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Aerosol black carbon at five background measurement sites over Finland, a gateway to the Arctic

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ABSTRACT

Aerosol equivalent black carbon (BC*e*) was measured at five different background stations in Finland, with the longest data set from Hyytiälä, December 2004–December 2008. Measurements were conducted either with an aethalometer or a Multi-Angle Absorption Photometer, MAAP. Measured black carbon concentrations were highest in Virolahti in southeastern Finland, with annual averages ranging from 385 to 460 ng m^{-3}, followed by Hyytiälä (250–370 ng m^{-3}), Utö (230–270 ng m^{-3}), Puijo (225–230 ng m^{-3}), and Pallastunturi (60–70 ng m^{-3}) in northern Finland. The BC*e* fractions of measured $PM_{2.5}$ concentrations were generally between 5 and 10%, with highest fractions at Virolahti close to the Eastern border. At all the stations, the highest concentrations were observed during the spring and the winter, and the lowest concentrations during the summer. The seasonal cycle could generally be attributed to the reaching of long-range-transported black carbon. Additional reasons were increasing domestic wood burning and reduced boundary-layer height during winter, and a more effective vertical mixing during summer. The highest concentrations for each station occurred with southerly winds, and on the basis of trajectory analyses, the source areas of BC*e* resided mostly in Central and Eastern Europe. Occasionally the long-range-transported BC*e* concentrations were elevated for short periods to fulfill the characteristics of pollution episodes. From these episodes, about 62% were a result of non-fire anthropogenic sources and 36% due to open biomass burning sources. Episodes from the biomass burning sources were most often observed during the spring.

1. Introduction

Black carbon (BC), a byproduct of fossil fuel combustion and biomass burning, is an important component of atmospheric particulate matter (Bond et al., 2004). Being a strong absorber of solar radiation, BC may have significant regional effects on temperature, cloud amount and precipitation (Menon et al., 2002; Ramanathan and Carmichael, 2008; Johnson, 2009; Jacobson, 2010; Koch and Del Genio, 2010). Over snow-covered areas, the surface albedo can be significantly reduced due to the deposition of BC onto snow (e.g. Warren and Wiscombe, 1980). This may significantly influence the local and regional climate (Flanner et al., 2009). Direct observations of reduced albedo resulting from long-range-transported BC into Arctic areas were reported by Stohl et al. (2006). More recently, it was estimated that BC may have contributed to more than half of the observed Arctic warming since 1890, most of this occurring during the last three decades (Shindell and Faluvegi, 2009).

There are large uncertainties associated with emissions of BC to the atmosphere, its aging during atmospheric transportation, and its removal by precipitation (Bond et al., 2004; Riemer et al., 2004; Hoelzemann et al., 2004; Generoso et al., 2003; Khalizov et al., 2009). All these uncertainties propagate directly into global model simulations (Stier et al., 2007; Koch et al., 2010; Bauer et al., 2010; Vignati et al., 2010). For a better understanding of the transportation, removal and climatic impacts of atmospheric BC, accurate and up-to-date knowledge of its global distribution is clearly needed. Concerning remote, northern parts of Europe, little information on the concentration levels and temporal variability of BC is available (Ricard et al., 2002; Eleftherias et al., 2009; Yttri et al., 2007; Hirdman et al., 2010). Such data would be of great

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value when studying the effects of BC on Arctic climate and when evaluating atmospheric models that simulate the long range atmospheric transport of BC.

This paper provides an overview on the temporal and spatial variability of BC in atmospheric aerosols over Finland in Northern Europe. The analysis is based on measurements made at five Finnish background stations until the end of 2008. The longest data set is from Hyytiälä, beginning December 2004. In addition to looking at BC concentration levels and their seasonal variability, we investigate the connection of BC with typical meteorological quantities and assess the major source types and -areas for BC observed in Finland. Pollution episodes of BC at the different stations are also examined.

2. Methods

2.1. Measurement sites

The measurement stations have been described in recent literature and only a short overview is given here. The measurements were conducted at five different locations in Finland (Fig. 1).

The GAW (Global Atmosphere Watch) station at Pallastunturi (e.g. Hatakka et al., 2003) is in the subarctic region at the limit of the northern boreal forest zone. Having multiple sub-stations, the measurements were conducted at the main station on Sammaltunturi, 565 m a.s.l. There are no significant local or regional pollution sources in the area. The SMEAR II (Station for Measuring Forest Ecosystem – Atmosphere Relations) station in Hyytiälä (e.g. Kulmala et al., 2001) is located in southern Finland. The terrain around the station is representative of the boreal forest. The largest city near the station is Tampere (population 212 000), ca. 60 km south-southwest of the measurement site. The SMEAR IV station in Puijo (Leskinen et al., 2009) is on the top of an observation tower, 306 m a.s.l. The city centre of Kuopio (population 91 000) is about 2 km southeast of the station. The EMEP (European Monitoring and Evaluation Programme) station in Utö (Engler et al., 2007) is situated on a small island some 60 km from the Finnish southwest coast, 8 m above the sea level. The closest city, Turku (population 176 000), is situated about 90 km to the northeast of the island. The Virolahti EMEP station (Anttila et al., 2008) lies in the southeastern corner of Finland, with the Russian border 6 km to the east. A wood heated farm-house is located 80 m east-south from the station. Another local aerosol source is the E18 highway 5 km to the north. A border crossing point between Finland and Russia is situated in Virolahti, which increases the truck traffic on the highway.

