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Interim Report **IR-11-007**

Assessing Transport of PM Pollution from Europe to the Arctic

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Contents

Abstract

Arctic pollution is a topic of high priority on the global agenda, especially due to its connection with the rapid warming the Arctic is experiencing. During recent decades, the Arctic has warmed about 1°C per decade, which is almost double the global average warming rate. Part of the warming is due to the deposition of black carbon to the ice, which decreases the surface albedo and thus leads to melting of the ice.

This study investigates the European origins of Arctic primary fine particulate matter ($PPM_{2.5}$) and black carbon aerosol (BC). Five years of monthly averaged output from the EMEP Chemical Transport Model are analyzed to calculate the source-receptor relationships of $PPM_{2.5}$ from European countries to the Arctic. These source-receptor relationships are then applied to BC emissions inventories in order to investigate the relevance of different source regions of Arctic BC both for the present and for future scenarios. Russia (European part) and Norway are identified as the largest European contributors to Arctic $PPM_{2.5}$ and BC, together accounting for more than 50 percent of the European $PPM_{2.5}$ input to the Arctic. The relative importance of these two countries for future contributions to Arctic BC depends on the emissions scenario used. As a rather unexpected result, ship emissions from the north-east Atlantic Ocean are among the largest contributors to Arctic PPM and BC, and are predicted to rank third by 2030. On a sectoral basis, emissions from the household sector dominate over industrial and other emissions. In addition to the emissions already accounted for in the EMEP model runs, vegetation fires are shown to play a significant role.

Furthermore, the variability of Arctic $PPM_{2.5}$ levels, transfer coefficients, and contributions is investigated. Large annual cycles of sectoral contributions can be observed, which are partly due to annual cycles of emissions and partly to meteorological variability. The North Atlantic Oscillation is shown to influence Arctic PPM2.5 concentrations in the sense that under highly positive NAO conditions, Arctic PPM levels are significantly enhanced by up to factors of 20 and more, as compared to highly negative NAO conditions.

Acknowledgments

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About the Author

Gregor Kiesewetter studied physics at the University of Vienna, Austria, from where he graduated in 2006. He is currently enrolled as a second-year PhD student in the Atmospheric Modeling Group at the Institute of Environmental Physics, University of Bremen, Germany.

At the time of this work, Gregor Kiesewetter participated in the Young Scientists Summer Program (YSSP) at IIASA.

Assessing Transport of PM Pollution from Europe to the Arctic

Gregor Kiesewetter

1 Introduction

1.1 Arctic Pollution and Climate Change

The subject of Arctic pollution has received increased research interest during recent years (e.g. Quinn et al. (2007, 2008), Shindell et al. (2008), Koch and Hansen (2005)), mainly due to its inherent connection with the rapid warming of the Arctic. Arctic surface temperatures are increasing nearly twice as fast as the global average (IPCC, 2007), and Arctic sea ice is shrinking at an alarming rate. The summers of 2006, 2007 and 2009 have seen the least extent (and also mass) of sea ice in the historical record so far. This decrease of sea ice leads to a strong decrease of surface albedo (from highly reflecting ice to highly absorbing ocean) and thus triggers a positive climate feedback cycle resulting in further warming. Loss of the Arctic sea ice has been identified as one possible climate 'tipping point' by Lenton et al. (2008), which, once crossed, may lead to unpredictable and irreversible consequences for the global climate.

Arctic climate is influenced by several mechanisms, among them forcing by long-lived well-mixed greenhouse gases (WMGHG, e.g. CO_2), forcing by short-lived pollutants and aerosols, and deposition of absorbing aerosols on ice or snow. The first mechanism describes what is known to the public as the "ordinary" greenhouse effect, acting globally independent of the location. Short-lived pollution is of concern to regions within reach of pollution sources, which is definitely the case for the Arctic. The effects of suspended aerosols are partially dependent on the albedo of the planetary surface below (and thus partially specific for the Arctic). Deposition of light-absorbing aerosols, especially black carbon, to ice decreases the albedo of the highly reflective surface and thus contributes to melting of the ice. This deposition effect is truly unique to ice-covered areas.

An overview of the mechanisms is given in Figure 1-1 (taken from Quinn et al. (2008)). It is the combination of these effects which is responsible for the increased Arctic warming rates.

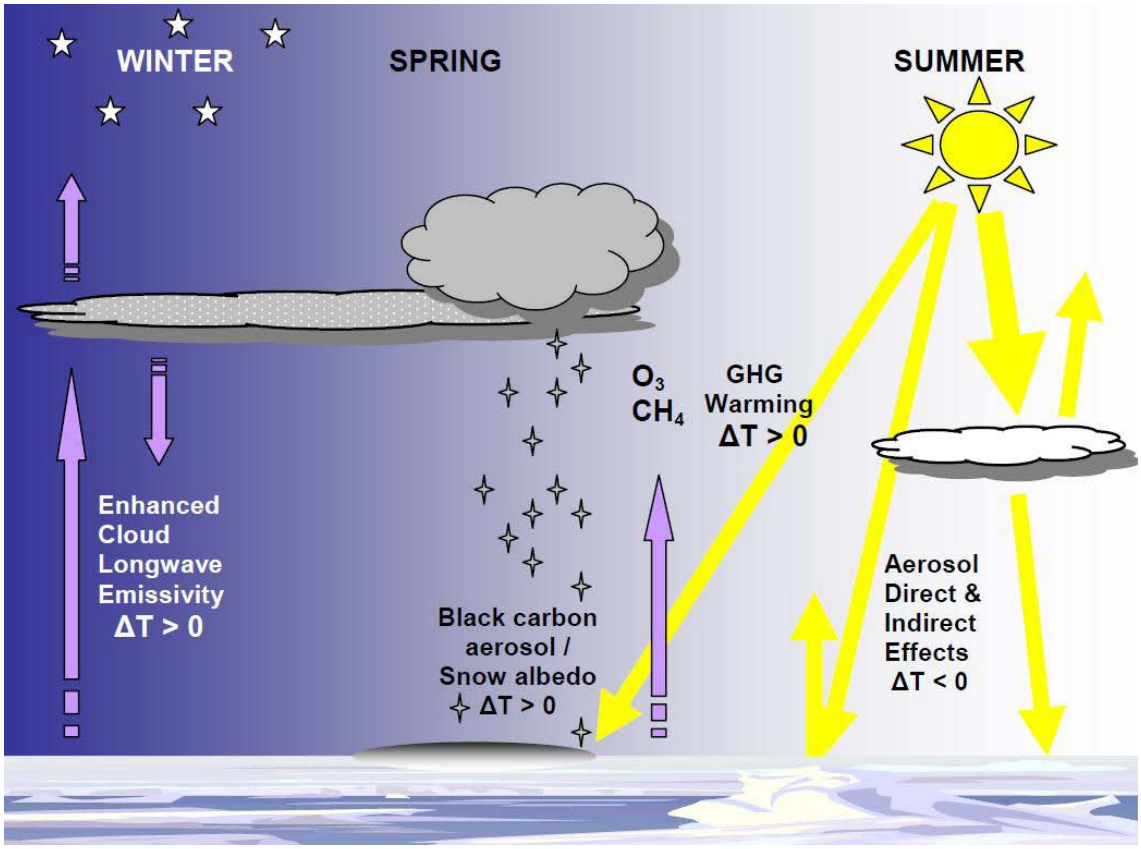

Figure 1-1: Forcing mechanisms in the Arctic environment. Figure taken from Quinn et al. (2008).

Since part of Arctic warming is just a manifestation of global average warming, decreasing global warming by decreasing well-mixed greenhouse gas emissions is an important factor in addressing Arctic warming. But due to their long residence time in the atmosphere, reductions of well-mixed greenhouse gases alone may not be effective in time to stop the rapid melting of the Arctic. Hence, it has been proposed that in addition, targeting the short-lived climate forcing agents (i.e., especially aerosols) may not only be effective but also necessary to delay Arctic warming, as their radiative forcing has been found to exceed that of WMGHGs by a factor of 1.3 to 5, depending on the season (Shindell (2007)), and in their case effects of reductions can be felt immediately. For these reasons, it is important to assess the sources of current short-lived pollution in the Arctic, and examine future development in order to arrive at conclusions about the sufficiency of current pollution control policies.

Short-lived pollutants relevant for Arctic climate include tropospheric ozone, methane (with a lifetime of about nine years not exactly “short-lived”), and aerosols (Quinn et al (2008)). Since this study is focused on black carbon, only the role of aerosols is discussed here. A comparison of the radiative forcing strengths of different short-lived climate agents is shown in Figure 1-2 (taken from Quinn et al (2008)).

Quantification of the role of tropospheric aerosols for climate forcing in general is challenging, due to the different physical properties of the particles themselves (e.g. reflectivity), and the fact that they can act through a variety of different effects. Aerosol particles influence radiative forcing directly through reflection and absorption of solar and infrared radiation in the atmosphere (direct effect). Some aerosols cause a positive forcing while others cause a negative

forcing. The direct radiative forcing summed over all aerosol types is negative, both globally and for polar regions, although the black carbon component itself produces a positive forcing. In addition to the direct effect, aerosols also act through indirect effects, such as causing an increase in cloud longwave emissivity. These effects are partly dependent on the altitude of the particle as well as on the albedo of the reflecting surface below.

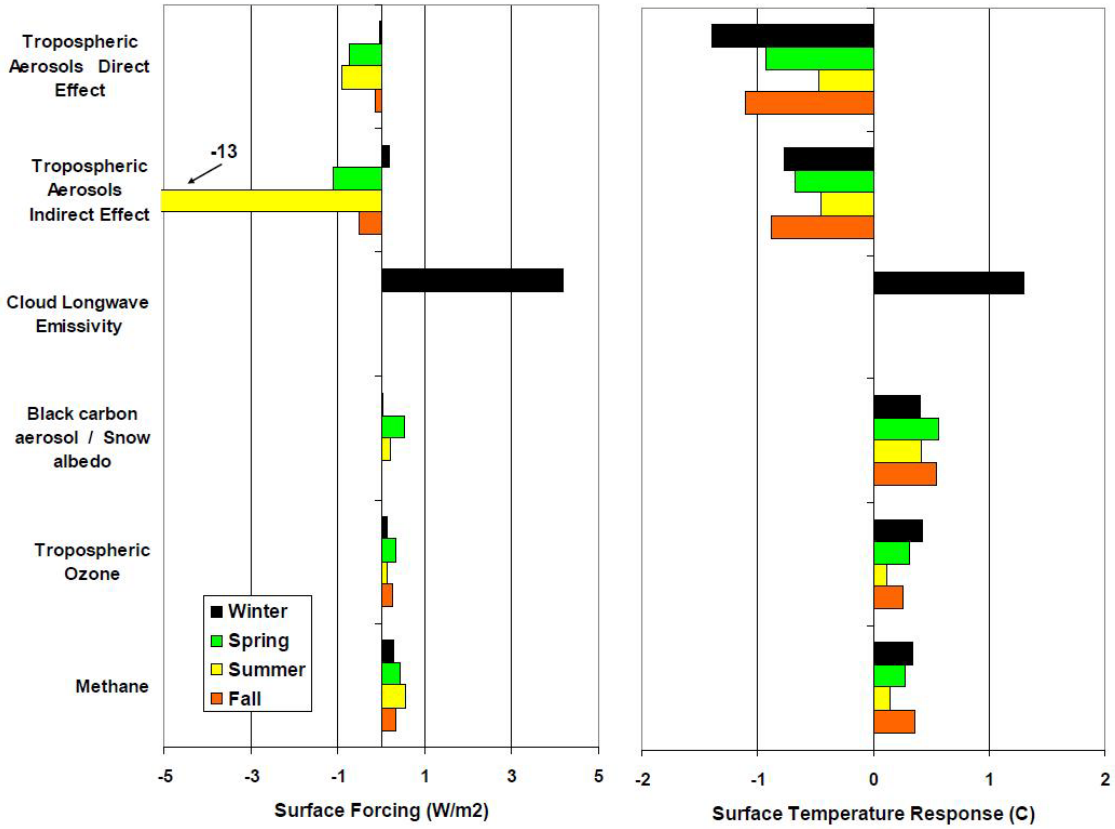

Figure 1-2. Seasonally averaged values of radiative forcing and temperature response at the surface (FS and 1TS, respectively) for 60 to 90°N. Values for Cloud Longwave Emissivity are not seasonal averages as they only include times when pollution aerosol and clouds were coincident. Figure taken from Quinn et al. (2008).

1.2 Black Carbon

Black carbon, better known to the general public as “soot”, is traditionally defined as the light absorbing portion of carbonaceous aerosols. However, a variety of partly overlapping or conflicting names can be found in the literature, referring to roughly the same substance (depending on the context). While “black carbon” is, according to its name, black, recently light-absorbing carbonaceous aerosol that is not black has been discovered (Andreae (2006)), leading to a discussion about the necessity of a different definition. Nevertheless, this paper will stick to the “sloppy” definition given above.

Black carbon is derived from the incomplete combustion of fossil fuels (primarily coal and diesel) and from the burning of biomass or biofuels. Its presence in remote locations was discovered in the 1970s and 1980s (Levin and Lindberg (1979); Heintzenberg (1982), Andreae (1983)). Black carbon usually takes the form of chains of a typical length of around 400 nanometers, which makes it distinctly smaller than most of the particles contained in $PPM_{2.5}$ and may lead to offsets in transport efficiency since it has a longer atmospheric lifetime than most of $PPM_{2.5}$. In this study, transfer coefficients for black carbon are assumed to resemble those of $PPM_{2.5}$ reasonably well.

Globally black carbon contributes to climate warming. In the Fourth Assessment Report of the IPCC (IPCC, 2007), its direct radiative forcing is estimated in the range between (+0.25 ±0.08) W/m^2 to (+0.44±0.13) W/m^2. However, as described above, the net climatic effect is dependent on the surface albedo below. For instance, the presence of BC in the atmosphere above highly reflective surfaces such as snow and ice, or clouds, may cause a significantly stronger positive radiative forcing. In addition, as already mentioned, BC strongly decreases the surface albedo when deposited to snow and ice, which is especially relevant for polar regions.

Bond et al. (2004) estimated the total current global emission of BC to be approximately 8 TgC yr^{-1}, with contributions of 4.6 TgC yr^{-1} from fossil fuel and biofuel combustion and 3.3 TgC yr^{-1} from open biomass burning, and estimated an uncertainty of about a factor of two.

1.3 Sources of Arctic pollution: State of knowledge

Several papers have investigated the source regions of Arctic PM pollution on a hemispheric or global scale. In this context, “source regions” usually refer to continents or parts of them, but not individual countries (a notable exception is a recent study by Tsyro (2009), who assessed European source regions of Arctic PM for the meteorological year 2006). Considerable differences regarding the relative importance of different emission regions have been reported, and although the findings seem to converge during recent years, the overall picture is not yet finalized. In this section, a short overview of the research efforts of various groups during recent years is given.

Koch and Hansen (2005) used the GISS modelE general circulation model (GCM) (Schmidt et al., 2006) to investigate the origins of Arctic BC and reported emissions from South Asia to be the predominant source of Arctic soot in the upper troposphere and at least comparable to European and North American sources near the surface. The authors argued that notwithstanding the geographical proximity of European sources to the Arctic, low-level transport of pollution from Europe to the Arctic is not efficient as most of the PM is washed out before reaching high latitudes due to predominant weather conditions. Contrary to this, using the FLEXPART Lagrangian particle dispersion model, Stohl (2006) found European BC contributions to exceed Asian contributions by far. In addition, he argued that due to the large difference in potential temperature between South Asian and Arctic lower troposphere, isentropic transport of South Asian pollution to the Arctic surface should be almost impossible.

In recognition of these conflicting results, Shindell et al. (2008) recently performed a multi-model intercomparison study to resolve the case. Although the individual models used (eight in total) showed considerable differences in absolute values, the relative importance of different source regions was similar. The majority of models found European emissions dominant for Arctic BC near the surface, while soot from South Asia dominated in higher altitudes. Average values from the model ensemble yielded 76% contribution to surface BC from Europe, 14% from East Asia, 9% from North America, and only 1% from South Asia (see Figure 1-3).

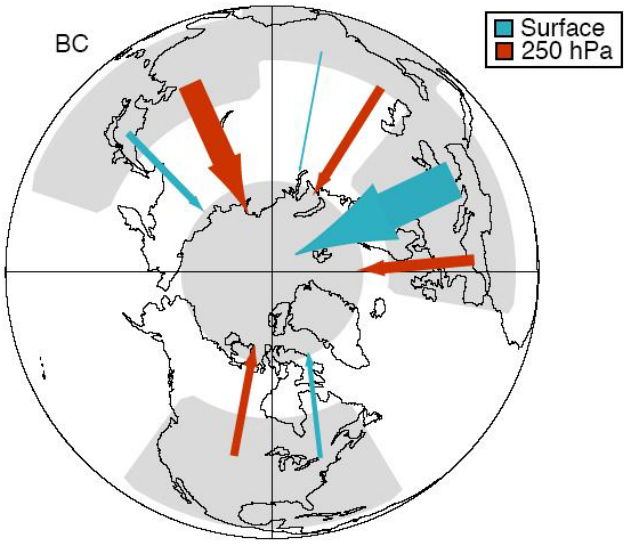

Figure 1-3. Relative importance of different source regions to annual mean Arctic BC concentration at the surface and in the upper troposphere (250 hPa). Figure taken from Shindell et al (2008).

