RC1:

RC1/1 Comment from the referee: The discussion about ARTP vs AGTP is confused, particularly since it is not clear whether this is due to latitudinal efficacies or different treatment of BC on snow. Is this discussion really necessary at all? Presumably the Aamaas et al. 2017 are the preferred metrics – so maybe stick with them to simplify the discussion?

If it is going to be included, the comparison with Sand et al. 2016 needs to be done better. In their figure 2 they show very much higher temperature response per unit emission for the Nordic Countries compared to Europe. It is surprising therefore that the BC response in this paper (figure 7) is so similar to that using Sand et al. It would seem much more appropriate to use Sand et al. to get the scaling between Nordic and Europe and apply this scaling to the values in this paper.

Author's response: Comment about ARTP vs AGTP - We agree with the reviewer that the Aamaas et al. (2017) paper has the preferred metrics for our case, and that we base most of our findings on that study. We have reduced the content on AGTP and differences between AGTP and ARTP. AGTP coefficients from Aamaas et al. (2016) are now only used in Figure 2 where we compare GWPs and GTPs.

Comment on scaling ARTP values with Sand et al. paper: We thank the reviewer for this good idea about scaling the Arctic responses using the Sand et al. (2016) paper. We did consider this approach in our initial work, but declined as the Sand et al. (2016) paper does not give complete datasets. We have been in contact with the first author to get out as much coefficients as possible. The limitations of the Sand et al. (2016) paper are that they only provide coefficients for ARTP calculations for the Arctic latitude band, they only provide coefficients for BC, OC, and SO2, not for the ozone precursors, and the emissions regions are also not matching completely with ours. However, after looking at this issue again, we agree with the reviewer that the scaling using Sand et al. (2016) paper is an improvement. We are only able to do this scaling for the Arctic. For the ozone precursors and NH3, this scaling must be based on assumptions and simplifications. As ozone is grouped together by Sand et al. (2016), we have used this averaged scaling for NOx, VOC, and OC. This scaling is 1.00, which also convinces us that the scaling approach is also ok for the ozone precursors. For NH3, we have used the average for BC, OC, and SO2 as a scaling factor.

Author's changes in manuscript: This comment has resulted in a number of changes in the manuscript. We have reduced the discussion on comparing Aamaas et al. (2017) and Sand et al. (2016) significantly, deleted Figure 7, as well as updated Figures 3-6 and 8. This scaling increases the ARTP values for the aerosols somewhat. We have updated all discussions, numbers, values in the Tables, given the slightly revised findings.

RC1/2 Comment from the referee: The mean(1-25) metric is not an obvious choice, and the authors have not explained how it fits in with any nationally or internationally agreed policies. Shindell et al. 2017 indeed admit: "We chose the mean temperature (rather than end-point temperature) to incentivize early action" rather than for any scientific or policy reason.

Author's response: The referee is right, we did not have any firm scientific basis to rely on the mean(1-25) metric. As air pollutants (SLCPs) were a key element in our work we wanted to have more emphasis on near-term climate change as pointed out in the last paragraph of section 2.2. As pointed out by Shindell et al. 2017 a mean metric, compared with an end-point metric, gives more weight to shorter lived species and thus incentivizes early action on for example BC.

Author's changes in manuscript: We have modified the last paragraph of Section 2.2: "Our climate impact dataset can be analyzed in many different dimensions, such as for different time scales, for different emission sectors, for different processes, for pulse or scenario emissions. We show some examples. As we focus on near term climate change and the global and regional temperature, most of the discussion in this paper utilizes ARTP for the mean warming in the first 25 years after a pulse emission, as recently proposed by Shindell et al. (2017). Mean(ARTP(1-25)) is the average temperature response over the time period, which differ from ARTP(25) being a snapshot at the time horizon of 25 years. We want to point out that our choice of metric is not based on a thorough scientific analysis, but rather a subjective choice to study in more detail the near-term climate impacts and the importance of short-lived species. To balance the choice we compare it with some other known climate metrics."

RC1/3 Comment from the referee: Line 32-36: I don't think there is any agreement on the definitions of SLCFs or SLCPs – maybe there should be. UNEP (2011) used SLCF when discussing warming agents, IPCC AR6 WG III report used SLCP to refer to warming agents, IPCC SR1.5 stated that SLCP was an equivalent alternative term to SLCF.

Author's response: We agree with the referee that there is no universal agreement on the use of the terms SLCFs or SLCPs. We have highlighted this in the text now. We chose to use the terms as in the IPCC SR1.5 (AnnexI, Glossary).

Author's changes in manuscript: We have replaced the end of the first paragraph of Introduction with "In this study we use the terms as in the IPCC Global Warming of 1.5°C Special Report (IPCC 2018) where: (1) SLCFs refer to both cooling and warming species and include methane (CH4), ozone (O3) and aerosols (i.e., black carbon BC, organic carbon OC and sulfate), or their precursors, as well as some halogenated species; (2) SLCPs refer only to the warming SLCFs. Policies focusing on SLCPs have been suggested as supplements to greenhouse gas reductions (UNEP/WMO 2011, Shindell et al. 2012, Rogelj et al. 2014, Stohl et al 2015, Shindell et al. 2017)."

Also we added the reference of the IPCC SR1.5 to the list of references: "IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press"

RC1/4 Comment from the referee: Line 51: "metrics is" should be "metrics are".
Author's response: Thank you for noting.

Author's changes in the manuscript: We have made the suggested correction.

RC1/5 Comment from the referee: Line 166: You are actually assuming the pattern is *exactly* the same for all GHGs.
Author's response: Thank you for noting.

Author's changes in the manuscript: We have removed the term "roughly".

RC1/6 Comment from the referee: Line 172: Re-phrase "our main pick".
Author's response: Thank you for noting.

Author's changes in the manuscript: We have changed "our main pick" to "we use"

RC1/7 Comment from the referee: Line 188: "the original" should be "their original"
Author's response: Thank you for noting.

Author's changes in the manuscript: We have made the suggested correction.

RC1/8 Comment from the referee: Line 195: "combining" should be "convolving"
Author's response: Thank you for noting.

Author's changes in the manuscript: We have made the suggested correction.

RC1/9 Comment from the referee: Lines 200-202: This description is too abrupt – the reader would need to be an expert in ARTPs to follow the argument. It either needs a longer explanation to guide the less expert or removing.

Author's response: The RTP concept is explained earlier in Section 2.2, but we agree that a longer explanation would make the case more understandable.

Author's changes in the manuscript: 2nd last paragraph of Section 2.2: "As noted, the ARTP method divides the world into four latitude bands, and thus the global temperature response can also be estimated by using the ARTPs and taking the area-weighted global mean basing on the results for the latitude bands."

RC1/10 Comment from the referee: Line 209: The AGTP(1-25) is presumably equal to the iGTP of Peters et al. (2011) divided by the time horizon. This should be mentioned.

Author's response: Yes, this is the case.

Author's changes in the manuscript: We have added the sentence: "It has similarities with the iGTP concept introduced by Peters et al. (2011)." to the last paragraph of Section 2.2.

Peters, G. P., Aamaas, B., Berntsen, T. and Fuglestvedt, J. S. 2011. The integrated global temperature change potential (iGTP) and relationships between emission metrics. Environmental Research Letters 6.

RC1/11 Comment from the referee: Lines 240-245: Some comment on the reasons for using emission pulses rather than emission steps should be provided here. While the pulse gives the mathematically useful Green's function, the convolution with a step emission could be considered more representative of the climate impact of Finland continuing to emit at 2010 levels.

Author's response: We decided to present the emission pulse figures in the beginning of the results section, as they are probably more familiar to many. Also the pulse emissions can give useful information for those working with emission reductions as they can study and compare the effect of emissions of individual years pointing out the sectors were the development has happened or more efforts could be considered. The figures also demonstrate the differences and similarities between the results obtained with the studied metrics, including the GWP100, and point out the particularly the different emphasis given for the SLCPs with the different metrics.

We agree that convolution is more representative for continuous emissions as presented in the study. Therefore in section 3.2.2, where we analyze the scenario, we move away from simple pulse considerations and use convolution of pulses for the emission scenarios (Fig. 4).

