Equivalent Black Carbon in the Arctic

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Highlights

- Equivalent Black Carbon (EBC) has declined by as much as 55% over the 23 year record at two high Arctic surface locations. This decline has been related to changes in BC emissions in the early 1990s in the mid-latitude source regions especially in the Former Soviet Union. Increases in BC emissions in the 2000s in East Asia have had no observed effect on the surface concentrations at three measurement locations.
- Averaged EBC concentrations in 2012 at all three locations are similar to the averaged EBC concentrations over the last decade.
- A comparison of anomalies in EBC concentration at the three Arctic locations indicates that each site is unique in terms of transport pathways of pollution from the mid-latitude BC source regions to the site and depositional loss of BC en route to or at the site.

Introduction

Aerosol black carbon (BC) can affect the radiation balance in the Arctic by absorbing solar radiation when suspended in the atmosphere [*Charlson et al.,* 1991; *Jacobson* 2000; *IPCC* 2001], by altering cloud properties [*IPCC,* 2007; *Liu* et al., 2011] and, when deposited on snow and ice, by darkening the surface and enhancing the absorption of solar radiation and melt rates [*Flanner et al.,* 2007; *Hegg et al.,* 2009; *Bond et al.,* 2013]. A large proportion of the Arctic Climate response to an increase in surface temperature is due to the snow/albedo effect [*Fletcher et al.,* 2009; *Serreze and Barry,* 2011]. In simpler terms, further warming occurs when darker exposed surface, due to snow/ice melt, absorb solar radiation. Climate simulations using Earth System Models indicate an enhancement in the snow/albedo effect when BC is deposited on snow/ice surfaces due to increased absorption and the associated feedback mechanisms [*Flanner et al.,* 2009; Mark and King, 2013; *Sand et al.,* 2013].

BC is released during the incomplete combustion of hydrocarbon-based including fossil fuels, biofuels, and biomass burning. The largest black carbon emission sources in the Arctic nations are agriculture burning and wildfires, on-road diesel vehicles, followed by residential burning, off-road diesel and industrial combustion. Gas flaring may currently be a significant source as well, with a significant share occurring at high latitudes [*Quinn et al.,* 2011; *Stohl et al.,* 2013]. The burden of atmospheric BC has been found to result from long range transport from the Former Soviet Union (FSU), Europe (EU), N. America (NA) and East Asia (EA) [*Sharma et al.,* 2013](Figure 1).

Despite uncertainties in the performance of coupled chemical-transport-climate models, the potential contribution of short-lived climate forcers, including BC, tropospheric ozone and methane, to observed accelerated warming in the Arctic may be significant [*Quinn et al.*, 2008; *Shindell et al.,* 2012]. Reductions in the emissions of short-lived climate forcers such as BC have been recognized as a potential mitigation strategy [*UNEP,* 2011] to slow the rate of near-term warming because the lifetime of BC is on the order of weeks.

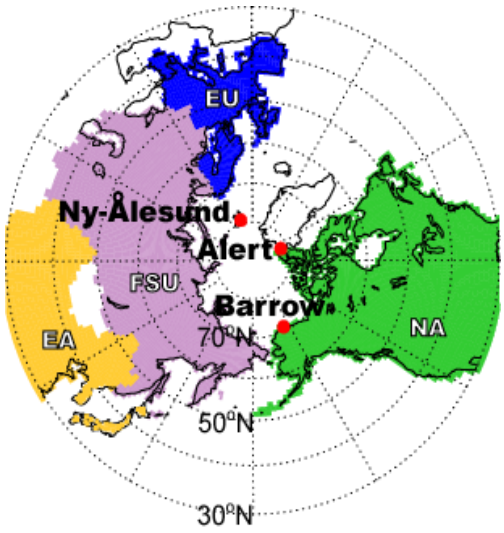

Figure 1: Source regions of BC to the Arctic include EU=Europe, FSU=Former Soviet Union, NA=North America and EA= East Asia. Also marked are locations of three long-term measurement sites in the Arctic (Alert (82°N, 62.3°W), Barrow (71°N, 156.6°W) and Ny-Ålesund (79°N, 12°E)).