1.4 Outline of this paper

In this study, the transport of black carbon from Europe to the Arctic is investigated by an analysis of a series of model runs of the EMEP model. Source-receptor relationships for primary fine particulate matter ($PPM_{2.5}$) from European source regions to the Arctic are calculated and applied to present and future emissions scenarios of BC, in order to determine present and future sources of Arctic BC. Since deposition of BC is not accounted for in the model runs available to this study, all analysis refers to suspended aerosol.

At this point it should be emphasized that this paper deals only with the European contribution to Arctic BC. Due to the geographical domain of the EMEP model used, no statement whatsoever can be made about the relative importance of emissions from other continents as compared to Europe. In fact, this paper can be viewed as complementary to the above-mentioned global studies, as it seeks to identify the European source countries and sectors of Arctic BC and assess their relative importance.

As mentioned above, a recent study by Tsyro (2009) assessed European source regions for Arctic PM pollution for the meteorological year 2006, using a slightly different version of the

EMEP model. This Interim Report, though partly overlapping with Tsyro (2009) in its research objective, takes a different approach in the sense that it takes into account five meteorological years, and also analyses the effects of future BC emissions scenarios.

Two different emissions scenarios are considered in order to derive an estimate for future changes in European contributions to Arctic BC pollution, one of which assumes reductions in emissions from former USSR countries while the other assumes largely business as usual.

In addition to national emissions, the contributions of ship emissions and vegetation fires are quantified.

Finally, the annual cycle and inter-annual variability of Arctic PPM levels as well as contributions is investigated.

Chapter 2 provides an overview of the data and methodology used in this study. In chapter 3, the results concerning the contributions of European countries to Arctic $PPM_{2.5}$ and BC are described. Chapter 4 deals with the variability of pollution transport to the Arctic, describing the annual cycle of contributions and trying to establish the role of the North Atlantic Oscillation. Chapter 5 attempts to sum up the findings of this study and draw conclusions.

2 Data and Methodology

This chapter provides an overview of the data and methodology used in this study, i.e., the EMEP Chemistry Transport Model (section 2.1), the analysis of its output (section 2.2), and the emission inventories and scenarios used (section 2.3).

2.1 The EMEP Eulerian Model

This study relies entirely on the analysis of gridded output from the EMEP (European Monitoring and Evaluation Programme) tropospheric model. Thus, a short overview of the model is provided here. In section 2.1.1 the model, its domain and treatment of transport are described. In section 2.1.2 the emission inventories used in the model are discussed briefly, as they later play an important role in the calculation of source-receptor relationships. The model output used in this study is briefly described in section 2.1.3.

2.1.1 Overview

The EMEP unified model is a Eulerian tropospheric chemistry transport model which has been developed at the Meteorological Synthesizing Center West (MSC-W). A detailed description is provided by Simpson et al. (2003). In the version used for this study, the model domain covers the whole of Europe, parts of North Africa, a large part of the North Atlantic Ocean, and a significant part of the North Polar Sea. It uses a polar stereographic projection with a grid

square size of 50 × 50 km (true at 60°N), with 132 × 111 grid cells in total. In the meantime, the domain has been expanded to the East, now covering a significant part of Russia and most of the North Polar Sea. In the vertical direction, the model uses 20 levels on sigma-coordinates (i.e., pressure levels parallel to the surface at low altitudes and gradually becoming independent of topography at higher altitudes), covering the entire troposphere from the surface to 100hPa.

Advection is forced by external reanalyzed wind fields from the PARLAM-PS Numerical Weather Prediction Model at the same spatial resolution with a temporal resolution of three hours.

2.1.2 Emissions

The emissions input used by the EMEP model consists of gridded annual national emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x=NO+NO_2), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), and particulates ($PM_{2.5}$, PM_{10}). These emissions are provided for ten anthropogenic source-sectors denoted by so-called SNAP codes given in Table 2-1.

Table 2-1: SNAP emissions sector codes

SNAP sector No.	*Name*
1	Combustion in energy and transformation industries
2	Non-industrial combustion plants
3	Combustion in manufacturing industry
4	Production processes
5	Extraction and distribution of fossil fuels and geothermal energy
6	Solvent and other product use
7	Road transport
8	Other mobile sources and machinery
9	Waste treatment and disposal
10	Agriculture
11	Natural

Emissions are distributed temporally according to monthly (Jan.-Dec.) and daily (Sun.-Sat.) factors derived from data provided by the University of Stuttgart (IER). These factors are specific to each pollutant, emission sector, and country, and thus reflect the very different climates and hence energy-use patterns in different parts of Europe.

Figure 2-1 shows an overview of the (annually averaged) gridded emissions of primary $PM_{2.5}$ used as input data for the model runs that are analyzed in this study (note the remark concerning Ukrainian emissions in the figure caption). Annual average numbers for all countries are given in Table 6-2.

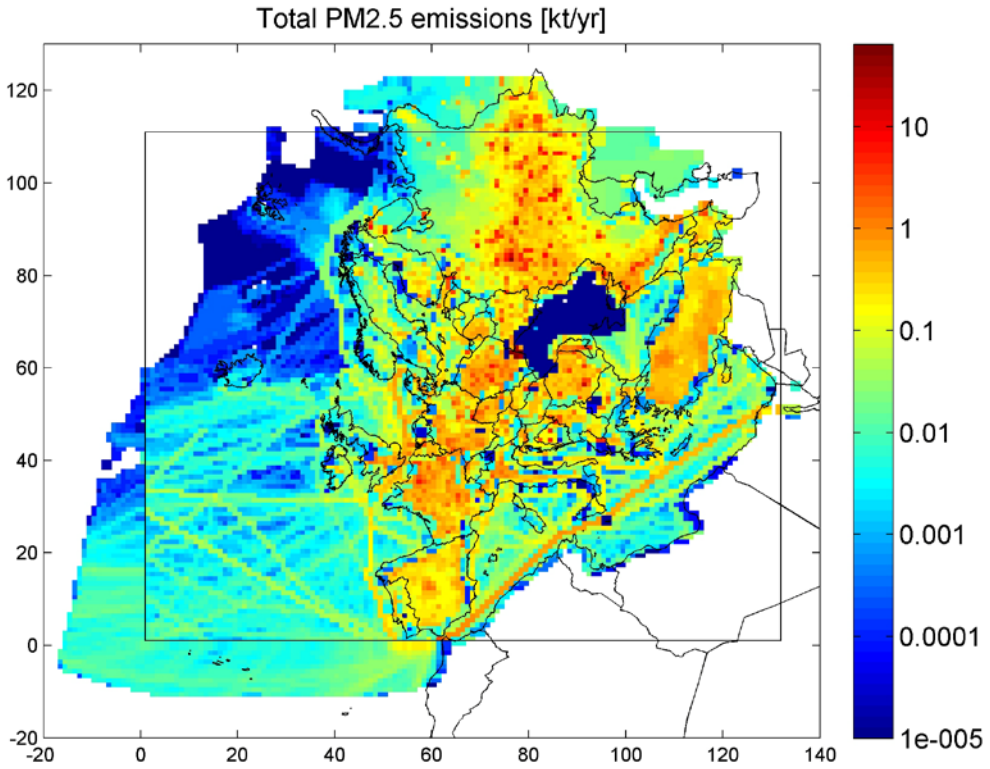

Figure 2-1. Emissions of PM2.5 used in the EMEP model runs. The emissions are supplied on a larger domain than the actual official EMEP domain, for which the model output is available. The official EMEP domain is indicated as a rectangle. Ukrainian emissions show some spatial inconsistency as they are obviously not distributed realistically throughout the country, but rather concentrated in a few grid points. Their sum, however, matches the tabled country total well (as it is the case for all other countries).

In Figure 2-2 the annual cycle of $PM_{2.5}$ emissions of the largest emitting countries is shown. It is obvious that due to different sectoral composition of the emissions and due to different geographical locations causing different behavior of emitting actors, the annual emission cycle varies considerably among countries.

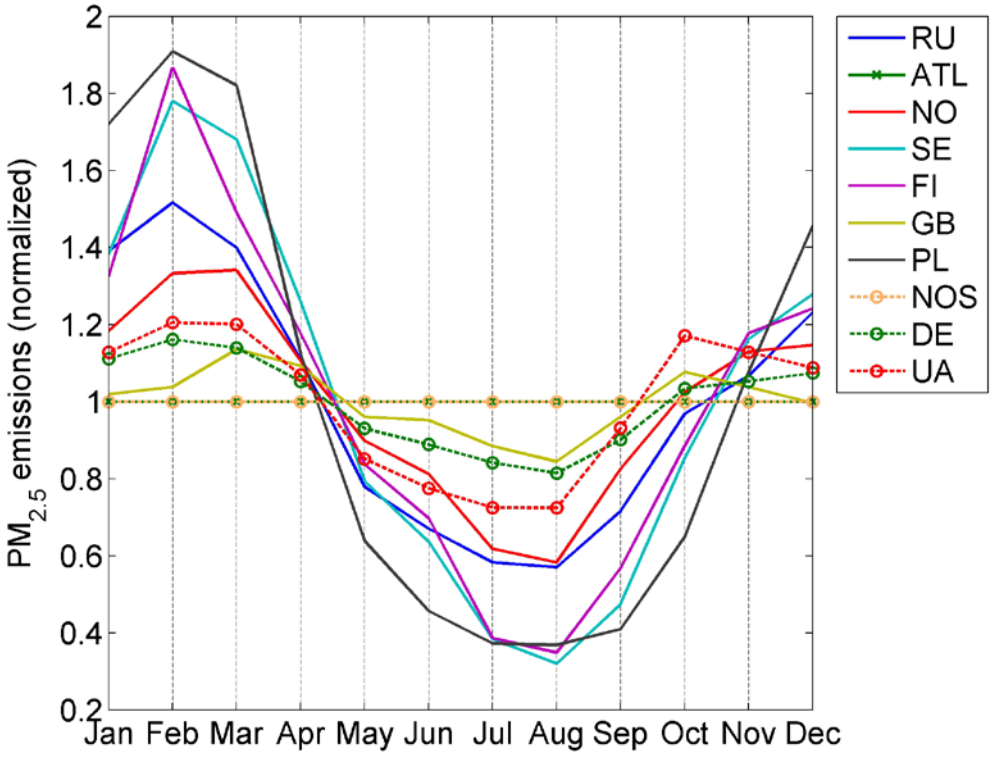

Figure 2-2. Annual cycle of PM2.5 emissions from ten regions (countries + seas). Emissions were normalized by the country annual mean emissions to show the different shapes of annual cycles (note, e.g., the constant emissions from the North Sea (NOS) and Atlantic (ATL)). Full names of the regions are provided in Table 6-1. Regions shown here as examples were selected by their contributions to Arctic $PPM_{2.5}$ (see section 3.2).

It should be emphasized that the EMEP model not only includes continental emissions, but also ship emissions from predefined sea regions (North East Atlantic Ocean, North Sea, Baltic Sea, Mediterranean Sea, Black Sea). Each sea region was treated as a separate source region, in the same way as individual countries, in the model runs used to analyze source-receptor relationships. Contrary to their land-based counterparts, emissions from sea regions do not follow an annual cycle in the EMEP model.

2.1.3 Model output used in this study

This study makes use of a large assembly of EMEP model runs, which were conducted by the Meteorological Synthesizing Center West (MSC-W) in Oslo with the specific purpose of providing source-receptor relationships for the RAINS/GAINS-Europe model developed at IIASA (e.g. Klaassen et al., 2004). For this purpose, a "base-case run" as well as "reduction runs" for all 44 European countries and sea regions were conducted. While for the base case all emissions are applied as described in the previous section, a reduction run for country A implies

that emissions of a given pollutant for country A are reduced by a certain percentage (in this case, 15 percent) while emissions from all other countries remain unchanged. This country-specific reduction then allows the pollution in a certain gridpoint to be attributed to its country of origin, as described in section 2.2.

In total, EMEP model output was available for five meteorological years (1996, 1997, 1998, 2000, 2003) as monthly means of pollutant concentrations estimated at a height of 1m. Out of the full set of variables, only the $PPM_{2.5}$ tracer fields were used in this study.

2.2 Source-Receptor Relationships

Source-receptor relationships, also called transfer coefficients, are the core quantity in this study. They provide a quantification of the influence a specific emitting region has on the total pollutant concentration at a selected grid cell, or how efficiently pollution from a certain source region is transported to a target location (grid cell).

In the general case, pollutants of interest (such as ammonia, ozone, etc) may be influenced by emissions of several precursor substances, and thus cross-dependencies usually have to be taken into account. However, with black carbon, the situation is easier as it is emitted and dispersed, but not influenced by chemical reactions once in the air. It is treated as part of the primary particulate matter 2.5µm ($PPM_{2.5}$) tracer in the EMEP model, which constitutes the smallest class of PM treated in the EMEP model. Although BC itself is usually of submicron size, the source-receptor relations for $PPM_{2.5}$ give a good approximation of those of BC.

Let us denote the amount (concentration) of a pollutant *x* at a grid point *i* as a function of the emissions *e* of country *c*, plus some natural background x_0,

$$x_i = x_i(e_c) + x_0 \qquad (2.1)$$

In such a 'one-dimensional' case the response of the concentration of *x* at a grid point *i* to a small perturbation in emissions from country *c* can be denoted as

$$\Delta x_{i,c} = \frac{dx_i}{de_c}\Delta e_c \qquad (2.2)$$

(in the general case, Eq. 2.2 would involve partial derivatives with respect to the different emitted pollutants relevant for x). The quantity

$$\alpha_{ic} := \frac{dx_i}{de_c} \qquad (2.3)$$

is henceforth called transfer coefficient (from country *c* to grid cell *i*).

In practice, the change in emissions *de* used in the reduction runs was chosen as 15 percent of the country total emissions, and linearity of the functional dependence $x_i(e_c)$ is assumed so that one reduction run is sufficient and $\alpha_{ic} = const$.

Transfer coefficients for $PPM_{2.5}$ are calculated from every country to every grid point and then averaged over all *n* "Arctic" grid points to arrive at transfer coefficients from all countries to the Arctic,

$$\alpha_c = \frac{1}{n} \sum_{i \in Arctic} \alpha_{ic} \qquad (2.4)$$

The definition of the Arctic is, of course, arbitrary and was varied between north of 68°N and north of 75°N in order to assure independence of the specific geographical choice of Arctic grid points.

Now the total contribution of a country *c* to concentration of *x* in the Arctic is formally an integral,

$$C_c = \int_0^{e_c} \alpha_c d\tilde{e}_c \qquad (2.5)\,,$$

which, however, with the assumption of linearity simplifies to

$$C_c = \alpha_c \cdot e_c \qquad (2.6)\,.$$

The assumption of linearity that was underlying the whole idea is, of course, rather strong. It is not obvious why the change of concentration of a pollutant at some location should respond linearly to a change in emissions in some distant country. However, it is an assumption usually employed in similar studies that within certain bounds the linearity condition is fulfilled. Especially in the case of PPM, no (possibly nonlinear) chemistry is involved. Indeed, the results of this study seem to confirm this assumption very well, as the sum of the linear contributions from all countries matches the total concentration of $PPM_{2.5}$ present in the Arctic to more than 97%, as shown in Figure 3-3. Apart from transported emissions from other continents, which are not considered in the model, there should be hardly any background concentration of $PPM_{2.5}$ in the Arctic.

2.3 BC Emissions Scenarios

Since BC is not treated explicitly in the EMEP model, the transfer coefficients for $PPM_{2.5}$ were applied to BC emissions scenarios in order to arrive at conclusions about contributions to Arctic BC pollution. Emissions scenarios used in this study typically extend to the year 2030, thus allowing forecasts for more than 20 years into the future (assuming that the overall meteorological conditions do not change. For a more detailed discussion of meteorological variability see also chapter 4.2).

Two different scenarios for land-based emissions are used in this study, which are identical for the EU countries but differ in projections of emissions from former USSR countries. It is currently unclear how strict and effective future regulations in these countries will be, and thus the best choice for this study is to explore the effects of an optimistic and a pessimistic scenario. In the following sections, the emissions scenarios used are described in detail.

In addition to land-based emissions, also emissions from sea regions (which are included in the EMEP model) are considered in this study. The respective emissions are taken from the RCP scenario, which is described in section 2.3.4.

