VACCIA

Action 13

Assessment of the impacts of climate change on pollution transport to the Arctic region

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Table of contents

1 Introduction

Climate change is predicted to cause significant changes in the climate of the Arctic region. These changes will change the climate of the subarctic Northern Finland, too. By the end of this century, the annual mean temperature in Finland is projected to increase by 2–6ºC compared to reference period 1970-2000. In Northern Finland the temperature increase is the strongest: during winter 3-10ºC and during summer 1-6ºC. It is projected that by the end of the century the temperatures in central Lapland would approximately match those in present-day southern Finland (Jylhä et al. 2009).

Precipitation amounts will also increase in Finland, in winter by 10-40% and in summer by 0-20% by the end of this century. Again, the changes in the north will exceed those in the south. However, during the next few decades, changes in precipitation will still be affected more strongly by natural variability than by climate change (Jylhä et al. 2009).

In Northern Finland the thermal winter (daily mean temperature below zero) is projected to shorten by one and a half month and number of snow cover days is projected to decrease by 20-30% by the end of the century (Jylhä et al. 2009). Wintertime weather will have more cloud cover, with less solar radiation. In summer, no major changes in cloudiness and radiation are expected (Jylhä et al. 2009).

These climate changes can result in changes in levels and loads of atmospheric pollutants for example due to changes in circulation patterns, increased marine transport, increased amount of forest fires and land-use changes.

This action focused on the Pallas-Yllästunturi national park and the adjacent forest region, located in Northern Finland north of the Arctic Circle. This site represents well the remote and pristine boreal and subarctic Eurasian environments. The site is particularly suitable for long-term ecological and atmospheric monitoring because the Pallas area has been a national park over six decades and thus represents a relatively pristine nature. There are very few local sources of air pollutants. The site incorporates a variety of biotopes, e.g. forests, bogs, barren mountain tops, lakes and rivers.

This report first summarizes the developments and major sources of the atmospheric pollution load detected at the Pallas measurement station since the middle of the 1990's. These changes were assessed in this action using information of the Pallas measurement site and different modelling techniques. These are described in more detail in the intermediate report of this Action (Anttila et al. 2010).

The arctic atmosphere is highly influenced by the overall hemispheric circulation. Atmospheric pollutants are transported to the Arctic area by air currents. The climate models predict also changes in the prevailing airflows, which changes may have effects on the pollution transport to Finland. In this study we present an estimate of the effects of the projected changes in the wind fields due to climate change on pollution transport to Northern Finland.

We also make an estimate of the possible effects of the increasing shipping in the Arctic Ocean on the pollutant dispersion to Northern Finland. Finally we discuss the impacts of other possible indirect effects of climate change on pollutant load in this area.

2 Present situation

During the past 10-20 years the development of the air pollution situation in Pallas area have been relatively favourable. In general, the pollutant concentrations in air have been decreasing or remained steady (Figure 1). Of the studied 57 pollutant concentration time series between 1994/1996 – 2009 only one statistically significant increasing concentration time series was detected.

