ACCESS
Arctic Climate Change
Economy and Society

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ACCESS

Arctic Climate Change, Economy and Society

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Contents

1 Introduction

Arctic air pollutants and their precursors impacts the climate by altering solar and terrestrial radiation budgets, and their distributions are in turn highly dependent upon regional climate. Climate change or natural variability can perturb the long-range transport, chemical processing and local meteorology that influence Arctic air pollution.

The relatively short lifetimes of radiatively active air pollutants and their precursors (days to weeks for ozone and aerosols, and approximately a decade for methane) imply that changes in their atmospheric abundances could induce rapid climate responses in the next few decades. These species are therefore referred to as "Near-Term Climate Forcers" (NTCFs). When considering strategies to abate NTCFs, policymakers face tradeoffs and synergies. Reducing some of them (e.g. sulfate) to obtain health benefits may actually lead to climate warming. In this report we focus on two NTCFs (black carbon and methane) for which there will be a win-win situation from emission reductions. Decreasing atmospheric methane (CH_4) would slow near-term warming, due to its strong climate impact on a 20-year time frame, reductions could help to slow Arctic sea ice loss over the next few decades. Reducing CH_4 would also decrease tropospheric ozone, including ozone levels in surface air, thereby also lessening the adverse impacts on vegetation and human health. Black Carbon (BC), sometimes named soot, impacts visibility, climate forcing and health. The strong warming due to the direct effect and ice and snow-albedo effect of BC imply that emission reductions could yield a short-term climate benefit (Fiore et al. 2012; Quinn et al. 2008; Bond et al. 2013). Models indicate that the Arctic and ice melting in the region is particularly sensitive to BC forcing (Flanner et al. 2007; Quinn et al. 2008; Jacobson et al. 2010; Sand et al. 2012; Bond et al. 2013)

From pre-industrial to present, the RF from the more-than-doubling of the atmospheric CH_4 abundance is estimated to be second after CO_2 in terms of anthropogenic RF from greenhouse gases. Much uncertainty remains in our understanding of the contributions from specific source sectors and regions to CH_4 emissions (Kirsche et al. 2013, Houwelling et al. 2014), the underlying factors contributing to recent observed trends (Dlugokencky et al. 2009; Righi et al. 2009; Kai et al. 2011, Aydin et al. 2011; Bousquet et al. 2011; Sussmann et al. 2013; Bergamachi et al. 2013), and in feedbacks from the biosphere (O'Connor et al. 2010) and

permafrost (Isaksen et al. 2011). The uncertainties with regards to understanding recent trends limit confidence in accurately projecting the future evolution of CH_4. This report provides a detailed analysis on CH_4 in the Arctic based on the work presented in Dalsøren et al. in prep. We compare model studies and observations to understand causes for recent trends and interannual variation of methane in the Arctic.

The magnitude of the climate forcing from BC is quite uncertain, but on global scale the direct radiative forcing of BC may be similar to methane (Bond et al. 2013). BC aerosols may also affects clouds and thereby have an indirect climate effect. Very little is known on the contribution of different aerosol components to the aerosol indirect effect. The sign of the cloud forcing is model-dependent and varies with the aerosol mass ratios, the size of the aerosols, cloud height, etc.

2 Methane

2.1 Setup of study

In the methane study (Dalsøren et al. in prep) we used methane emissions for anthropogenic sources from Edgar4.2 (http://edgar.jrc.ec.europa.eu/overview.php?v=42) and biomass burning and natural sources from Bousuqet et al (2011). In addition we used soil uptake from Bousquet et al. (2011). The Edgar inventory covers the period 1970-2008 while the Bousquet data covers the period 1984-2009. Since we focus on the period 1970-2012 extrapolations were made for the years not covered by the datasets. For all years from 1970 to 1984 we used natural and biomass burning emissions and soil uptake for 1984. For 2010-2012 we used 2009 data for these sources. For the anthropogenic emissions we extrapolated the change from 2007-2008 to the period 2009-2012.

Combining two emission inventories (Edgar 4.2 and Bousquet) makes it possible to study the impacts of many emission sectors (18 in total). In the chemical transport model used and described below the emissions from each of the 18 sectors were added as a passive tracer with an e-folding lifetime of 1 month. The passive tracers were used as a proxy for the different sector's contribution to monthly mean surface methane concentrations. The idea was to reveal key sectors behind changes in spatial distribution or temporal evolution in the Arctic.

Anthropogenic emissions of CO, NOx, sulfur and NMVOCs were taken from the EDGAR4.2 inventory. Similar extrapolation was done as for the methane emissions to cover the period 2009-2012. For biomass burning emissions we used GFEDv3 (van der Werf et al. 2010) for the period 1997-2012. In the period 1970-1996 we used year 2001 emissions from GFEDv3. 2001 was used since this is a year with weak ENSO index for all months. For natural emissions we used emission data for 2000 for all years. The emissions from vegetation of CO and NMVOCs come from MEGAN (http://lar.wsu.edu/megan/).

The emission data over the period 1970-2012 was used as input in a Chemical Transport Model (CTM), the OsloCTM3 model. A coupled tropospheric and stratospheric version was used. In addition to the 18 passive tracers described above the model was run with 109 chemical active species affecting methane and atmospheric oxidation capacity. OsloCTM3 was described and evaluated in Søvde et al. (2012) and used for studying methane lifetime changes in Holmes et al. (2013). OsloCTM3 is an update of OsloCTM2 which has been used in a number of previous studies of stratospheric and tropospheric chemistry, including studies on methane (Dalsøren and Isaksen 2006, Dalsøren et al. 2009, Dalsøren et al. 2010, Isaksen et al. 2011).

OsloCTM3 was driven with meteorological forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) model (see Søvde et al. 2012 for details). The meteorological data used in this study cover the period 1997-2012. For the years ahead of 1997, year 2001 meteorology was used. 2001 was chosen since this is a year with weak ENSO index for all months. Studies (e.g. Holmes et al. 2013) have shown a strong influence of ENSO events on methane.

2.2 Evolution of methane in the Arctic

Many models struggle reproducing even the broad lines of global and regional methane evolution over the decades and the causes are much debated. Our model generally reproduces the different periods of growth and stagnation in the Arctic (figure 1). The model best

reproduces the evolution for the period (1997-2012) with interannual variation of meteorological input. This is promising and gives us confidence when evaluating the decisive drivers explaining the variable evolution over time. That being said, the model fails to reproduce the strength of the growth rate during some eras, for instance the recent growth is overestimated. Over the whole period the model also underestimate the observed methane level. This is the case for most models in use and is believed to be caused by the models having too short methane lifetime (Holmes et al. 2013), i.e. underestimating the chemical methane loss in the atmosphere. However, there are also large uncertainties in total emission levels (Kirsche et al. 2013)

