pit collection done by Warren and Doherty (2008). Their team collected 300 samples at 24 sites at different depths and in different seasons to look at seasonal variation and obtain a detailed vertical profile. Data collected from near the Greenland Summit Station site during the summer of 2008 was used. Data was collected from 12-800 m away from a road to make sure that background levels were not influenced. Sampling at 100 m can be well representative of the frequency of source distribution (Warren et al. 2008).

Utilizing the HySplit aerosol ready trajectory model, backward trajectories were run for a location in central Greenland. PC and web-based platforms were used with mapping images enabled. Location coordinates were set for 168-hour runs at 6-hour intervals. To match trajectories within field data gathered from previous studies, GDAS archived meteorological data from 2006, 2007 and 2008 was used. Within the HySplit settings, precipitation was enabled. Trajectories were run with a single trajectory protocol over a 12-month period for

2006, 2007 and 2008 to identify if trajectory patterns followed a seasonality or had a random variability of dispersion. Trajectories were saved as .PDF file format with end point plot with precipitation detail and coordinates enabled. Endpoint plot files were then used to overlay the four trajectories per month on one coordinate plot. This allowed for patterns to be more easily recognized within the trajectories. Trajectories were compared on a year and month basis to identify patterns of seasonality.

Results from the air trajectories provided latitude and longitude coordinates for the location of the trajectory at 6-hour intervals over the 168 hour period. Once the backward trajectories were collected, they were classified into three groups: 1. Trajectory originated over Greenland; 2. Trajectory originated over the ocean; and 3. Trajectory originated over a land mass. Trajectories that fell into category (1) were dismissed as potential sources of BC because of the lack of large industrial or biomass sources located within Greenland. While category (2) may have had emissions from marine shipping, it was dismissed due to the lack of major source possibilities. Category (3) was further divided into two subcategories: (a) The point of origin in populated area (b) The point of origin in the unpopulated region. Out of the two subcategories, category (b) was dismissed while subcategory (a) was further analyzed to determine if the altitude of the air mass at the origin was low (below 1000 m) or high (higher than 1000 m). Air trajectories that originated over a populated area on a land mass with wind currents originating close to the ground (1000 m or less) were determined to be likely areas of the BC source. With these trajectories identified, in situ data was analyzed to estimate when mass deposition events, events resulting in >10 ng of BC within the snow pack, occurred. The dates of mass deposition from in situ data was then compared to the dates of target trajectories to determine if the trajectories coincided with the deposition events. Trajectories that did coincide with deposition events were gathered and analyzed further for possible source attribution. Coordinates of the Air masses that originated with low altitude over populated land masses were mapped, and a search was done of nearby industrial processes using Google Earth. If industrial processes were readily found within a 50 km area, the source type and location was noted. Searches were also done knowing the time and date of the air mass origination to determine if large biomass sources (i.e. wildfires) may have been present in the area.

Annual wind roses were collected from the ESRL Global Monitoring Division of NOAA Greenland Summit Station data files for 2008. Meteorological data from Greenland Summit Station was used to generate annual wind roses for 2006 and 2007 in EXCEL. Wind roses were analyzed to determine mean annual wind direction and speed to provide a climatology of wind flow over the area.

Results

Over the course of the study, 177 backwards trajectories were run. Trajectories were run for every week totaling in 52.258 weeks per year for the years 2006, 2007, and 2008. 59 trajectories were run for 2006, 58 for 2007, and 60 for 2008. 63 trajectories fell into category 1 designation with 22 in 2006, 18 in 2007, and 23 in 2008 (Table 1). 59 trajectories were given a category 2 designation with 25 in 2006, 13 in 2007 and 21 in 2008 (Table 1). Category 3 designated trajectories totaled 55. Category 3 subcategory (a): low altitude start, totaled 11, with 1 trajectory in 2006, 6 in 2007, and 4 in 2008 (Table 1). Category 3 subcategory (a): high altitude start, totaled in 8 trajectories with 2 in 2006, 5 in 2007, and 1 in 2008 (Table 1). Category 3 subcategory (b) had 36 trajectories designated, with 9 in 2006, 16 in 2007, and 11 in 2008 (Table 1).