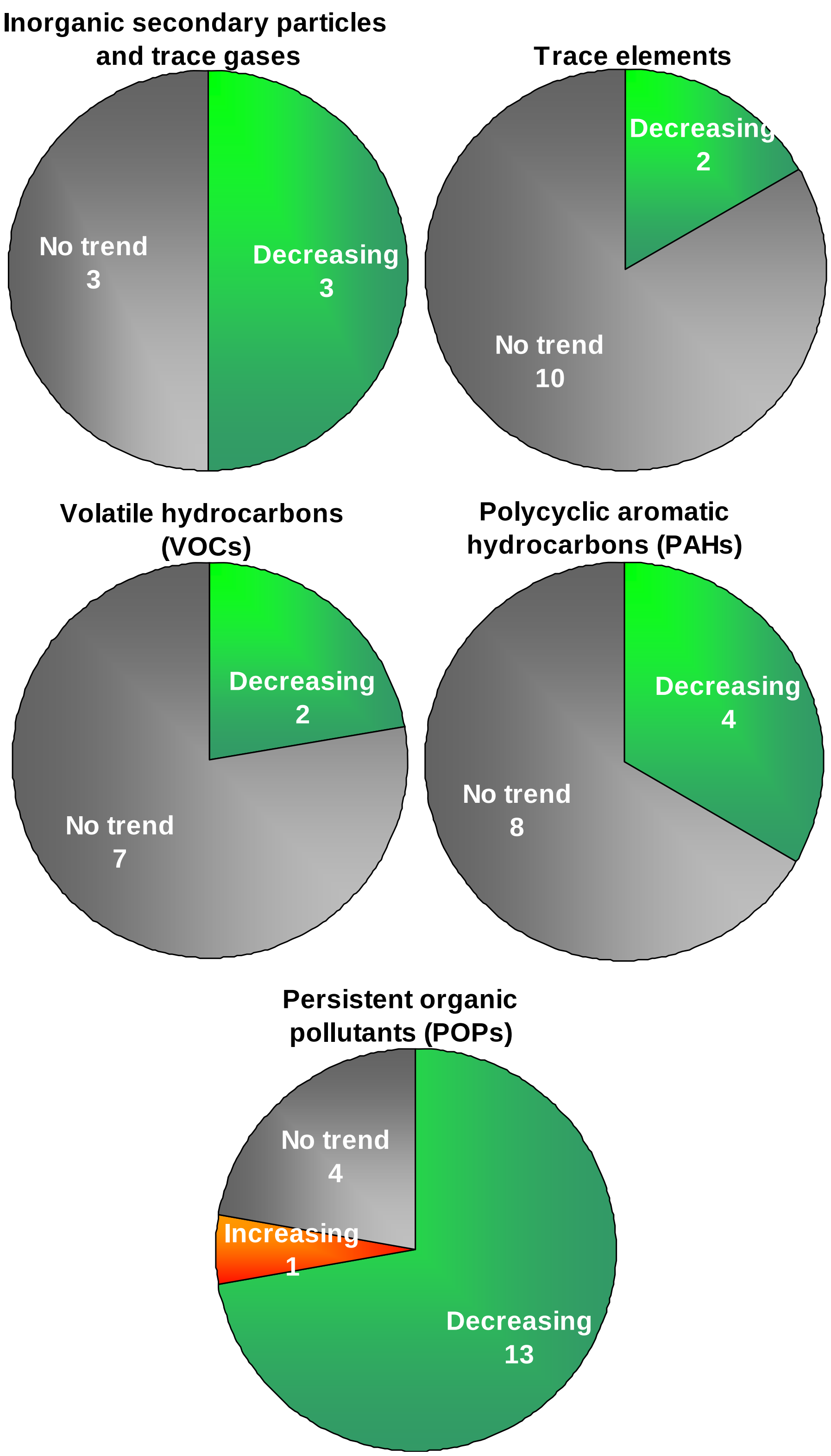

Figure 1. Summary of the detected trends (at 95% confidence level) of the 57 chemically speciated concentration time series in air at Pallas in 1996-2009 (Anttila et al. 2010).

For sulphur dioxide and arsenic and copper the decreasing trends can be related to the decreasing emissions of the Russian copper-nickel industry on Kola peninsula. Also the long-range transported sulphate has been decreasing during the study period which reflects the successful emission reductions in a wider regional and hemispheric scale. For inorganic nitrogen compounds the situation is not as good, no trends were detected for nitrogen dioxide, nitrate and ammonium. For NO_2 the densely populated continental Europe was identified to be the dominating source area (Figure 2).

So, the sulphur related pollution has followed a decreasing development path while the major efforts to reduce nitrogen dioxides' emission has not resulted the desired decrease in the regional NO_2 or NO_3 concentrations. In spite of effective VOC emission reductions in Europe, at Pallas only two decreasing trends of VOCs were detected (Figure 1). As a consequence, also ozone concentrations have remained at the high level typical to these high latitudes in the northern hemisphere.

The concentrations of polycyclic aromatic hydrocarbons (PAH compounds) have been stable or weakly decreasing since the mid 1990's at Pallas. Some of the heavier PAHs were partly associated to the Kola peninsula industrial sources, these were also the ones with significant decreasing trends. However, majority of the PAHs arrived at Pallas with southern or south western air masses associated with NO_2 and NO_3, and thus suggesting that traffic exhaust is the dominating source.

Regarding the other persistent organic pollutants (POP compounds) the global trend has been to reduce the production and use of these harmful compounds. This has resulted also similar development in the concentrations detected at Pallas; the majority of POP concentrations were decreasing. In the source apportionment analysis many of these compounds became connected to soil, biota and water related elements which may indicate slow extinction of these pollutants from the ecosystems, too.

However, there was one exception in this positive development; the atmospheric concentration of DDD (which is the breakdown product of DDT) behaved differently from the rest of the POPs; it's concentration showed statistically significant increase during the latter part of the study period, 2002-2009.

While a number of harmful compounds are detected in the air of Pallas it should be kept in mind that, as a whole, the atmosphere of Pallas area as well as the whole Arctic is very clean due to the relatively small atmospheric emissions of the polar region and its remoteness from the lower latitude emissions. Typically at Pallas the concentrations of short-lived pollutants are only fractions of those detected at background areas of Southern Finland.