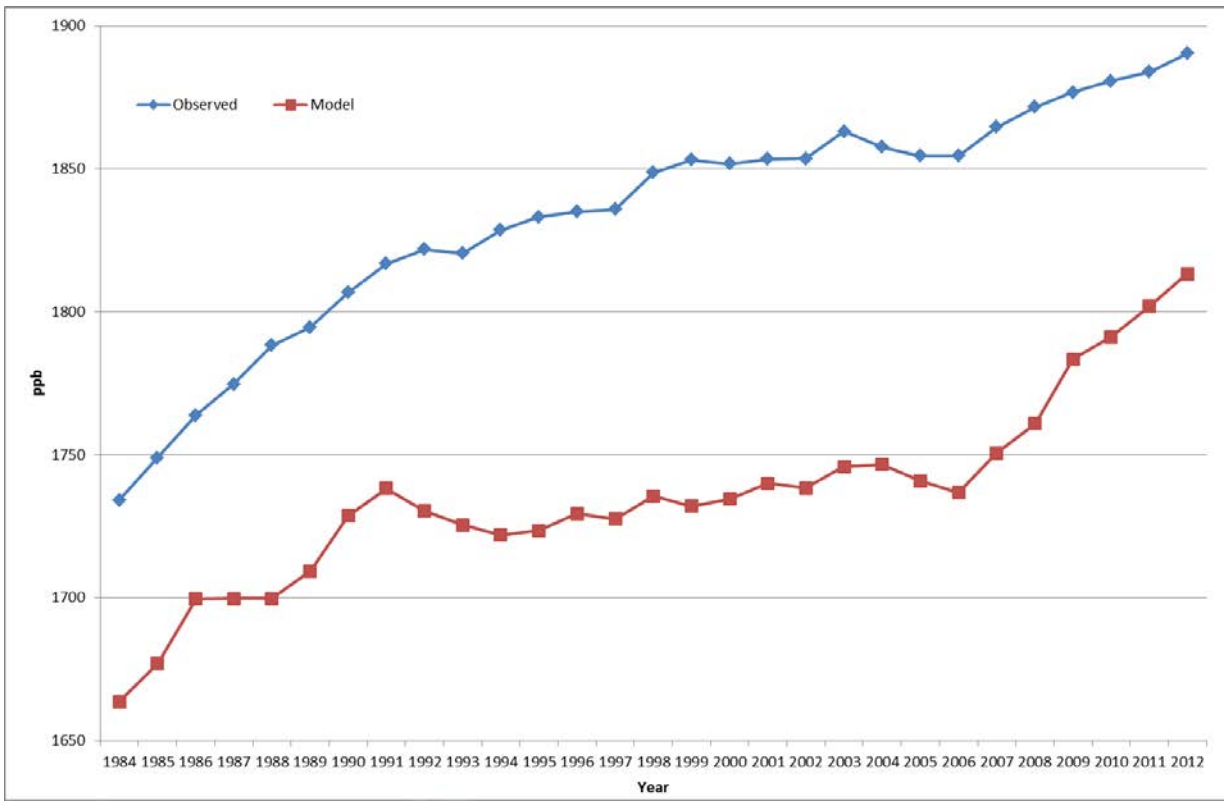
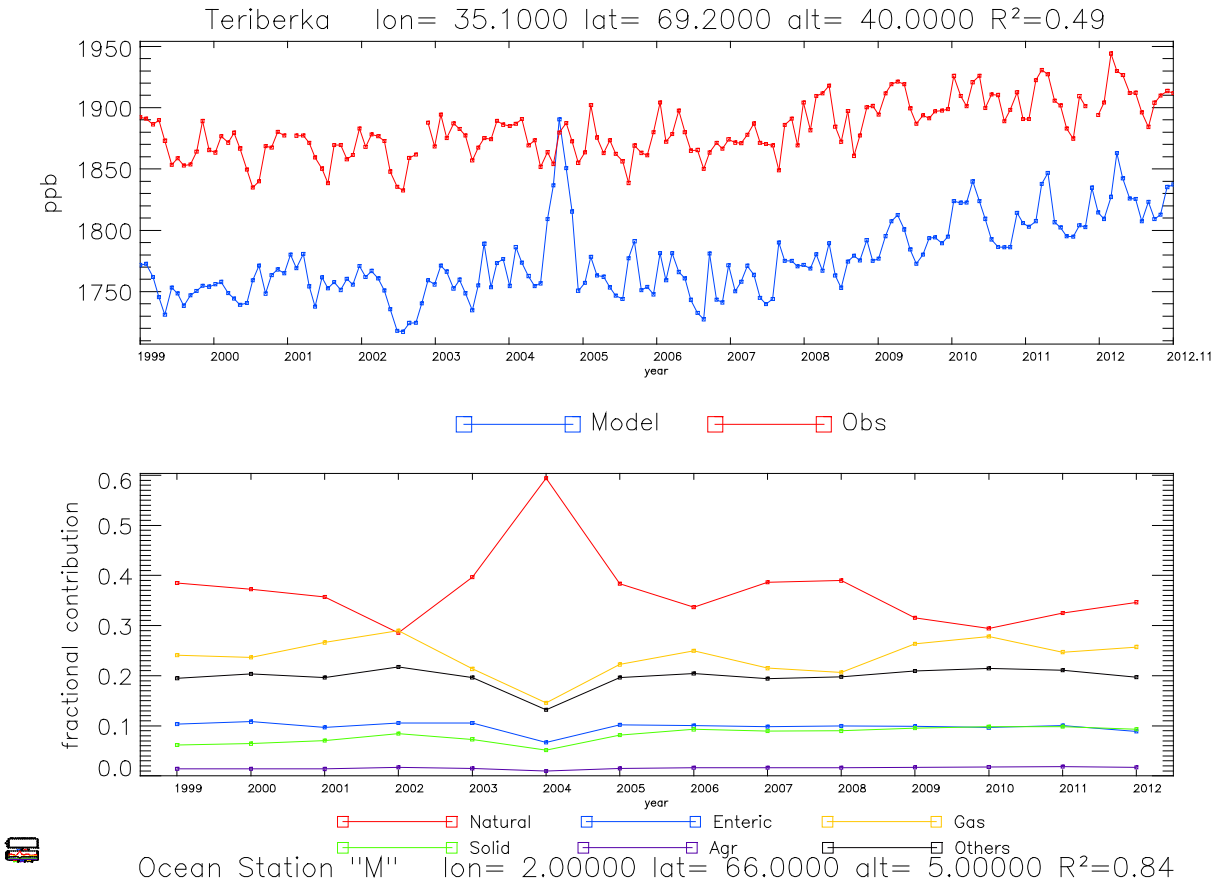


Figure 1: Comparison of yearly mean surface methane in the Arctic (north of 58ºN). The observed values are calculated from stations within the NOAA ESRL network and available from http://www.esrl.noaa.gov/gmd/ccgg/mbl/data.php.

2.3 Causes for interannual variation and recent trend at individual Arctic stations

Figure 2 shows detailed comparisons from different stations in the Arctic (station north of 60° N with long term data). In general the model reproduces the seasonal and year to year