In order to estimate the role of vegetation fires (which are not included in the EMEP model runs), projections of present and future emissions from fires are taken from the FT 2000 scenario, which is described in section 2.3.5.

As a general remark, it should be emphasized that BC emission estimates are subject to large uncertainties – e.g. Bond et al. (2004) estimated an uncertainty factor of 2. Results regarding BC in this report can only be as exact as the emission data they are based on; if emission estimates are updated at a later time, also the conclusions drawn in this study may change.

2.3.1 CLE 2007 Baseline (GAINS)

This is an emission scenario that assumes the successful implementation of current legislation (in 2007) but no further changes. It assumes an energy projection that does not meet the objectives of the Climate and Energy (C&E) Package of the European Commission. The scenario employs the PRIMES model baseline projection of November 2007, which illustrates a business as usual case without further climate measures, and an agricultural projection that reflects national perspectives on the development of the agricultural sector that have been provided to IIASA. A detailed description is available in the NEC (National Emissions Ceilings) Report #6 (Amann et al., 2008). As a side note, it should be mentioned here that while the EC C&E Package seeks to curb greenhouse gas emissions, its effect on future BC emissions is small. A scenario which takes into account the C&E Package was only available for a reduced number of years, and since emissions changes with respect to the CLE 2007 Baseline scenario were minimal, it was decided to use the CLE 2007 Baseline scenario as the scenario for European BC emissions.

While this scenario was compiled for the European domain in order to demonstrate effects of European air pollution regulations, the projections of emissions from the former USSR countries do not assume any regulatory policy or technological change. In this sense, the NEC6 CLE Baseline scenario adopts a very pessimistic point of view for these non-EU countries. However, even in the worst case of total absence of regulations and business as usual, some emission reductions may be expected to happen by the export of technology that meets the higher European standards.

Exact numbers (country totals) of the BC emissions under this scenario are provided in Table 6-3 for all scenario years used.

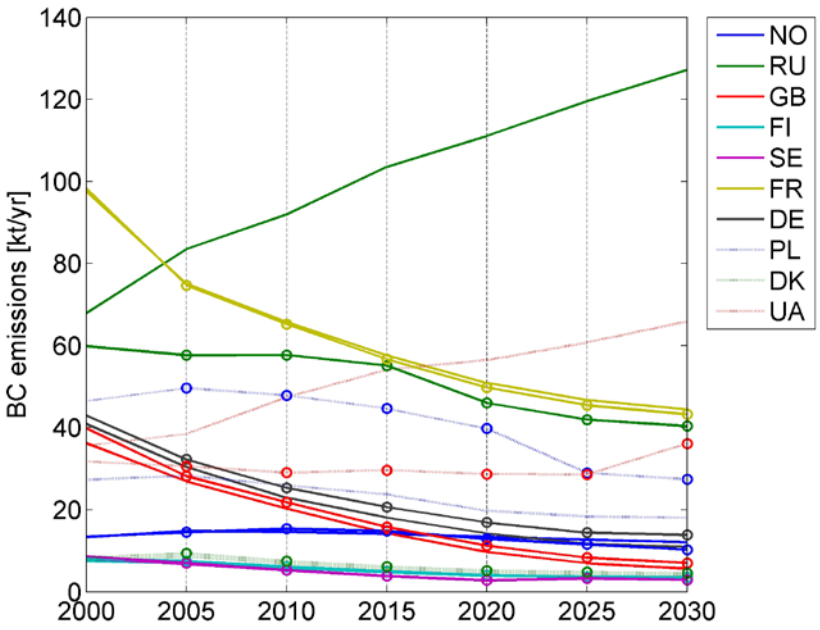

Figure 2-3. BC emissions from the CLE 2007 Baseline scenario (lines without symbols) and the WEO 2008 scenario (lines with symbols). Note the large differences for past emissions, which make the scenarios difficult to compare.

2.3.2 WEO 2008 (GAINS)

This scenario is equivalent to the current policy (CP) baseline scenario with the addition that IEA World Energy Outlook 2008 (WEO 2008) (IEA, 2008) projections are implemented. The original (starting point) scenario was a baseline scenario for the Annex I countries to the Kyoto protocol, and the respective energy pathways were used to provide fuel-sector-regional pattern for the new WEO data.

The emission projections from the WEO 2008 scenario are shown in Figure 2-3, compared to the CLE 2007 Baseline scenario. Since this scenario is not consistent with NEC, it is not 100% comparable with the CLE 2007 baseline scenario described above. Emission inventories used are different, and thus also past emissions do not agree. Nevertheless, the WEO 2008 scenario is of interest to this study since it contains an estimate of future reductions in Russian BC emissions – in contrast to the CLE Baseline, in which Russia as a non-EU member is only included as an external country and no emission reductions are imposed. Since Russia is identified in chapter 3 as one of the most important source regions for Arctic BC, a realistic estimate of future Russian emissions was regarded as important for this study.

2.3.3 Baseline – WEO combined scenario (GAINS)

In order to overcome the discrepancies in emissions estimates between the CLE 2007 Baseline scenario and the WEO 2008 scenario and more explicitly address the differences in future Russian emissions, a combined scenario was created which uses the emissions inventories from the Baseline scenario but applies the reductions in former USSR emissions as used in the WEO

2008 scenario. This scenario is used as an optimistic scenario for comparison with the "pessimistic" CLE 2007 Baseline scenario throughout the following sections and is named "Baseline / RU red". Exact numbers (country totals) of the BC emissions under this scenario are given in Table 6-4 for all scenario years used.

A comparison of the emissions from Baseline and Baseline / RU red scenarios for selected countries is provided in Figure 2-4.

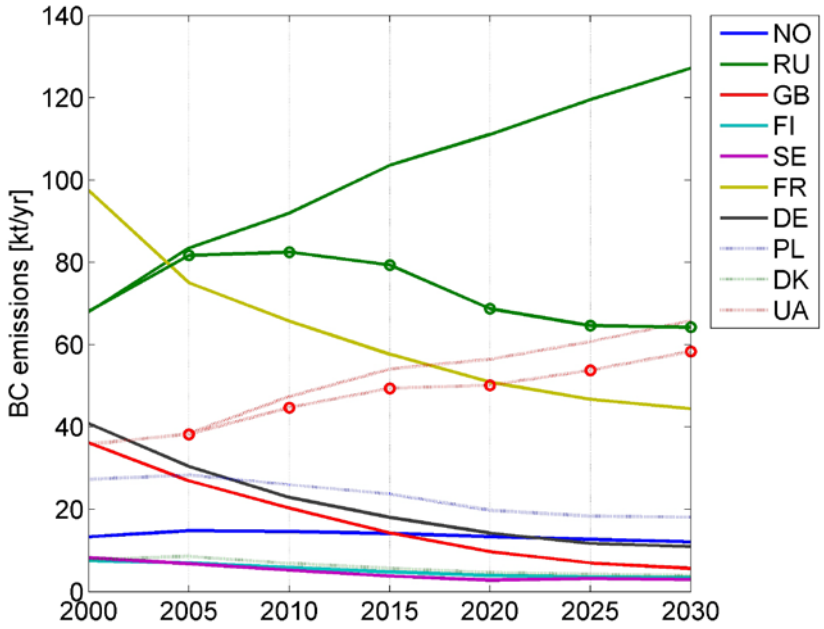

Figure 2-4. Emissions scenarios used in this study. No symbols: NEC6 CLE 2007 Baseline scenario. With symbols: Baseline / RU red scenario, composed from the NEC6 CLE 2007 Baseline scenario with estimates of future emission cuts in the former USSR countries.

2.3.4 RCP Database

While the NEC and WEO scenarios taken from the GAINS database contain emissions for all European countries, they do not include the maritime regions which are, however, included as source regions in the EMEP model. In particular, since the contribution of the North-East Atlantic Ocean to Arctic $PPM_{2.5}$ is significant (cf chapter 3), a realistic estimate of present and future BC emissions from ships is important for this study. Such an estimate was taken from the RCP (Representative Concentration Pathways) database, available online at http://www.iiasa.ac.at/web-apps/tnt/RcpDb (Riahi et al., 2007). The RCP database aims at documenting the emissions, concentrations, and land-cover change projections of the so-called "Representative Concentration Pathways" (RCPs). The Representative Concentration Pathways

are based on selected scenarios from four modeling teams/models (NIES/AIM,

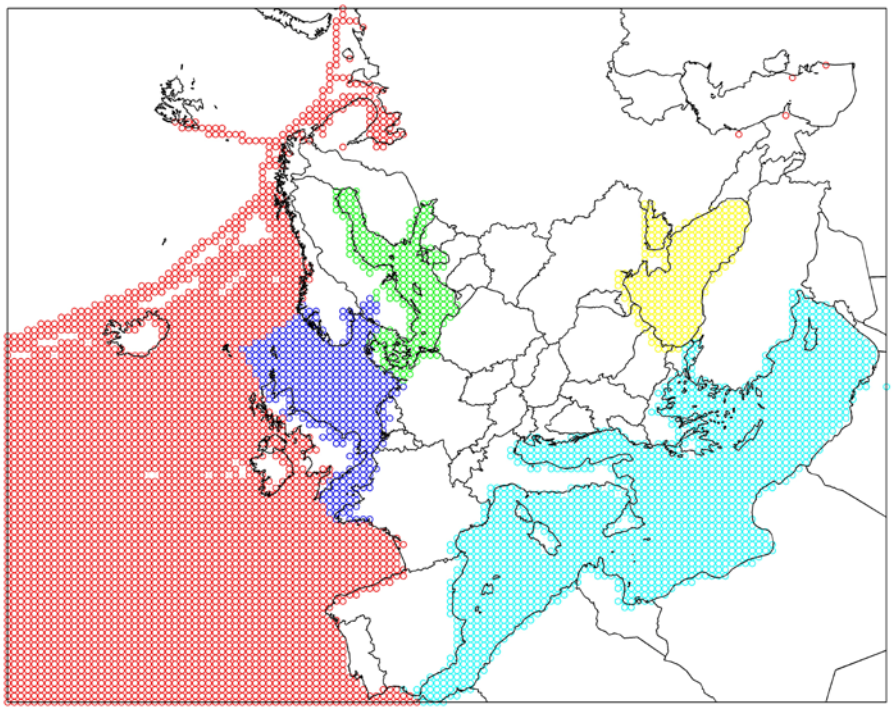

Figure 2-5. Sea regions as defined in the EMEP model. Red: North East Atlantic Ocean, blue: North Sea, green: Baltic Sea, cyan: Mediterranean Sea, yellow: Black Sea. RCP emission data were summed up over these regions in order to include ship emissions in the emissions scenarios. A few emission grids of the North East Atlantic Ocean are misallocated to the Caspian Sea, which is otherwise not considered as an emission region. Due to the very limited shipping emissions in the Caspian Sea, the four grid points do not alter the results in any significant way.

IIASA/MESSAGE, PNNL/MiniCAM, and PBL/IMAGE). The RCPs are meant to serve as input for climate and atmospheric chemistry modeling as part of the preparatory phase for the development of new scenarios for the IPCC's Fifth Assessment Report and beyond. Detailed information can be found in the IPCC Meeting Report: Towards New Scenarios (Moss et al., 2008). Each of the RCP scenarios has a different radiative forcing in 2100, which also determines its name. For this study, only the RCP8.5 ($8.5 Wm^{-2}$) scenario was taken into account.

The RCP 8.5 is developed by the MESSAGE modeling team and the IIASA Integrated Assessment Framework at the International Institute for Applied Systems Analysis (IIASA), Austria. The RCP 8.5 is characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels.

Contrary to the emissions scenarios taken from the GAINS database which contain emissions per source region (identical to those used in the EMEP model), RCP supplies the emissions on a gridded base with a 0.5°×0.5° resolution. For further use in this study, for each of the five sea

regions in EMEP the gridded emissions from RCP were summed over all grid cells allocated to the corresponding sea region (see Figure 2-5). Resulting emission projections for the different sea regions are shown in Figure 2-6.

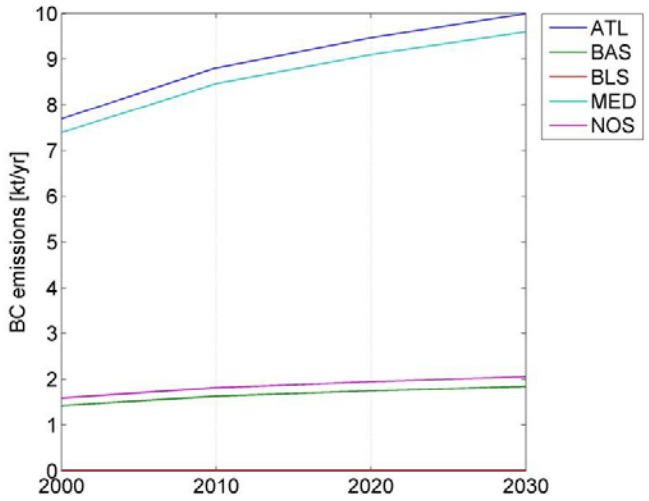

Figure 2-6. BC emissions as obtained from the RCP8.5 scenario.

2.3.5 FT 2000: Vegetation fires

BC emissions from vegetation fires were taken from the I-E FT 2000 (EDGAR / Fast Track 2000) scenario, which has been described by Niemi (2006). I-E FT2000 is based mainly on remote sensing of fires during 1997-2002. The extension of these base years into the future relies on IMAGE 2.2 (Integrated Model to Assess the Global Environment) model implementations on SRES scenarios for fire activity in different burning categories and for total forest areas. They were provided as estimates of annual emissions per country for the scenario years considered here (2000 to 2030, in five-year intervals); values are listed in Tables 6-5 and 6-6. It should be noted that emissions from vegetation fires generally underlie large uncertainties and thus results should be treated with caution, especially when comparing them to country emissions from different scenarios. Nonetheless the FT 2000 vegetation fire scenario was included in order to provide a rough estimate on the importance of vegetation fires for future Arctic BC pollution.

3 Results I. Contributions to Arctic Pollution

In this chapter, the principal findings of this study are presented. These include the transfer coefficients for $PPM_{2.5}$ from European countries to the Arctic (section 3.1), contributions of the European countries to Arctic PPM2.5 pollution using the PPM2.5 emissions as used in the

EMEP model runs (section 3.2), and contributions of European countries to Arctic BC pollution using BC emissions scenarios for present and future emissions (section 3.3).

Since this chapter deals with average contributions and not their variability, all results were obtained by averaging the monthly results over the five available meteorological years.

3.1 Transfer coefficients for Arctic PPM2.5

Source-receptor relationships, or transfer coefficients, allow for the quantification of the sensitivity of Arctic pollution levels to emissions from individual countries (or sea regions). Their calculation has been described in detail in section 2.2.

In most papers dealing with the subject, the Arctic is defined as the region north of 67-68°N. This definition has been adopted in this study; however, as mentioned above, it was varied (North of 68°, 72°, and 75°) to ensure consistency of the results. Naturally, absolute values of transfer coefficients decrease when the border of the Arctic is shifted northwards, but the relative values (and thus also the order of countries) remain almost unchanged.

In Figure 3-1, bar charts of transfer coefficients for several countries are shown for all three definitions of the Arctic (exact numbers for all countries are provided in Table 6-2). Note that this gives a depiction of the sensitivity of Arctic $PPM_{2.5}$ to different countries, but not yet the total contributions, as some of the countries with highest transfer coefficients (like Sweden) have only small emissions. It comes as no surprise that Arctic pollution levels are most sensitive to the northernmost European countries, with Norway ranking first before Finland and Sweden. In all cases, Norway dominates the transfer coefficients by more than a factor of 2, showing the very high sensitivity of Arctic $PPM_{2.5}$ levels to Norwegian emissions. The Atlantic Ocean is rather unexpectedly found at the fourth (68° definition) or even third position, before Russia, Estonia, the Baltic Sea, Denmark, the United Kingdom, and Latvia.

Since relative transfer coefficients are very similar for the different definitions of the Arctic, the 68° definition is followed throughout the rest of this paper.