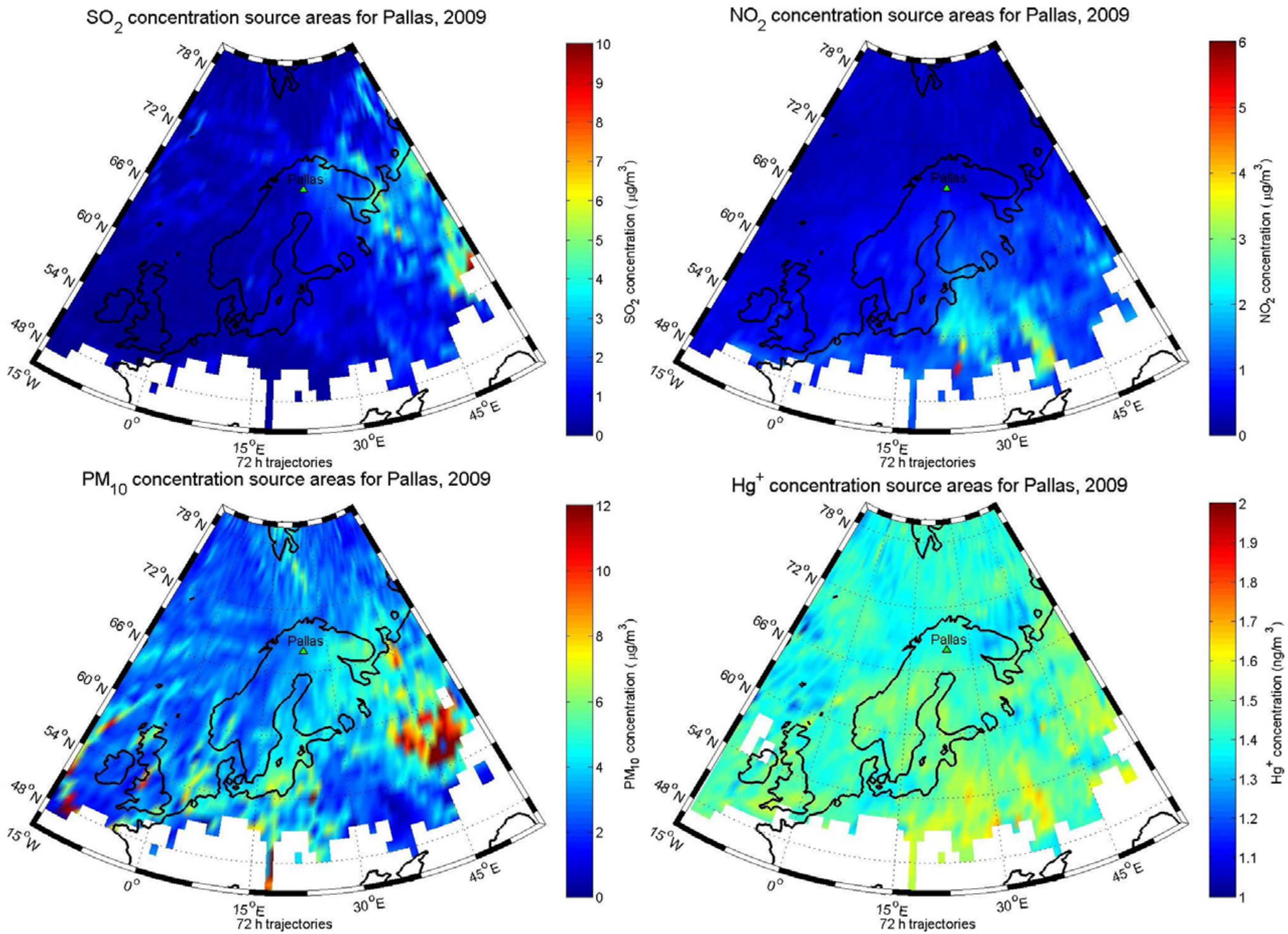

Figure 2. Source areas of SO_2, NO_2, PM_{10} and total elemental mercury (Hg^+) at Pallas in 2009 (Anttila et al. 2010). A high concentration value in a grid cell means that, on average, air masses crossing over this cell result in high concentrations at Pallas measurement site.

3 Effect of future changes in atmospheric circulation on pollutant transport to Pallas

The future projections of wind speed and direction were based on the wind observations at Sodankylä Observatory (67.4°N, 26.6°E) in 1998-2009. Sodankylä observatory is located at the distance of 130 kilometres to the south-east of Pallas and provides the needed high quality wind observations to compile the wind distribution representative for Central and Northern Lapland. Wind direction and speed were measured every third hour; for this study hourly values were interpolated from these. Future projections of wind speed and direction were derived by utilizing the instantaneous wind observations from 1998-2009 together with the climate model simulations. This is a so-called delta-change method that is intended to take into account the changes in atmospheric circulation as projected by climate models and, on the other hand, to preserve qualitatively the instantaneous variability of observed weather parameters.

The future projections of wind speed and direction for 2030, 2050 and 2100 were derived assuming that the greenhouse gas and aerosol concentrations will follow the A2-scenario presented by the Intergovernmental Panel of Climate Change (IPCC, 2007). The changes in wind parameters for the years 2030, 2050 and 2100 were calculated by linear interpolation and extrapolation from the simulated changes between the periods 1971–2000 and 2081–2100. The projections were calculated as an average of simulations performed with nine CMIP3 climate models (see Jylhä et al. 2011, Appendix 6).