Author's changes in the manuscript: We reworded the start of Section 3.2.2: "While most of our study focuses on emission pulses, we will in this section discuss global temperature responses given a convolution of a Finnish emission scenario and ARTP values." The convolution method is also mentioned in the Methods section. We have also added to the abstract: "We consider both emission pulses and emission scenarios."

RC1/12 Comment from the referee: Lines 258-262: Again, if you really need to compared AGTPs vs ARTPs then this needs to be explained for those readers who haven't read Aamaas et al. 2017.

Author's response: We agree (see also our replies to referee comment RC1/9).

Author's changes in the manuscript: We have added the sentence: "The ARTP method divides the world into four latitude bands, and the global temperature response is estimated by taking the area-weighted global mean basing on the results for the latitude bands."

RC1/13 Comment from the referee: Line 274: If authors consider the relative importance of BC using AGTP and ARTP to be an important point they need to explain why, otherwise this just seems to be a random fact. Alternatively this sentence can be removed.

Author's response: The sentence seemed to miss context. See also reply to RC1/1.

Author's changes in the manuscript: We have removed the sentence.

RC1/14 Comment from the referee: Section 3.2.4: This section seems to suggest that the main difference between AGTP and ARTP is not the latitudinal dependence of the efficacy, but the different treatments of BC on snow in Aamaas et al. 2016 and 2017. If so, then this should be made more explicit earlier on.

Author's response: We agree with the reviewer that a discussion of AGTP and ARTP is unnecessary, and we have removed most of the comparison between AGTP and ARTP. See also our reply to RC1/1.

Author's changes in the manuscript: Section 3.2.4 has been shortened, and it now focuses on comparing the results obtained for different seasons.

RC1/15 Comment from the referee: Lines 356-357: This seems a confusing policy message – why should a Finnish policy maker need to know which metric is being used when implementing wintertime BC control measures in Finland?

Author's response: Both metrics point out to the same conclusion: "From a mitigation perspective, these estimates indicate that attention should be placed on reducing winter emissions of BC."

Author's changes in the manuscript: We have modified the sentence accordingly.

RC1/16 Comment from the referee: Lines 392: Why do Sand et al. 2016 have a much larger indirect effect? Is it due to a different model?

Author's response: We have removed this paragraph as a response to the comment RC1/1 about using Sand et al. (2016) for scaling. We considered a discussion of the indirect effects in Sand et al. (2016) now unnecessary, as we are only interested in the ratios between European emissions and Nordic emissions.

Author's changes in the manuscript: We have removed this paragraph as a response to RC1/1 on using Sand et al. (2016) as scaling.

RC1/17 Comment from the referee: Section 4: This section needs to be structured. There is no obvious story being told here. I suggest having the Discussions and Conclusions separately so the Conclusions can be more tightly written in such a way that the reader is clear what the key messages are they should take from this paper.

Author's response: We agree that this section is long and conclusions are not evident from the discussion. We have followed the referee's suggestion and have written a separate Conclusions chapter that highlights our key conclusions from the work. Also we have reduced content in the Discussion sections. In drafting the conclusions we have concentrated on those that we think might be of interest for a more general audience rather than those interested in the Finnish situation.

Author's changes in the manuscript: We have renamed section 4 as "Discussion" and added a section 5 "Conclusions". We have reduced the content of Section 4.

RC1/18 Comment from the referee: Lines 445-449: This justification of the mean(1-25) metric is very weak. The argument seems to be purely that Shindell et al. 2017 suggested it.

Author's response: That is correct. See also reply to Referee comment R1/2. This is a subjective choice to study in more detail the near-term climate impacts and the importance of short-lived species.

Author's changes in the manuscript: Sentence "This is a subjective choice to study in more detail the near-term climate impacts and the importance of short-lived species." added to the paragraph.

RC1/19 Comment from the referee: Lines 481-483: The mean(1-25) metric wasn't "evaluated to be useful" in Shindell et al. 2017, it was simply devised "to incentivize early action".

Author's response: We agree.

Author's changes in the manuscript: We have removed the part "evaluated to be useful" from the sentence.

RC1/20 Comment from the referee: Lines 483-484: Surely the appropriate metrics for Arctic warming by 2040 or 2050 should be endpoint metrics for 21 or 31 years (e.g. for a start in 2019) rather than a mean over that period.

Author's response: We agree that this wording does not reflect mean(1-25) metric. We have reworded the sentence

Author's changes in the manuscript: The last part of the sentence is changed to: "…from today and until 2040 or 2050."

RC1/21 Comment from the referee: Figure 7: This needs labelling on the figure to distinguish the Aamaas and Sand values.

Author's response: We have decided to delete the Figure

Author's changes in the manuscript: Figure 7 has been deleted as a response to RC1/1 on the Sand et al. (2016) scaling. We have included new numbering for all Figures.

RC2:

RC2/1 Comment from the referee: The analysis focused mainly on Global Warming Potential (GWP), the Global Temperature change Potential (GTP) and the Regional Temperature change Potential (RTP) metrics. However, new metrics have been proposed recently, and the authors should have considered including these new metrics in this work to increase the overall robustness of the findings, or at the minimum, the authors should have provided justification on why they did not consider these new metrics relevant to this present work. See for example,
(1) https://www.nature.com/articles/s41612-018-0026-8
(2) https://www.nature.com/articles/nclimate2998
(3) https://www.oxfordmartin.ox.ac.uk/publications/view/2601 for these recently proposed metrics

Author's response: Thank you for pointing out these recent important and interesting papers. The new usage of the GWP metric seems interesting. We have included an analysis of the Finnish emissions in the period 2000-2030 to the paper (see new Figure 3 and corresponding text).

Author's changes in the manuscript: We have added a new figure (new Figure 3) that compares SLCFs with emissions of CO2 and N2O in the period 2000-2030 with the metric GWP(100) as well as corresponding text. We have also introduced this metric in Section 2 Methodology.*

Climate Impact of Finnish Air Pollutants and Greenhouse Gases using Multiple Emission Metrics

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Abstract. We present a case study where emission metric values from different studies are applied to estimate global and Arctic temperature impacts of emissions from a Northern European country. This study assesses the climate impact of Finnish air pollutant and greenhouse gas emissions in 2000-2010 as well as future emissions until 2030. We consider both emission pulses and emission scenarios. The pollutants included are SO2, NOX, NH3, NMVOC, BC, OC and CO as well as CO2, CH4 and N2O, and our study is the first one for Finland to include all of them in one coherent dataset. These pollutants have different atmospheric lifetimes and influence the climate differently; hence, we look at different climate metrics and time horizons. The study uses the Global Warming Potential (GWP and GWP*), the Global Temperature change Potential (GTP) and the Regional Temperature change Potential (RTP) with different time scales for estimating the climate impacts by species and sectors globally and in the Arctic. We compare the climate impacts of emissions occurring in winter and summer. This assessment is an example of how the climate impact of emissions from small countries and sources can be estimated, as it is challenging to use climate models to study the climate effect of national policies in a multi-pollutant situation. Our methods are applicable to other countries and regions and present a practical tool to analyse the climate impacts in multiple dimensions, such as assessing different sectors and mitigation measures. While our study focuses on short-lived climate forcers, we find that the CO2 emissions have the most significant climate impact, and the significance increases with longer time horizons. In the short term, emissions of especially CH4 and BC played an important role as well. The warming impact of BC emissions is enhanced during winter. Many metric choices are available, but our findings hold for most choices.~~There can be relatively large differences between results from studies using different metrics, which can partly be explained by different study setup and inherent uncertainty.~~