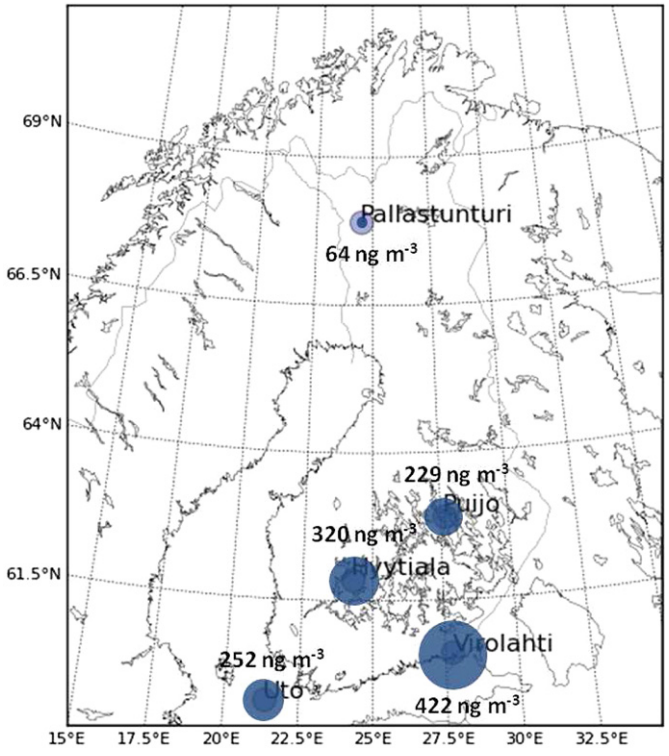

Fig. 1. Locations of the measurement stations. In addition, the average annual BC*e* concentration from each station is shown.

2.2. Instrumentation

The black carbon measurements were conducted with two different instruments: the AE 31 aethalometer (Magee Scientific) and the multi-angle absorption photometer (MAAP) (Thermo Scientific). As BC by definition cannot be unambiguously measured with these instruments, it's customary to call the measured light absorbing constituent as equivalent BC, or BC*e*. The AE 31 aethalometer measures the absorption of light at the wavelengths of 370, 470, 520, 590, 660, 880 and 950 nm. Black carbon should be the sole absorbent of light at 880 nm, which is the channel used in this study. The aethalometer BC*e* measurement is known to suffer from a filter loading artifact, i.e. the BC*e* concentration decreases with increasing filter load. This artifact can be corrected using different methods (e.g. Weingartner et al., 2003; Arnott et al., 2005; Virkkula et al., 2007). Here, the approach presented by Weingartner et al. (2003) was chosen.

The MAAP measures the aerosol black carbon concentration at the wavelength of 637 nm (Supplementary material). It is also a filter-based instrument, and utilizes a combination of reflection and transmission measurements together with a radiative transfer model to yield the BC*e* concentration (Petzold and Schönlinner, 2004). In inter-comparison tests, MAAP has been found to give reliable results of the aerosol absorption (e.g. Sheridan et al., 2005). In fact, as both the aethalometer and MAAP utilize a light absorbance method on a filter strip, they yield very comparable data of the aerosol BC*e*, see Supplementary material.

The measurement details of BC*e* from each station are specified in Table 1. Most of the instruments were positioned behind a $PM_{2.5}$ inlet. Exceptions to this were Hyytiälä and Pallastunturi. In Hyytiälä the aethalometer was behind a PM_{10} inlet; and in Pallastunturi the so-called Gas Line (station main inlet), Total Air inlet and PM_{10} inlet were used (see Table 1 for sampling times). The higher cut-off of the Gas Line inlet is around 7 μm (Lihavainen et al., 2008). The Total Air inlet has no nominal cut-off, and the air is consequently dried by heating. The concentrations measured behind the different inlets are still comparable; around 90% of the BC*e* mass is typically accounted in $PM_{2.5}$ (Putaud et al., 2004), as long as there are no

Table 1
Measurement details from each station.

Station	Instrument	Inlet	Inlet height from the ground/sea level	Measurements started
Pallastunturi	Aethalometer AE 31[a]	Gas line	7 m/572 m	18.08.2005
		Total Air		07.01.2008
	MAAP	PM_{10}	7 m/572 m	04.09.2007
Hyytiälä	Aethalometer AE 31	PM_{10}	4 m/179 m	08.12.2004
Puijo	MAAP	$PM_{2.5}$	75 m/306 m	25.08.2006
Utö	Aethalometer AE 31	$PM_{2.5}$	2 m/7 m	11.01.2007
Virolahti	Aethalometer AE 31	$PM_{2.5}$	2 m/4 m	26.08.2006

Total air inlet has no cut-off, and has consequent heating for drying of the aerosol.
[a] In the Total Air Inlet since 7.1.2008. Gas line inlet has a cut-off size of about 7 μm.

sources of primary soot from e.g. incomplete combustion. In order to maintain comparability of the aethalometer results from the Total Inlet at Pallastunturi, the periods when station was inside a cloud were removed from the data.

The measurement resolution of the instruments was typically 1 min. Five-minute average data were checked and data with outliers or instrument problems were removed. Consequently more than 20 min data coverage was demanded for calculation of hourly averages.

In addition to BC*e* data, other auxiliary data were available from each station. In this paper, we looked at basic meteorological quantities (temperature, pressure, wind speed, wind direction and relative humidity), available $PM_{2.5}$ concentrations (Dekati impactor in Hyytiälä; Eberline FH 62 IR in Utö and Virolahti) and, in the case of Pallastunturi and Kuopio, also visibility (Vaisala FD12P present weather sensor).