3.1 Calculation of future wind parameters

The wind speeds and directions in the future climate were calculated as follows. First, the observed instantaneous wind is presented in component form:

$$u_{obs}(t) = V_{obs}(t)\cos\alpha(t) \qquad (1)$$

$$v_{obs}(t) = V_{obs}(t)\sin\alpha(t) \qquad (2),$$

where u and v are the western and southern components of the wind vector **V**, $V = \sqrt{(u^2 + v^2)}$ is the wind speed and $\alpha = 270° - \phi$, where ϕ is the observed wind direction.

Then the model-projected changes were added to the hourly wind vector components given by equations 1 and 2:

$$u^*(t) = u_{obs}(t) + \Delta\overline{u} \qquad (3)$$

$$v^*(t) = v_{obs}(t) + \Delta\overline{v} \qquad (4),$$

where $\Delta\overline{u}$ and $\Delta\overline{v}$ are the monthly average changes of each component. In order to produce the average scalar wind speed change as projected by the models, these preliminary values were corrected by the factor

$$u_{proj} = u^* \frac{\overline{V}_{obs} + \Delta\overline{V}}{\overline{V}^*} \qquad (5)$$

$$v_{proj} = v^* \frac{\overline{V}_{obs} + \Delta\overline{V}}{\overline{V}^*} \qquad (6).$$

More details can be found in Jylhä et al. (2011).

3.2 Wind directions and speeds in 2030, 2050 and 2100 at Sodankylä

The distributions of wind directions and speeds in 2030, 2050 and 2100 at Sodankylä, compared to the reference period 1998-2009, are presented in Figure 3. In the changing climate the south-westerly winds become more frequent, however, the projected change is reasonably small. By 2100 the frequency of the winds between 180° and 270° increases from 35% to 39% (Figure 3). Also moderate and high wind speeds ($v > 6$ m/s) become more common. Largest changes occur during autumn and winter while in spring and summer the wind distributions remain virtually unchanged.