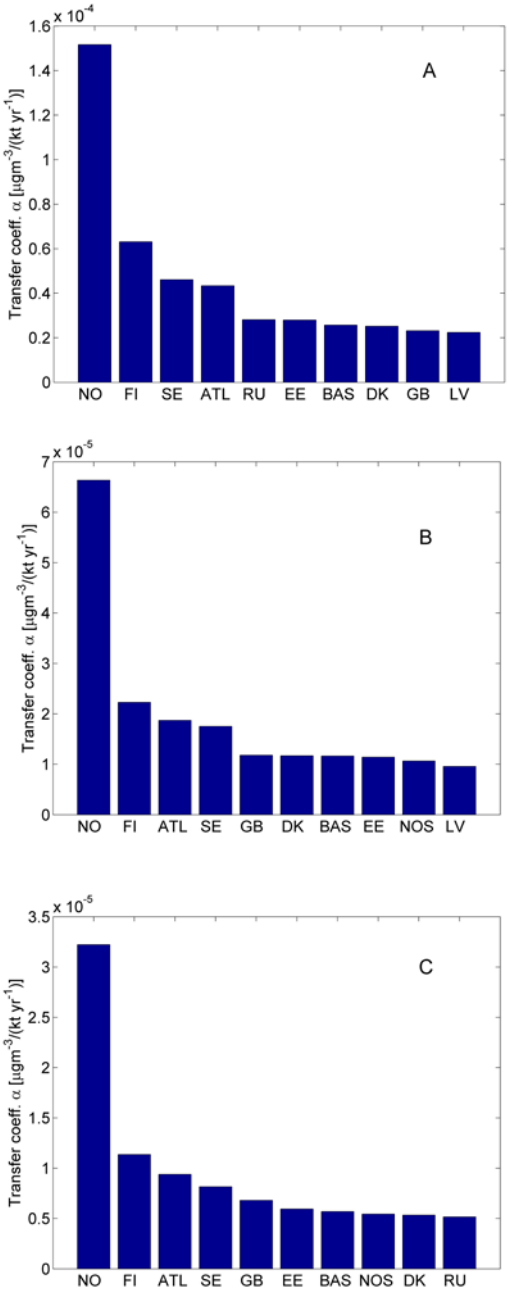

Figure 3-1. Transfer coefficients from European source regions to the Arctic, for three different definitions of the Arctic. A…north of 68°N, B…north of 72°N, C…north of 75°N.

3.2 Contributions to Arctic $PPM_{2.5}$

3.2.1 Country contributions to Arctic $PPM_{2.5}$

From the transfer coefficients, the contributions of each country to Arctic $PPM_{2.5}$ can be calculated by multiplying them with the total national $PM_{2.5}$ emissions. In Figure 3-2, the country contributions to Arctic $PPM_{2.5}$ pollution are shown.

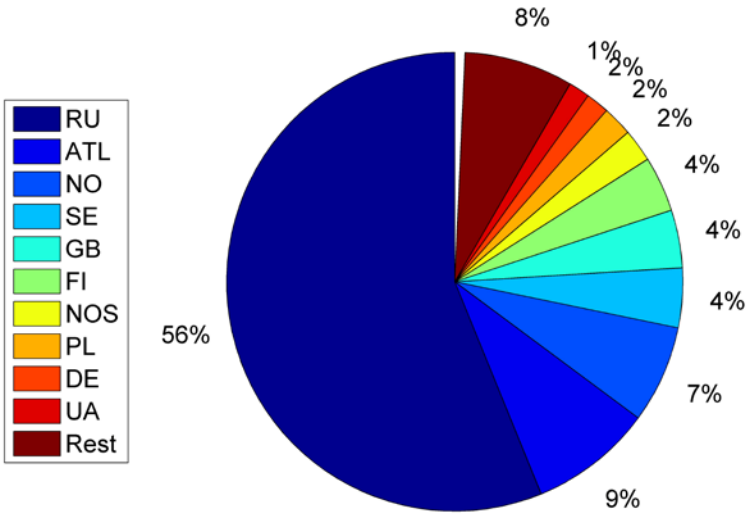

Figure 3-2. Country contributions to Arctic $PPM_{2.5}$. The Arctic is defined as north of 68°N. Full country names are given in Table 6-1. "Rest" denotes the rest of the 44 EMEP source regions (European countries and seas). The contributions add up to ~99.5%, the remaining 0.5% is natural background (visible as the small gap between RU and Rest sections).

Russia (the European part) turns out to dominate the contributions, supplying more than 50 percent of the Arctic $PPM_{2.5}$ present in the EMEP model. Notably ship emissions from the north-east Atlantic Ocean rank second (nine percent contribution), before all EU countries. Together with the North Sea, ranking seventh (2 percent), there are two sea regions among the top ten source regions of Arctic $PPM_{2.5}$. This finding clearly underscores the need to include shipping emissions in any assessment of Arctic pollution.

A very rough check on the consistency of the country contributions can be performed by comparing the sum of all contributions to the baseline concentrations of $PPM_{2.5}$ that are present in the Arctic. Since the background concentrations of $PPM_{2.5}$ should be very low in the Arctic, in the ideal case the sum of country contributions should match the total concentration almost perfectly. This comparison is shown in Figure 3-3. The sum of all country contributions explains 97 to 99.9 percent of the total $PPM_{2.5}$, which is very well in line with the expected result.

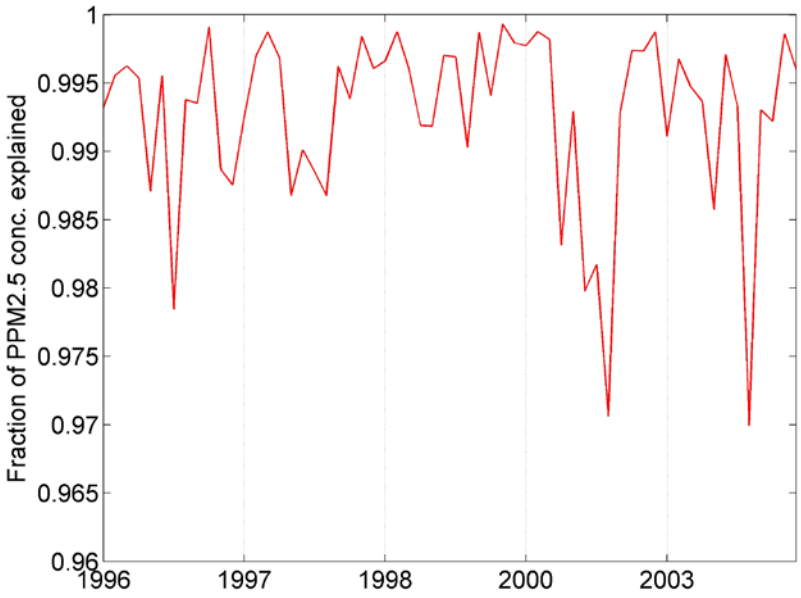

Figure 3-3. The fraction of Arctic $PPM_{2.5}$ explained by country contributions. It is obtained as the sum of country contributions, divided by the average Arctic $PPM_{2.5}$ concentration. Ticks are at January of each year.

3.2.1.1 Comparison to Tsyro (2009)

In a recent study, Tsyro (2009) assessed the transport of PM pollution to the Arctic with a slightly different version of the EMEP model. Her study focused on the year 2006, which is not included in the five meteorological years available to this study. This fact makes a direct comparison to this study difficult due to the large inter-annual variability of Arctic $PPM_{2.5}$ levels and transfer coefficients, as described in chapter 4. Figure 3-4 is taken from Tsyro (2009) and shows the relative country contributions to Arctic $PPM_{2.5}$ obtained in her study. Russian contributions are significantly lower than the 5-year average shown in Figure 3-2 (only 31% as compared to 56%), while Norwegian (12% / 7%) and Finnish contributions are higher (9% / 4%). For most other source regions results match well (e.g Atlantic Ocean 9% / 9%, Sweden 6% / 4%, GB 4% / 4%, Poland 4% / 2%, North Sea 2% / 2%, Germany 2% / 2%). Given the large variability of transfer coefficients, results seem to agree well; in particular, the order of countries is similar in both cases, and the orders of magnitudes of the country contributions match very well.

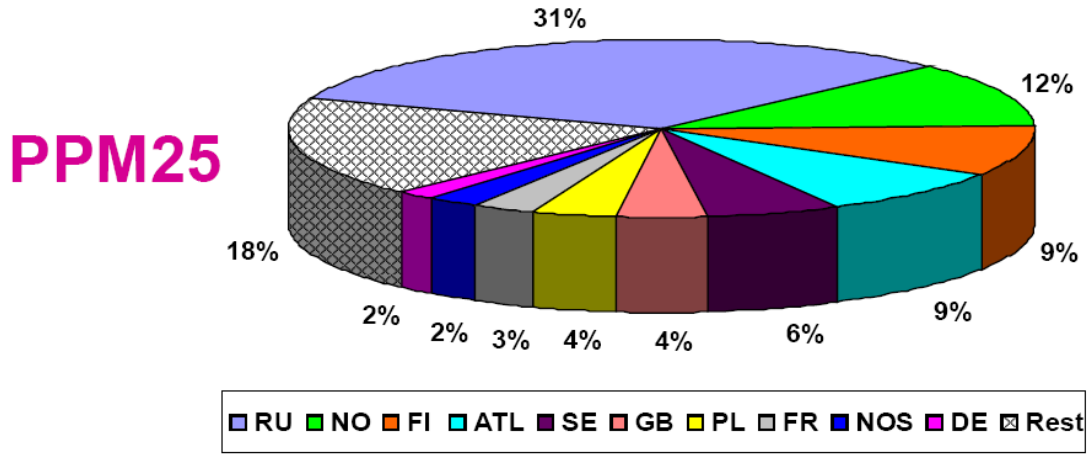

Figure 3-4. Relative country contributions to Arctic PPM2.5 in Tsyro (2009). The Arctic is defined as the area north of 66°32' here. Given the large inter-annual variability of Arctic PPM2.5, the contributions agree well to those found in this study (see Figure 3-2).

3.2.2 Sectoral contributions to Arctic PPM2.5

Since the distribution of the country emissions between different activity sectors is known, contributions of different sectors to Arctic PPM2.5 can be calculated by multiplying country emissions with the activity distribution and then summing over all countries. The contribution C_s of emissions sector s to the concentration of pollutant x is

$$C_s = \sum_c C_c \frac{e_{c,s}}{e_c} \qquad (3.1)\,,$$

where $e_{c,s}$ denotes the emissions of sector s in country c, e_c the total emissions of country c and C_c the contribution of country c to x.

It should be mentioned that this method can only provide approximate information as (contrary to the calculation of transfer coefficients for whole countries) it does not take into account the spatial distribution of sectoral emissions within countries. Instead, it treats countries as a whole and allocates the same sectoral distribution of emissions in a country to the contributions. In the case of large countries with very incoherent distribution of household and industrial emissions, this may lead to offsets in the results. Furthermore, the emission height is not equal for all sectors, as necessarily assumed here. Nevertheless, we can expect that in most cases the results are reasonable since the distribution of household and industrial emissions is similar in most countries. Exact results could only be obtained with reduction runs for each SNAP sector, which were not available.

Figure 3-5 shows the overall sectoral contributions to Arctic $PPM_{2.5}$. It is obvious that combustion in non-industrial plants (SNAP sector 2, household sector) constitutes the largest contribution, amounting to 36 percent, followed by "other mobile", i.e. off-road traffic and ships (19 percent). Only at the third position, the first industrial contributor may be found, production industry (16 percent). The sum of all industrial inputs (energy industry, manufacturing industry, production, fossil fuel extraction and distribution) amounts to 26 percent of total $PPM_{2.5}$

contributions. Traffic contributes ~27 percent in total, agricultural emissions contribute six percent, and contributions from waste treatment and disposal amount to 4%.

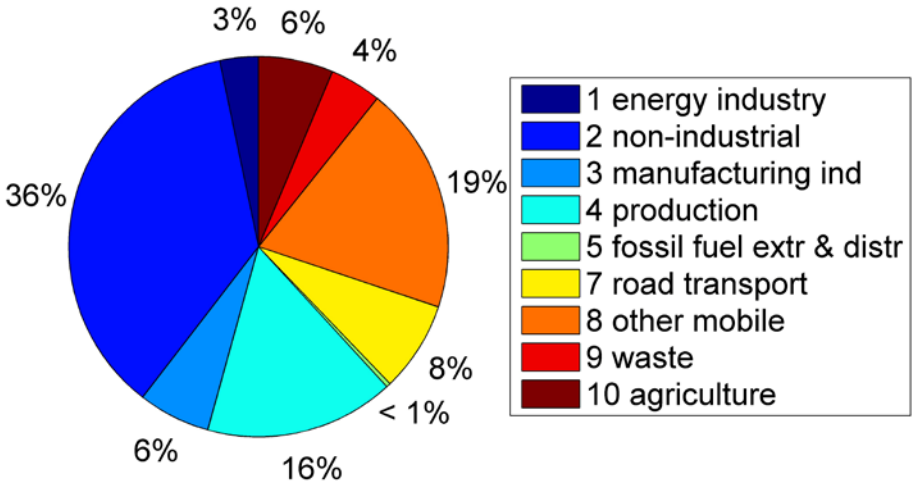

Figure 3-5. Sectoral attribution of Arctic $PPM_{2.5}$. Numbers refer to the SNAP sectors (for enhanced readability, only abbreviations are shown here. Full names are listed in Table 2-1).

3.3 Contributions to Arctic Black Carbon

3.3.1 Country contributions

The transfer coefficients for $PPM_{2.5}$ were applied to emission scenarios of BC in order to estimate contributions of European countries to Arctic BC. In Figure 3-6, the contributions to Arctic BC as derived from the CLE 2007 Baseline scenario as compared to the Baseline / RU red scenario are shown for the period of 2000 to 2030.

In both cases, emissions from ships were added from the RCP 8.5 scenario. Note that since they are taken from completely independent scenarios, one should be cautious about directly comparing country to ship contributions.

Comparing the two scenario outlooks, large differences are visible, mainly resulting from the large difference in future Russian emissions. In the baseline scenario, Russian emissions grow unabatedly, and Russia (i.e. the European part) dominates European contributions from 2010 on. Under the combined Baseline / RU red scenario, Norway contributes the largest fraction to Arctic BC, with Russia in the second position. In the baseline case, the growth in Russian emissions completely offsets the reductions in European emissions which are implemented over time. It is remarkable that in both cases, ship emissions from the Atlantic Ocean eventually become the third largest contributor.

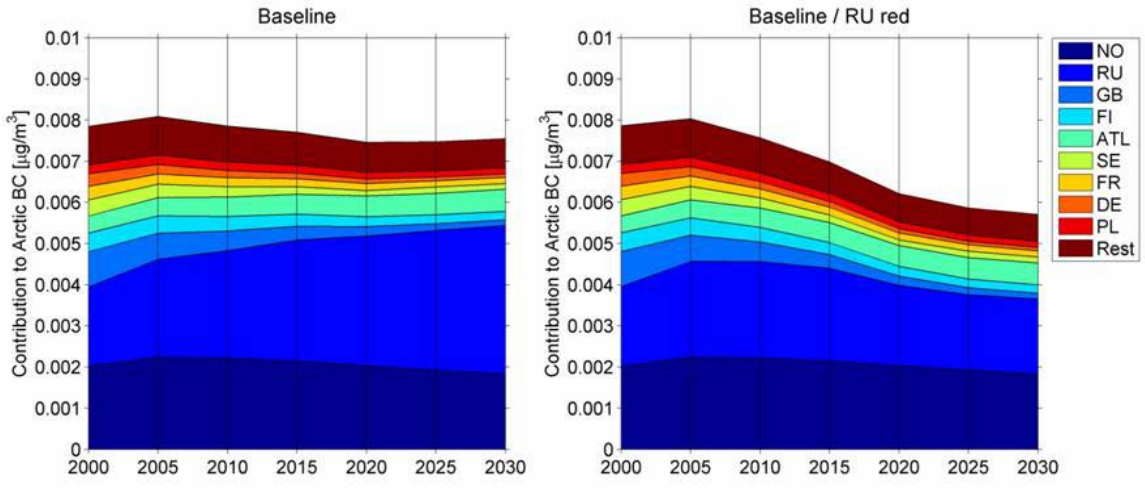

Figure 3-6. Contributions to Arctic BC concentration as obtained from the CLE 2007 Baseline scenario (left) and the CLE 2007 Baseline / RU red scenario (right). "Rest" denotes the rest of Europe as considered in the EMEP model. In both scenarios, ship emissions from the RCP 8.5 scenario were added (showing up explicitly as Atlantic emissions, ATL).

This finding implies that the most important countries to be addressed in order to reduce European inputs to Arctic BC are Norway and Russia. In terms of Arctic sensitivity, emissions from these countries easily offset abatement efforts by other European countries. Furthermore, ship emissions should be observed closely and integrated in regulatory policies. Since the ATL region in the EMEP model covers only parts of the North Atlantic Ocean, and also the more frequent opening of the Northeast shipping passage along the Russian North coast in the future is not accounted for in the EMEP model, the real contribution from ship emissions may be considerably higher.

Although reductions in Arctic BC concentrations are to be expected in the more optimistic Baseline/RU red scenario, it is questionable whether these reductions will be sufficient for a delay of Arctic warming. However, quantification of the radiative forcing effect exerted by the BC concentration as well as deriving limits for future BC concentrations (and thus, emissions) is a task which can only be addressed with global climate models and is clearly beyond the scope of this study.