2.3. Source region analysis

72 h backward trajectories with 3 h intervals were calculated with the FLEXTRA model (Stohl, 1995) for each station for a source region analysis. The pressure level for arriving trajectories was 950 hPa for all

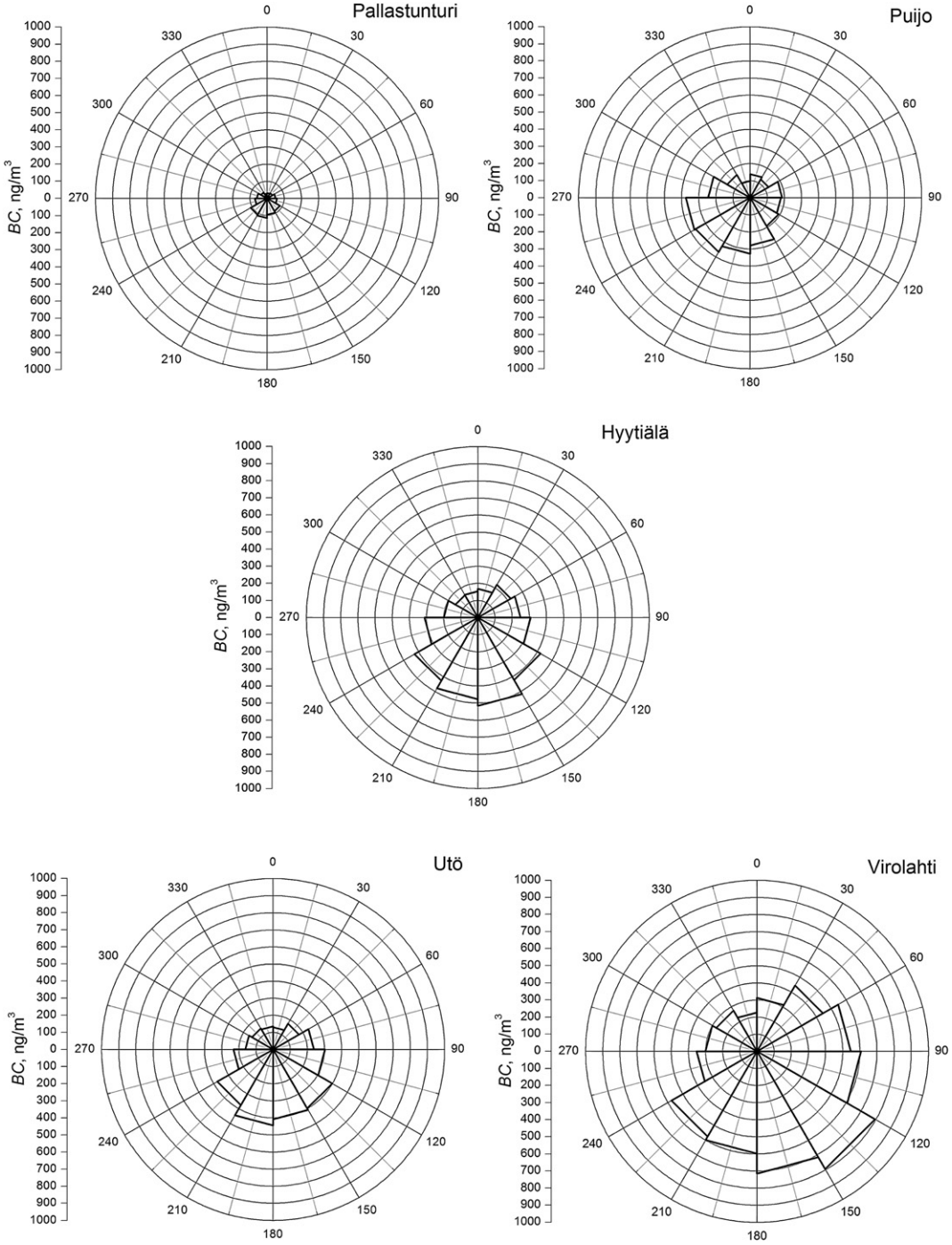

Fig. 2. BC*e* concentration as a function of wind direction at each station.

stations but Pallastunturi, where the pressure level was 925 hPa. Sources of aerosol components from air mass backward trajectories can be determined using the so-called source region analysis (Ashbaugh, 1983; Stohl, 1996). Here, the principles of the analysis were used to derive a method for determining qualitatively the sources of black carbon at the Finnish measurement stations (See Supplementary material).

In addition to FLEXTRA, the FLEXPART model (Stohl et al., 1998, 2005, Stohl and Thomson, 1999) was used for tracking of the origin/type of pollution events (Chapter 3.5). FLEXPART data is available through the European Integrated project on Aerosol Cloud Climate and Air Quality Interactions (EUCAARI) for Hyytiälä and Pallastunturi from March 2006 onwards. FLEXPART is a Lagrangian Particle Dispersion Model (LPDM) that is run backward in time from a measurement location. Output from the model produces 'Potential Emissions Sensitivity' plots using CO as a tracer. Emissions from the EMEP inventory are used to produce "Potential Source Contribution" (PSC) products. A biomass burning CO PSC is developed from the MODIS Rapid Response System (Justice et al., 2002) data. From the stations and time when FLEXPART was unavailable, the basic FLEXTRA trajectories were visually observed together with MODIS fire records with the Fire Information for Resource Management System (FIRMS) Web Fire Mapper (http://firefly.geog.umd.edu/firemap/).