1. Introduction

The Paris Agreement and its target of "holding the increase in the global average temperature to well below 2° C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5° C above pre-industrial levels" (UNFCCC, 2015) provides an important framework for individual countries to consider the climate impacts and mitigation possibilities of its emissions. Globally CO2 and greenhouse gas emissions are key components in achieving the targets of the agreement, but the role of short-lived climate forcers (SLCFs) should also be studied as additional drivers of the surface temperatures. The climate effect of emission reductions of air pollutants, particularly black carbon and tropospheric ozone, have been a focus of research in last few years (Shindell et al. 2012, Bond et al. 2013, Smith and Mizrahi, 2013, Stohl et al. 2015). Since air pollutants can either cool or warm the climate on different timescales depending on the species, emission reduction policies from a climate perspective have to be designed to take into account the net-effect of multiple pollutants (UNEP/WMO 2011, Stohl et al. 2015). The pollutants considered to have most climate relevance are termed Short-lived Climate Pollutants (SLCP) or Short-lived Climate Forcers (SLCF), depending on the context. However, there is no common agreement on the definition of SLCPs or SLCFs. In this study we use the terms as in the IPCC Global Warming of 1.5°C Special Report (IPCC 2018) where: (1) SLCFs refer to both cooling and warming species and include methane (CH4), ozone (O3) and aerosols (i.e., black carbon BC, organic carbon OC and sulfate), or their precursors, as well as some halogenated species; (2) SLCPs refer only to the warming SLCFs. Policies focusing on SLCPs have been suggested as supplements to greenhouse gas reductions (UNEP/WMO 2011, Shindell et al. 2012, Rogelj et al. 2014, Stohl et al 2015, Shindell et al. 2017).~~SLCPs consist of the warming components black carbon (BC), methane (CH4), ozone (O3), and sometimes also include HFC compounds. SLCFs include the warming components, but also the ones that cool the climate, such as organic carbon (OC) and sulfate. Policies focusing on warming SLCPs have indeed been suggested as supplements to greenhouse gas reductions (UNEP/WMO 2011, Shindell et al. 2012, Rogelj et al. 2014, Stohl et al 2015, Shindell et al. 2017). Since in this study we are interested on both warming and cooling effects of the air pollutants we use the term SLCFs.~~

Modelling studies by UNEP/WMO (2011) and Stohl et al. (2015) suggested that the climate response of SLCF mitigation is strongest in the Arctic region. The Arctic region is of particular interest, since in the past 50 years the Arctic has been warming twice as rapidly as the world as a whole, and has experienced significant changes in ice and snow covers as well as permafrost (AMAP, 2017). AMAP (2011 and 2015) as well as Sand et al. (2016) demonstrated that emission reductions of SLCFs in the Northern areas have the largest temperature response on the Arctic climate per unit of emissions reduced, with the Nordic countries (Denmark, Finland, Iceland, Norway, and Sweden) and Russia having the largest impact when compared with the other Arctic countries, Unites States and Canada.

Shindell et al. (2017); Ocko et al. (2017) have argued for assessing both near- and long-term effects of climate policy. However, comparing the climate impacts of SLCFs, CO2, and other pollutants is not straightforward. Emission metrics are one way of enabling a comparison as they provide a conversion rate between emissions of different species into a common unit, for example CO2-equivalent emissions. Common emission metrics are the Global Warming Potential (GWP) (IPCC, 1990) and the Global Temperature change Potential (GTP) (Shine et al., 2005). The GWP compares the integrated radiative forcing (RF) of a pulse emission of a given species relative to the integrated RF of a pulse emission of CO2. Since the UNFCCC reporting procedure uses the GWP with a 100 yr time horizon (GWP100) as a reporting guideline, it has become the most common metric to report greenhouse gas emissions. The GTP is an alternative to GWP and it compares the temperature change at a point in time due to a pulse emission of a species relative to the temperature change of a pulse emission of CO2. The GTP combines the changes in the radiative forcing induced by the different species with the temperature response of the climate system and thus has been argued to relate better with climate effects (Shine et al., 2005). Both GWP and GTP focus on the global response, while the temperature impact can also be analyzed on a regional scale, i.e. the Arctic, applying Regional Temperature change Potential (RTP) (Shindell and Faluvegi, 2010). Even for ~~an~~a uniform forcing, there will be spatial patterns in the temperature response. The metrics can be presented in absolute forms of radiative forcing (AGWP) or temperature perturbation (AGTP, ARTP) as well as normalized to the response of CO2 (GTP, GWP, RTP). Especially for short-lived species, the climate impact depends on the location and timing of the emissions, which is reflected in the RTPs as well as in the global response for GTP and GWP. On a global scale, Unger et al. (2009) attributed the RF to different economic sectors, while Aamaas et al. (2013) estimated the climate impact of different sectors based on different emission metrics for global emissions, as well as regionally for the United States of America, China and the European Union.

In this study we assess the climate impact of Finnish air pollutants (SO2, NOX, NH3, NMVOC, BC, OC and CO) and greenhouse gas emissions (CO2, CH4 and N2O) in the past (2000-2010) and until 2030, according to a baseline emission projection. We utilize emission metric values from several new studies relevant for Finland.

Finnish emissions and their climate response are relatively small compared with emissions from larger regions, let alone the globe. Therefore it is challenging to use climate models to study the climate effect of national policies and to analyze the role of each pollutant and sector. This study demonstrates a method to overcome this challenge by the use of emission metrics. The method is applicable in other countries or regions as well and has been used in connection with the Norwegian work on SLCPs (Norwegian Environment Agency, 2014) (Hodnebrog et al., 2014).

The Methodology section describes the construction and background data of the emission inventory and the future scenario as well as the emission metrics used. In Results we describe the emissions and their climate impacts first focusing at the historical emissions (2000-2010) and then at a future projection until 2030. We also discuss separately the regional temperature effect of emissions on the Arctic and compare the results obtained with different metric studies. In the Conclusions section we will summarize the main findings and conclude on the major scientific and policy relevant messages.

The objectives of this study were to (1) produce an integrated multi-pollutants emission dataset for Finland for 2000 to 2030, (2) compare multiple climate metrics and assess their suitability for a Northern country like Finland, (3) estimate the climate impact of Finnish air pollutants and greenhouse gases for the period 2000 to 2030 utilizing selected climate metrics, and (4) suggest a set of global and regional climate metrics to be used in connection with Finnish SLCF emissions.

2. Methodology

Finland is one of the Nordic countries situated, between latitudes 60°N and 70°N. It has a population of 5.5 Million people with an average population density 17.9 inhabitants per square kilometer (for comparison: EU average is 117 inhabitants per square kilometer). Although much of the population is concentrated to the South of the country, the scarce population compared with the size of the country makes transport of goods and people an important activity. The Northern location of the country in turn results in a high demand for energy to heat households, and the economy is largely based on energy-intensive industry.

2.1 Emissions

The historical emissions of SO2, NOX, BC and OC in 2000, 2005 and 2010 are estimated based on the data in the Finnish Regional Emission Scenario (FRES) model (Karvosenoja, 2008). Emissions of NH3, VOC, CO2, CH4 and N2O are from the national air pollutant and greenhouse gas emission inventories as reported to the UNFCCC and the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). The CO emission data is estimated with the GAINS model (http://gains.iiasa.ac.at; Amann et al. 2011). The data sources by pollutant are presented in Table 1. Emissions of CO2 are presented according to the IPCC guidelines, which assume biomass as carbon neutral. However, this definition is disputed and e.g., Cherubini et al. (2011) present emission metric values that account for CO2 emissions from biomass. Although the historical emission data emanates from different data sources (Table 1), they have been checked for consistency and are based essentially on the same statistical sources. We aggregated the data and performed specific analyses for the following eight major economic sectors: energy production (ENE IND), industrial processes (PROC), road transport (TRA RD), off-road transport and machinery (TRA OT), domestic combustion (DOM), waste (WST), agriculture (AGR), and other (OTHER).

Table 1. Data sources of the historical emission data for 2000-2010

The assumptions about the future energy use, transport and other activities in Finland follow Finland's 2013 National Climate and Energy Strategy (Ministry of Employment and the Economy, 2013) and its' baseline scenario that fulfils the agreed EU targets and specific national targets for share of renewables and emission reductions in the non-ETS sector. Table 2 shows the primary energy consumption by fuel in Finland in 2010 and 2030. The 2013 National Climate and Energy Strategy assumes the future prevalence of wood heating to remain at 2011 level, which is estimated to lead to a decreased wood consumption, due to increasing energy efficiency in housing. The future emission projection was estimated with the Finnish Regional Emission Scenario (FRES) model which used the activity estimates from the 2013 National Climate and Energy Strategy (Table 2) as a basis.