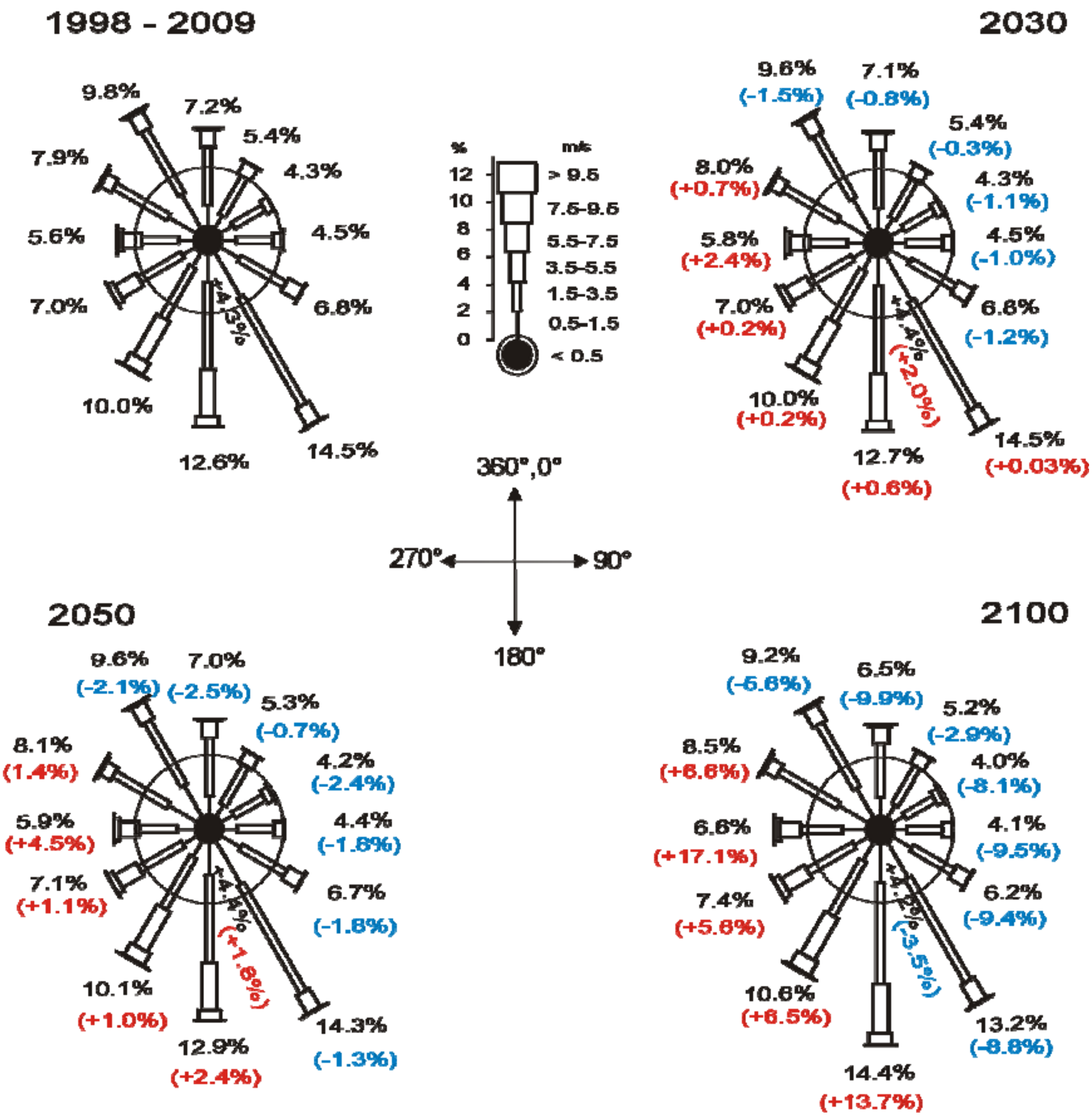

Figure 3. The annual mean distribution of wind speed and direction at Sodankylä in 1998-2009 and projections for 2030(2015–2044), 2050(2035–2064) and 2100 (2085–2114). Red (blue) letters denote an increase (decrease) in the frequency of winds blowing from each sector relative to the reference period.

Major sources of uncertainty in this estimate include

- Here we have assumed that the greenhouse gas and aerosol emissions follow the rather pessimistic A2 scenario. In the case of successful emission reduction, the changes in the wind distribution would be smaller.

- The climate models used in this study predict quite uniformly that the western and south-western wind direction become more common; however, the simulated magnitude of the change varies among the nine models.
- The delta-change method used here assumes that the short term variation (from hour to hour) of weather parameters remains qualitatively unchanged, being merely modified by the model-projected change.

3.3 Estimated average concentrations

We first estimate the impact of the changing wind directions on SO_2, NO_x and soot (black carbon, BC) concentrations resulting at Pallas. In this approach we assume that the location and magnitude of the emissions remains unchanged. The average concentration was calculated from $<C>=\sum f_i <C>_i$ where f_i is the fraction of all wind observations in sector i at wind speed > 0.5 m/s and $<C>_i$ is the average concentration from sector i. The total average concentration was calculated assuming that the fractions f_i change according to the climate models projections for the years 2030, 2050 and 2100 described in earlier section.

Figure 4 shows the pollution roses (the average concentration of a pollutant as a function of the corresponding wind direction) for the reference period 1998-2009. Also the average concentration of the reference period is given (black letters in Figure 4) as well as the projected changes of concentrations (red and blue letters) in 2030, 2050 and 2100 due to the changing wind directions.

The pollution roses for 1998-2009 show that the highest SO_2 concentrations have originated from north-eastern sector, i.e. from the industry in Kola Peninsula. Highest NO_x concentrations come from southern sector and the BC from southeast. These distributions based on surface wind directions are quite well in line with the source area maps (Figure 2) based on trajectory calculations. Highest concentrations of BC come from south-eastern sector, which is in line with the source area analysis of BC presented by Hyvärinen et al. (2011).

For SO_2 and BC the average concentrations decrease slightly whereas the NO_x concentrations increase slightly (by 2100 -3%, -1% and +0.5%, respectively) (Figure 4). As easterly winds become more infrequent a decreasing amount of the eastern (SO_2, BC) emissions will be transported to Pallas while more NO_x is dispersed from the southern source areas. As a whole, however, we find that the long term trend in the atmospheric circulation due to climate change will cause only minor changes in the short-lived pollutant concentrations at the Pallas site.