3. Results and discussion

3.1. BCe at individual sites

First, we analyzed the results from each station individually. This was done in light possible correlations of BC*e* on wind direction (Fig. 2) and diurnal variations (Supplementary material). The possible local and regional sources and locations of major cities were checked. As expected, emissions from the Kuopio city were observed in the BC*e* data from Puijo. This was mostly seen as concentration peaks during morning and evening. The peaks were related to work-related traffic and utilization of wood burning in small-house areas. Interestingly, comparison to wind direction (Fig. 2) revealed that the highest concentrations did not come from the city centre or the close-by highway (120–210°) but a small-house area (domestic wood burning) located within 5 km southwest of the station. For more detailed site information, see Leskinen et al. (2009).

Similar diurnal peaks were observed in Virolahti, due to a wood heated farm-house 80 m southwest of the station. This also coincided with an elevated BC*e* sector (Fig. 2). As a precaution, Virolahti data with wind direction ± 15° from the farm-house were filtered out. Surprisingly, the wind sector with the metropolitan area of Helsinki did not appear with a particularly elevated BC*e* concentration in Virolahti.

No clear local sources were found from data at the other stations. This indicates that the observed BC*e* was rather from regional sources or from long-range transport. In Utö and Pallastunturi, no clear regional sources exist. In Hyytiälä, a possible regional source is the closest town of Orivesi (population 9000), located about 20 km southeast of Hyytiälä. This is also the direction of the highest BC*e* concentrations. Finnish towns typically consist of small houses, which utilize wood burning for partial heating. It has to be noted that the emissions of Tampere city (population 213 000) 60 km from the southwest do not appear in the Hyytiälä BC*e* data. Therefore, it's also possible that elevated BC*e* in the southeast wind sector in Hyytiälä is due to long-range-transported black carbon.

3.2. Spatial and temporal variation of BCe

Pallastunturi station had the lowest BC*e* concentrations due to its remote, Arctic location, with annual averages ranging from 60 to 70 ng m^{-3}. BC*e* concentrations measured in Virolahti were the highest (annual averages 385–460 ng m^{-3}), due to its closer proximity to more densely populated areas and major emission sources in Central and Eastern Europe. Interestingly, BC*e* concentrations measured in Hyytiälä (annual averages 250–370 ng m^{-3}) were higher than those in Utö (annual averages 230–270 ng m^{-3}), especially during winter. This might be due to regional emissions from near-by municipalities and small towns, as mentioned in the previous chapter. The BC*e* concentrations in Utö resembled more those measured further north in Puijo (annual averages 225–230 ng m^{-3}). The low concentrations measured at Puijo suggest that the local city emissions – even though clearly observed from the diurnal variation – did not increase the overall concentrations considerably.

The BC*e* concentrations observed in the southern part of Finland are comparable to European natural background values of about 320–480 ng m^{-3}, but lower than European rural background values of 640–1600 ng m^{-3} (Putaud et al., 2004). For comparison, these values are similar to those measured in urban sites in Helsinki, where BC concentrations have been found to average at around 1000 ng m^{-3} (Viidanoja et al., 2002; Järvi et al., 2008). Somewhat lower background concentrations (<200–300 ng m^{-3} of EC) have been reported for more western parts of northern Europe (Yttri et al., 2007). The average BC*e* concentration measured at Pallastunturi was about half of that reported for north-eastern Finland (146 ng m^{-3}; Ricard et al., 2002), and roughly twice that observed in Spitzbergen (39 ng m^{-3}; Eleftherias et al., 2009 and 45 ng m^{-3}; Hirdman et al., 2010). Put together, these observations indicate a clear concentration gradient in BC*e* concentrations in northern Europe, decreasing from south to north and from east to west.

Campaign-time averages were calculated for different seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February), see Table 2. Fig. 3 shows the time series of BC*e* concentrations measured at each station as monthly statistics. In Fig. 3, all months with less than 50% data coverage were left out.

The BC*e* concentrations exhibited a clear seasonal trend. At all the stations, BC*e* concentrations were at their highest during the spring and winter, and lowest during the summer. This can be attributed to stronger BC sources from Central and Southern Europe during spring and winter; see Section 3.4. Also the boundary layer during different seasons plays a role; the boundary-layer height decreases during winter and increases during summer. In addition, Finnish households utilize wood burning for heating especially during the winter. Occasional peaks could be attributed to forest/agricultural fires in Eastern Europe (see Sections 3.4 and 3.5). The fire season in Eastern Europe is another reason for the high BC*e* concentrations during the spring in the Arctic (Warneke et al., 2010).

Table 2
Seasonal means and standard deviations of BC (ng m^{-3}) at each station during the measurement periods.