3.3.2 Sectoral contributions

Since BC scenarios contain sectoral information, the same procedure as described above for the sectoral attribution of $PPM_{2.5}$ can be applied to BC emissions. By splitting up the country contributions into sectors and then summing up over all countries, an estimate of the relative importance of different sectors is derived. Of course, this calculation uses the same approximation as described in section 3.2.2.

Figure 3-7 shows the sectoral attribution of Arctic BC concentrations in the two scenarios. As for $PPM_{2.5}$, the household sector (SNAP sector 2, non-industrial combustion) shows up as the most important contributor, contributing 45% in 2000 and the same in 2030 in the Baseline scenario. Emission reductions taken from the WEO 2008 scenario affect only the road transport

sector, thus the relative importance of the household sector rises to 59% in 2030 in the Baseline / RU red scenario.

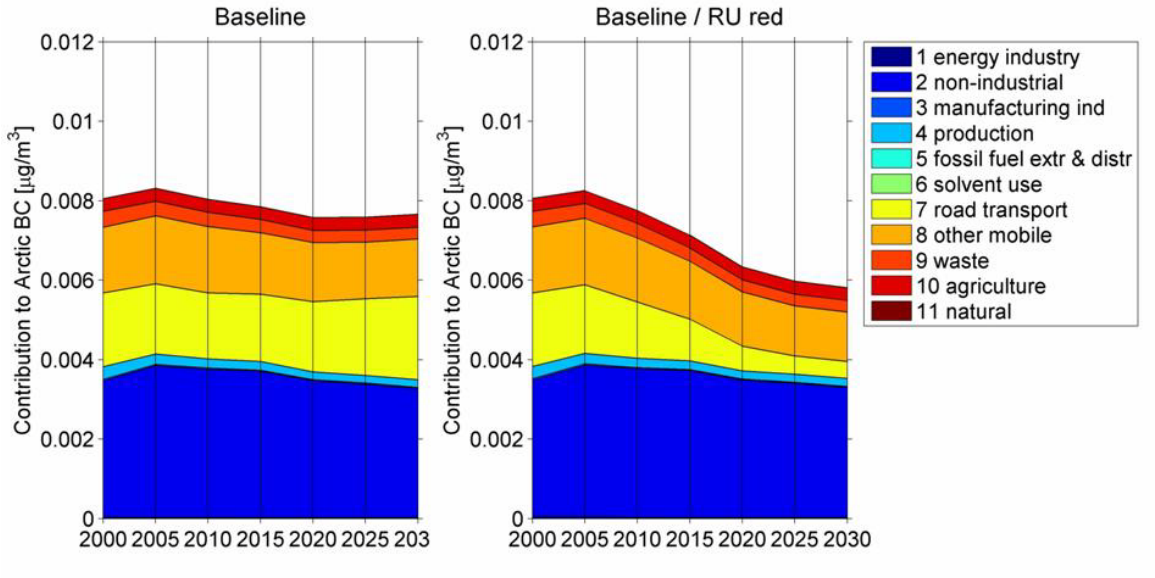

Figure 3-7. Sectoral contributions to Arctic BC in the two scenarios. The household sector (sector 2) dominates, large differences only affect the road transport sector.

3.4 The role of vegetation fires

In the EMEP model runs available to this study, emissions from vegetation fires were not included. However, since wildfires are potentially a large source of BC emissions, an attempt to quantify their role for Arctic BC pollution shall be made here.

Wildfire emissions are supplied in two categories (forest and grassland fires) as annual emissions per country. By multiplying these emissions with the transfer coefficients calculated before, we obtain Arctic BC concentrations due to wildfires in each country. Summing up over all countries then yields the total contribution by vegetation fires.

This method can only provide rough estimates for the role of wildfires, since source regions are treated as a whole without considering the spatial distribution of wildfire emissions. The underlying spatial emission patterns used for calculating the transfer coefficients are implicitly assumed to match those of the fires, which is probably not the case. Further possible sources of error include the seasonality of wildfires (due to a lack of information on the temporal distribution of the emissions, annual average transfer coefficients are used here), and the different emission heights as compared to those from which the transfer coefficients were calculated. However, this method presently represents the only way to include vegetation fires in this assessment at all, and we can assume that at least for smaller and medium-sized countries errors due to the geographical distribution of emissions should be small.

Figure 3-8 shows the contribution of forest and grassland fires for both BC scenarios on top of the national emissions used so far. Contributions are large, amounting to roughly a third of all national plus shipping emissions in 2000, and even more in 2030 in the Baseline / RU red

scenario as national emissions decline while vegetation fire emissions are projected to increase slightly.

This finding clearly shows the importance of considering vegetation fires in any assessment of Arctic pollution, and also in possible future regulations of national emission limits.

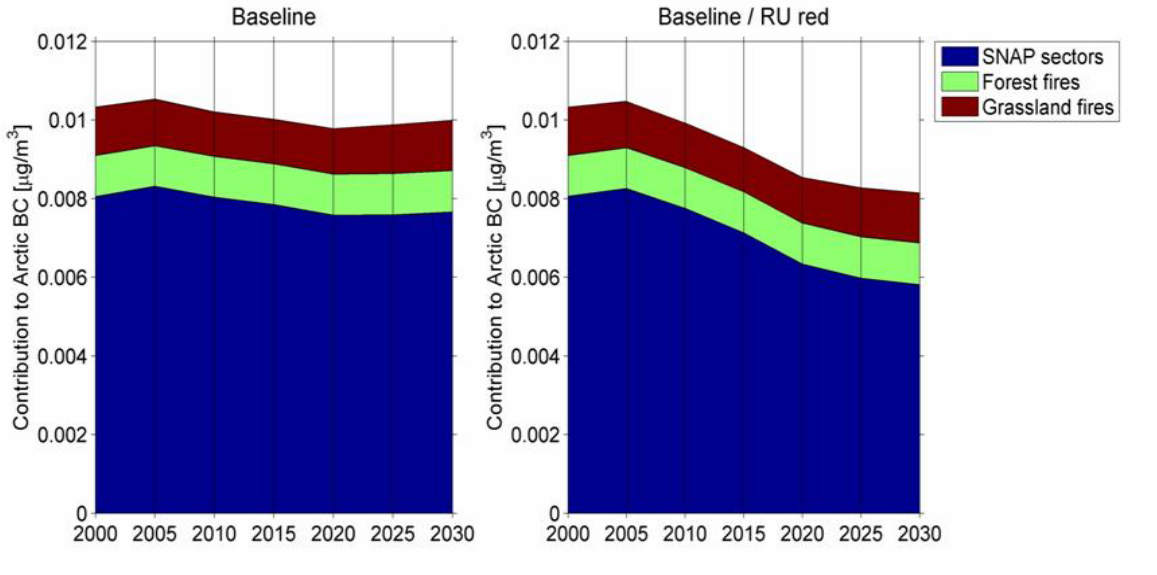

Figure 3-8. Contributions of forest and grassland fires to Arctic BC concentrations, on top of the emissions considered in the SNAP sectors, as shown in Figure 3-7.

4 Results II. Variability of Arctic PPM Pollution

Arctic pollution levels are known to be subject to large variability, which is a result of the annual cycle of emissions (as described in section 2.1.2) as well as variability in transport. Due to more favorable meteorological conditions, episodes of high pollution transport to the Arctic generally take place in the non-summer months (Quinn et al., 2008). Apart from the seasonal cycle of meteorological conditions, a recurring climate pattern called the North Atlantic Oscillation (NAO) has repeatedly been mentioned as a possible driver of transport of European pollution to high latitudes (e.g. Eckhardt et al, 2003).

Section 4.1 investigates the annual cycle of Arctic $PPM_{2.5}$ levels and contributions as seen in the EMEP model runs, while section 4.2 looks into the variability of transfer coefficients and in section 4.3 a possible influence of the North Atlantic Oscillation on transport patterns is discussed.

As a general remark, it should be noted here that the timespan of the available model runs is limited (five years of monthly output), and all conclusions drawn here should also be viewed in this light. Nevertheless, the analysis of the variability of transport from the available model runs

yielded some interesting results, e.g. concerning annual cycles of contributions, which are worth discussing here.

4.1 Annual cycle of Arctic PPM2.5 and contributions

The timeseries of Arctic PPM2.5 in the EMEP model (Figure 4-1) displays very high month-to-month variations, covering more than one order of magnitude. Obviously, transport of PPM2.5 to the Arctic takes place in large single events which are scattered more or less randomly in time. The annual cycle of Arctic PPM2.5 concentrations as obtained from this timeseries is shown in Figure 4-2, split up into the sectoral attribution. In the light of the large variability of PPM2.5 levels, it may be viewed as a probability distribution of large transport events rather than a regular annual cycle; according to this figure, pollution levels tend to reach their highest values in early and late winter (November and March), mainly due to large increases in household contributions (sector 2) during these periods.

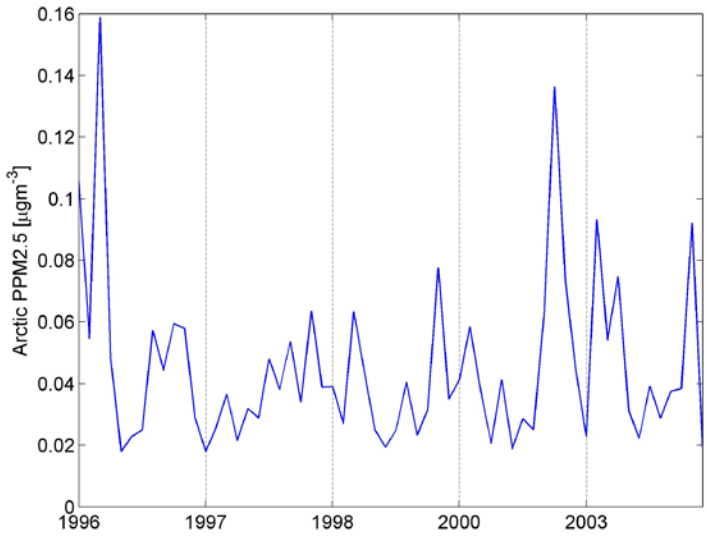

Figure 4-1. Time-series of Arctic $PPM_{2.5}$ levels, averaged north of 68°N. A huge month-to-month variability is observed.

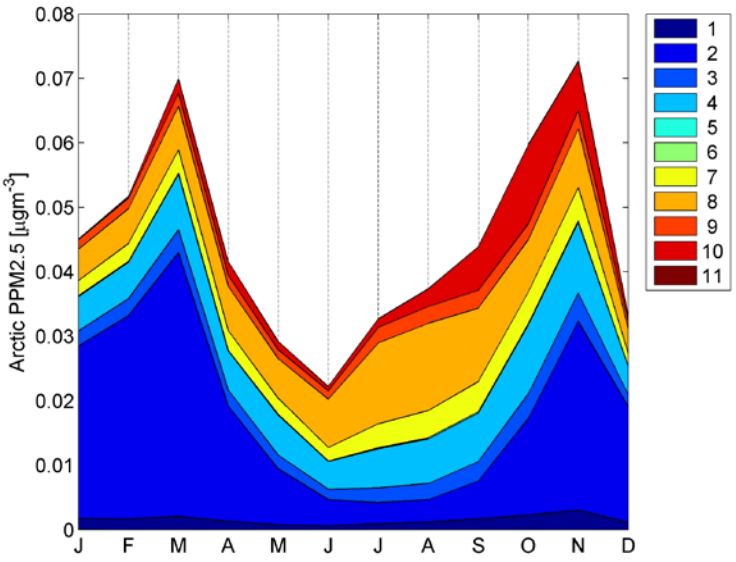

Figure 4-2. Annual cycle of Arctic $PPM_{2.5}$ concentration, split up by sectoral contributions. Sector codes according to SNAP sectors as listed in Table 2-1.

A more robust statement is obtained by considering the relative importance of different source regions and sectors. Figure 4-3 (right figure) displays the annual cycle of the relative importance of different emission sectors, expressed in percent of the total $PPM_{2.5}$ contribution. A large seasonal variation of the contribution of household emissions (SNAP sector 2) is visible. Qualitatively, the shape of this curve seems very reasonable as it reflects the increased PM emissions from heating during winter, while during summer households create only minor emissions. In contrast, the importance of off-road transport (especially shipping) emissions (sector 8) peaks during summer months. Note the peaking of the contributions from agriculture (sector 10) during the harvest season in late summer and autumn.

The two factors leading to this large annual cycle are the annual cycle of sectoral emissions and meteorology. The relative importance of these two factors can be distinguished by repeating the source-receptor calculations without taking into account the annual cycle of emissions. This is justified by the fact that considering the annual cycles of emissions does not change country contributions significantly (which is equivalent to the statement that annual cycles of emissions of individual countries do not differ enough to lead to detectable changes in source attributions). In this case, all variability in sectoral contributions must be due to meteorological variability (Figure 4-3, left).

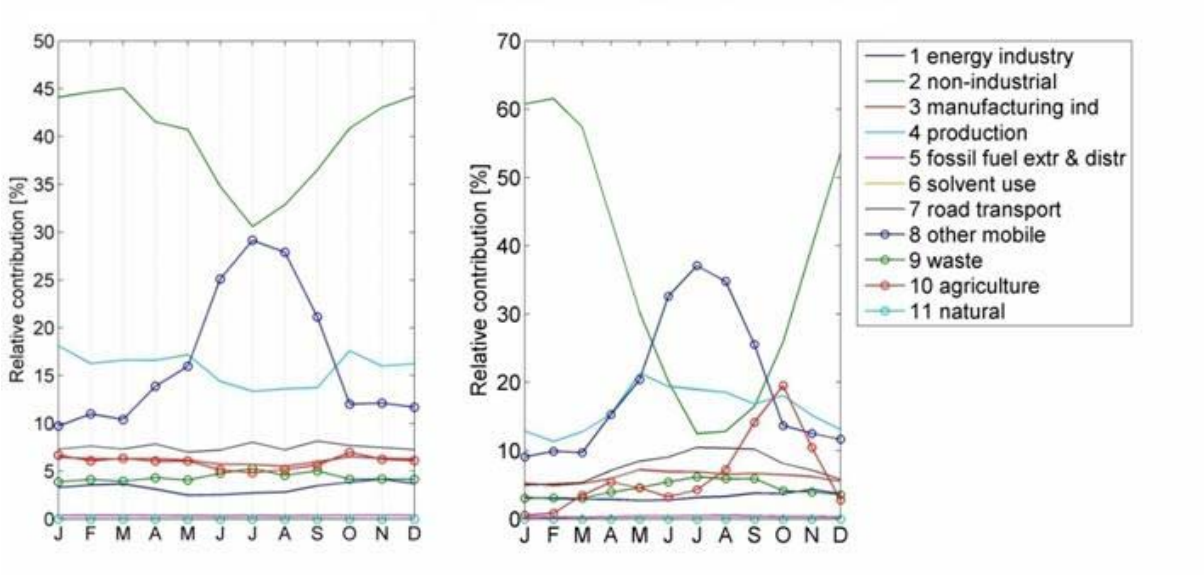

Figure 4-3. Annual cycle of the relative contributions of different emissions sectors (sector codes according to SNAP sectors, as listed in Table 2-1). Left: without considering the annual cycle of emissions, right: annual cycle of emissions considered. Note the strong anti-correlation between household emissions (sector 2) and off-road mobile (esp. ship) emissions (sector 8). The annual cycle in the left figure is only due to meteorology.

4.2 Variability of transport to the Arctic

Transport of pollution from Europe to the Arctic exhibits strong variability. Figure 4-4 shows the time series of transfer coefficients for the ten largest contributing countries. It is obvious that transport coefficients vary strongly for all countries, but not necessarily synchronized between different countries. From the five different meteorological years, no distinctive trend is visible.

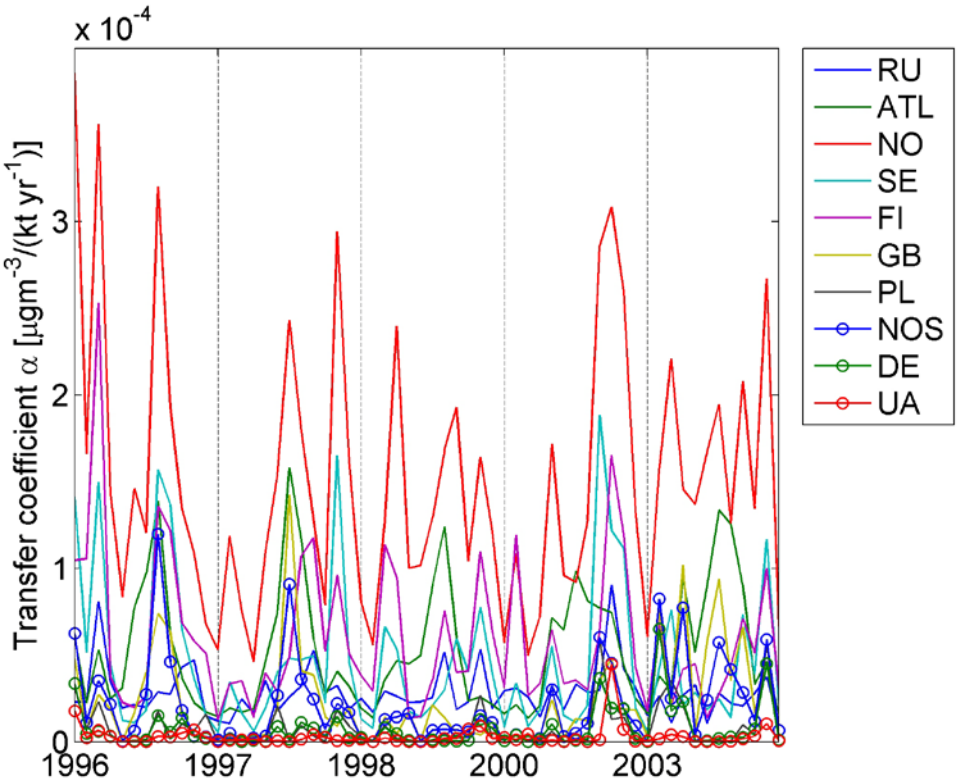

Figure 4-4. Time series of monthly $PPM_{2.5}$ transfer coefficients for the ten largest contributing source regions. Large month-to-month variations in transport are visible, but no trend. Ticks correspond to January of the respective year.