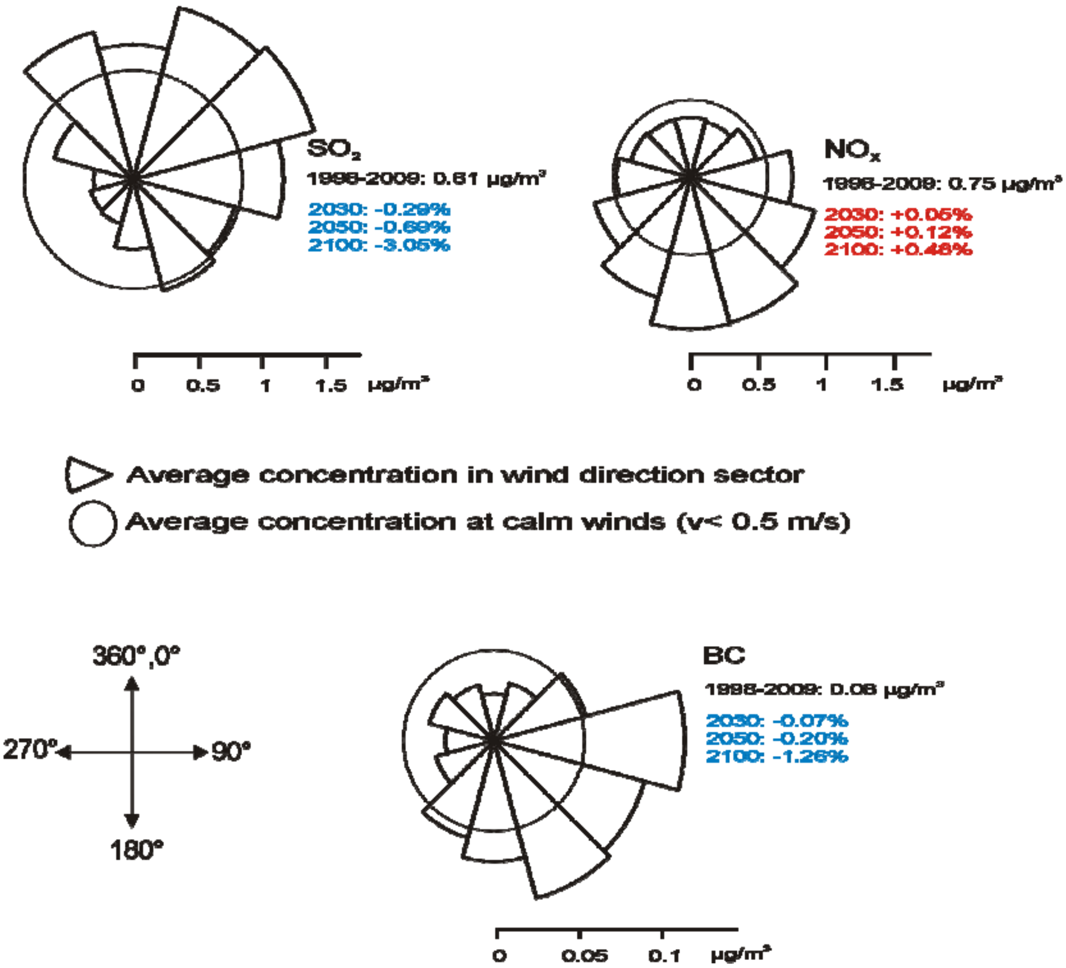

Figure 4. Average concentrations of SO_2 NO_x and BC in each wind sector in 1998-2009 (black letters) at Pallas, and the resulting changes of concentrations (as a percentage relative to the reference period) in 2030, 2050 and 2100 due to the projected changes of wind direction frequencies (blue and red letters).

4 Effect of future changes in ship emissions on pollutant transport to Pallas

The Arctic Ocean is projected to become nearly ice-free in summer within this century, likely within the next thirty to forty years (SWIPA, 2011). This change raises the possibility of economically viable trans-Arctic shipping as well as increasing access to the natural resources of the Arctic area. Significant growth of international shipping in the Arctic Ocean would also increase the environmental burden of the area. Here we make a first-order estimate of how the predicted growth of shipping will impact short-lived pollutant concentrations detected in the Pallas area in future.

The future emissions are adopted from Corbett et al. (2010), who present the emission inventories of black carbon and other pollutants under existing and future (up to 2050) scenarios that account for growth of shipping in the Arctic region, potential diversion traffic through emerging routes and possible emission control measures.

The emission growth factors of 1.7, 0.4, and 2.3 by the year 2030 and 3.8, 1.0 and 5.3 by the year 2050 for NO_x, SO_2, and BC, respectively, were calculated from the the high-growth scenario of shipping emissions presented by Corbett et al. (2010). In this study we assume that the concentrations observed presently in the polar sectors 270° to 60° at Pallas are due to the present-day shipping at the Arctic Ocean. If the shipping emissions grow as listed above, we get an average growth factor for concentrations and thus the average concentration for the whole period. The average concentrations from the other sectors are assumed to remain the same as in 1998-2009. This approach produces upper limit of the concentration increases caused by the growing shipping in the Arctic Ocean. The calculation was not done for SO_2 because it is so clearly dominated by emissions from Kola Peninsula and, besides, no net increase of shipping emissions is predicted for SO_2 by 2050 (Corbett et al. 2010) .

The results are shown in Figure 5. For comparison we first reproduce the present pollution roses of NO_x and BC.