Long term records of BC atmospheric concentrations in the Arctic combined with transport modeling have improved our understanding of the impact of emission changes in a source region on observed Arctic concentrations [*Sharma et al.*, 2004; 2006; 2013; *Stohl* 2006; *Koch and Hansen*, 2005]. These data can help inform and develop strategies for mitigating the impacts of BC on Arctic Climate. The longest records of BC concentrations are measured in the Arctic by using an Aethalometer [*Magee Scientific Inc.*]. The Aethalometer uses a filter based optical technique where changes in light attenuation are measured over time as the loading of BC-containing aerosols increases on the filter matrix [*Hansen et al.,* 1984]. BC derived from Aethalometer measurements is referred to as Equivalent Black Carbon (EBC) [*Petzold et al.,* 2013]. Atmospheric aerosols are comprised of chemical components other than BC that may also absorb or scatter. Usually, correction schemes are applied to Aethalometer data to account for enhanced light absorption due to the non-BC components [*Weingartner et al.,* 2003; *Collaud Coen et al.,* 2010; *Müller et al.,* 2011]. Due to the wide variety of sampling schemes used in the collection of data presented here, no corrections have been applied. The change in optical transmission was assumed to be due solely to BC. In addition, a mass absorption coefficient (MAC) provided by the manufacturer for the specific Aethalometer model at the locations was assumed to convert measured light absorption to EBC mass concentrations [*Petzold et al.,* 2013]. By not applying the correction, artifacts which might be present can affect the EBC measurements by a factor of 2 [*Louisse et al.,* 1993; *Sharma et al.,* 2002; *Weingartner et al.,* 2003].

EBC Measurements

Seasonal Cycle

Equivalent BC data from direct observations of atmospheric aerosols in the Arctic are harmonized for inter-comparison through the International Arctic Systems for Observing the Atmosphere (IASOA) and Global Atmosphere Watch (GAW) working groups. This chapter will summarize EBC results from long term monitoring at three high Arctic locations; Alert (Nunavut), Canada; Barrow (Alaska), USA; and Ny-Ålesund (Svalbard), Norway. The highest EBC concentrations are measured at all locations during winter/spring (Figure 2) due to the seasonal influence of Arctic haze, which is transported from mid-latitude source regions [*Barrie* 1986; *Rahn* 1981; *Sirois and Barrie* 1999]. Transport to the Arctic occurs along the surfaces of constant potential temperature that create a dome known as the Arctic front [*Klonecki et al.,* 2003]. During winter/spring the Arctic front can extend as far south as 40^{o} N, encompassing source regions in the FSU and Europe [*Sharma et al.,* 2004; 2006] (Figure 1). BC emissions from the FSU are transported into the high Arctic at low altitudes [*Sharma et al.,* 2013; *Sand et al.,* 2013]. In winter/spring, Asian emissions influence the Arctic only at higher altitudes and have minimal influence at the surface [*Stohl,* 2006; *Shindell et al.,* 2008; *Sharma et al.,* 2013]. During the summer, the Arctic front is confined to higher latitudes and wet deposition is more frequent [*Garrett et al.,* 2011; *Sharma et al.,* 2013]. Surface BC is an indicator of larger scale BC transport to the region and minimal influence of EA aerosol at the surface makes it difficult to gage its influence on the radiative forcing only based solely on the surface observations.

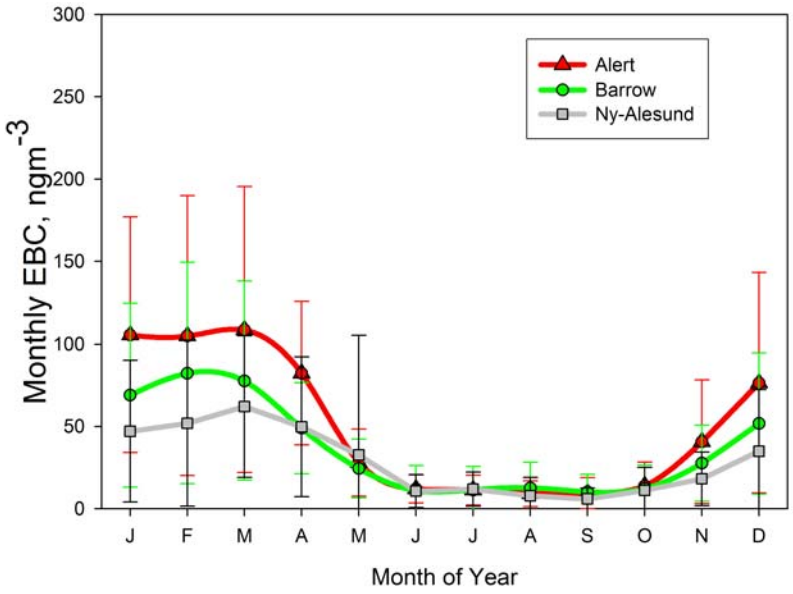

Figure 2: Seasonal variations in monthly averages of equivalent black carbon (EBC) at Alert in red (1989-2012), Barrow in green (1989-2012) and Ny-Ålesund in gray (1998-2011) show higher EBC measurements during the Arctic haze time period. The error bars represent 1σ in the mean EBC value. EBC at Barrow were measured by aethalometer until 2001 and after then by a Particle Soot Absorption Photometer (PSAP). Mass Absorption Coefficient (MAC) values used in the Aethalometer measurements at Alert=19m^2g^{-1} (model AE-6) until 2009 and thereafter 15.9 m^2g^{-1} (model AE-31), Barrow=19m^2g^{-1}(AE-8) until 2001 and thereafter 10 m^2g^{-1} (PSAP) and Ny-Ålesund=15.9 m^2g^{-1} (model AE-31) respectively