4.3 The role of the North Atlantic Oscillation

The North Atlantic Oscillation (NAO) (e.g. Wallace and Thompson, 2002; van Loon and Rogers, 1978) constitutes the principal pattern of atmospheric variability on the northern hemisphere. It is usually defined as the difference in sea level pressure between the Icelandic Low and the Azores High. Through shifts in position and strength of these two pressure systems, the NAO moderates the frequency and direction of storms crossing the Atlantic into Europe, and thus exerts control on the general weather conditions in Europe. Especially during the months of November to April, the NAO is responsible for much of the variability of weather in the North Atlantic region, affecting wind speed and wind direction changes, changes in temperature and moisture distribution and the intensity, number and track of storms.

The phase of the NAO can be described by an index, of which, however, different definitions exist. Most modern NAO indices are derived either from the simple difference in surface pressure anomalies between various northern and southern locations (e.g. Reykjavik/Lisbon or Reykjavik/Ponta Delgada, Azores), or from the principal component time series of the leading (usually regional) empirical orthogonal function of sea level pressure (SLP).

A positive NAO index corresponds to a stronger than average SLP gradient, while a negative NAO index corresponds to a weaker than usual gradient.

During the high NAO phase, the westerly winds blowing across the Atlantic are increased, resulting in cool summers and mild and wet winters in Central and West Europe. In contrast, if the NAO is in its negative phase, westerlies tend to be suppressed, storm tracks are shifted south, and consequently central Europe experiences cold winters while southern Europe is subject to increased storm activity and rainfall.

Eckhardt et al (2003) investigated the role of the North Atlantic Oscillation for the transport of pollution to the Arctic using a 15-years run of the Lagrangian particle dispersion model FLEXPART. In their study, an idealized tracer was released according to European, North American, and South Asian carbon monoxide (CO) emission patterns, and then followed in the model for 50 days. They found a positive correlation between Arctic tracer concentrations and the NAO index, and arrived at the conclusion that the NAO exerts some control on the transport of pollution to the Arctic. Furthermore, they demonstrated that plumes of pollution are transported very differently under extremely positive NAO conditions, as compared to extremely negative NAO phases.

A similar analysis was conducted in this study in order to investigate a possible role of the NAO for the transport of $PPM_{2.5}$ to the Arctic. Due to the much shorter time span available to this study, all results should be treated with caution.

Since the NAO index used by Eckhardt et al. (2003) has not been updated after 2002 due to unavailability of the Ponta Delgada meteorological station, the NAO index used in this study was obtained from NOAA Climate Prediction Center (CPC), available online at ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh.. The NAO index time series for the five meteorological years considered here is shown in Figure 4-5.

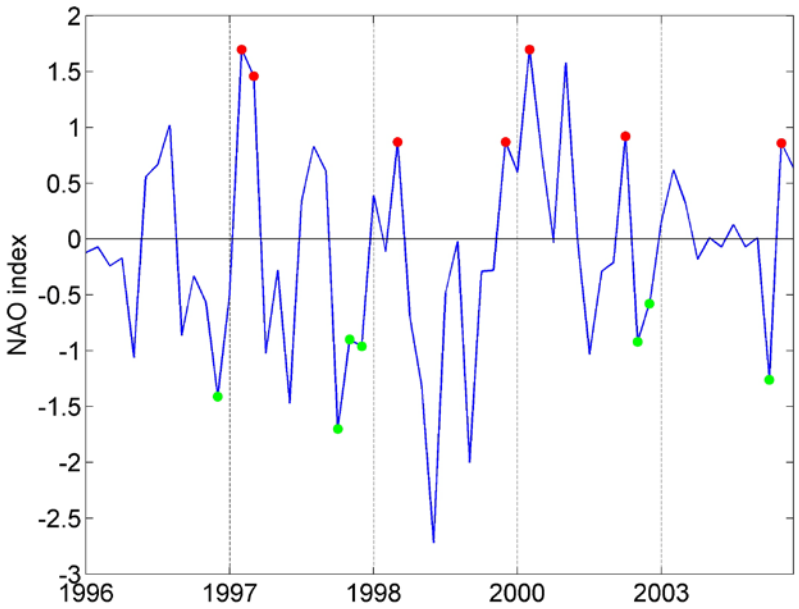

Figure 4-5. Monthly NAO index values (NOAA CPC) for the five meteorological years considered in this study. Ticks correspond to January of each year. Extreme positive and extreme negative phases of the NAO during winter months (October-March) are highlighted as red and green circles, respectively.

Since strong NAO phases supposedly lead to anomalies in Arctic pollution, the annual cycle was subtracted from the $PPM_{2.5}$ time series to obtain the time series of deviations. A first test for influence of the NAO on Arctic pollution levels can be obtained by taking the linear correlation coefficient of the NAO index to the deviations. However, this correlation coefficient is only 0.15, which would imply that these quantities are basically uncorrelated. A backup check with the shorter NAO timeseries from UCAR gives an even lower correlation coefficient of 0.06.

Thus we can conclude that from the 60 months available, no direct correlation of Arctic PPM2.5 levels to the NAO is visible in the EMEP model. This result does not change if only winter months (October to March) are considered.

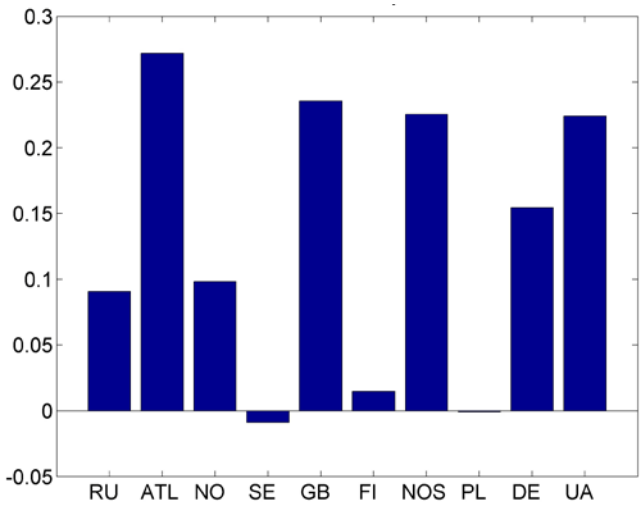

Figure 4-6. Correlation coefficients of anomalies in country contributions to the NAO index. No significant correlation is observed.

In order to detect an influence of the NAO on the temporal variability of individual country contributions, the anomalies in country contributions were calculated by subtracting the annual cycle from the time series of country contributions. Then the linear correlation coefficient between anomalies in country contributions and the NAO was calculated for every country (Figure 4-6). Although it appears that some European source regions such as the North East Atlantic Ocean and the United Kingdom show a slightly higher correlation coefficient, none of the correlations exceed 0.27 and thus can hardly be considered significant.

All analysis presented so far tried to establish a linear correlation coefficient between the NAO time series and anomalies in $PPM_{2.5}$ concentrations or contributions, averaged over the Arctic. Such a linear correlation is not supported by the EMEP model output available to this study. However, in addition to reporting a linear correlation, Eckhardt et al. (2003) reported a significant shift of transport patterns under extreme phases of the NAO during winter months.

In order to test whether an effect of extreme NAO conditions is visible in the EMEP model runs, the following paragraphs discuss composite plots of $PPM_{2.5}$ concentrations under extreme NAO phases.

Figure 4-7 shows a composite plot of relative $PPM_{2.5}$ concentration differences under high- vs. low-NAO conditions. The way this figure was obtained is as follows: First, the seven months of highest and lowest NAO indices attained during October to March of the available years were selected and are henceforth referred to as “high-NAO” and “low-NAO” regimes, respectively. High-NAO and low-NAO months are marked as red and green dots in Figure 4-5. Average values of the NAO index are +1.20 in the high-NAO regime and -1.10 in the low-NAO regime. $PPM_{2.5}$ fields were averaged over the respective months to yield high-NAO and low-NAO fields. The difference between high-NAO and low-NAO fields is shown as a multiple of the low-NAO fields, in order to account for the small absolute values attained. In this sense, Figure 4-7 shows the factor by which $PPM_{2.5}$ levels are enhanced under high-NAO conditions as compared to low-NAO conditions. While relative differences are of the order of +1 to –1 for

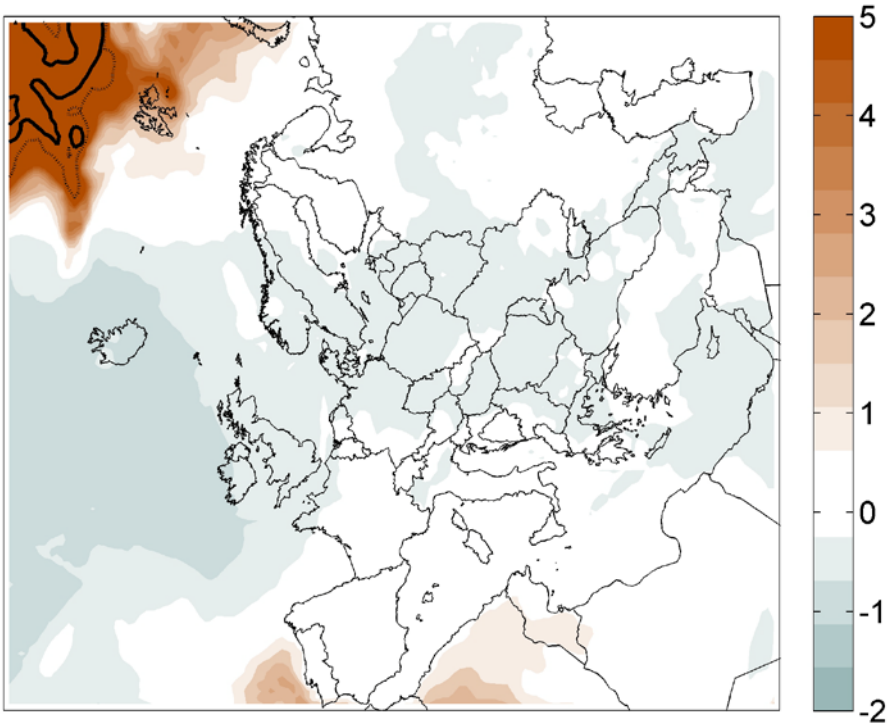

Figure 4-7. Enhancement factor of PPM2.5 levels under high NAO conditions: Difference between $PPM_{2.5}$ concentration levels under the high-NAO regime as compared to the low-NAO regime, expressed as multiples of low-NAO $PPM_{2.5}$ concentrations. Values exceeding the color scale are indicated by black contour lines. Dotted black line: enhancement factor 10, solid black line: enhancement factor 20.

most of Europe, a strong enhancement is visible in high Arctic areas, reaching more than a factor of 20 there (note the black lines indicating values exceeding the color scale).

Of course one must be careful when interpreting these results, for two reasons. Firstly, the statement that $PPM_{2.5}$ is enhanced in the high Arctic under high-NAO conditions is a statistical one, and the statistical significance of the difference should be established. Secondly, the areas showing high enhancement are located close to model boundaries and should thus generally be treated with caution.

While the latter issue cannot be resolved here due to the fixed model domain, the first issue is addressed mathematically in the following paragraph by calculating the significance of the observed differences.

Even though two time series yield a different mean value, their distribution must not necessarily be different. The statistical significance of the difference between means of two time series can be established by a Student's t-test. This test yields the probability that the observed difference in mean values of two series *A* and *B* of data points (length N_A and N_B, respectively) is *not* just by chance. Input values for the t-test are a combined standard deviation of the two time series of

concentrations, and the number of degrees of freedom ($N_A + N_B - 2$). The standard error of the difference of the means is given by

$$s_D = \sqrt{\frac{\sum_{i \in A} (x_i - \bar{x}_A)^2 + \sum_{i \in B} (x_i - \bar{x}_B)^2}{N_A + N_B - 2} \left(\frac{1}{N_A} + \frac{1}{N_B} \right)} \qquad (4.1)$$

from which the parameter *t* can be computed,

$$t = \frac{\bar{x}_A - \bar{x}_B}{s_D} \qquad (4.2)$$

which serves as input value for the t-test. Formulae (4.1) an (4.2) are taken from the Numerical Recipes (Press et al., 1992, p.616); see also this reference for details on the Student's t-test.

In Figure 4-8, the statistical significance of the $PPM_{2.5}$ concentration differences shown in Figure 4-7 is depicted. A significance of 0.9, for instance, is equivalent to a probability of 10% that the observed difference is just due to chance (assuming distributions for PPM concentrations actually do not differ between high- and low-NAO regimes). Large areas where significances exceed 0.95 are found over southwest Europe/north Africa, over the North Atlantic Ocean west of the British islands, and over parts of the high Arctic.

Since areas of high significance (>0.95) overlap with the areas of high enhancement factors in the Arctic, we can conclude that from the model runs available to this study (and if we trust the EMEP model close to its boundaries), there is significant enhancement of $PPM_{2.5}$ levels in the high Arctic.

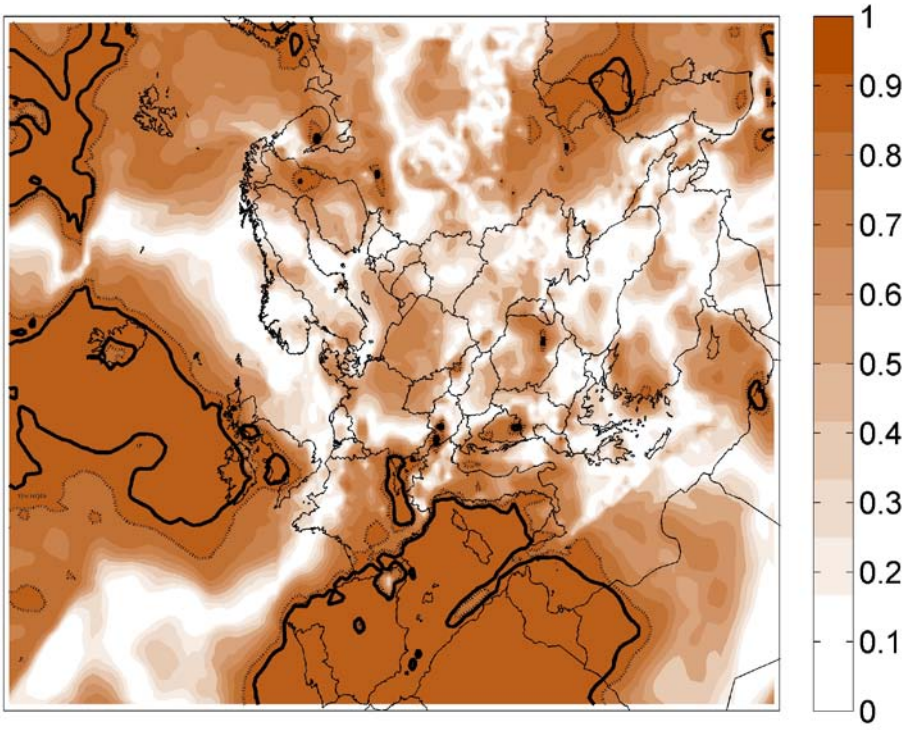

Figure 4-8. Statistical significance of the $PPM_{2.5}$ differences shown in Figure 4-7, representing the probability that the observed difference is not by chance. Dotted black line: 0.9, solid black line: 0.95.

Finally, it should be noted that the number of seven "extreme" months was chosen arbitrarily, with the idea that out of the 30 "winter" months available, not more than half should be considered "extreme". On the other hand, too few months in each regime decrease the statistical value of the analysis. Selecting five or ten months as "extreme" does not change the results significantly.