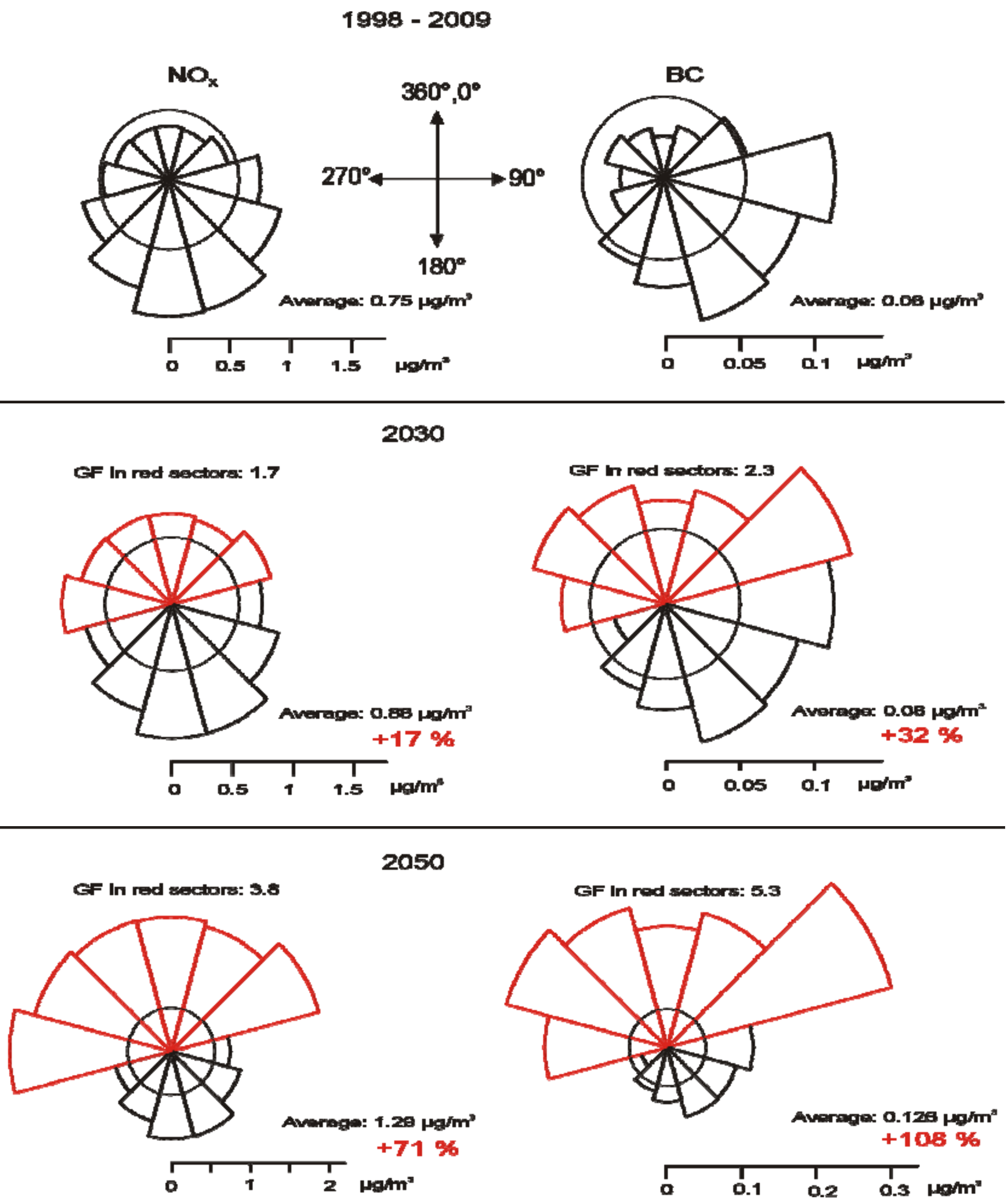

Figure 5. Average concentrations of NO_x and BC in wind sectors in 1998-2009 at Pallas (top). Projected concentrations of NO_x and BC in 2030 (middle) and 2050 (bottom) due to the climate model-projected changes of wind direction frequencies and increasing shipping emissions in the Arctic Ocean. Total annual means are given in black letters and the percentage changes relative to the reference period in red.

This estimate shows that future shipping emissions have the potential to double the atmospheric NO_x and BC load at Pallas by 2050. At highest the concentrations caused by the predicted shipping emissions may be comparable to the net import of the presently long-range transported NO_x and BC.

5 Other impacts

Climate change has large potential to indirectly increase the atmospheric pollutant load in the Arctic region. Perhaps the largest threats are posed by the climate change induced changes in the pollutant emission patterns. The majority of these alterations cannot be quantified yet.

One example of the potential increase of atmospheric pollution load is the re-emission of long-lived and accumulative pollutants from environmental reservoirs due to increased temperature. After primary release, the long-lived POPs and mercury disperse regionally and globally until deposited to environmental reservoirs. Large quantities of these substances are by now stored in ecosystems and man-made environments. A portion of these stores can be re-emitted to the atmosphere in warming climate

Climate change can also induce expanded use and release of these harmful substances. Increasing global temperatures are likely to intensify propagation of vector-borne diseases such as malaria and, thus, enhance the demand for insecticides likely to include DDT. So climate change may counteract the presently continuing emission reductions. There is considerable uncertainty whether primary or secondary releases of long-lived pollutants will dominate in future (AMAP, 2011; UNEP/AMAP 2011).