	Pallastunturi	Hyytiälä	Puijo	Utö	Virolahti
	Aeth	Aeth	MAAP	Aeth	Aeth
Spring avg.	86	339	280	313	469
St dev.	127	378	380	421	542
Summer avg.	60	219	174	187	297
St dev	65	187	154	161	292
Autumn avg.	51	330	225	234	343
St dev	73	354	230	299	423
Winter avg.	81	386	234	271	468
St dev	133	364	262	348	425
Annual avg.	64	320	229	252	422
St dev	103	337	273	327	445

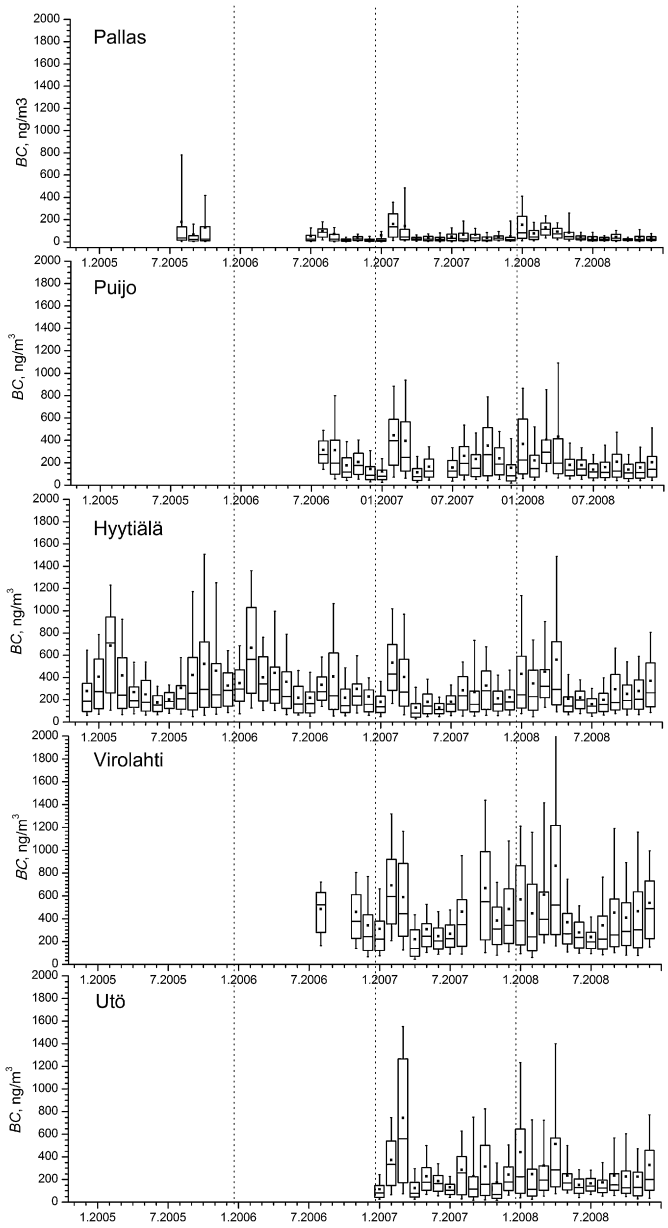

Fig. 3. Aerosol black carbon at the background stations in Finland. 10 % percentile (error bar), 25 % percentile (box bottom), median (horizontal line), mean (rectangle), 75 % percentile (box top), and 90 % percentile (error bar) calculated from hourly averages are presented for each month. Only months with data coverage > 50 % are considered.

3.3. Relation of BCe to other measured quantities

The most important meteorological quantity related to BC*e* was the wind direction illustrated in Fig. 2. The highest BC*e* concentrations were observed during southerly winds (wind sectors from roughly 120–270°). In addition to possible local and regional sources, this indicates the direction of long-range-transported BC. No clear relation between BC*e* and any other meteorological quantities were observed, except that the BC*e* concentration had a weak anti-correlation with the temperature. This is likely to be partly due to the lowered boundary-layer height and domestic wood burning during cold weather conditions. Furthermore, high wind speeds were associated with an upper limit to the measured BC*e* concentrations, due to effective mixing of air. During the wintertime, on average, temperatures were at their lowest and wind speeds at their highest, having compensating effects on BC*e* concentrations.

The $PM_{2.5}$ concentration was measured at three stations. In Virolahti nearly 10% of the total $PM_{2.5}$ mass was BC*e* (See Supplementary material). The average percentage of BC*e* in $PM_{2.5}$ varied from an autumn high of 9.3% to a summer low of 4.1% in Hyytiälä, and from an autumn high of 6.5% to a summer low of 5.0% in Utö. High BC*e* fractions are typical for biomass burning unlike for urban emission (Schwarz et al., 2008). As open biomass burning rarely occurs during wintertime, it is likely that the high BC*e* to $PM_{2.5}$ mass ratios observed in Virolahti and Hyytiälä during the winter are at least partly due to influence of domestic wood burning.

3.4. Source region analysis

At each station the prevailing trajectory direction was 240–300° with about 35% contribution. This is the clean sector from the Atlantic Ocean. During winter, the portion of southerly trajectories increased due to the Arctic front moving to more southern latitudes. More importantly, the length of the southerly trajectories increases during winter. In the summer, the average length of trajectories with main direction in the 150–210° was 3055 km while in the winter the average length was 3670 km. The difference between these southerly summer and winter trajectory lengths was highest at Pallastunturi (1035 km) and lowest at Utö (200 km). A source region analysis based on backward trajectories was performed as described in Section 2.2. After checking that the analysis did not differ significantly for any individual station, the full data set for all the stations was used.

The relative black carbon concentrations of the source regions were determined for each of the four seasons: spring, summer, autumn, and winter (Fig. 4). The source areas of BC*e* seemed to reside mostly in Central and Eastern Europe.

During the spring and summer, increased source contribution could be seen in Eastern Europe. During this time of the year the land in the region is cultivated by agricultural fires and forest fires occur often, too. During the winter, the source region emphasis moves towards south due to evolution of the Arctic front, allowing strong anthropogenic emissions to be transported to the Subarctic. Furthermore, the contribution from St. Petersburg could be observed throughout the year. Compared to known anthropogenic emission inventories (Schaap et al., 2004), we find a higher fraction of source areas in Eastern Europe. This indicates the importance of open biomass burning sources as well as the general pathways of air masses.