Table 2. Primary energy consumption in Finland (TWh a-1) (Ministry of Employment and the Economy, 2013)

2.2 Emission metrics

This work studies Finnish emissions with several climate metrics and focuses particularly on three of them, the Absolute Global Warming Potential (AGWP) (IPCC, 1990), Absolute Global Temperature change Potential (AGTP) (Shine et al., 2005), and Absolute Regional Temperature change Potential (ARTP) (Shindell and Faluvegi, 2010). AGWP at time horizon H for emissions of pollutant i in emission season s from emission sector t is defined as

$$\mathrm{AGWP}_{i,s,t}(H) = \int_0^H \mathrm{RF}_{i,s,t}(t)\,dt\ , \qquad (1)$$

where RF is the time-varying radiative forcing given a unit mass pulse emission at time zero. Since two recent studies (Aamaas et al., 2016;Aamaas et al., 2017) have separated between emission during summer (May-October) and winter (November-April), we make this separation when possible. AGTP is given as

$$\mathrm{AGTP}_{i,s,t}(H) = \int_0^H \mathrm{RF}_{i,s,t}(t)\,\mathrm{IRF}_T(H-t)\,dt\ . \qquad (2)$$

IRFT(H-t) is the temperature response, or impulse response function for temperature, at time H to a unit radiative forcing at time t. The ARTP is similar to AGTP, but gives the temperature response in latitude bands m:

$$ARTP_{i,m,s,t}(H) = \sum_l \int_0^H \frac{F_{l,i,s,t}(t)}{E_{i,s,t}} \times RCS_{i,s,l,m} \times R_T(H-t)\,dt, \qquad (3)$$

where Fl,i,s,t(t) is the radiative forcing in latitude band l and RCSi,l,m is matrix of unitless regional response coefficients based on the ARTP concept (Collins et al., 2013). In one of the papers (Sand et al., 2016), RCS differ for some of the different sectors, such as BC emissions in the Nordic countries from the domestic sector have about 15 percent higher sensitivity than BC emissions from energy and industry. Aamaas et al. (2017)~~Other papers~~ do not provide this information on a sector level, and we must therefore use the same RCS for all emission sectors.

The ARTP method divides the world into four latitude bands: southern mid-high latitudes (90-28° S), the Tropics (28° S-28° N), northern mid-latitudes (28-60° N), and the Arctic (60-90° N). We will focus on the temperature response in the Arctic, as well as the global mean response.

Some of the studies separate the net response for a pollutant into various processes. For the aerosols, the radiative efficiencies often include the aerosol direct and 1st indirect (cloud-albedo) effect. In addition, BC deposition on snow and semi-direct effect may also be considered for BC. The ozone precursors build on the processes short-lived ozone effect, methane effect, and methane-induced ozone effect, as well as the aerosol direct and 1st indirect effects.

All these emission metrics (AGWP, AGTP, ARTP) can be normalized to the corresponding effect of CO2, where M is GWP, GTP, or RTP:

$$M_i(t) = \frac{AM_i(t)}{AM_{CO_2}(t)}. \qquad (4)$$

For GWP, we have included an additional analysis with the newly suggested metric GWP* (Allen et al., 2016; Allen et al., 2018). They argue for an alternative use of GWP to better compare CO2 and SLCFs, which can be done by comparing the cumulative warming of CO2 with the emission level change of SLCFs. For CO2 and N2O, we have calculated GWP*(H) based on Equations 1 and 4, which lead to CO2-equivalent emissions for pollutant i_L between time t1 and t2:

$$E_{CO2-eq*,i_L} = \sum_{t1}^{t2} E_{i_L} \times GWP_{i_L}(H). \qquad (5)$$

For SLCFs, the CO2-equivalent emissions are

$$E_{CO2-eq*,i_S} = \Delta E_{i_S} \times GWP_{i_S}(H) \times H. \qquad (6)$$

ΔE_{iS} is the change in emission level for SLCP i_S between time t1 and t2. We have compared emissions for the 2000-2030 period and with a time horizon of H=100 years.

The pollutants we include in our analysis (SO2, NOX, NH3, NMVOC, BC, OC, CO, CO2, CH4, and N2O) have very different atmospheric lifetimes and impact pathways. For the GHGs (CO2, CH4, and N2O), we use the climate metric parameterization in IPCC AR5 (Myhre et al., 2013), but with an upward revision of 14% for CH4 to account for the larger radiative forcing calculated by Etminan et al. (2016). The atmospheric decay of CO2 is parameterized based on the Bern Carbon Cycle Model (Joos et al., 2013) as reported in Myhre et al. (2013). We assume that the relative temperature response pattern in the four latitude bands is the same for all the GHGs, and we base our calculations on the latitude pattern for CH4 in Aamaas et al. (2017).

For all the other pollutants (SO2, NOX, NH3, NMVOC, BC, OC, and CO), we use several recent studies that are relevant for the emission location, Finland (Aamaas et al., 2016;Aamaas et al., 2017;Sand et al., 2016). We have examined how metric values from all those studies can be used for Finnish emissions and compared those, but we will mainly present the combinations of these studies that we think combine the strengths of the different datasets. For a general and global view, we have used the GWP and GTP values from Aamaas et al. (2016). The rest of the paper utilizes ARTP values from Aamaas et al. (2017) to estimate temperature responses, with scaling from Sand et al. (2016) for temperature responses in the Arctic.

Aamaas et al. (2017) is our starting point as this study has the full set of emissions and separate between summer and winter emissions.

~~The different studies are also compared, and we discuss how the choice of metric dataset influences the results. For the global temperature response, we use the ARTP values published in Aamaas et al. (2017), while for the Arctic response, we compare ARTP values from Aamaas et al. (2017);Sand et al. (2016). These studies separate between different processes for each pollutant, such as the direct atmospheric RF and snow albedo effect of snow for BC. In our results, we include some discussion of these different processes.~~

No studies have presented climate metric values specific for Finnish emissions. The default choice would be to use climate metric values based on global emissions, while we believe using smaller emission regions near or including Finland is more representative than applying the global average. The most relevant emission regions in the three selected studies are Europe (consisting of the Western Europe, Eastern members of the European Union, and Turkey, up to 66°N) for Aamaas et al. (2016); Aamaas et al. (2017) and the Nordic countries for Sand et al. (2016). The Nordic countries is a smaller region and geographically more representative for Finland than Europe~~;~~. Therefore ~~W~~we have calculated ratios between metrics for the Nordic region vs. Europe in the Sand et al. (2016) and used those ratios to scale the metric values from Aamaas et al. (2017) to better represent Finnish emissions.~~ however,~~ However, Sand et al. (2016) provided ~~only~~ climate metric values only for the Arctic response, their set of pollutants was limited to ~~and only includes~~ BC, OC, and SO2, and for the ozone precursors they included only a ~~,~~combined response~~For the ozone precursors the response is lumped together in Sand et al. (2016)~~. To solve this ~~We have calculated ratios between metrics for the Nordic region vs. Europe in the Sand et al. (2016) and used those ratios to scale the metric values from Aamaas et al. (2017) to better represent Finnish emissions. W~~we have used averages, such as taking a weighted average of the different emission sectors for each pollutant and assuming that NH3 can be scaled by an average of BC, OC and SO2. The scaling we have done for the Arctic responses are 2.22 for BC, 3.09 for BC deposition in snow, 2~~,~~.32 for OC, 1.94 for SO2, 2.16 for NH3, and 1.00 for NOx, CO, and NMVOC. This scaling for the Arctic will also increase the global responses, but not affect the coefficients for the other temperature response bands.

For all the pollutants, the IRF for temperature comes from the Hadley CM3 climate model (Boucher and Reddy, 2008). Hence, our temperature calculations are based on a climate sensitivity of 3.9 K warming for a doubling in CO2 concentration. ~~We apply the same climate sensitivity to all cases since we want to make the different literature sources comparable. As a result, we scale up the metric values in Sand et al. (2016) by about 34 percent, as their original climate sensitivity was 2.9 K.~~

Most emissions stay relatively constant throughout the year, while the changing seasons result in much larger emissions from the domestic sector in winter than in summer. We account for this seasonality for those metric datasets compatible with this, otherwise, annual emission and metric values are applied.

The global and regional temperature responses of Finnish emissions are estimated by convolving ~~AGTP and~~ ARTP values with emissions. For an emission scenario E(t), the global temperature response is

$$\Delta T_{i,s,t}(t) = \int_0^t E_{i,s,t}(t') \times AGTP_{i,s,t}(t - t')dt' \quad (~~5~~7)$$

based on AGTP values. Similarly, the temperature responses in latitude bands can be estimated by replacing AGTP with ARTP values. As noted, the ARTP method divides the world into four latitude bands, and thus the global temperature response can also be estimated by using the ARTPs and taking the area-weighted global mean basing on the results for the latitude bands. As the forcing-response coefficients are different and the ARTP concept can better parameterize varying efficacies, the estimate global temperature response may vary whether based on AGTPs or ARTPs.