Table 1 HySplit backward trajectories totals, categorical designation and year

Trajectory Designation	Category 1	Category 2	Category 3a: low altitude start	Category 3a: high altitude start	Category 3b
2006	22	25	1	2	9
2007	18	13	6	5	16
2008	23	21	4	1	11

Results show reoccurring potential sources located in the Northeastern United States, Nova Scotia, Northern United Kingdom, and the Scandinavian Peninsula (Figure 3). Out of the trajectories designated category 3 (a): low altitude start, ~45.45% began in the Northeastern United States, ~18.18 % beginning in Nova Scotia, the Northern United Kingdom, and the Scandinavian Peninsula (Table 1). Northern central Russia was a reoccurring starting point for air trajectories in category 3 subcategory (b): high altitude start.

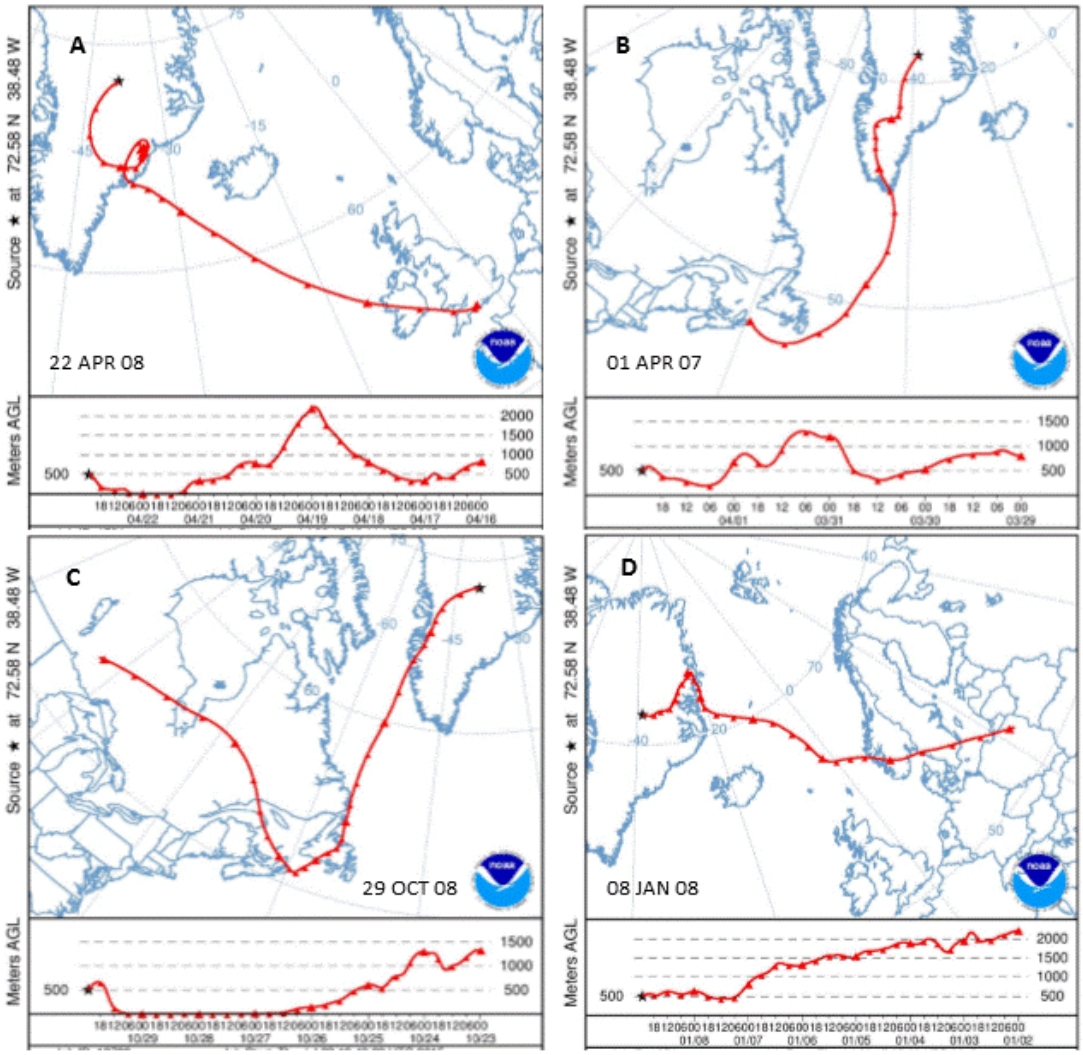

Figure 3 Backward trajectory Output from HySplit of Possible Source Areas of BC. The starting point for the trajectory is Greenland Summit Station with a 168 hour backwards trajectory ending in the location of the starting air mass. Bottom graph provides the altitude of the air mass in meters.