variations well with high correlation coefficient, R^2, at most stations. The model also reproduces the evolution of methane seen in the observations but overestimates the increase after 2005 at most/all stations.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Enteric
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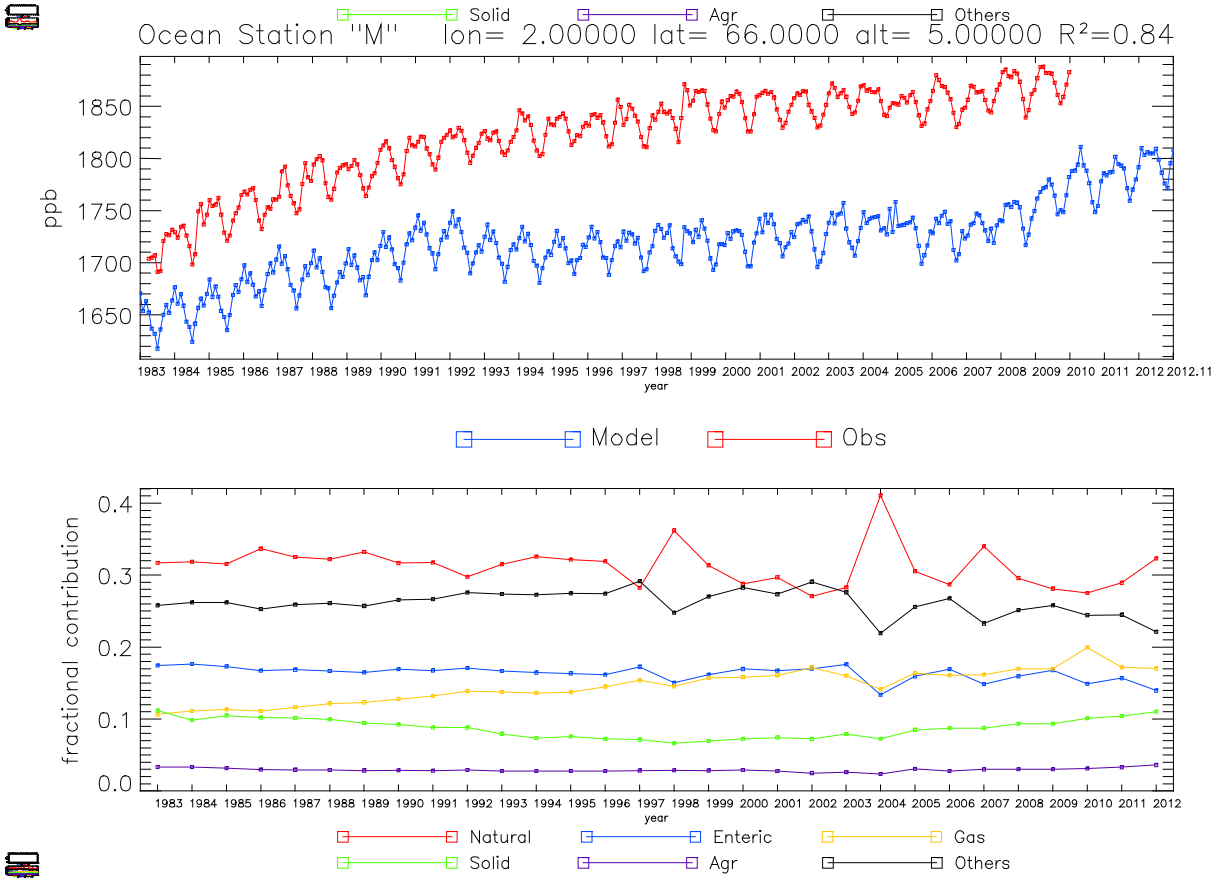
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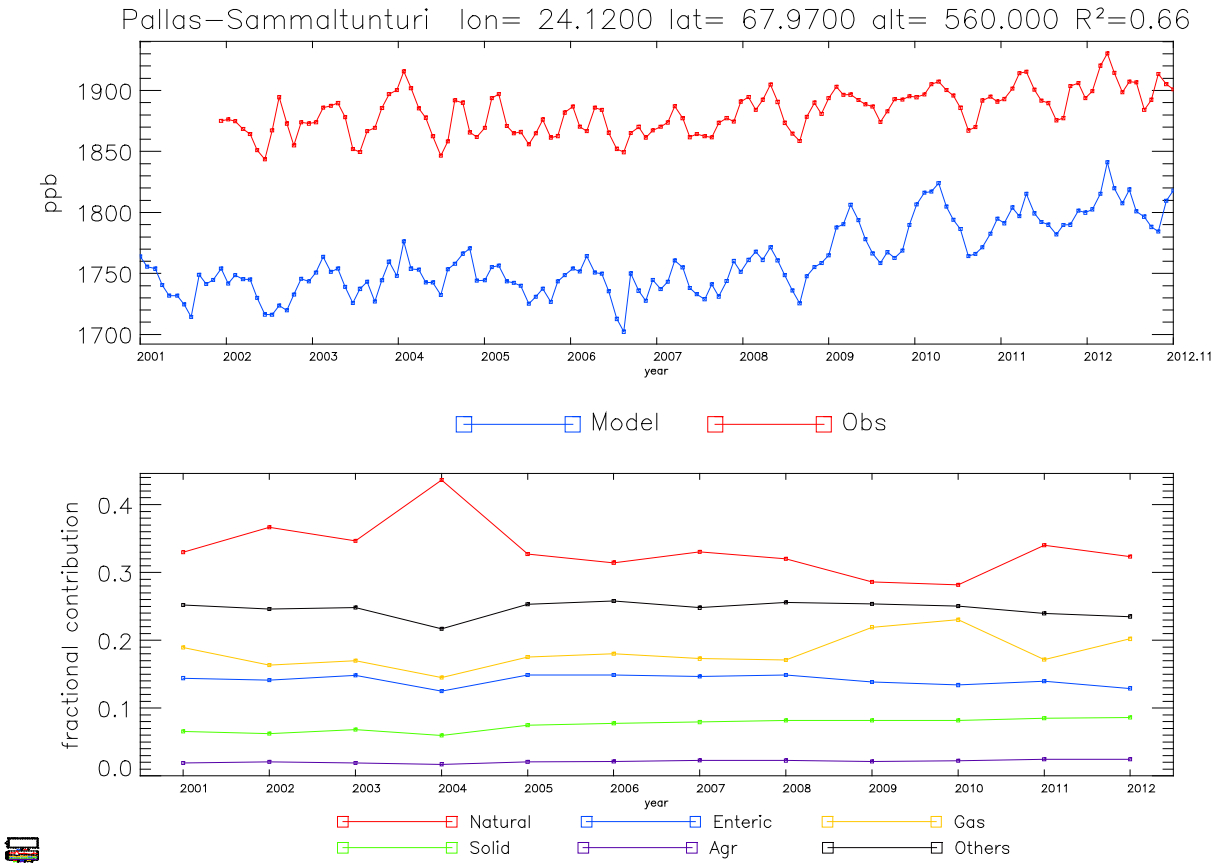