Long-Term EBC Trend analysis

Time series of daily averages of EBC are shown in Figure 3. Alert and Barrow have the longest measurement records enabling determination of longer-term trends. Interannual variability in EBC concentration is a function of BC source strength, transport pathways from source to receptor, and BC deposition [e.g., *Stohl,* 2006; *Garrett et al.,* 2010; *Sharma et al.,* 2013]. Declining trends from the early 1990s to 2012 were identified in the long-term measurements of EBC at Alert and Barrow (Figure 3). Three colored lines are shown, the red line includes all EBC measurements, the green line is averaged EBC data over the months of January to April, and blue line is averaged EBC data over the months of June to September. Overall, there has been 55% decline in EBC at Alert and a 45% decline in EBC at Barrow considering the EBC trend values averaged between 1990-1993 and 2009-2012 periods. This decline has been shown to be related to declining emissions in the FSU during the early 1990s due to the economic collapse [*Sharma et al.,* 2004; 2006; 2013; *Quinn et al.*, 2008; *Hirdman et al.,* 2010]. Despite the overall increase in fossil fuel BC emissions since 2000 in the source regions [*Sharma et al.,* 2013], especially in the EA source region, the observed concentrations at the three Arctic locations have not increased. This finding confirms the minimal influence from the EA source region on EBC concentrations at the surface. Measurements of EBC at Ny-Ålesund did not start until 1998 and thus could not be compared directly to the other two sites. However, daily averages of EBC concentrations at Ny-Ålesund were very similar to Barrow and Alert in spite of the geographical separation, indicating omnipresence of EBC in the high Arctic. On average, in 2012 EBC concentrations measured 61±84, 23±17 and 23±32 ng m^{-3} at Alert, Barrow and Ny-Ålesund in comparison to averaged EBC of 42±38, 35±46 and 27±41 ng m^{-3} measured in the last decade (2002-2012) at the three locations. The EBC levels during winter/spring (green trace) are measured the highest at Alert, followed by Barrow and Ny-Ålesund. This is not due to the choice of MAC values used by the aethalometer and is most likely due to the influence of source regions of BC transported to each of the site.

Anomalies in EBC

Monthly anomalies in EBC were determined by taking the difference in monthly EBC concentrations with respect to mean values for the 23 year period extending from 1989 to 2012. At Alert and Barrow, the anomalies in the 1990s were significantly different ($P(t<0.01)$) from other time periods indicating that prior to 2000, monthly EBC concentrations were significantly higher than the 23 year mean for that month. The anomalies in EBC concentrations in the post-2000 period were closer to the 23 year averages at Alert and Barrow. The EBC anomalies at Ny-Ålesund were determined by using a 10 year continuous measurement period from 2002 to 2012.