5 Summary and Conclusions

This study established transfer coefficients for $PPM_{2.5}$ from Europe to the Arctic, using output from the EMEP tropospheric model. The European part of Russia was found to dominate contributions to Arctic $PPM_{2.5}$ concentrations.

Estimates for present and future contributions to BC concentrations in the Arctic were calculated by applying $PPM_{2.5}$ transfer coefficients to BC emissions. Two different scenarios were employed, an "optimistic" one which assumes emission reductions in the former USSR countries, and a pessimistic one assuming business as usual. Emissions from EU countries follow current legislation in both cases.

Norway and Russia were found to supply the largest contributions to Arctic BC, at present and even more so in the future. In the Baseline scenario, despite reductions in EU countries the overall BC input to the Arctic remains largely unchanged due to growing Russian emissions. Even in the more optimistic scenario, total BC input into the Arctic is only reduced by ~25%, leading to the conclusion that emission reductions as estimated in the World Energy Outlook 2008 will not suffice to reduce Arctic BC levels effectively, which may be necessary in order to delay the rapid warming of the Arctic and prevent complete loss of Arctic sea ice. As mentioned above, the most important countries to address are Norway and Russia, as due to their proximity to the Arctic, each of these countries can easily offset emission reduction efforts from other European countries.

Furthermore, ship emissions from the North East Atlantic Ocean were found to contribute significantly both to Arctic $PPM_{2.5}$ and BC levels. In both scenarios, emissions from the Atlantic ranked third in the contributions to Arctic BC by 2030, exceeding contributions from all European countries except Russia and Norway. In reality, contributions from shipping may be higher since only parts of the North Atlantic Ocean are contained in the EMEP model domain, and the more frequent opening of Arctic shipping routes due to retreat of sea ice in the future is not accounted for.

In terms of activities, the household sector was shown to contribute most – starting from about 45 percent in 2000, its relative contribution may rise up to 60% in 2030, depending on the emissions scenario used. This implies that an effective reduction in BC emissions will hardly be possible without inclusion of the household sector.

Transport of $PPM_{2.5}$ to the Arctic is subject to large month-to-month variability. From the five years of data available, it is not possible to distill any trend in transfer coefficients. The annual cycle of PPM concentrations in the Arctic indicates a tendency towards episodes of high pollution in early and late winter, which is well in line with results from other studies. Sectoral contributions exhibit a large annual cycle. The relative importance of the household sector peaks during winter, when it accounts for more than 60 % of all $PPM_{2.5}$ present, and reaches values below 15% in summer. Contributions from off-road transport, including ships, display a reversed annual cycle, ranging from less than 10% in winter to more than 35% in July. These annual cycles are in part due to the different annual cycles of emissions (household emissions peak in winter while transport emissions remain largely unchanged) and partly due to meteorological variability.

The North Atlantic Oscillation (NAO) climate pattern was investigated as a possible driver for the observed variability of Arctic pollution levels. Due to the short time span available to this study, results are not fully conclusive. A linear correlation of the NAO index to Arctic $PPM_{2.5}$ anomalies, as reported by Eckhardt et al. (2003), is not supported in the available dataset. However, Arctic $PPM_{2.5}$ levels are found to be significantly enhanced during extreme positive phases of the NAO, as compared to extreme negative phases, which is in agreement with Eckhardt et al (2003). Further investigation seems necessary, but if this finding proves robust, it may become more important in a future climate, since most long-term climate model runs suggest a tendency of the NAO towards high index values as a result of increasing greenhouse gas concentrations (Osborn, 2004).

6 Appendix

6.1 References

Amann, M., I. Bertok, J. Cofala, C. Heyes, Z. Klimont, P. Rafaj, W. Schöpp, and F. Wagner (2008): National Emissions Ceilings for 2020 based on the 2008 Climate & Energy Package. NEC Scenario Analysis Report Nr. 6. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. http://www.iiasa.ac.at/rains/reports/NEC6-final110708.pdf

Andreae, M. O. (1983): Soot carbon and excess fine potassium: Longrange transport of combustion-derived aerosols, Science, 220, 1148–1151

Andreae, M. O. and A. Gelencsér (2006), Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols. Atmos. Chem. Phys., 6, 3131–3148

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J. H., and Klimont, Z. (2004): A technology-based global inventory of black and organic carbon emissions from combustion, J. Geophys. Res., 109, D14203, doi:10.1029/2003JD003697

Eckhardt, S., A. Stohl, S. Beirle, N. Spichtinger, P. James, C. Forster, C. Junker, T.Wagner, U. Platt, and S. G. Jennings (2003): The North Atlantic Oscillation controls air pollution transport to the Arctic, Atmos. Chem. Phys., 3, 1769–1778

Heintzenberg, J. (1982): Size-segregated measurements of particulate elemental carbon and aerosol light absorption at remote locations, Atmos. Environ., 16, 2461–2469

IEA (International Energy Agency) (2008): World Energy Outlook 2008. OECD. ISBN: 978-92-64-04560-6. http://www.worldenergyoutlook.org

IPCC (2007): Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.,

Klaassen, G., Amann, M., Berglund, C., Cofala, J., Höglund-Isaksson, L., Heyes, C., Mechler, R., Tohka, A., Schöpp, W., Winiwarter, W. (2004): The Extension of the RAINS Model to Greenhouse Gases**.** IIASA Interim Report IR-04-015, International Institute for Applied Systems Analysis, Laxenburg, Austria. http://www.iiasa.ac.at/rains/reports/ir-04-015.pdf

Koch, D. and J. Hansen (2005): Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment. J. Geophys. Res., 110, D04204, doi:10.1029/2004JD005296

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber (2008): Tipping elements in the Earth's climate system. Proc. Nat. Acad. Sciences, 105 (6), 1786-1793

Levin, Z. and Lindberg, J. D. (1979): Size distributions, chemical composition, and optical properties of urban and desert aerosols in Israel. J. Geophys. Res., 84, 6941–6950

van Loon, H, and J. Rogers (1978): The seesaw in winter temperature between Greenland and northern Europe. Part I: general description. Mon Weather Rev 106: 296–310

Moss, R., M. Babiker, S. Brinkman, E. Calvo, T. Carter, J. Edmonds, I. Elgizouli, S. Emori, L. Erda, K. Hibbard, R. Jones, M. Kainuma, J. Kelleher, J. F. Lamarque, M. Manning, B. Matthews, J. Meehl, L. Meyer, J. Mitchell, N. Nakicenovic, B. O'Neill, R. Pichs, K. Riahi, S. Rose, P. Runci, R. Stouffer, D. v. Vuuren, J. Weyant, T. Wilbanks, J. P. v. Ypersele, and M. Zurek (2008): *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. Intergovernmental Panel on Climate Change, Geneva, 132 pp. http://www.aimes.ucar.edu/docs/IPCC.meetingreport.final.pdf.

Niemi, J. (2006): Atmospheric Emissions from Open Biomass Burning. Development of Datasets for RAINS Model, IIASA Interim Report IR-05-007, (unpublished)

Osborn, T. J. (2004): Simulating the winter North Atlantic Oscillation: the roles of internal variability and greenhouse gas forcing. Climate Dynamics, 22, 605-623

Press, William H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery, Numerical Recipes in C. The Art of Scientific Computing. Cambridge University Press, Second Edition, 1992

Quinn, P. K., Shaw, G., Andrews, E., Dutton, E. G., Ruoho-Airola, T., Gong, S. L. (2007): Arctic Haze: Current trends and knowledge gaps, *Tellus*, 59B, 99–114

Quinn, P.K., Bates, T.S., Baum, E., Doubleday, N., Fiore, A.M., Flanner, M., Fridlind, A., Garrett, T. J., Koch, D., Menon, S., Shindell, D., Stohl**,** A. and Warren, S.G. (2008): Short-lived pollutants in the Arctic: Their climate impact and possible mitigation strategies. *Atmospheric Chemistry and Physics*, 8 (6), 1723-1735

Riahi, K. Gruebler, A. and Nakicenovic N. (2007): Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change* 74, 7, 887-935

Schmidt, G.A., R. Ruedy, J.E. Hansen, I. Aleinov, N. Bell, M. Bauer, S. Bauer, B. Cairns, V. Canuto, Y. Cheng, A. Del Genio, G. Faluvegi, A.D. Friend, T.M. Hall, Y. Hu, M. Kelley, N.Y. Kiang, D. Koch, A.A. Lacis, J. Lerner, K.K. Lo, R.L. Miller, L. Nazarenko, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, G.L. Russell, Mki. Sato, D.T. Shindell, P.H. Stone, S. Sun, N. Tausnev, D. Thresher, and M.-S. Yao (2006). Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. *J. Climate* 19, 153-192.

Shindell, D. (2007): Local and remote contributions to Arctic warming. Geophys. Res. Lett., 34, L14704, doi:10.1029/2007GL030221

Shindell, D., H. Teich, M. Chin, F. Dentener, R. M. Doherty, G. Faluvegi, A. M.Fiore, P. Hess, I. A. MacKenzie, M. G. Sanderson, M. G. Schultz, M. Schulz, D. S. Stevenson, C. Textor, O.'Wild, D. J. Bergmann, H. Bian, C. Cuvelier, B. N. Duncan, G. Folberth, L. W. Horowitz, J. Jonson, J. W. Kaminski, E. Marmer, R. Park, K. J. Pringle, S. Schroeder, S. Szopa, T. Takemura, G. Zeng, T. J. Keating, and A. Zuber (2008): A multi-model assessment of pollution transport to the Arctic. Atmos. Chem. Phys., 8, 5353-5372

Simpson, D. et al. (2003), EMEP Report 1/2003. Online at http://www.emep.int/publ/reports/2003/ emep_report_1_part1_2003.pdf)

Stohl, A.: Characteristics of atmospheric transport into the Arctic troposphere. J. Geophys. Res. 111, D11306, doi:10.1029/2005JD006888, 2006

Tsyro, S.: Assessment of PM pollution in the Arctic from European sources with the EMEP model (2006). Oral presentation at the TF-HTAP Workshop in St. Petersburg, 1 – 3 April 2009

Wallace, J. M., and D. W. J. Thompson (2002), Annular modes and climate prediction, Phys. Today, 57 (8), 28– 33

6.2 EMEP ISO Country codes

Table 6-1. EMEP ISO Country Codes as used in the model runs.

Country Code	*Country Name*
AL	Albania
AT	Austria
ATL	Remaining North-East Atlantic Ocean
BA	Bosnia and Herzegovina
BAS	Baltic Sea
BE	Belgium
BG	Bulgaria
BLS	Black Sea
BY	Belarus
CH	Switzerland
CY	Cyprus
CS	Serbia and Montenegro
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GB	United Kingdom
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IS	Iceland
IT	Italy
LI	Liechtenstein
LT	Lithuania
LU	Luxembourg
LV	Latvia
MD	Republic of Moldova
MED	Mediterranean Sea
MK	The former Yugoslav Republic of Macedonia
MT	Malta
NL	Netherlands
NO	Norway
NOS	North Sea
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation[1]
SE	Sweden
SI	Slovenia
SK	Slovakia
TR	Turkey
UA	Ukraine

[1] European part of Russia, consisting of the EMEP regions Kaliningrad, Kola/Karelia, St. Petersburg/Novgorod-Pskov, and "Rest of the Russian Federation" (European part)

6.3 Emissions, Transfer Coefficients and Contributions

Table 6-2 Annual average PPM2.5 emissions, PPM2.5 transfer coefficients, and contributions. Transfer coefficients are given for three different definitions of the Arctic. Contributions are given only for the 68° definition, both in absolute and relative numbers.

Country Code	PPM2.5 emissions [kt/yr]	α (68°)	α (72°)	α (75°)	c (68°)	
		[µgm^{-3}/(kt yr^{-1})]			[µgm^{-3}]	Rel [%]
AL	5.43E+00	2.96E-07	1.44E-07	6.67E-08	1.86E-06	2.22E-03
AT	3.06E+01	2.06E-06	7.65E-07	2.87E-07	7.16E-05	1.10E-01
ATL	7.16E+01	5.40E-05	2.33E-05	1.17E-05	3.11E-03	8.69
BA	1.69E+01	6.27E-07	2.65E-07	1.16E-07	1.17E-05	1.71E-02
BAS	2.30E+01	2.17E-05	9.85E-06	4.82E-06	5.92E-04	1.15
BE	2.82E+01	6.29E-06	2.70E-06	1.19E-06	1.83E-04	3.09E-01
BG	4.64E+01	3.74E-07	1.58E-07	7.83E-08	1.90E-05	3.19E-02
BLS	7.71E+00	3.37E-07	1.48E-07	7.44E-08	3.13E-06	6.47E-03
BY	3.36E+01	1.13E-05	5.40E-06	2.42E-06	4.17E-04	6.82E-01
CH	7.43E+00	1.93E-06	7.49E-07	2.75E-07	1.52E-05	2.38E-02
CS	3.93E+01	6.04E-07	2.42E-07	1.03E-07	2.68E-05	4.03E-02
CY	1.84E+00	1.13E-08	5.17E-09	2.61E-09	2.20E-08	3.13E-05
CZ	3.44E+01	4.78E-06	2.31E-06	1.07E-06	1.87E-04	2.92E-01
DE	1.33E+02	7.37E-06	3.36E-06	1.46E-06	1.01E-03	1.66
DK	1.64E+01	2.64E-05	1.29E-05	6.01E-06	4.12E-04	7.33E-01
EE	1.29E+01	2.71E-05	1.15E-05	5.97E-06	3.60E-04	6.33E-01
ES	1.10E+02	8.02E-07	3.81E-07	1.28E-07	8.94E-05	1.59E-01
FI	3.08E+01	6.04E-05	2.24E-05	1.16E-05	1.95E-03	3.91
FR	2.02E+02	3.21E-06	1.35E-06	5.60E-07	7.13E-04	1.17
GB	7.86E+01	2.40E-05	1.24E-05	7.25E-06	1.82E-03	4.08
GR	4.91E+01	1.92E-07	8.21E-08	3.52E-08	1.04E-05	1.38E-02
HR	1.44E+01	9.69E-07	3.48E-07	1.26E-07	1.57E-05	2.46E-02
HU	2.58E+01	1.81E-06	6.47E-07	2.53E-07	5.53E-05	9.30E-02
IE	1.13E+01	1.94E-05	9.91E-06	5.47E-06	2.08E-04	4.65E-01
IT	1.31E+02	7.05E-07	2.47E-07	8.15E-08	1.03E-04	1.55E-01
LT	1.44E+01	1.83E-05	8.47E-06	3.69E-06	2.64E-04	4.42E-01
LU	2.54E+00	4.12E-06	1.79E-06	8.31E-07	1.05E-05	1.78E-02
LV	5.90E+00	2.08E-05	9.16E-06	4.48E-06	1.32E-04	2.24E-01
MD	2.11E+01	1.36E-06	6.19E-07	3.21E-07	3.25E-05	6.04E-02
MED	1.54E+02	1.81E-07	7.41E-08	2.87E-08	2.53E-05	3.99E-02
MK	8.15E+00	2.90E-07	1.24E-07	5.68E-08	2.70E-06	3.50E-03
MT	4.20E-01	5.11E-08	1.95E-08	9.19E-09	2.10E-08	3.56E-05
NL	2.72E+01	9.44E-06	4.25E-06	1.88E-06	2.49E-04	4.28E-01
NO	1.87E+01	1.65E-04	7.54E-05	3.73E-05	2.83E-03	6.90
NOS	5.17E+01	2.17E-05	1.07E-05	5.47E-06	1.12E-03	2.32
PL	1.47E+02	8.49E-06	3.95E-06	1.76E-06	1.29E-03	2.13

Country Code	PPM2.5 emissions [kt/yr]	α (68°)	α (72°)	α (75°)	c (68°)	
		[$\mu gm^{-3}/(kt\ yr^{-1})$]			[μgm^{-3}]	Rel [%]
PT	3.85E+01	6.64E-07	3.61E-07	7.22E-08	2.21E-05	4.11E-02
RO	8.61E+01	9.41E-07	4.12E-07	2.10E-07	9.85E-05	1.72E-01
RU	8.64E+02	2.84E-05	9.26E-06	5.28E-06	2.43E-02	56.2
SE	4.72E+01	4.74E-05	1.87E-05	8.87E-06	2.17E-03	4.19
SI	1.00E+01	1.37E-06	4.77E-07	1.83E-07	1.67E-05	2.71E-02
SK	1.38E+01	2.91E-06	1.16E-06	5.01E-07	4.50E-05	7.68E-02
TR	2.58E+02	1.37E-07	5.07E-08	1.93E-08	3.99E-05	7.17E-02
UA	2.73E+02	3.07E-06	1.37E-06	6.89E-07	9.36E-04	1.50

6.4 Black carbon emissions, Baseline scenario

Table 6-3. BC emissions [kt/yr] from the Baseline scenario (countries) combined with the RCP8.5 scenario (sea regions).