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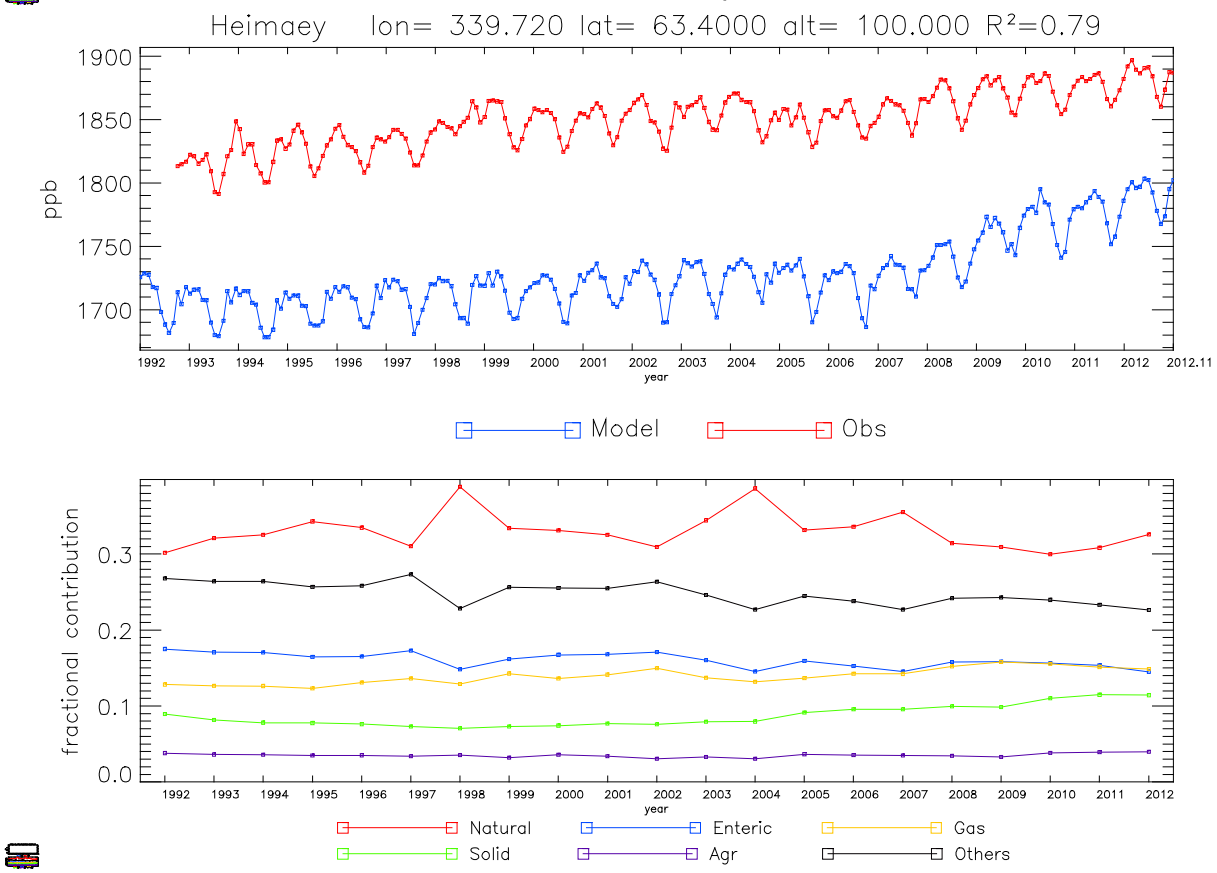
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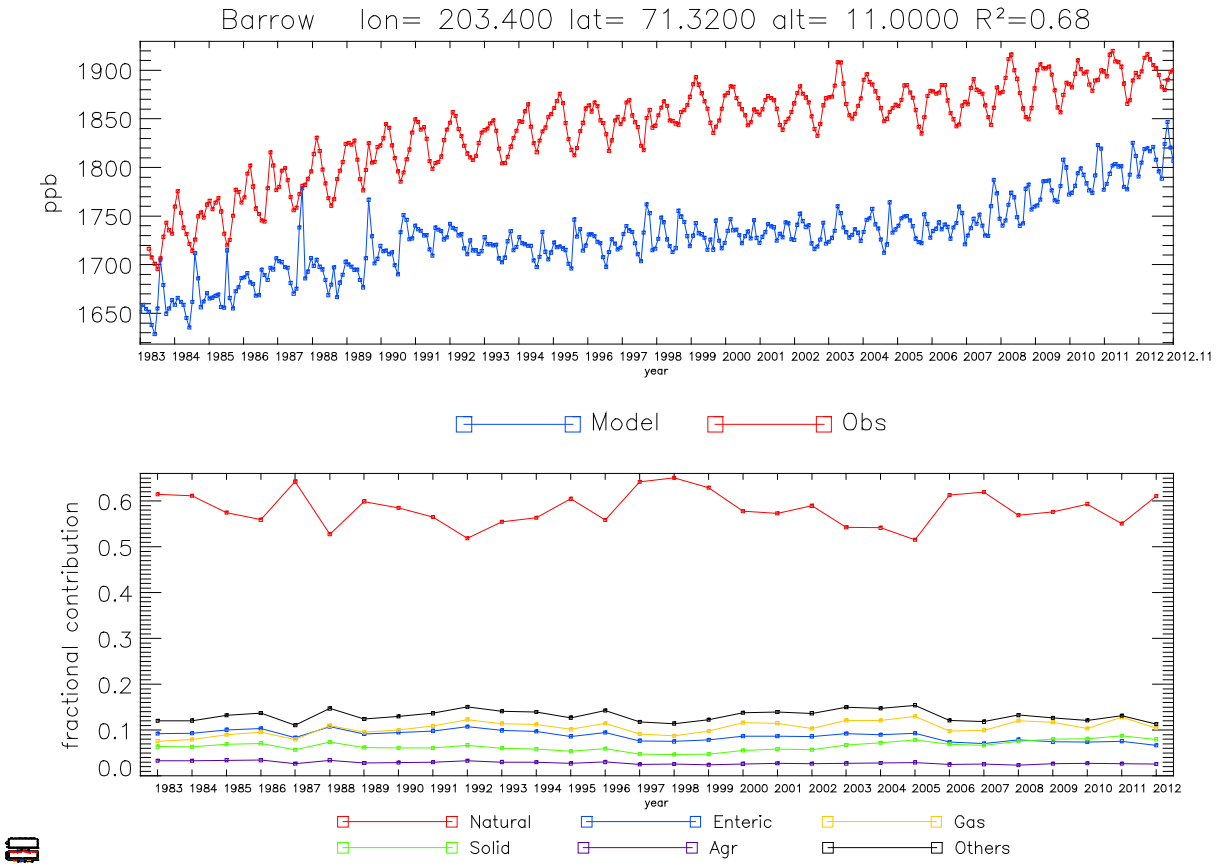
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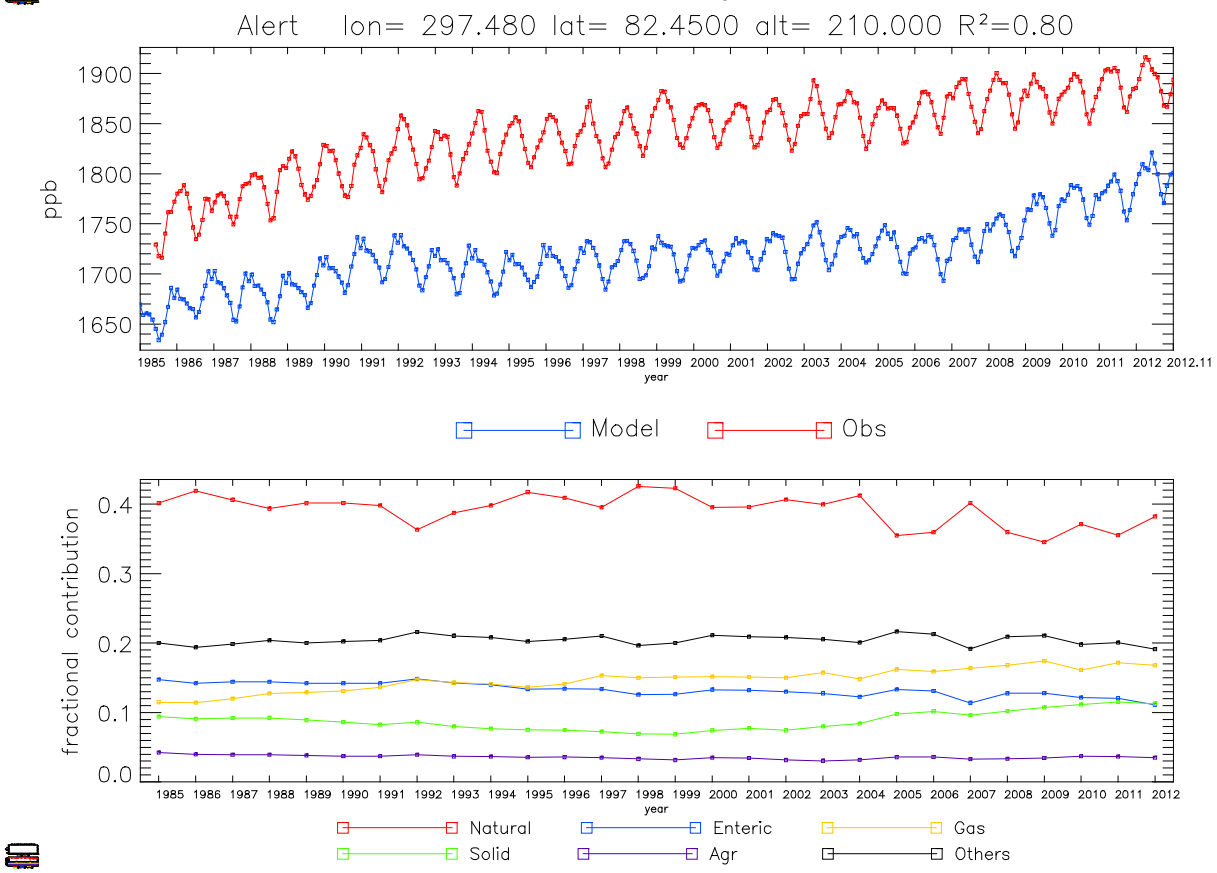
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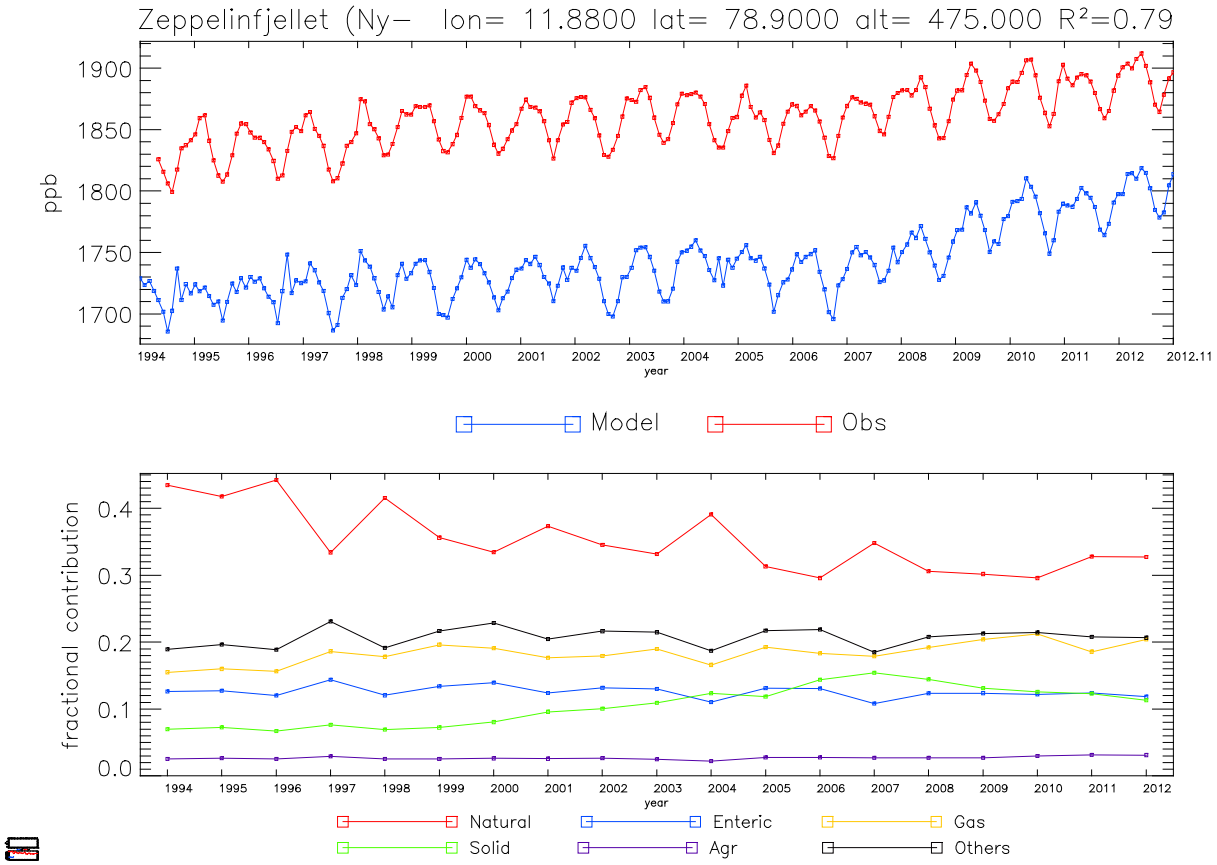