Our climate impact dataset can be analyzed in many different dimensions, such as for different time scales, for different emission sectors, for different processes, for pulse or scenario emissions. We show some examples. As we focus on near term climate change and the global and regional temperature, most of the discussion in this paper utilizes ~~AGTP and~~ ARTP for the mean warming in the first 25 years after a pulse emission, as recently proposed by Shindell et al. (2017). Mean(AR~~G~~TP(1-25)) is the average temperature response over the time period, which differ from A~~G~~RTP(25) being a snapshot at the time horizon of 25 years. It has similarities with~~been developed from~~ the iGTP concept introduced by Peters et al. (2011). We want to point out that our choice of metric is not based on a thorough scientific analysis, but rather a subjective choice to study ~~in more detail~~ the near-term climate impacts and the importance of short-lived species in more detail. To balance the choice we compare it with some other known climate metrics.

3. Results

3.1 Emissions

Fig.. 1 shows the Finnish emissions and their trends from 2000 until 2030 for the studied pollutants. Emissions by sector for 2000, 2010 and 2030 can be found in Table A1 of the Supporting material. Emission reductions are expected for practically all of the pollutants and greenhouse gases, especially between 2010 and 2030, but the magnitude differs between the species. Reductions of CO2 and SO2 take place to large extent in the energy production sector following the reduction of energy consumption of fossil fuels, i.e. coal, oil and peat (Table 2).

CH_4 emissions have declined mostly due to developments in waste sector. Amounts of methane recovered from landfills have increased during the study period following EU and national regulations. Methane emissions from landfills have also declined because the energy use of municipal solid waste has increased instead of landfilling; a development that is expected to continue also until 2030. Another factor explaining the declining emissions by 2030 is the prohibition of disposal of organic wastes to landfills after 2016.

The transport sector is responsible for the decline of the emissions of CO, NO_X, VOC as well as the particle species, black carbon (BC) and organic carbon (OC). The modernization of the vehicle fleet and consequent introduction of stricter emission controls required by the EURO-standards explain the decline in CO, NO_X and NMVOC emissions. The standards do not directly regulate BC or OC emissions, but since they are the main constituents of the regulated particulate emissions, reductions in emissions of BC and OC are expected, especially after the introduction of the diesel particulate filters for on-road light duty vehicles from 2010 onwards. The stoves and boilers in the residential sector will remain significant emitters of several pollutants, since the regulation following the European Union Ecodesign directive will not have major impact by 2030, due to the relatively long lifetime of Finnish heaters (Savolahti et al. 2016).

NH_3 and N_2O emissions remain relatively stable throughout the study period, since either much of the emission reductions have already taken place before the study period or no major changes are expected in the main emission sectors (agriculture for NH_3).

Figure 1. Finnish emissions (Gg a^{-1}) of air pollutants and greenhouse gases in the period 2000 to 2030 in the baseline scenario. Emissions by sector for 2000, 2010 and 2030 can be found in Table A1 of the Supporting material.

3.2 Climate impact of Finnish emissions

Figure 2 shows pulses of~~the~~ 2010 emissions weighted with the global metrics, GWP and GTP, to CO_2 equivalents using 10, 20, 50 and 100 year perspectives. Aamaas et al. (2013) studied global emissions with these metrics, while we focus in detail on Finnish emissions. In addition, we show the emission metric mean (GTP(1-25 yrs)), which gives the SLCFs a relatively large weight, similar to GTP(10 yrs) for the aerosols and in between GTP(10 yrs) and GTP(20 yrs) for CH_4. In Figure 2 the emissions are considered as a pulse and the figure does not take into account any emissions after 2010. Figure 2 demonstrates that the SLCFs have a larger relative importance with the metrics for shorter time horizons. However, in all cases CO_2 still is the most important species. With the emission metric with the 10 year horizon (GTP10) the warming SLCFs comprise more than two thirds of the warming effect of CO_2, but overall the net-impact of all short-lived species is about 30 percent of CO_2, due to the partly counteracting cooling effect of NH_3, SO_2, NO_X and OC. The relative importance of the SLCFs decreases with time, especially with GTP, as expected, and the relative effect is lowest with the temperature change metric with 100 year time horizon (GTP100), being about 6 percent of CO2. Among the non-CO2 emissions, the relative impact of N2O increases with increasing time horizon due to the much longer atmospheric lifetime than for the other pollutants.

Figure 2. Finnish 2010 emission (Mt CO2-eq) as a pulse emission weighted by various global metrics. CO2 is separated out and the net impact of the non-CO2 is given by the star.

An alternative to comparing emissions pulses with GWPs and GTPs is to consider the impact over some emission time period with GWP* (Allen et al. 2016 and 2018). Figure 3 presents an GWP* based analysis of Finnish emissions. As we have looked at emissions for the period 2000-2030, the CO2-eq emissions given in Figure 3 are not directly comparable to those based on pulses in Figure 2. We find that changes in global temperature in this period is mostly governed by the cumulative emissions of CO2. The emissions ~~level~~ of multiple SLCFs ~~is~~decline ~~reduced~~ in this period (Figure 1), ~~lead~~resulting to a net cooling ~~in this period,~~and counteracting 4 percent of the warming ~~from~~by CO2 and N2O. If emissions of all SLCFs w~~ere~~ould hypothetically be reduced to zero in this period, this emission change could ~~have reduced~~would counteract the warming ~~from~~ by CO2 and N2O by about a third. Similarly ~~A~~as for ~~applying~~ GWPs and GTPs (Figure 2), we find that emission of CO2 has the largest impact of all pollutants.

~~New~~ Figure 3. The CO2-equivalent emissions for the period 2000-2030 given the alternative metric GWP*(100). The net impact of SLCFs (left) and CO2 and N2O (right) is given by the star.

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As we focus on near term climate change and the global and regional temperature, the remaining paper utilizes ~~AGTP and~~ ARTP with a time horizon of mean(GTP(1-25 yrs)), as proposed by Shindell et al. (2017). ~~The rest of the paper is mostly applying~~ ARTP values are applied, following the argumentation by Aamaas et al. (2017) that ARTPs may give a better estimate of the global impact than AGTPs since they account for varying efficacies with latitude to a larger degree. The ~~AGTP(1-25 yrs) and~~ ARTP(1-25 yrs) used in this study are presented in Table~~s A2 and A~~3 ~~of the Supporting material~~. GWP* could also be a basis to estimate global temperature changes, but that would not give us regional temperature changes.

3.2.1 Climate impacts by emission sector

This section discusses the global temperature response of the emissions by pollutant and emission sector based on weighted ARTP values (Aamaas et al., 2017). The general findings described in the following paragraphs would be similar with AGTPs, and similar figures based on the AGTP values (Aamaas et al., 2016) ~~are given~~can be found in Figure A1 of the Supporting material for comparison. Figures 4~~3~~A, ~~3B~~4B, and ~~3C~~ 4C show the warming due to emissions in 2000, in 2010, and in 2030 following the baseline projection, respectively. The sum of all sectors is given in Figure ~~3D~~4D. The pollutant mix varies for the different sectors. CO2 is the most important pollutant for combustion in energy production and industry (ENE IND) and road transport (TRA RD), while methane is most important for waste (WST) and agriculture (AGR) sectors. BC emissions cause more than two thirds~~half~~ of the warming and increasing with time~~ (about two thirds in 2030)~~ in the domestic sector (DOM) and a significant share of the warming in the on-road (TRA RD) transport as well as off-road transport and machinery (TRA OT) sources. Rest of the warming effect for these sectors is due to CO2 emissions from fossil fuels, especially diesel and light fuel oil. Wood is an important fuel in the domestic sector, and since this study considers wood fuel as CO2 neutral, the CO2 warming effect is not as pronounced as, for example, in the on-road transport sector. Organic carbon has been the most important cooling agent in domestic and the transport sectors, as fuelwood does not contain much sulfur, and it has been phased out from liquid fuels in the transport sector as well. Overall, SO2 is the major cooling pollutant, mainly due to emissions from energy production (ENE IND) and industrial processess (PROC). Agriculture is an important source of ammonia (NH3), which has a cooling effect (Fig. ~~4~~4A-4C and Fig. 5A) via its participation in formation of cooling atmospheric aerosols like ammonium sulphates and nitrates.