It has been estimated that wildfire potential will increase globally under future climate. Fire potential will increase overall from low to moderate in the United States, central Asia and southern Europe, and from moderate to high in South America, southern Africa and Australia by 2100 (e.g. Liu et al. 2010). There is also an emerging body of evidence suggesting that Arctic tundra ecosystems can burn more frequently under the warming climate (e.g. Hu et al. 2010).

The two major identified wild fire episodes in Finland (in August 2006 and 2010) have had weak but detectable impact on the PM concentrations also in Northern Finland. For example in August 2010 when record high concentrations of $PM_{2.5}$ (e.g. 8 Aug 2010 daily mean 62 $\mu g/m^3$) were detected at Virolahti in north-eastern Finland due to fires in north-western Russia, elevated concentrations of PM_{10} were detected also at Pallas. On 2, 8, 14 and 21 August 2010 the daily means of PM_{10} concentrations at Pallas were 7–8 $\mu g/m^3$, which are low values but , on the other hand, belong to the highest ten percent measured since 2006 at Pallas. In future the projected increasing fire frequency and the transition of fire-sensitive areas towards north would also increase the long range transport of aerosols to Northern Finland and other Arctic regions.

6 Summary

During the past 10–20 years the development of the air pollution situation in Pallas area have been relatively favourable. In general, the pollutant concentrations in air have been decreasing or remained steady. Of the studied 57 pollutant concentration time series 24 had decreasing trend, one increasing and 32 had no statistically significant trend since the middle of 1990's.

For sulphur dioxide and arsenic and copper the decreasing trends can be related to the decreasing emissions of the Russian copper-nickel industry on Kola peninsula. Also the long-range transported sulphate has been decreasing during the study period which reflects the successful emission reductions in a wider regional and hemispheric scale.

For inorganic nitrogen compounds the situation is not as good, no trends were detected for nitrogen dioxide, nitrate and ammonium. In spite of effective VOC emission reductions in Europe, at Pallas only two decreasing trends of VOCs were detected. As a consequence, also ozone concentrations have remained at the high level typical to these high latitudes in the northern hemisphere.

The concentrations of polycyclic aromatic hydrocarbons (PAH compounds) stayed stable or were weakly decreasing since the mid 1990's at Pallas. Some of the heavier PAHs were partly associated to the Kola peninsula industrial sources, these were also the ones with significant decreasing trends.

The majority of persistent organic pollutants (POPs) concentrations were decreasing. These compounds were strongly related to soil, biota and water sources so it is evident that the slow extinction of these pollutants from the ecosystems has been underway. However, the atmospheric concentration of DDD (which is the breakdown product of DDT) was increasing during the latter part of the study period, 2002-2009.

As a whole, the atmosphere of Pallas area is very clean due to the relatively small atmospheric emissions in the polar region and its remoteness from the lower latitude emissions. Typically at Pallas the concentrations of short-lived pollutants are only fractions of those detected at background areas of Southern Finland.

Climate change will induce changes in the prevailing airflows, which changes may have effects on the pollution transport to Northern Finland. In the changing climate the south-westerly winds become more frequent, however, the projected change is reasonably small. By 2100 the frequency of the winds between 180° and 270° increases from 35% to 39%. Also moderate and high wind speeds (v>6m/s) become more common. Largest changes occur during autumn and winter while in spring and summer the wind distributions remain virtually unchanged.

As easterly winds become more infrequent a decreasing amount of the eastern (SO_2, BC) emissions will be transported to Pallas while more NO_x is dispersed from the southern source areas. As a whole, however, we find that the long term trend in the atmospheric circulation due to climate change will cause only minor changes in the short-lived pollutant concentrations at the Pallas site.

Climate change has large potential to indirectly increase the atmospheric pollutant load in the Arctic region. Perhaps the largest threats are posed by the climate change induced changes in the pollutant emission patterns.

The Arctic Ocean is projected to become nearly ice-free in summer within this century, which raises the possibility of significant growth of international shipping in the Arctic Ocean. We estimate that future shipping emissions have the potential to double the atmospheric NO_x and BC load at Pallas by 2050. At highest the concentrations caused by the predicted shipping emissions may be comparable to the net import of the presently long-range transported NO_x and BC.

Majority of the potential indirect effects of climate change on the pollution load in Pallas area cannot be quantified yet. These include the potential increase of re-emission of long-lived and accumulative pollutants like POPs and mercury from environmental reservoirs due to increased temperature. Climate change can also induce expanded use and release of these harmful substances. For example, increasing global temperatures enhance the demand for insecticides likely to include DDT. So climate change may counteract the presently continuing emission reductions.

It has been estimated that wildfire potential will increase globally under future climate. For example, fire potential will increase from low to moderate in southern Europe and central Asia by 2100. It has been suggested that also that Arctic tundra ecosystems can burn more frequently under the warming climate . The projected increasing wildfire frequency and the transition of fire-sensitive areas towards north would also increase the long range transport of aerosols to Northern Finland and other Arctic regions.

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