Figure 2: Comparison of monthly mean surface methane in model and observations at stations in the Arctic. Lower: Fractional contribution from various tracers to total tracer concentration: Natural=Natural sources, mostly wetlands. Solid= solid fuel use, mostly coal. Enteric=Enteric fermentation. Agr=Agricultural soils, mostly rice fields. Gas=gas installations and use. Others=Sum of 13 other sources.

At all stations and especially those in northern America (Barrow, Alert) natural emissions (wetlands) is the main contributor to the modeled concentrations. Due to large year to year variation in amount and location of emissions this source explains much of the modeled and observed interannual variability. Interestingly the contribution from this source decreases over time at several stations. For the stations on the European continent (Zeppelin, Pallas, Teriberka), mainly gas and to some extent high wetlands emissions in 2007 and 2008 and coal (only up to 2007 for Zeppelin) are the major sources causing the modeled growth after 2006. Around 2010-2011 there is a pause in growth of observed and modeled methane at these stations. This seems to be caused by a drop in contribution from gas. Comparison to a simulation without interannual variability in meteorology points to unusual meteorological

conditions in 2011 resulting in less transport from gas fields in northern Russia. At the stations in northern America (Barrow, Alert) it seems to be soild fuels (coal) that is causing much of the recent growth in surface methane. Gas also likely plays a role at Alert. These stations are more prone to transport from emission sources in eastern Asia. The coal emissions in the Edgar 4.2 inventory have a large increase in eastern Asia in the same period. At the stations in the Atlantic (station M and Iceland) both gas and coal use seems to be important drivers for the growth in modeled methane after 2006. There is also enhanced contribution from wetlands in 2007 due to large wetland emissions that year in the Northern Hemisphere.

Other recent studies (Bergamaschi et al. 2013) indicate that the Edgar4.2 emission inventory we use as input in our model overestimates the emission growth in Asia. This could be a plausible explanation why the recent methane growth is higher in our model than for the observations. However, some of the increase in the model in the Northern Hemisphere is driven by high natural (wetland) emissions in 2007 and 2008. Our natural emissions are from Bousquet et al. (2011) who attributes much of the recent increase in total emissions to wetlands. According to Bergamaschi et al. a substantial fraction of the total increase is attributed to anthropogenic emissions. There is therefore a possibility that we combine two emission inventories (anthropogenic from Edgarv4.2 and natural from Bousquet et al.) that both have too large growth in the period 2006-2008. After 2008 it is difficult to be conclusive as we due to missing emission data kept natural emissions at 2009 level and just extrapolated the trend in anthropogenic emissions.

The other reasons for not reproducing observed trends are possibilities of inadequate representation of the methane loss in the model. The loss (methane lifetime) is dependent on a number of factors controlling the hydroxyl radical (OH) in the atmosphere (Isaksen and Dalsøren 2011). Due to the reactivity of OH, measurements on large scale are impossible. To get an idea of its likely evolution over time observations of methylchloroform and ^{14}CO can been used. This is not discussed further here but will be discussed in Dalsøren et al. in prep.

3 Black carbon

3.1 Evolution of black carbon in the Arctic atmosphere

Model studies have also been done with OsloCTM3 and its predecessor OsloCTM2 to understand recent trends and interannual variation of black carbon in the Arctic (Skeie et al . 2011; Dutkiewicz et al. 2014). There are few direct long-time measurements of BC in the atmosphere available to compare with the model. The longest record is found at Kevo in Finland. Annual mean BC form Kevo over the period 1965-2010 is shown in figure 3. Wood was burned at the site for heating during winter months until the end of 1970 so the high values observed during this period likely has some contribution from this source. From ~1970 to 2010 the BC decreased by ~1.8% yr^{-1}. However, the decrease was not monotonic. Instead, cyclical peaks occurred around 1976–1977, 1985–1987, and 1999. During such periods, nickel concentrations were well correlated with BC. This, and back trajectories suggest that emissions from extensive ore smelting on the Kola Peninsula were significant contributors of particulate matter observed at Kevo. Simulations of BC at Kevo using the OsloCTM3 model with different emission inventories and meteorological data sets were performed (Dutkiewicz et al. 2014). The results indicated that circulation changes can explain year to year variability, but the downward trend in the observations is mostly explained by emissions.

BC data sets from other Arctic sites (figure 3) show similar trends, but concentrations at Kevo are generally higher since Kevo is located closer to major source regions. At Alert in Canada BC decreased by 61 % (~3.4% yr^{-1}) from 1989 to 2007. For the combined 17 years of BC measurements at Ny Ålesund there is a 56 % decrease (~3.3% yr^{-1}). While all three sites shown in figure 3 show a decreasing trend after 1990, the trends are smoother at Alert and Ny Ålesund. The observed annual mean BC concentration at Barrow (not shown) decreased by 27% (19% per decade) from 1989 to 2003. The OsloCTM2 model (Skeie et al. 2011) showed a BC increase by 4% from 1990 to 2000 at Barrow. This is due to an increase in the concentration in the summer months associated with open biomass burning. The observations did not show any clear trend for the summer months at Barrow. A strong downward trend in winter is seen in both the model and observations for Barrow and also Alert (Skeie et al. 2011).

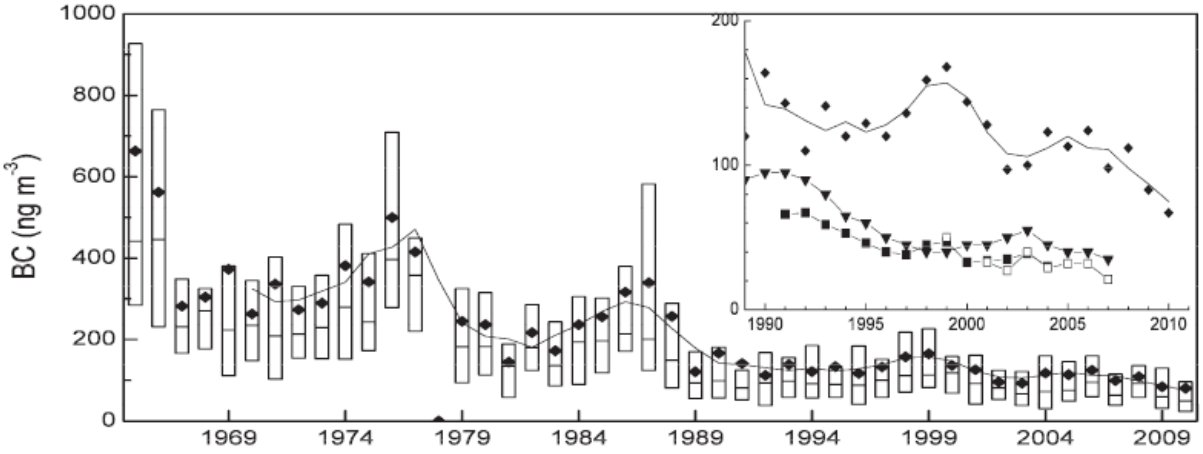

Figure 3: Annual mean [BC] at Kevo for 1965–2010. Bars show 25th and 75th percentile ranges; horizontal lines are medians and diamonds are means. Trend line is 3 years running mean starting in 1970 as earlier data may have local wood burning component. Insert shows 1989 until 2010 on an expanded scale with data from Alert, Canada (trinagles) and Ny Ålesund, Svalbard, Norway (squares) from two different methods. Figure is from Dutkiewicz et al. 2014.