Year 2000 was relatively warm and 2010 relatively cold in Finland, which is reflected as a higher use of coal, peat and wood fuels in 2010, and consequently also as higher emissions for some species. From 2000 to 2010, CO2 emissions from ENE IND increased by 22 percent and BC emissions from DOM by 37 percent. However, because of additional mitigation measures following legislation, CH4 emissions from the WST decreased by 38 percent. Also, despite the higher fuel use, improved flue gas cleaning measures caused SO2 emissions in ENE IND to decrease by 18 percent. On the other hand, the reduction of SO2 has increased the warming effect of the ENE IND sector in 2010 compared with 2000. The increasing SLCF emissions in the DOM sector, particularly black carbon, have led to additional net warming despite the fact that the organic carbon emissions offset about a fifth of the black carbon effect in both years. The decreasing trend for the use of heating oil in the domestic sector has reduced CO2 emissions between 2000 and 2010. Emissions from the PROC sector are relatively neutral in terms of their climate effect. In general, taking into account all sectors, the emission changes between 2000 and 2010 in Finland have led to net-warming (increase by ~~3~~ 7 percent), mostly due to the increase of CO2 emissions (warming) and decrease in SO2 emissions (warming) from the ENE IND sector, which have offset the reduction of CH4 emissions (cooling) in the WST sector.

The baseline projection will lead to emission reduction of all pollutants between 2010 and 2030, from more than a 50 percent reduction of BC to a small reduction for N2O (Fig. 1 and Table A1). Because of climate policies, CO2 is reduced following the declining use of fossil fuels (Table 2, Fig. ~~3B~~4B, ~~3C~~ 4C and ~~3D~~4D). The SO2 emissions continue their decline between 2010 and 2030, particularly in the ENE IND sector, which leads to additional warming, but only partly offsetting the reduced CO2 (Fig. 4~~3~~B, ~~3C~~ 4C and ~~3D~~4D). In the on-road (TRA RD) and off-road (TRA OT) transport sector, particularly the warming effect from the SLCFs declines, because the new vehicles, in order to comply with the European emission legislation, are equipped with efficient emission reduction technologies (Fig. 4~~3~~B and ~~3C~~4C). The amount of domestic wood combustion is expected to decrease in the baseline due to improved energy efficiency in housing, which is the main reason for the reduced SLCF emissions in the sector (Fig. ~~3B~~ 4B and ~~3C~~4C). However, when interpreting these results it is important to note that the prevalence of domestic wood combustion has been increasing during the 2000's and the future wood use in households is challenging to predict. Therefore the emissions from the domestic sector should be considered uncertain. This is demonstrated in a sensitivity analysis of future particle emissions from the domestic sector presented by Savolahti et al. (2016). Also the methane emissions in the WST sector continue their decline (Fig. ~~3B~~ 4B and ~~3C~~4C). As a consequence of the emission changes, the net-temperature impact of 2030 emissions is ~~32~~ 35 percent lower compared with the 2010 emissions (Fig. ~~3D~~4D). Practically all sectors but AGR contribute to the reduced warming (Fig~~.~~. ~~3B~~4B, ~~3C~~4C).

Figure ~~3~~4. The temperature response (μK) due to emissions in 2000 (A), 2010 (B), and 2030 (C) from sectors energy and industry (ENE IND), industrial processes (PROC), transport road (TRA RD), off-road transport and machinery (TRA OT), domestic (DOM), waste (WST), agriculture (AGR), and other (OTHER). The sum of all sectors is shown in (D). The climate metric applied is the global mean(ARTP(1-25 yrs)) for pulse emissions.

3.2.2 Cumulative temperature development 2000-2030

While most of our study focuses on emission pulses, in this section we will~~ in this section~~ discuss global temperature responses given a convolution of a Finnish emission scenario and ARTP values~~So far we have shown the global temperature response for pulse emissions, while the temperature impact over time will depend on continuous emissions from every single year~~. The cumulative global temperature impact by pollutants and sectors for Finnish emission in 2000-2030 is shown in Fig~~.~~ure ~~4~~5, based on ARTPs in Aamaas et al. (2017); Sand et al. (2016). Similar figures based on AGTP values (Aamaas et al., 2016) are given in Figure A2 of the Supporting material. Fig~~.~~ure ~~4~~ 5 demonstrates why emission reductions of CO_2 and other long-lived greenhouse gases are key for limiting the long-term surface temperature increase. As more years are added, the relative importance of CO_2 increases, since a large portion of it stays in the atmosphere for hundreds of years. This relative importance over time also occurs in case of N_2O. The air pollutants become of less relative significance with time, which is mostly because of those pollutants being quickly removed from the atmosphere, but also because of the reduced emissions levels in the later period. Almost all sectors have a net-warming temperature response, with the exception of cooling from ENE IND sector for more than~~in~~ the first ten years and a slight cooling from PROC sector ~~nearly~~ until 2030 (Fig~~.~~ure ~~4B~~5B). Cooling from mainly SO_2 emissions is offsetting the warming impact of CO_2 from those sectors. Over time, ENE IND becomes the most influential sector, being the single largest contributor of CO_2. BC is the most significant warming pollutant in the domestic sector and CH_4 for the agriculture and waste sectors.

Figure ~~4~~5: The global temperature development (mK) of Finnish emissions for the period 2000-2030. Temperature is given by pollutants in (A) and by sectors in (B). The global temperatures are estimated as a convolution of ARTP values and an emission scenario.

3.2.4 Seasonal temperature response from Finnish emissionsEstimated climate impacts depend on the chosen metrics

The estimated temperature response of Finnish emissions is dependent onvaries between the seasons emission season,depends on the metric parameterization applied. In Fig. ure 56, we compare how the results applying Finnish SLCF emissions for the year 2010 during summer (May-October) and winter (November-April) vary for two different metric approaches. A decomposition into different atmospheric forcing processes is also included. When we do not consider CO2, N2O, and N2OCH4, the pollutants give a net cooling for emissions in summer and a net warming of equal size for emissions in winter. The main driver for this is larger BC emissions in winter combined with much stronger response from the snow albedo effect. The reason is that more than 70 percent of the annual emissions in the domestic sector occur in winter. Another important difference is the much stronger cooling by SO2 in summer. We compare global temperature responses using AGTPs from Aamaas et al. (2016) and ARTPs from Aamaas et al. (2017). A decomposition into different processes is also included. Some pollutants have both warming and cooling processes, such as BC and NOX. The same process can be warming for one pollutant and cooling for another, for example NOX emissions remove CH4 from the atmosphere (cooling), while VOC and CO emissions add CH4 (warming). Changes in the methane concentration will also influence ozone, giving rise to the methane-induced ozone effect and reinforcing the methane effect.

Since the ARTPs account for varying efficacies with latitude, Aamaas et al. (2017) argue that ARTPs may give a better estimate of the global impact. However, as the regional response coefficients behind the ARTP studies are mostly built on results from one model, we acknowledge that our results have potentially significant uncertainties. The differences between the temperature impact of summer and winter emissions in Fig. 5 are not only caused by different climate metric values, but also that the domestic emissions are largest in winter (>70 percent of annual emissions). Applying AGTPs or ARTPs give mostly similar results, with the exception of BC, especially for emissions occurring in winter. For a ton of BC emission with the AGTP metric the summertime warming impact is 16 percent higher compared with winter whereas with the ARTP metric the wintertime impact is higher by more than 9120 percent than the summertime. The difference is driven by a more detailed parameterization of the effect of BC deposition in the Arctic. In case of ARTP mAlmostore than 8070 percent of the net impact for winter emission comes for BC deposition on snow. The annual impact of winter emissions of BC is 59 percent with the AGTPs but almost 8076 percent with the ARTPs. From a mitigation perspective, these estimatesboth cases indicate that attention should be placed on reducing winter emissions of BC.