Major deposition events occurred in early to mid-2006, 2007 and 2008 (Table 2). These large in situ measurements coincided with trajectories that started with low altitude winds over populated land masses. The largest deposition events within the three years occurred within early-2008 according to an analysis of the meteorological snowfall record comparison with in-situ data (Table 2).

Table 2 Excerpt from in-situ data highlighting large deposition event in in-situ measurements for Greenland 2008 from Doherty and Warren (2008)

entry	Region	newly fallen snow =1; snow=2, melting snow =3, sea ice=4, uncertain=9	Year	Month	Day	Lat N	Lon E	sample depth, top (cm)	sample depth, bottom (cm) (0=surface sample)	fraction of total snowpack depth (n/a = 9)	fraction non-BC absorption (999=n/a)	Absorp. Angstrom exponent (450:600nm)	equivalent BC (ng/g) (999=n/a)	maximum BC (ng/g)	estimated BC (ng/g)
337	Greenland	2	2006	8	7	79.878	333.991	0	3	9	0.4	2.22	26.6	19	15.9
339	Greenland	2	2006	8	7	79.878	333.991	0	3	9	0.34	1.97	43.4	33	28.9
342	Greenland	2	2006	8	7	79.878	333.991	30	40	9	0.38	2.16	15.6	11	9.7
354	Greenland	2	2007	4	27	63.149	315.183	0	0	9	0.4	2.02	10.8	8.2	6.5
370	Greenland	9	2007	7	9	76.402	291.943	0	10	9	0.53	2.62	11.1	7.3	5.2
374	Greenland	9	2007	7	9	76.415	292.261	0	10	9	0.48	2.44	12.2	8.4	6.4
377	Greenland	2	2008	5	3	66.481	313.72	0	0	9	0.55	2.75	12.4	7.8	5.6
378	Greenland	2	2008	5	5	69.898	313.086	0	0	9	0.42	2.23	13.4	9.7	7.7
380	Greenland	3	2008	7	24	66.474	313.72	2	4	9	0.35	1.94	21.3	16	13.8
381	Greenland	9	2008	7	24	66.474	313.72	4	7	9	0.4	2.12	15.3	11	9.2
403	Greenland	3	2008	7	25	65.952	313.567	7	9	9	0.3	1.76	16.3	13	11.5
404	Greenland	3	2008	7	25	65.952	313.567	9	10	9	0.33	1.92	34.2	26	22.8
405	Greenland	3	2008	7	25	65.952	313.567	10	11	9	0.4	2.13	26.1	18	15.7
406	Greenland	3	2008	7	25	65.952	313.567	10	11	9	0.39	2.12	26.6	19	16.2
407	Greenland	3	2008	7	25	65.952	313.567	11	13	9	0.41	2.18	21.6	15	12.8
408	Greenland	3	2008	7	25	65.952	313.567	11	13	9	0.41	2.19	15.6	11	9.2
409	Greenland	9	2008	7	25	65.952	313.567	13	14	9	0.42	2.22	17.5	12	10.1
430	Greenland	3	2008	7	26	66.22	313.654	9	11	9	0.38	2.09	24.7	19	15.3
431	Greenland	3	2008	7	26	66.22	313.654	9	11	9	0.43	2.24	16.1	12	9.2
432	Greenland	3	2008	7	26	66.22	313.654	11	14	9	0.44	2.28	14.8	11	8.3
433	Greenland	3	2008	7	26	66.22	313.654	11	14	9	0.45	2.3	11.6	8.2	6.4
443	Greenland	9	2008	7	26	66.22	313.654	53	61	9	0.41	2.18	2.1	1.6	1.3

Deposition event frequency increased during the first six months of the year. Trajectories that began in the later part of the year from land mass versus open sea tended to start at around 1000 to 1500 m. The height of these early trajectories makes them unlikely to have carried aerosols.