One of the conclusions from the comparisons is that emission inventories are poorly constrained and appear to need revision in order to match observed trends in atmospheric BC concentrations. Recently, attention has been drawn both to a likely underestimation of global BC emissions in emission inventories, and an overestimation of BC at high altitudes. In a recent study (Hodnebrog et al. 2014) increased emissions, together with increased wet removal that reduces the lifetime, yields modelled BC vertical profiles that are in strongly improved agreement with recent aircraft observations.

3.2 Evolution of black carbon in Arctic snow and ice

Figure 4 shows the time evolution of mean BC concentration in surface snow in spring in four different Arctic regions, from 1750 until 2000. From the model results the concentration in snow on the sea ice in the Arctic Ocean has decreased since 1960. Over the continents the concentrations in the European sector were greatest in 1960 followed by a sharp decrease until 2000. The concentration of BC in snow in North America showed no trend between

1900 and 2000. Data on BC concentrations in snow at Central Greenland since pre-industrial times are derived from two ice cores. Figure 5 shows the annual concentration of BC from 1850 until 2000 at the location of the D4 ice core together with the decadal median of the

BC derived from the ice core. There is a maximum in the early 20th century followed by a decline, related to the emission trends in North America. Towards the end of the 20th century the BC concentrations were reduced by a factor of 2.5 and almost back to the pre-industrial concentrations in the D4 ice core from Greenland. Averaged over the whole Arctic north of 65 °N the modelled burden of BC in the air and snow reached its maximum in the 1960s, about 4–5 decades later than the observations from ice core measurement from Greenland. This clearly shows that the BC deposition in snow in the Arctic is dominated by source regions that continued to increase significantly longer than the North American sources.

The concentrations of BC in snow and ice depend on the deposited BC in snow, total precipitation, snow depth and how the BC particles are redistributed as the snow melts. Skeie et al. (2011) modeled large interannual variations of BC in surface snow for the spring months which is the most intense period for melting. An example is shown in the right panel of figure 5 for the period 2001-2008 where the model was run with constant fossil fuel emissions to discern the impacts of variation in meteorology and biomass burning emissions.

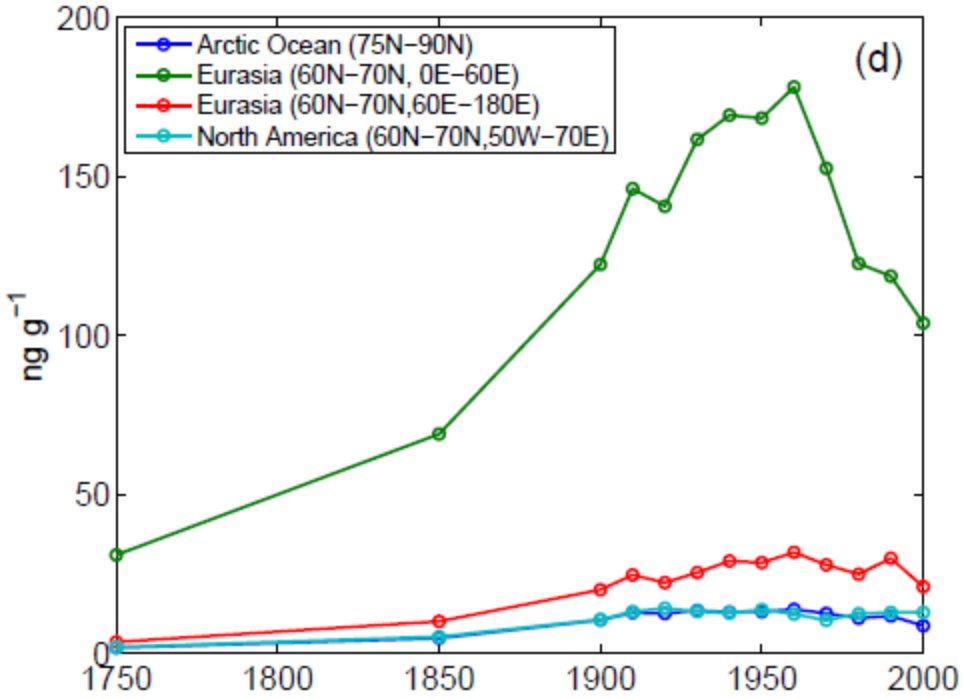

Figure 4: Averaged concentration of BC in surface snow (uppermost 5 cm) for March, April and May in 4 different regions from 1850 until 2000. Figure is from Skeie et al. (2011).

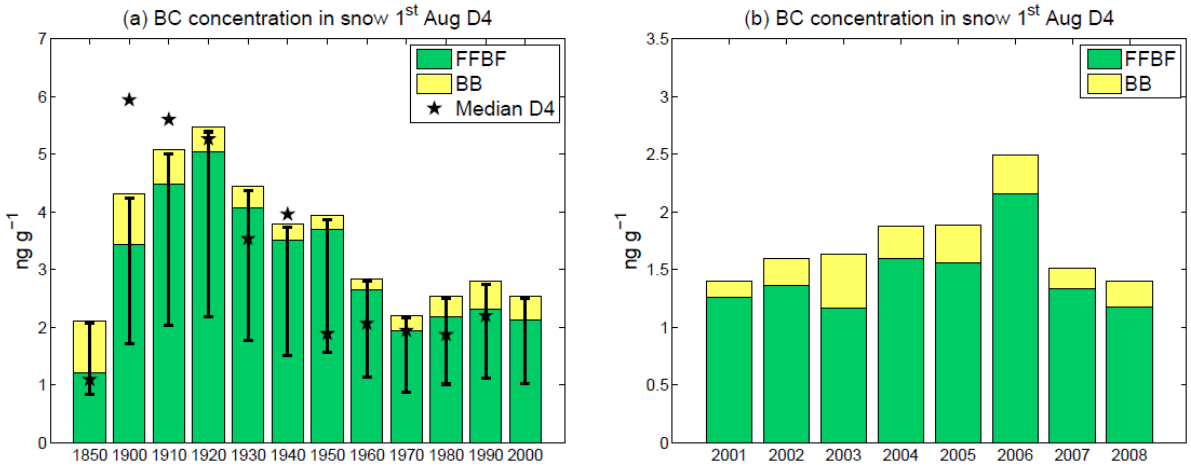

Figure 5: Modelled annual concentrations of BC in the snow at the location of the D4 ice core using 2006 meteorology. Contribution from biomass burning (yellow) and fossil fuel and biofuel (green). Error bars indicate two standard deviation around the mean of the modelled concentrations for the year 2001–2008 scaled to the historical concentrations assuming that the relative variability is constant in time. Decadal median of the BC concentration derived from the ice core is indicated by a star. Figures are from Skeie et al. (2011).

3.3 Contribution from different regions

The contribution from source regions to accumulated BC in the snow at the location of the D4 ice core at Greenland for year 1930 and 2000 are shown in Figure 6 a, b. According to the model, North American sources were responsible for approximately 80% of the BC deposited in Greenland snow in 1930. In year 2000 the North American contribution of BC deposited in the snow has decreased to approximately 60% due to the decrease in emissions from this region.