Figure 56: The global temperature response (µK) of Finnish emissions in 2010 by applying the mean temperature 1-25 yrs after the pulse emission. This figure compares emissions occurring in summer (S) vs. winter (W) by applying, as well as global temperature estimated by either AGTP (Aamaas et al., 2016) or ARTP values (Aamaas et al., 2017; Sand et al., 2016). The emission region for the climate metrics is Europe for all cases. We present four cases for each pollutant from left to right: 1) summer emissions with AGTP, 2) winter emissions with AGTP, 3) summer emissions with ARTP, 4) winter emissions with ARTP. The responses are divided into six different processes.

3.2.5 Arctic temperature response from Finnish emissions

The seasonal differences for the SLCFs are also clearly seen in the Arctic temperature response (Fig. 7)We continue the comparisons of different climate metric studies, focusing on SLCFs, with the attention on the Arctic area. Finland is closely situated to the Arctic as practically the whole country is north of the 60°N latitude and a significant area lies north of the Arctic Circle. Fig. ure 6 7 shows the Arctic (between 60° to 90°N) temperature response based on the ARTP metrics from Aamaas et al. (2017); and Sand et al. (2016). As a general observation the temperature responses are larger in the Arctic (Figure Fig. 76) compared with the global ones (Figure Fig. 65). The trends are also similar, with net cooling of summer emissions and net warming of winter emissions, but. tThe Arctic warming in winter is up to about 3 times 300 percent larger than the cooling in summer. The main reason is the mostly due to the outsized impact of wintertime Eemissions of BC become even more important in the Arctic perspective, especially for Finnish emissions during winter (82 percent of the annual impact). The warming from BC deposition of snow is equal in size asMore than 80 percent of the net impact forof winter emission comes for BC deposition of snow. However, Fduringor emissions in summer, the cooling from by SO2 emissions outweighis larger than the warming from by BC emissions.

Figure 67: The temperature response (μK) in the Arctic of Finnish emissions in 2010, by applying the mean temperature 1-25 yrs after the pulse emission. This figure compares emissions occurring in summer (S) vs. winter (W) by applying ARTP values (Aamaas et al., 2017; Sand et al., 2016). The emission region for the climate metrics is Europe for all cases.

As the Sand et al. (2016) study also provides ARTP values for BC, OC and SO2 in the Arctic (Table A3 of the Supplementary material), we compare the annual temperature responses in the Arctic for those pollutants with input from Aamaas et al. (2017). Unfortunately, Sand et al. (2015) did not include climate metric values for other pollutants. Three differences between the two studies were identified, some of which led to adjustments in the parametrizations, namely: (1) Aamaas et al. (2017) provided ARTPs for emissions in Europe whereas Sand et al. (2016) analyzed the temperature impacts of emissions from the Nordic countries; (2) The climate sensitivities in the studies are different, and we adjusted the climate sensitivity upwards in the Sand et al. (2016) study to make its parameterization more comparable to the ones in Aamaas et al. (2017) and used in this study; Finally (3) the aggregation of atmospheric forcing processes between Aamaas et al. (2017) and Sand et al. (2016) is different, such as Sand et al. (2016) do not account for the semi-direct effect from BC. In Fig. 7 we have summed the direct and indirect effects in Sand et al. (2016) into "aerosol effects";

Fig. 7 shows that BC emissions from Finland lead to significant warming with both parameterizations. However, the net-impact of BC emissions with the adjusted Sand et al. (2016) approach is 18 percent higher compared with Aamaas et al. (2017). The largest difference is for SO2, where Sand et al. (2016) estimate a much larger indirect effect (Fig. 7).

~~Unfortunately, Sand et al. (2016) did not provide global temperature responses. But we can see that in short term, these larger sensitivities for SO2 would probably lead to a negative temperature response for the PROC sector (see Fig. 3), while the warming of CO2 would to a larger extent be counteracted by cooling from SO2 in the ENE IND sector. As the magnitude of this indirect effect is uncertain, the difference in the two estimates gives an indication of the uncertainty. The Arctic temperature response is also larger for OC (by 58 percent) than estimated based on Aamaas et al. (2017).~~

~~As this study focuses on Finland, the ARTPs in Sand et al. (2016) could be considered more representative. However, differences between the two studies and as a consequence in the results may also be due to different study designs, such as partly different selection of climate models, and not necessary only a result of a different representation of the geographical location of the source region.~~

~~**Figure 7: The temperature response (μK) in the Arctic (60-90° N) due to Finnish emissions of BC, OC, and SO2. The column to the left for each pollutant is based on ARTPs for Europe by Aamaas et al. (2017) and to the right ARTPs for Nordic countries by Sand et al. (2016).**~~

Fig~~.~~ ure 8 compares global and Arctic temperature responses to Finnish emissions of all pollutants considered in this study, using the Aamaas et al. (2017) approach. It demonstrates that the temperature response in the Arctic is typically stronger than the global average. If we apply the ARTP methodology for GHGs, the response in the Arctic is up to 50% larger than the global average due to stronger local feedback processes in the Arctic (Boer and Yu, 2003). The ozone precursors have similar or weaker efficacies in the Arctic compared with the GHGs. However, the aerosols and sulfur emissions stand out ~~(Fig. 6 and 7) with~~with the largest differences (Fig. 8). By applying ARTP values from Aamaas et al. (2017) with scaling from Sand et al. (2016), we find that Finnish emissions of SO2 and OC have a 300 percent stronger efficacy in the Arctic than the global average, and even higher for BC with 700 percent. A limitation with this method is that the scaling from Sand et al. (2016) is only applicable for the Arctic temperature response, which add some uncertainties to these Arctic vs. global ratios.~~Applying this method, Finnish emissions of BC, SO2, and OC have a 310%, 120%, and 100% stronger efficacy in the Arctic than the global average (Fig. 6 and 7).~~ For BC, this amplification in the Arctic is even stronger for emissions occurring in winter. Hence, the results indicate that mitigation of Finnish BC emissions is especially beneficial for limiting Arctic warming.

Fig 8. Global and Arctic (60-90° N) temperature responses (μK) to Finnish emissions based on ARTP values in Aamaas et al. (2017); Sand et al. (2016). As for most of the figures, the temperature response is the mean response 1 to 25 years after a pulse emission.

4. Discussion

The first objective in our study was to produce an integrated multi-pollutants emission dataset for Finland for 2000 to 2030. We were able to achieve this aim, but it required the use of several data sources and studies that are not necessarily maintained at a regular basis. Future efforts should pursue to maintain the integrated multi-pollutant database developed for this work. This would require an integrated modelling environment, for example the Finnish Regional Emission Scenario model (FRES), and further work to fill in the gaps for the missing sectors and pollutants via developing relevant activity and emission factor databases into the FRES framework.

Our second set of objectives for this study was to compare different climate metrics and to assess their suitability for calculating the climate impact of a multi-pollutant emission set. Several air pollutants and greenhouse gases have detrimental impacts on global and regional climate, human health and wellbeing as well as crop yields (see i.e. Shindell et al. 2012). Since the magnitudes and pathways of the effects differ between the constituents, integrated modelling is needed to understand the consequences and form the basis for robust climate and air quality policies. This paper applied and compared various climate metrics to study the approximate integrated climate impact of Finnish air pollutant and greenhouse gas emissions globally and in the Arctic area. The results demonstrated that the relative impacts and importance of individual species as well as sectors can differ significantly between the studied temporal response scales, emission seasons as well as geographical~~ response~~ scales for both emissions sources and temperature responses. Especially the warming or cooling impact of SLCFs is sensitive to the studied time scale, with shorter time spans showing greater importance compared with GHGs.

Finnish emissions and their climate responses are relatively small; therefore it is challenging to use climate models to study the climate effect of national policies and to analyze the role of each pollutant and sector. This study demonstrated a method to overcome this challenge by utilizing emission metrics. All studied metrics provided interesting insights into the impacts of Finnish emissions and which aspects could be emphasized when formulating mitigation strategies. We assessed that particularly the ~~AGTP and~~ ARTP based metrics provided useful information~~, although one should not rule out the significance of the other radiative forcing based metrics due to their relevance in connection with climate change mitigation work of the UNFCCC and IPCC~~. We preferred to use ARTP approaches to assess the impacts of Finnish emissions to both global and Arctic climate, because it includes the regional or latitudinal dimension of emission impacts in more detail. We also chose to use the mean(1-25 yrs) timeframe, since for the time being there is no established climate metrics for air pollutants, and this approach was recently suggested by Shindell et al. (2017) to be used in connection with SLCFs. This is a subjective choice to study ~~in more detail~~ the near-term climate impacts and the importance of short-lived species in more detail. To our knowledge, we are the first to present metric values with mean(ARTP(1-25yrs)) and among the first to use the GWP*~~for this climate metric~~.