Country Code	2000	2005	2010	2015	2020	2025	2030
AL	2.16E+00	2.25E+00	2.08E+00	2.13E+00	2.14E+00	2.19E+00	2.23E+00
AT	8.44E+00	8.38E+00	7.08E+00	5.80E+00	4.82E+00	3.94E+00	3.45E+00
ATL	7.69E+00	8.25E+00	8.81E+00	9.14E+00	9.47E+00	9.73E+00	9.99E+00
BA	9.50E-01	9.48E-01	9.93E-01	1.04E+00	1.12E+00	1.22E+00	1.32E+00
BAS	1.42E+00	1.52E+00	1.62E+00	1.68E+00	1.75E+00	1.79E+00	1.84E+00
BE	8.24E+00	6.76E+00	5.32E+00	4.02E+00	3.03E+00	2.39E+00	2.24E+00
BG	5.83E+00	7.57E+00	6.45E+00	5.26E+00	4.73E+00	4.61E+00	4.36E+00
BLS	8.57E-03	9.20E-03	9.82E-03	1.02E-02	1.06E-02	1.08E-02	1.11E-02
BY	7.70E+00	8.35E+00	8.58E+00	8.79E+00	8.95E+00	9.29E+00	9.64E+00
CH	3.68E+00	3.17E+00	2.21E+00	1.73E+00	1.36E+00	2.10E-01	2.10E-01
CS	3.91E+00	3.88E+00	3.81E+00	3.82E+00	3.95E+00	4.06E+00	4.17E+00
CY	7.72E-01	5.56E-01	3.47E-01	2.73E-01	2.36E-01	2.08E-01	2.07E-01
CZ	1.20E+01	1.28E+01	1.15E+01	8.94E+00	6.93E+00	6.14E+00	5.92E+00
DE	4.09E+01	3.04E+01	2.29E+01	1.80E+01	1.42E+01	1.17E+01	1.10E+01
DK	7.75E+00	8.60E+00	6.90E+00	5.64E+00	4.60E+00	4.23E+00	4.00E+00
EE	2.78E+00	2.69E+00	2.14E+00	1.79E+00	1.49E+00	1.39E+00	1.31E+00
ES	3.76E+01	4.19E+01	3.45E+01	2.29E+01	1.63E+01	1.16E+01	9.58E+00
FI	7.57E+00	7.01E+00	5.86E+00	4.79E+00	3.95E+00	3.60E+00	3.49E+00
FR	9.75E+01	7.50E+01	6.57E+01	5.77E+01	5.09E+01	4.67E+01	4.44E+01
GB	3.62E+01	2.69E+01	2.03E+01	1.43E+01	9.71E+00	6.97E+00	5.66E+00
GR	8.96E+00	8.62E+00	7.06E+00	5.85E+00	5.12E+00	4.68E+00	4.40E+00
HR	3.56E+00	3.59E+00	3.00E+00	2.53E+00	2.12E+00	1.97E+00	1.81E+00
HU	6.81E+00	6.60E+00	5.03E+00	3.91E+00	3.14E+00	2.86E+00	2.78E+00
IE	4.25E+00	3.68E+00	2.69E+00	1.77E+00	1.14E+00	8.03E-01	7.12E-01
IT	4.31E+01	3.91E+01	3.22E+01	2.46E+01	1.92E+01	1.56E+01	1.40E+01

Country Code	2000	2005	2010	2015	2020	2025	2030
LT	3.32E+00	3.11E+00	2.99E+00	2.82E+00	2.55E+00	2.58E+00	2.67E+00
LU	9.68E-01	1.07E+00	7.36E-01	4.56E-01	2.92E-01	1.91E-01	1.85E-01
LV	4.37E+00	4.84E+00	4.84E+00	4.58E+00	3.94E+00	3.67E+00	3.38E+00
MD	2.25E+00	2.53E+00	2.34E+00	2.08E+00	1.89E+00	1.72E+00	1.70E+00
MED	7.39E+00	7.93E+00	8.46E+00	8.78E+00	9.10E+00	9.35E+00	9.60E+00
MK	5.86E-01	6.49E-01	6.83E-01	7.20E-01	7.58E-01	7.94E-01	8.33E-01
MT	2.34E-01	2.57E-01	1.49E-01	8.80E-02	4.60E-02	3.00E-02	2.80E-02
NL	8.44E+00	7.56E+00	5.11E+00	3.77E+00	2.65E+00	2.13E+00	2.05E+00
NO	1.33E+01	1.48E+01	1.46E+01	1.42E+01	1.34E+01	1.27E+01	1.21E+01
NOS	1.58E+00	1.70E+00	1.81E+00	1.88E+00	1.95E+00	2.00E+00	2.06E+00
PL	2.73E+01	2.83E+01	2.60E+01	2.37E+01	1.98E+01	1.84E+01	1.81E+01
PT	1.10E+01	9.95E+00	8.03E+00	6.76E+00	5.95E+00	5.36E+00	5.12E+00
RO	2.16E+01	2.49E+01	2.57E+01	2.64E+01	2.64E+01	2.61E+01	2.58E+01
RU	6.79E+01	8.35E+01	9.20E+01	1.04E+02	1.11E+02	1.20E+02	1.27E+02
SE	8.23E+00	6.82E+00	5.23E+00	3.79E+00	2.80E+00	3.20E+00	2.95E+00
SI	2.16E+00	2.01E+00	1.92E+00	1.70E+00	1.45E+00	1.17E+00	1.11E+00
SK	2.48E+00	1.77E+00	1.64E+00	1.43E+00	1.19E+00	1.06E+00	9.57E-01
TR	4.83E+01	4.48E+01	3.90E+01	3.71E+01	3.49E+01	3.47E+01	3.69E+01
UA	3.56E+01	3.85E+01	4.74E+01	5.41E+01	5.65E+01	6.07E+01	6.59E+01

6.5 Black carbon emissions, Baseline/RU Red scenario

Table 6-4. BC emissions [kt/yr] from the Baseline/RU Red scenario (countries) combined with the RCP8.5 scenario (sea regions)

Country Code	2000	2005	2010	2015	2020	2025	2030
AL	2.16E+00	2.25E+00	2.08E+00	2.13E+00	2.14E+00	2.19E+00	2.23E+00
AT	8.44E+00	8.38E+00	7.08E+00	5.80E+00	4.82E+00	3.94E+00	3.45E+00
ATL	7.69E+00	8.25E+00	8.81E+00	9.14E+00	9.47E+00	9.73E+00	9.99E+00
BA	9.50E-01	9.48E-01	9.93E-01	1.04E+00	1.12E+00	1.22E+00	1.32E+00
BAS	1.42E+00	1.52E+00	1.62E+00	1.68E+00	1.75E+00	1.79E+00	1.84E+00
BE	8.24E+00	6.76E+00	5.32E+00	4.02E+00	3.03E+00	2.39E+00	2.24E+00
BG	5.83E+00	7.57E+00	6.45E+00	5.26E+00	4.73E+00	4.61E+00	4.36E+00
BLS	8.57E-03	9.20E-03	9.82E-03	1.02E-02	1.06E-02	1.08E-02	1.11E-02
BY	7.69E+00	8.07E+00	8.00E+00	7.59E+00	7.12E+00	6.75E+00	6.70E+00
CH	3.68E+00	3.17E+00	2.21E+00	1.73E+00	1.36E+00	2.10E-01	2.10E-01
CS	3.91E+00	3.88E+00	3.81E+00	3.82E+00	3.95E+00	4.06E+00	4.17E+00
CY	7.72E-01	5.56E-01	3.47E-01	2.73E-01	2.36E-01	2.08E-01	2.07E-01
CZ	1.20E+01	1.28E+01	1.15E+01	8.94E+00	6.93E+00	6.14E+00	5.92E+00
DE	4.09E+01	3.04E+01	2.29E+01	1.80E+01	1.42E+01	1.17E+01	1.10E+01

Country Code	2000	2005	2010	2015	2020	2025	2030
DK	7.75E+00	8.60E+00	6.90E+00	5.64E+00	4.60E+00	4.23E+00	4.00E+00
EE	2.78E+00	2.69E+00	2.14E+00	1.79E+00	1.49E+00	1.39E+00	1.31E+00
ES	3.76E+01	4.19E+01	3.45E+01	2.29E+01	1.63E+01	1.16E+01	9.58E+00
FI	7.57E+00	7.01E+00	5.86E+00	4.79E+00	3.95E+00	3.60E+00	3.49E+00
FR	9.75E+01	7.50E+01	6.57E+01	5.77E+01	5.09E+01	4.67E+01	4.44E+01
GB	3.62E+01	2.69E+01	2.03E+01	1.43E+01	9.71E+00	6.97E+00	5.66E+00
GR	8.96E+00	8.62E+00	7.06E+00	5.85E+00	5.12E+00	4.68E+00	4.40E+00
HR	3.56E+00	3.59E+00	3.00E+00	2.53E+00	2.12E+00	1.97E+00	1.81E+00
HU	6.81E+00	6.60E+00	5.03E+00	3.91E+00	3.14E+00	2.86E+00	2.78E+00
IE	4.25E+00	3.68E+00	2.69E+00	1.77E+00	1.14E+00	8.03E-01	7.12E-01
IT	4.31E+01	3.91E+01	3.22E+01	2.46E+01	1.92E+01	1.56E+01	1.40E+01
LT	3.32E+00	3.11E+00	2.99E+00	2.82E+00	2.55E+00	2.58E+00	2.67E+00
LU	9.68E-01	1.07E+00	7.36E-01	4.56E-01	2.92E-01	1.91E-01	1.85E-01
LV	4.37E+00	4.84E+00	4.84E+00	4.58E+00	3.94E+00	3.67E+00	3.38E+00
MD	2.25E+00	2.53E+00	2.34E+00	2.08E+00	1.89E+00	1.72E+00	1.70E+00
MED	7.39E+00	7.93E+00	8.46E+00	8.78E+00	9.10E+00	9.35E+00	9.60E+00
MK	5.86E-01	6.49E-01	6.83E-01	7.20E-01	7.58E-01	7.94E-01	8.33E-01
MT	2.34E-01	2.57E-01	1.49E-01	8.80E-02	4.60E-02	3.00E-02	2.80E-02
NL	8.44E+00	7.56E+00	5.11E+00	3.77E+00	2.65E+00	2.13E+00	2.05E+00
NO	1.33E+01	1.48E+01	1.46E+01	1.42E+01	1.34E+01	1.27E+01	1.21E+01
NOS	1.58E+00	1.70E+00	1.81E+00	1.88E+00	1.95E+00	2.00E+00	2.06E+00
PL	2.73E+01	2.83E+01	2.60E+01	2.37E+01	1.98E+01	1.84E+01	1.81E+01
PT	1.10E+01	9.95E+00	8.03E+00	6.76E+00	5.95E+00	5.36E+00	5.12E+00
RO	2.16E+01	2.49E+01	2.57E+01	2.64E+01	2.64E+01	2.61E+01	2.58E+01
RU	6.81E+01	8.17E+01	8.25E+01	7.93E+01	6.87E+01	6.46E+01	6.43E+01
SE	8.23E+00	6.82E+00	5.23E+00	3.79E+00	2.80E+00	3.20E+00	2.95E+00
SI	2.16E+00	2.01E+00	1.92E+00	1.70E+00	1.45E+00	1.17E+00	1.11E+00
SK	2.48E+00	1.77E+00	1.64E+00	1.43E+00	1.19E+00	1.06E+00	9.57E-01
TR	4.83E+01	4.48E+01	3.90E+01	3.71E+01	3.49E+01	3.47E+01	3.69E+01
UA	3.59E+01	3.82E+01	4.47E+01	4.94E+01	5.02E+01	5.38E+01	5.83E+01

6.6 Emissions from Vegetation Fires (FT-2000)

Table 6-5. BC emissions [Mt/yr] from forest fires (deforestation fires + wildfires), as taken from the FT-2000 scenario. Only countries with nonzero emissions are shown.

Country Code	2000	2005	2010	2015	2020	2025	2030
FI	8.62E-06	8.7E-06	8.73E-06	8.71E-06	8.6E-06	8.41E-06	8.22E-06
IT	8.29E-06	8.36E-06	8.39E-06	8.37E-06	8.26E-06	8.08E-06	7.9E-06

Country Code	2000	2005	2010	2015	2020	2025	2030
NO	4.54E-06	4.57E-06	4.59E-06	4.58E-06	4.52E-06	4.42E-06	4.33E-06
RU	0.036625	0.03647	0.036442	0.036358	0.036742	0.037055	0.037359
SE	1.29E-06	1.3E-06	1.3E-06	1.3E-06	1.28E-06	1.26E-06	1.23E-06
CH	1.96E-05	1.98E-05	1.99E-05	1.98E-05	1.95E-05	1.91E-05	1.87E-05

Table 6-6. BC emissions [Mt/yr] from savanna and grassland fires, as taken from the FT-2000 scenario. Only countries with nonzero emissions are shown.

Country Code	2000	2005	2010	2015	2020	2025	2030
AL	0.000205	0.000129	5.24E-05	4.77E-05	4.77E-05	4.29E-05	4.29E-05
AT	0.000268	0.000266	0.000258	0.000251	0.000239	0.000224	0.000212
BY	0.000118	0.000113	0.000108	0.000109	0.000111	0.000119	0.000122
BE	3.64E-05	3.62E-05	3.51E-05	3.41E-05	3.26E-05	3.05E-05	2.88E-05
BG	0.000397	0.000249	0.000102	9.23E-05	9.23E-05	8.31E-05	8.31E-05
HR	5.74E-05	3.6E-05	1.47E-05	1.33E-05	1.33E-05	1.2E-05	1.2E-05
CZ	8.09E-05	5.08E-05	2.07E-05	1.88E-05	1.88E-05	1.69E-05	1.69E-05
EE	1.65E-06	1.59E-06	1.52E-06	1.53E-06	1.56E-06	1.68E-06	1.72E-06
FI	6.89E-06	6.85E-06	6.64E-06	6.45E-06	6.16E-06	5.77E-06	5.44E-06
FR	0.000205	0.000204	0.000198	0.000192	0.000184	0.000172	0.000162
GE	2.33E-05	2.24E-05	2.15E-05	2.15E-05	2.21E-05	2.37E-05	2.42E-05
DE	0.000543	0.00054	0.000523	0.000509	0.000486	0.000455	0.000429
GR	0.000201	0.0002	0.000194	0.000188	0.00018	0.000168	0.000159
HU	8.05E-05	5.06E-05	2.06E-05	1.87E-05	1.87E-05	1.69E-05	1.69E-05
IE	7.04E-06	7E-06	6.78E-06	6.6E-06	6.29E-06	5.9E-06	5.57E-06
IT	0.001448	0.00144	0.001396	0.001357	0.001295	0.001213	0.001145
LV	1.53E-05	1.47E-05	1.41E-05	1.41E-05	1.45E-05	1.56E-05	1.59E-05
LT	2.14E-05	2.05E-05	1.97E-05	1.97E-05	2.02E-05	2.17E-05	2.22E-05
LU	0.00011	0.000109	0.000106	0.000103	9.81E-05	9.19E-05	8.67E-05
NL	1.22E-05	1.21E-05	1.17E-05	1.14E-05	1.09E-05	1.02E-05	9.61E-06
NO	1.35E-06	1.34E-06	1.3E-06	1.26E-06	1.21E-06	1.13E-06	1.07E-06
PL	0.000122	7.65E-05	3.12E-05	2.83E-05	2.83E-05	2.55E-05	2.55E-05
PT	0.000539	0.000536	0.000519	0.000505	0.000482	0.000451	0.000426
MD	6.35E-05	6.11E-05	5.86E-05	5.86E-05	6.01E-05	6.45E-05	6.6E-05
RO	0.000154	9.65E-05	3.93E-05	3.57E-05	3.57E-05	3.22E-05	3.22E-05
RU	0.042411	0.040794	0.039114	0.039144	0.040132	0.043041	0.044097
CS	0.00018	0.000113	4.6E-05	4.18E-05	4.18E-05	3.77E-05	3.77E-05
SK	6.73E-06	4.22E-06	1.72E-06	1.56E-06	1.56E-06	1.41E-06	1.41E-06
ES	0.001425	0.001417	0.001373	0.001335	0.001274	0.001193	0.001126
SE	3.13E-05	3.11E-05	3.01E-05	2.93E-05	2.8E-05	2.62E-05	2.47E-05
MK	0.000115	7.23E-05	2.95E-05	2.68E-05	2.68E-05	2.41E-05	2.41E-05

Country Code	2000	2005	2010	2015	2020	2025	2030
TR	0.000611	0.000471	0.000451	0.000496	0.000469	0.000419	0.000375
UA	0.000752	0.000723	0.000693	0.000694	0.000711	0.000763	0.000782
GB	0.000258	0.000257	0.000249	0.000242	0.000231	0.000216	0.000204