The source region analysis made in this paper can be assumed to be only qualitative, as there are no deposition schemes taken into account. Furthermore, it emphasizes the sources that are important from the point of view of our measurement locations, and thus does not represent the actual emission strengths. However, the analysis does give an implication that trans-boundary transport is an important issue. If model studies of BC were to be conducted for the subarctic and Arctic regions, the emissions should be considered as far as from the Mediterranean areas.

3.5. Pollution episodes of BCe

While pollution episodes of particulate matter have been studied quite extensively in Finland during the recent years (see Niemi et al., 2009, and references therein), black carbon concentrations have been reported for only few individual episodes (Sillanpää et al., 2005; Saarikoski et al., 2007). Here, BC*e* pollution

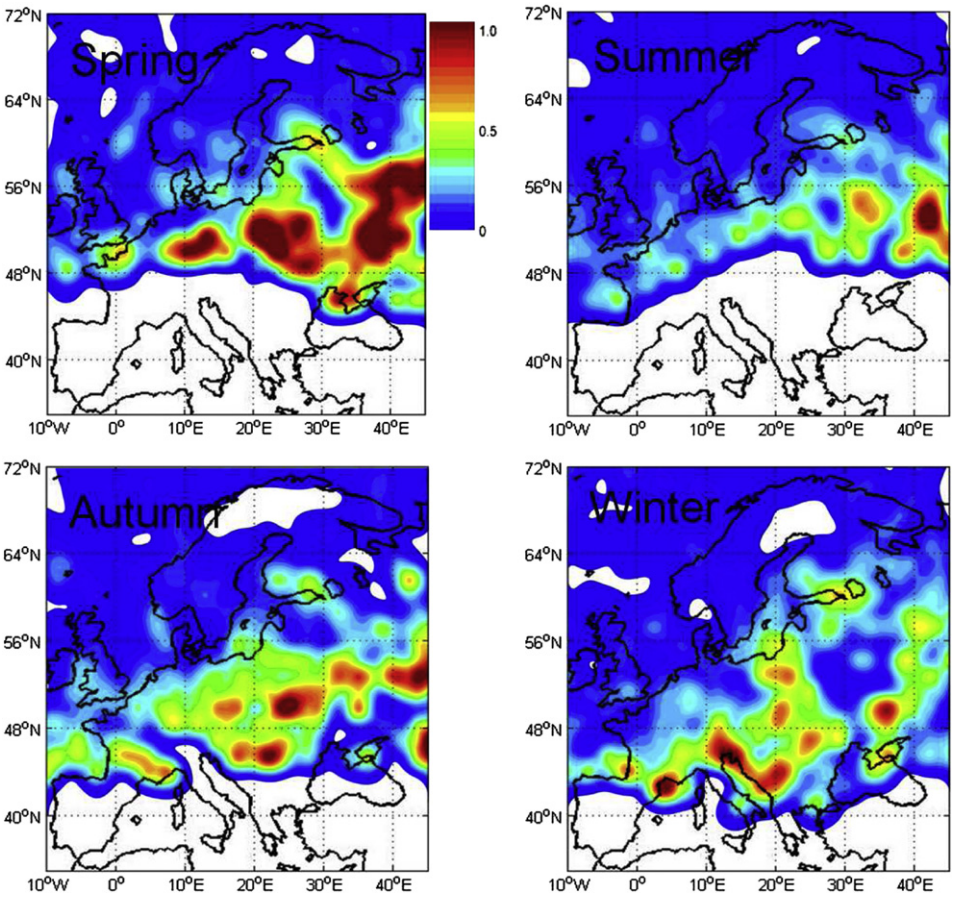

Fig. 4. Source region maps according to different seasons. Color scale in a.u. White color means there was an insufficient number of trajectories (<10) from the area.

episodes were determined for each station separately. There are no clear guidelines on how pollution episodes should be defined. In principle, any criterion should first discriminate the background concentrations. Further on, the episode should last long enough not to be mixed with any possible short time contaminants. Following the approach by Niemi (2007), we classified a pollution episode as such, if the 24-h running average of the BC*e* was at least three times the mean concentration of the prevailing season. Furthermore, episodes had to be at least 24 h apart from each other to be counted as separate.

An overview of the observed pollution episodes is presented in Table 3. Episodes were observed most frequently at Utö in winter, mostly due to the proximity of the station to the southerly source regions, and the fact that during other times, the concentrations were relatively low. Consistent with general concentration levels, the episodic concentrations were highest in Virolahti. A high number of pollution events were observed at Pallastunturi in the summer, mostly because of the otherwise very low background concentrations. Due to our definition, a "pollution episode" at Pallastunturi may actually be considered quite clean at another station.

Table 3
Average number, #, of BC pollution events observed at each background station per year together with their average concentration.