For BC in snow in the whole Arctic region, we look at the contribution from each region to the modelled burden of BC in snow north of 65°N at the end of April (Fig. 6c,d). In 1930 Western Europe (EU17) was the main contributor to BC in the snow north of 65º N (37 %), followed by Russia and FSU (28 %). The North American region contributed only 18% of the BC in snow in the Arctic region, which is much lower than the contribution to BC in snow in Greenland (80 %) at the same time. In the year 2000, the contribution from EU17 has decreased to 24% due to emission reductions. Together, EU17, Russia, and the rest of the FSU contribute half of the BC in snow in the Arctic region. Shifting the focus to the atmosphere, the contribution to annual global mean BC in the atmosphere north of 65° N is shown in Fig. 6e for 1930 and Fig. 6f for year 2000. As for the burden of BC in the snow, EU17 was the main contributor to total burden of BC in the atmosphere in the Arctic region in 1930 (40 %). Russia and FSU and North America followed with 22 % and 19 % of the total burden north of 65°N. In year 2000 the contribution from EU17 is reduced to 17% and Russia and FSU is the main contributor with 24 %. China, a region with increasing emissions, contributes 15 % of the atmospheric burden of BC north of 65°N in year 2000. Comparing the contribution from regions to the atmospheric burden and the burden in snow in the Arctic region, we can see that regions inside or close to the Arctic region have a larger or similar contribution to BC in snow than BC in the atmosphere. In contrast, regions further south, for example South Asia, contribute 7% to the atmospheric burden of BC in the Arctic but only 2% to the BC in the snow. This contrast is related to the height distribution of the BC in the Arctic and the possibility for BC deposition in snow. BC emitted at low latitudes may be transported to the Arctic at higher altitudes where minimal precipitation occurs. For further detail see Skeie et al. (2011).

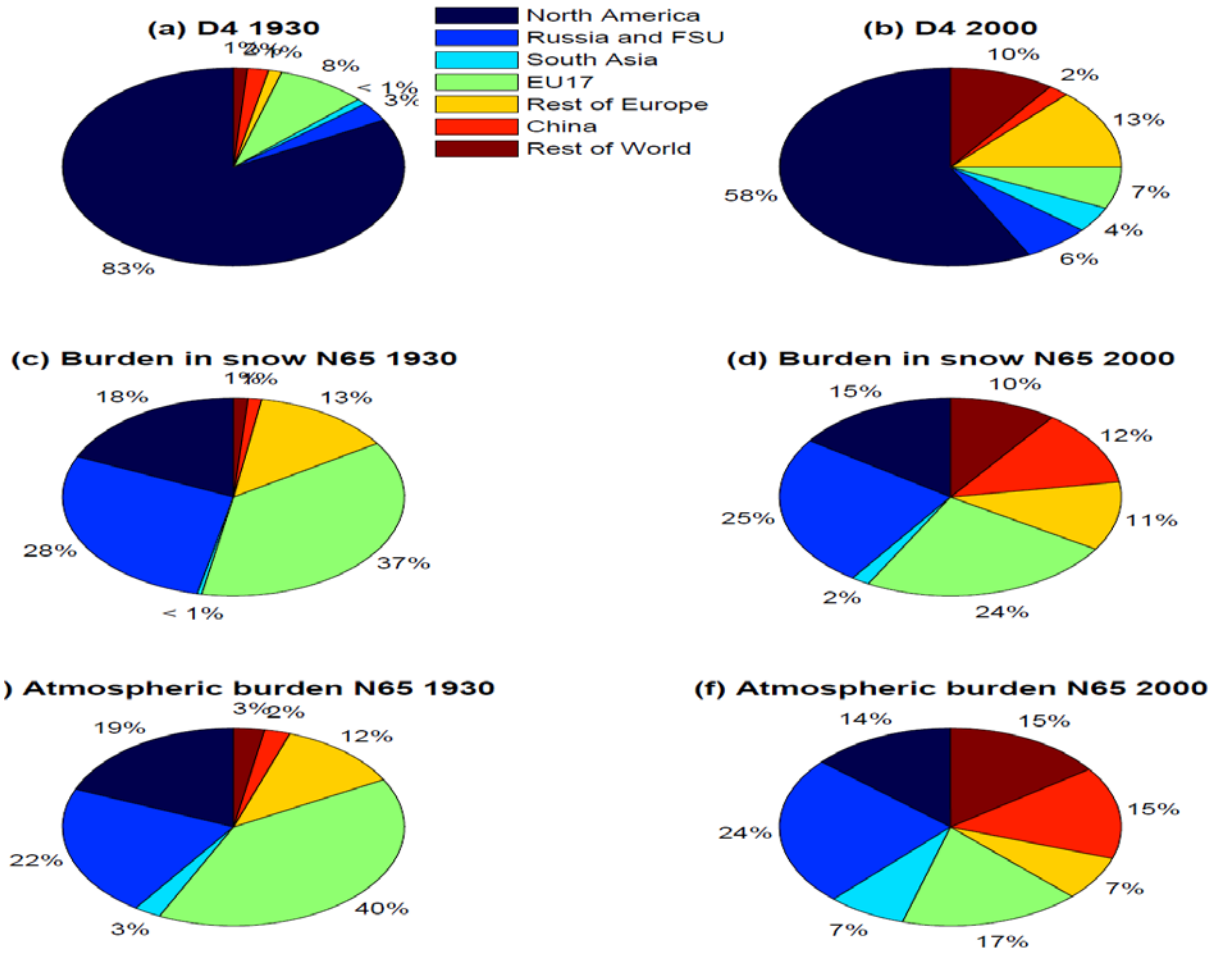

Figure 6: Contribution of regions to BC at the location of the D4 ice core **(a, b)**, BC in the snow north of 65 degrees (N65) end of April **(c, d)** and BC in the atmosphere north of 65 degrees **(e, f)**. The left column shows results from the 1930 simulation and the right column for the year 2000 simulation. Figures are from Skeie et al. (2011).

4 Summary

We focus on two pollutants and near term climate forcers (black carbon and methane) for which there will be a win-win situation from emission reductions. Decreasing their concentrations in the atmosphere and snow/ice (black carbon) will reduce pollution levels and slow near-term warming and Arctic sea ice loss over the next few decades. Uncertainties with regards to understanding recent trends in concentrations limit confidence in accurately projecting the future evolution of these two important components. We therefore compared model studies and long term observations to understand causes for trends and inter-annual variation of methane and black carbon in the Arctic region.

Our model studies generally reproduce the different periods of observed growth and stagnation of methane in the Arctic. However, the model fails to reproduce the strength of the growth rate during some eras. At all stations studied our model points to natural emissions (wetlands) as the main contributor to the methane levels. Due to large year to year variation in amount and location of emissions this source explains much of the modeled and observed inter-annual variability. Interestingly, the modeled contribution from this source decreases over time at several Arctic stations. There is a strong growth in observed methane after 2005 over the whole Arctic. The model shows an even stronger growth caused by increases in emissions from the gas and coal sectors in combination with large wetland emissions in the Northern Hemisphere in 2007 and 2008. Other recent studies indicate that the emission inventory we use as input in our model overestimates the emission growth in Asia (especially the coal emissions). This could be a plausible explanation why the recent methane growth is higher in our model than for the observations. However, there are also large uncertainties regarding the wetland emissions.

There are few direct long-time measurements of Black Carbon (BC) in the Arctic atmosphere. Over the last decades observed atmospheric BC has decreased quite steadily with trends in the range -1.4 %/yr to -3.4 %/yr. The model studies indicate that circulation changes can explain year to year variability, but the downward trend in the observations is mostly explained by emissions. One of the conclusions from the comparisons is that emission inventories are poorly constrained and appear to need revision in order for model studies to match observed trends. Averaged over the whole Arctic the burden of BC in the air and snow reached its maximum in the 1960s. This is 4–5 decades later than seen in observations from ice core measurements on Greenland. The major contributor to BC in Greenland is emissions in North America. The studies revealed that the BC load in much of the Arctic is dominated by source regions in EurAsia that continued to increase significantly longer than the North American sources. Regarding inter-annual variability a study was set up for recent years and modelled large inter-annual variations of BC in surface snow for the spring months which is the most intense period for snow and ice melting.

5 References

Aydin, M., Verhulst, K.R., Saltzman, E.S., Battles, M.O., Montzka, S.A., Blake, D.R., Tang, Q. and Prather, M.J. (2011). Recent decreases in fossil-fuel emissions of ethane and methane derived from firn air. *Nature,* 476, 198-201.

Bergamaschi, P., S. Houweling, A. Segers, M. Krol, C. Frankenberg, R. A. Scheepmaker, E. Dlugokencky, S. Wofsy, E. Kort, C. Sweeney, T. Schuck, C. Brenninkmeijer, H. Chen, V. Beck and C. Gerbig, Atmospheric CH_4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements, *J. Geophys. Res.*, doi:10.1002/jgrd.50480, 2013.