No large forest fires were noted during a search for large biomass burning events that aligned with trajectories that began with low altitude air masses. Industrial processes were

found within 50 km of trajectories that originated in the North Eastern United States and the United Kingdom, and to a lesser extent, Nova Scotia and the Scandinavian Peninsula.

According to annual wind roses, winds in 2008 are strongest from the SE and S followed by the NE (Figure 5). Similar patterns were seen in 2006, and 2007 wind rose data.

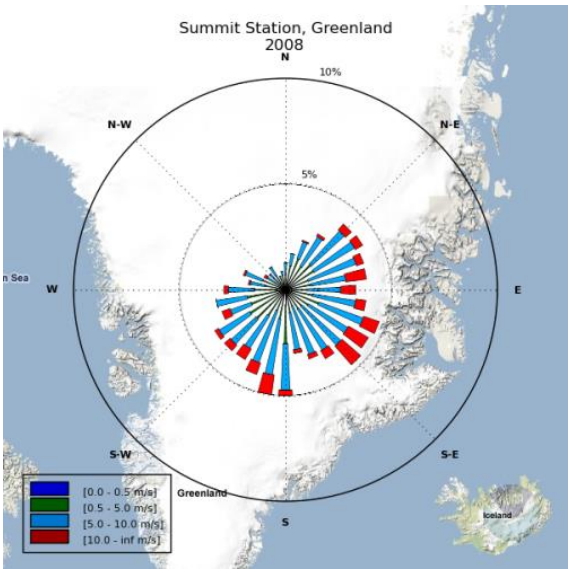

Figure 5 Annual Wind Rose for Summit Station, Greenland 2008 from ESRI NOAA

Discussion

According to the trajectory analysis, given a week's lifetime in the atmosphere, if particles were injected higher into the atmosphere due to local convection currents, Northern Russia, and the Scandinavian Peninsula could be possible sources, or finally, there could be an injection from shipping in the region. Northern central Russia was a reoccurring starting point for air trajectories in category 3 subcategory (b): high altitude start. However, because the air mass was at a high altitude (<1000 m) at the beginning at the week, it is an unlikely source of BC and was dismissed. On the Scandinavian Peninsula air trajectories originating in the region reoccurred four times during the 2006-2008 period. Air trajectories began with low altitudes and may have been a possible source of BC. While the country of Norway has one of the highest air quality standards in the world, however because the analysis was done from 2006-2008 this may have been prior to standards or variance in the areas industrial areas. Since industrial processes, coal power plants and steel manufacturing, were found within 50 km of trajectories that originated in the North Eastern United States and the United Kingdom, and to a lesser extent, Nova Scotia and the

Scandinavian Peninsula, industrial processes account for the most likely source of BC for the 2006, 2007, and 2008, time period. Within the United States and Nova Scotia, coal burning power plants were the most common industrial sources noted in the regions where low altitude air masses were modeled to have begun.

Shipping emissions as a source of BC to Greenland may be a possibility due to an increase in shipping in the Arctic in the last 20 years. Emission factors for shipping were not considered for this study due to time and resource constraints.

The analysis was limited due to time and access to in-situ and meteorological data for daily trajectories. Conclusions drawn from this study can be extrapolated to give a general understanding of the variability of trajectories of BC into the Greenland Ice Sheet (GIS) area and potential sources, but further in-depth analysis needs to be done for other study areas to be more representative of GIS as a whole.

Conclusion

BC from thousands of miles away have a direct impact on snow and ice in the Arctic via long-range transportation and deposition events. Sources of black carbon can be identified utilizing air trajectory models. By understanding the direction and strength of prevailing winds that carry aerosols such as BC into the Arctic, we can begin to narrow down locations and source types of BC from the temperate regions. Industrial processes and coal burning power plants were located in many of the source regions identified by this study. Knowing the sources of BC affecting the Arctic may be important in future mitigation policies by countries around the globe. As climate change continues, monitoring ice melt rates and the rate of deposition of BC on snow and ice covered areas will become increasingly important.

To complement this study, future research should include more in-depth analysis with daily backward trajectories and seasonal wind rose data. Analysis of the years since 2008 to present a more up to date idea of what the deposition rates are currently. Shipping emissions are an increasingly important factor to the aerosol rates in the Arctic but were largely left out of this study due to time and resource constraints.

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