	Pallastunturi		Puijo		Hyytiälä		Virolahti		Utö	
	#	ng m^{-3}	#	ng m^{-3}	#	ng m^{-3}	#	ng m^{-3}	#	ng m^{-3}
Spring	2.3	491	2.5	1304	2.3	1427	2.5	1516	2.5	1326
Summer	3.5	275	1.0	694	1.0	980	1.5	1450	2.0	644
Autumn	2.8	249	2.3	850	1.8	1291	1.7	1787	4.0	939
Winter	2.4	355	2.6	878	2.5	1367	1.7	1545	4.5	1008
Annual	11.0	325	8.4	956	7.6	1317	7.4	1590	13.0	994

The spatial distribution of the episodes was further studied. Only times when all the stations were active were chosen for analysis. By comparing the backward trajectories from different stations during simultaneous pollution events, we confirmed that the air mass arrived from the same source area. Of the total of 34 episodes observed, 40% were seen only at a single station: Pallastunturi, Utö or Virolahti. 9% were observed at all the stations, and rest of the episodes were observed at 2 to 4 stations. If the episode was observed at two stations, these were typically Pallastunturi and Utö, or Utö and Virolahti. Otherwise, Pallastunturi was isolated from episodes that were seen at other stations. During simultaneous episodes, Virolahti had the highest concentrations, on average about 1800 ng m^{-3}. The concentrations were reduced to about 80% at Hyytiälä, 70% at Utö, 60% at Puijo and 20% in Pallastunturi. An example of elevated BC*e* concentrations during an episode can be seen in Fig. 5a. The episode was a result of intense forest fires in Russia, close to the Belarus border early April 2008. The BC from the fires was subsequently transported to southern and central Finland (Fig. 5b). The episode caused increased BC*e* concentration for ten days. Peak concentrations occurred on 2.4.2008, reaching about 3000 ng m^{-3} at all stations except Pallastunturi, which was not in the route of this polluted air mass.

In order to track the nature of the pollution episodes, the FLEXPART model (Stohl et al., 1998, 2005, Stohl and Thomson, 1999), the basic FLEXTRA trajectories, MODIS fire records with FIRMS Web Fire Mapper (http://firefly.geog.umd.edu/firemap/) were used. If an event-time trajectory traveled through a considerable fire source, the event was categorized accordingly.

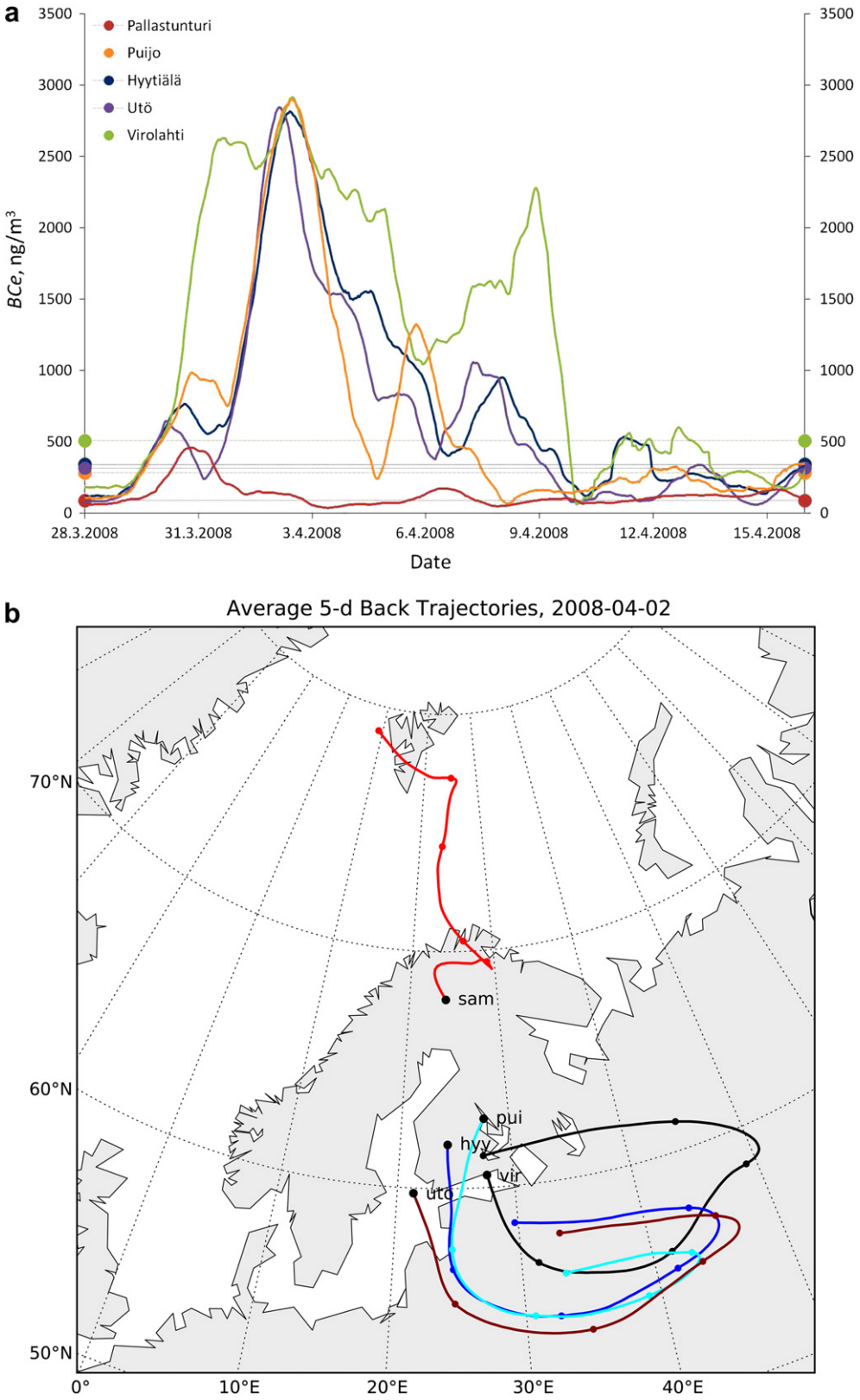

Fig. 5. a. 24-h running average of BC*e* during a pollution episode. Horizontal lines are spring averages for each station. b. Representative backward trajectories for each station on 2.4.2008.