Bond, T., C., Doherty, S., J., Fahey, D., W., Forster, P., M., Berntsen, T., Boucher, O., Jacobson, M. Z.2013
Bounding the role of black carbon in the climate system: A scientific assessment *J. Geophys. Res.*

Bousquet, P., Ringeval, B., Pison, I., Dlugokencky, E. J., Brunke, E.-G., Carouge, C., Chevallier, F., Fortems-Cheiney, A., Frankenberg, C., Hauglustaine, D. A., Krummel, P. B., Langenfelds, R. L., Ramonet, M., Schmidt, M., Steele, L. P., Szopa, S., Yver, C., Viovy, N., and Ciais, P.: Source attribution of the changes in atmospheric methane for 2006–2008, Atmos. Chem. Phys., 11, 3689-3700, doi:10.5194/acp-11-3689-2011, 2011.
CH4 burden. *Geophys. Res. Lett*. 36, L18803. (doi:10.1029/2009GL039780)

Dalsøren, Stig B. and Ivar S. A. Isaksen, 2006. CTM study of changes in tropospheric hydroxyl distribution 1990-2001 and its impact on methane. *Geophysical Research Letters*, 33: pp. 7.

Dalsøren, Stig B., Ivar S. A. Isaksen, Liu Li and Andreas Richter, 2009. Effect of emission changes in southeast Asia on global hydroxyl and methane levels. *Tellus B*, 61 (4): pp. 588-601.

Dalsøren, Stig B., Magnus Strandmyr Eide, Gunnar Myhre, O Endresen, Ivar S. A. Isaksen and Jan S. Fuglestvedt, 2010. Impacts of the large increase in international ship traffic 2000-2007 on tropospheric ozone and methane. *Environmental Science & Technology*, 44 (7): pp. 2482-2489.

Dalsøren, Stig B. et al. in prep. Methane evolution the last 40 years. Modeling of decisive factors.

Dlugokencky, E. J. *et al*. 2009 Observational constraints on recent increases in the atmospheric

Dutkiewicz, V. A., A. M. DeJulio, T Ahmed, J Laing, P. K. Hopke, Ragnhild Bieltvedt Skeie, Y Viisanen, J. Paatero and Liaquat Husain, 2014. Forty-seven years of weekly atmospheric black carbon measurements in the Finnish Arctic: Decrease in black carbon with declining emissions. *Journal of Geophysical Research - Atmospheres*,

Fiore, Arlene M., Vaishali Naik, Dominick V. Spracklen, Allison Steiner, Nadine Unger, Michael Prather, Dan Bergmann, Philip J. Cameron-Smith, Irene Cionni, William J. Collins, Stig B. Dalsøren, Veronika Eyring, Gerd A. Folberth, Paul Ginoux, Larry W Horowitz, Béatrice Josse, Jean-François Lamarque, Ian Mackenzie, Tatsuya Nagashima, Fiona M. O'Connor, Mattia Righi, Steven T. Rumbold, Drew T. Shindell, Ragnhild Bieltvedt Skeie, Kengo Sudo, Sophie Szopa, Toshihiko Takemura and Guang Zeng, 2012. Global air quality and climate. *Chemical Society Reviews*, 41 (19): pp. 6663-6683.

Flanner, M. G., C. S. Zender, J. T. Randerson, and P. J. Rasch (2007), Present day climate forcing and response from black carbon in snow, J. Geophys. Res., 112, D11202, doi:10.1029/2006JD008003.

Hodnebrog, Øivind, Gunnar Myhre and Bjørn Hallvard Samset, 2014. How shorter black carbon lifetime alters its climate effect. *Nature Communications*, 5 (5065)
Holmes, C.D., Michael J. Prather, Ole Amund Søvde and Gunnar Myhre, 2013. Future methane, hydroxyl, and their uncertainties: key climate and emission parameters for future predictions. *Atmospheric Chemistry And Physics*, 13 (1): pp. 285-302.

Houweling, S., Krol, M., Bergamaschi, P., Frankenberg, C., Dlugokencky, E. J., Morino, I., Notholt, J., Sherlock, V., Wunch, D., Beck, V., Gerbig, C., Chen, H., Kort, E. A., Röckmann, T., and Aben, I.: A multi-year methane inversion using SCIAMACHY, accounting for systematic errors using TCCON measurements, Atmos. Chem. Phys., 14, 3991-4012, doi:10.5194/acp-14-3991-2014, 2014.

Isaksen, Ivar S. A. and Stig B. Dalsøren, 2011. Getting a Better Estimate of an Atmospheric Radical. *Science*, 331 (6013): pp. 38-39.

Isaksen, Ivar S. A., M. Gauss, Gunnar Myhre, Katey M Walter Anthony and Carolyn Ruppel, 2011. Strong atmospheric chemistry feedback to climate warming from Arctic methane emissions. *Global Biogeochem. Cycles*, 25 (2): pp. GB2002.

Jacobson, M.Z., 2010. Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. J. Geophys. Res. 115, D14209, doi:10.1029/2009JD013795.

Kai, F.M., Tyler, S.C., Randerson, J.T. and Blake, D.R. (2011). Reduced methane growth rate explained by decreased Northern Hemisphere microbial sources. *Nature*, 476, 194-197.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., Bergamaschi, P., Bergmann, D., Blake, D. R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Fraser, P. J., Krummel, P. B., Lamarque, J.-F., Langenfelds, R. L., Le Quéré, C., Naik, V., O'Doherty, S., Palmer, P. I., Pison, I., Plummer, D., Poulter, B., Prinn, R. G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Simpson, I. J., Spahni, R., Steele, L. P., Strode, S. a., Sudo, K., Szopa, S., van der Werf, G. R., Voulgarakis, A., van Weele, M., Weiss, R. F., Williams, J. E. and Zeng, G.: Three decades of global methane sources and sinks, Nature Geoscience, 28 (September), doi:10.1038/ngeo1955, 2013.

O'Connor et al. 2010. Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: A review. Reviews of Geophysics (48): 4. DOI:10.1029/2010RG000326

Quinn, P.K., T.S. Bates, E. Baum, N. Doubleday, A.M. Fiore, M. Flanner, A. Fridlind, T.J. Garrett, D. Koch, S. Menon, D. Shindell, A. Stohl, and S.G. Warren, 2008: Short-lived pollutants in the Arctic: Their climate impact and possible mitigation strategies. *Atmos. Chem. Phys.*, 8, 1723-1735, doi:10.5194/acp-8-1723-2008

Rigby, M., Prinn RG, Fraser PJ, Simmonds PG, Langenfelds RL, Huang J, Cunnold DM, Steele LP, Krummel PB, Weiss RF, O'Doherty S, Salameh PK, Wang HJ, Harth CM, Muehle J, Porter L, Renewed growth of atmospheric methane, Geophys. Res. Lett., 35, L22805, doi:10.1029/2008GL036037, 2008

Sand, Maria, Terje Berntsen, J.E. Kay, J. F. Lamarque, Øyvind Seland and Alf Kirkevåg, 2013. The Arctic response to remote and local forcing of black carbon. *Atmospheric Chemistry And Physics*, 13 (1): pp. 211-224.

Skeie, Ragnhild Bieltvedt, Terje Berntsen, Gunnar Myhre, Christina Alsvik Pedersen, Johan Ström, Sebastian Gerland and John A Ogren, 2011. Black carbon in the atmosphere and snow, from pre-industrial times until present. *Atmospheric Chemistry and Physics*, 11: pp. 6809-6836.

Søvde, Ole Amund, Michael J. Prather, Ivar S. A. Isaksen, Terje Berntsen, Frode Stordal, Xin Zhu, Chris D. Holmes and Juno Hsu, 2012. The chemical transport model Oslo CTM3. *Geoscientific Model Development*, 5: pp. 1441-1469.

Sussmann, R., Forster, F., Rettinger, M., and Bousquet, P.: Renewed methane increase for five years (2007–2011) observed by solar FTIR spectrometry, Atmos. Chem. Phys., 12, 4885-4891, doi:10.5194/acp-12-4885-2012, 2012.
van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707-11735, doi:10.5194/acp-10-11707-2010, 2010.