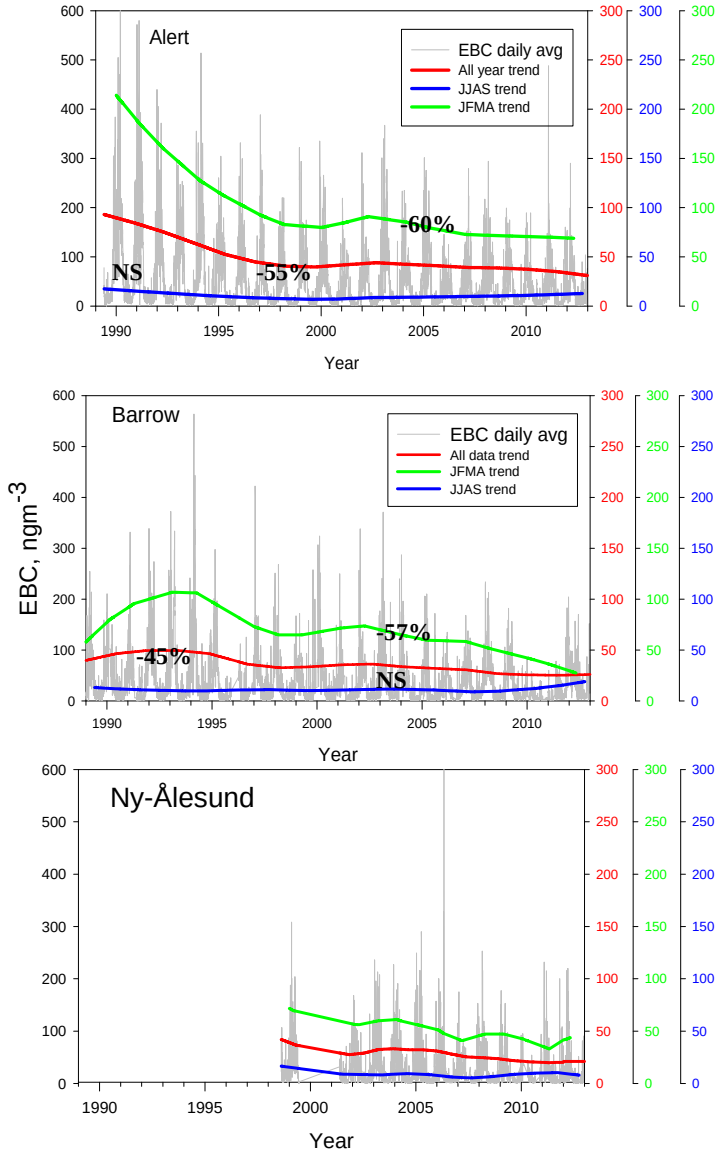

Figure 3: Surface daily EBC measurements at three Arctic locations. Each trace is marked with % change in EBC determined from change in 1990-1993 and 2009-2012 periods. Summertime change is not significant. The trends were determined by using LOWESS technique (LOcally Weighted Exponentially Scatterplot Smoothing).

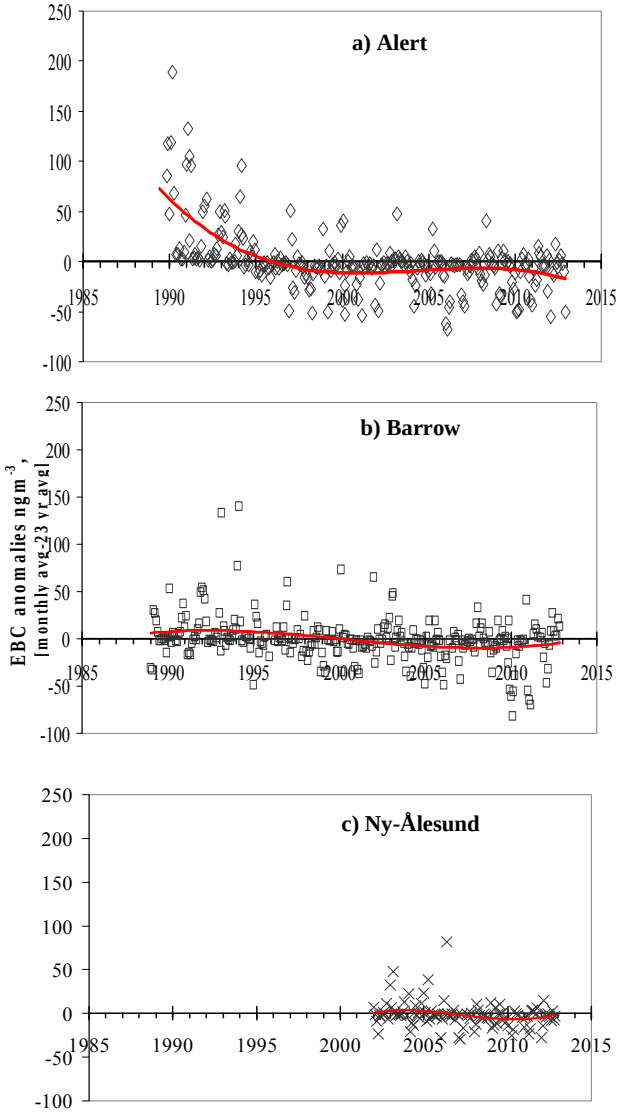

Figure 4: Time-series of anomalies in EBC at three Arctic locations a) Alert, b) Barrow and c) Ny-Ålesund. Monthly EBC at Alert were significantly higher pre-2000 than post-2000 time-periods. A t-test for samples with unequal variances was used to determine that the EBC anomalies were significantly different between periods at each site and among sites for the same time-periods.

Comparing sites, the anomalies in EBC at Alert and Barrow were significantly different for the pre-2000 and post-2000 periods indicating that the sites could have been influenced by different transport pathways and therefore, different source regions. Alternatively, EBC concentrations measured at the two sites could have been impacted by different deposition mechanisms or frequency of deposition en route to or at the site.

However, Hirdman et al. (2010) and Sharma et al. (2013) found that only a minor fraction of the long term trend in EBC at the three sites could be explained by changes in the transport patterns. Thus, the differences among the sites are largely influenced by BC source strength and the depositional losses.

Emerging new sources such as increasing ship emissions and planned resource development will alter the state of the Arctic atmosphere *[Shaw et al.,* 2010; *Eckhardt et al.,* 2013; *Browse et al.,* 2013]. Long term monitoring of EBC is critical to understanding the impacts of changes in sources of BC to the Arctic and provide information critical to guide the development or implementation of mitigation options.

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