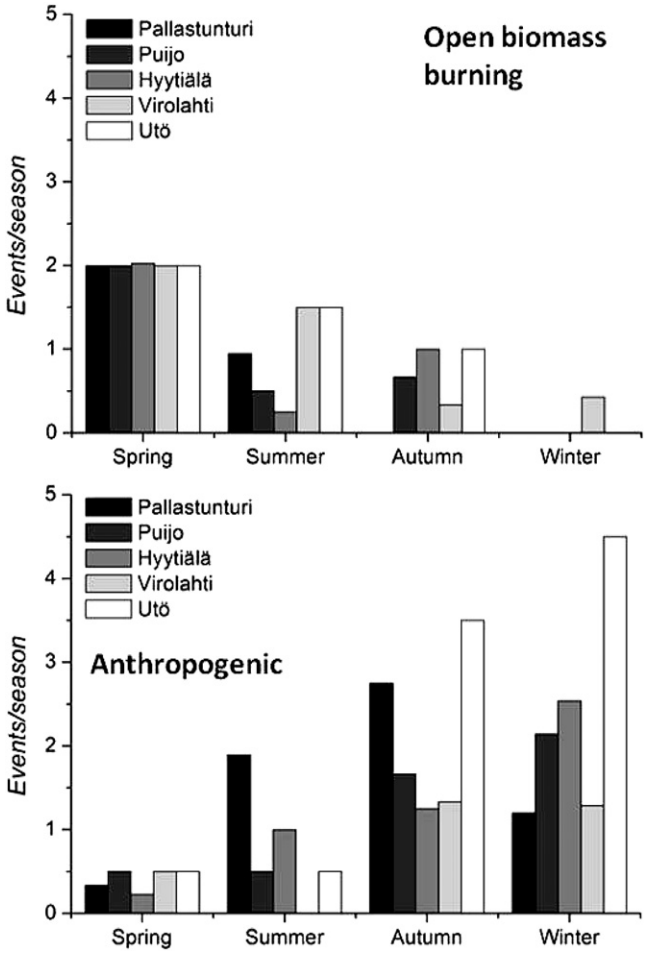

Fig. 6. The average number of open biomass burning events and non-fire anthropogenic events observed at the stations during different seasons.

From the analysis with both methods, the pollution episodes observed at the Finnish background stations were either a result of long-range transport of anthropogenic pollution from Central or Eastern Europe, or of biomass burning emissions from agricultural or forest fires mainly in Eastern Europe. Out of all the episodes seen in the BC*e* data in Finland, about 62% were a result of non-fire anthropogenic sources (no significant signal in the FIRMS Web Fire Mapper) and 36% from open biomass burning sources (intense signal in the FIRMS Web Fire Mapper). The remaining 2% were undefined and probably resulted from local sources. The open biomass burning episodes were most often observed in spring (Fig. 6).

Non-fire anthropogenic episodes were most frequent during the winter. This is an expected result, as the winter is anyway more susceptible to southerly air masses. The average elevated 24-h concentrations from anthropogenic sources were nearly equal to those from the open biomass burning; the mean from all the stations was 1035 ng m^{-3} for anthropogenic episodes and 1065 ng m^{-3} for open biomass burning episodes. A bigger difference was seen if maximum concentrations during the episodes were compared: open biomass burning yielded ~20% higher maximum BC*e* concentrations (1640 ng m^{-3}) averaged overall the stations than anthropogenic episodes (1350 ng m^{-3}).

4. Conclusions

Aerosol black carbon was measured at five different background stations in Finland with the longest data set from Hyytiälä covering a period from 8 December 2004 to 31 December 2008. BC*e* concentrations measured in Southern Finland, Virolahti were the highest, and in Northern Finland, Pallastunturi the lowest. At all the stations, highest concentrations were observed during the spring and the winter, and the lowest ones during the summer.

None of the major Finnish cities seemed to have a substantial effect on the measured BC*e* concentrations. Instead, some increased BC*e* values were probably from local or regional domestic wood combustion. On the basis of statistical trajectory analyses, the source areas of long-range-transported BC seemed to reside mostly in Central and Eastern Europe. During the spring and summer, increased source contribution was seen from the Eastern Europe, which was mostly due open biomass burning in the region. Due to evolution of the Arctic front, the source region emphasis moved toward south during the winter, allowing the strong anthropogenic emissions from Central Europe to be transported to Finland. In Pallastunturi, this mechanism together with stable Arctic air may create a situation of Arctic haze. During favorable transport conditions, the long-range-transported BC showed elevated values filling the characteristics of pollution episodes.

This study demonstrates the importance of long-range transport in establishing background BC*e* concentrations in northern Europe, with source regions extending down to southern Europe during the wintertime. Furthermore, over our study region, the average BC*e* concentration field was shown to display a strong decrease (a factor of 4–5) in the south–north direction and less so (factor of about 2) in the east–west direction. Our findings and data are useful for evaluating how regional and large-scale atmospheric models are able to simulate the transport of BC to Arctic areas, which is essential when assessing the role of BC in Arctic climate change.

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Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atmosenv.2011.04.026.

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