Comment [BA1]: This is also stated in the conclusion. Can we remove here?

The use of ARTPs to study the impacts of Finnish emissions is useful for designing national emission mitigation strategies also from a regional perspective. Finland is an Arctic country and a member of the Arctic Council, which is why there is high interest on understanding the Arctic impacts.

The third set of objectives was to estimate the climate impact of Finnish air pollutants and greenhouse gases utilizing the selected metrics. Our analysis across climate metrics, time horizons, pollutants and Finnish emission pathways demonstrated that carbon dioxide emissions have the largest climate response also in the ~~short~~ near term (10 to 20 years), and its relative importance increases the longer the time span gets. Hence, mitigation of carbon dioxide is crucial for reducing the climate impact of Finnish emissions. In the near or medium term, i.e. 25 year perspective, especially methane and black carbon have relatively significant warming impacts in addition~~al~~ to those of carbon dioxide. SO2, on the other, hand is an important precursor to light reflecting sulphate aerosol, thus having a cooling impact and~~,~~ offsetting part of the warming impact of the other species.

Of Finnish emissions, the combustion in energy production and industry has the largest global temperature impact in the medium and long term due to ~~biggest~~ significant carbon dioxide emissions, while sulfur dioxide emissions induce a shorter term cooling. Transport has the second biggest warming impact, and although that is expected to decrease notably by 2030 due to stricter control on particulate and consequently black carbon emissions, it will remain a major source of carbon dioxide. Emissions from domestic and agriculture sectors also have a considerable warming impact, and they will remain so, due to the relatively large respective emissions of black carbon and methane from the combustion of solid fuels, especially wood.

For all of the species the temperature response of Finnish emissions is generally stronger in the Arctic than globally, but most significantly so in case of black carbon and sulfur dioxide. Results obtained with the ARTP metric indicated that especially mitigation of wintertime black carbon emissions are important for reducing the temperature increase in the Arctic. Emissions of sulfur dioxide are expected to continue decreasing and this has many benefits (Ekholm et al. 2014). However, it will offset some of the climate benefits of the reduced carbon dioxide emissions, and this should be taken into consideration in climate assessments.

The fourth major objective of this study was to recommend a set of global and regional climate metrics to be used in connection with Finnish SLCF emissions. As a preparation for~~In~~ writing this paper we compared~~provide a comparison and discussion of~~ several climate metrics to be used in connection with Finnish SLCF emissions. We ended up ~~mostly~~ relying on those presented in Aamaas et al. (2017) that in our understanding is currently the most complete set of climate metrics available for assessing the global and Arctic temperature responses of European emissions. However, we have scaled those values with ratios from Sand et al. (2016) for the Arctic temperature response because that study provided ARTPs for Nordic emissions, which is ~~even~~ more representative for the Finnish ~~emissions~~case. For the GHGs, we argue to apply the metric parameterization from IPCC AR5 (Myhre et al., 2013), but with an upward revision for CH4 (Etminan et al., 2016). The coefficients for mean(ARTP(1-25 yrs)) (see also Shindell et al. 2017) in Table 3 ~~have been evaluated to be~~were ~~useful~~ used for assessing different mitigation pathways in a 25 year time span. This time window is relevant for policies that focus on reducing global or Arctic warming in the near or medium term, from today and until~~by~~ 2040 or 2050. Corresponding mean(RTP(1-25 yrs)) values are shown in Table A2.

Table 3. The climate metric values (°C/Tg) used in this study. Mean(ARTP(1-25yrs)) ~~and mean(AGTP(1-25yrs))~~ values for SLCF and GHG emissions. The Arctic response for the GHGs is based on the latitudinal pattern for CH4. The annual average is based on emissions in 2010. Normalized values (CO2-equivalents) are shown in Table A2.

The assessed temperature impact of an emission dataset depends on the set of metrics available, as well as the applied metric setup, which bring uncertainties to the results. As there is no consensus on one individual set of metrics, especially in case of air pollutants, the results will differ between different studies. This work estimated the global and regional temperature impacts of Finnish emissions based on methodologies in three recent papers (Sand et al., 2016; Aamaas et al., 2016; Aamaas et al., 2017). As all of these studies utilize partly the same radiative forcing datasets and partly similar general circulation models and chemistry transport models, we welcome other studies to complement the basis for our findings~~the uncertainties may be in fact be larger than our results indicate if a larger set of background studies would be utilized~~. Future work should continue to explore ~~these~~ uncertainties and provide improved metrics.

Since the atmospheric lifetime of SLCFs is relatively short, their climate impact is more dependent on the emission region than with GHGs. Using Europe and the Nordic region as ~~a~~ proxies~~y~~ for the emission region, as in this study, gives us a more representative picture of the Finnish case than would the global average. Further development of the metrics should use more precisely the geographical location of Finland as the emission region in order to provide more precise temperature estimates for the Finnish emissions. ~~This is mostly because the snow albedo effect of BC emissions is expected to be larger for Finland, compared with to the source regions used in our study.~~ The snow albedo effect of BC is expected to be much larger for the northernmost emissions, as~~This is~~ indicated by a study for Norway by Hodnebrog et al. (2014). Future work should also focus on providing metrics for potentially missing species that could be important, for example dust aerosol.

Comment [MS2]: This is probably no longer valid?

Scientific literature has demonstrated that the climate impact of biomass combustion may depend on the timescale and forestry practices (i.e. Cherubini et al. 2011, Repo et al. 2012 and Repo et al. 2015), which have not been a focus of this study. Since the use of biomass for energy is important in Finland and will likely remain so in the coming decades, future studies could utilize metrics to study its climate impacts. This study has mostly focused on surface temperature metrics, however, ~~interesting~~ other interesting impacts could be studied using the metric approach. For example Shine et al. (2015) has recently presented a new metric named the Global Precipitation change Potential (GPP), which is designed to gauge the effect of emissions on the global water cycle. ~~Allen et al. (2016 and 2018) have suggested a new use of the GWP metric that relates cumulative CO2 emissions to date with the current rate of emissions of SLCPs and links them directly to future warming.~~

Comment [BA3]: Delete or reword if we include discussion on GWP*

The ~~improved~~ understanding of the impact pathways of different pollutants has improved in recent years, which ~~further~~ has led to further revisions of the climate impact estimates. Such development is expected to continue. The metric studies, however, are often based on earlier ~~RF~~ radiative forcing studies, and a time lag from new scientific understanding to this being reflected in the climate metrics exists. This study has utilized the latest metric studies, but there are already ~~studies~~ literature available, for instance on BC, indicating that the temperature response may be smaller than demonstrated by the metrics used in this work (e.g., Stjern et al., 2017). As the understanding of the climate system improves, the estimated we give here for Finland should be ~~updated~~revisited.

5. Conclusions

All studied metrics provided interesting insights into the impacts of Finnish emissions and which aspects could be emphasized when formulating mitigation strategies. We assessed that particularly the ~~AGTP and~~ ARTP based metrics provided useful information, although one should not rule out the significance of the other temperature and radiative forcing based metrics, for the latter due to their relevance in connection with climate change mitigation work of the UNFCCC and IPCC. In the future also other climate impact metrics should be explored and utilized. To enable such policy analyses an integrated multi-pollutant emission and metrics database, similar to the one used in this work, should be maintained.

Our analysis across climate metrics, time horizons, pollutants and Finnish emission pathways demonstrated that carbon dioxide emissions have the largest climate response also in the ~~short~~ near term, 10 to 20 year time perspective, and its relative importance increases the longer the time span gets. Hence, mitigation of carbon dioxide is crucial for reducing the climate impact of Finnish emissions. In the near or medium term, i.e. 25 year perspective, especially methane and black carbon have relatively significant warming impacts additional to those of carbon dioxide.

Comment [MS4]: The same comment as previously about the wording

For all of the species the temperature response of Finnish emissions is generally stronger in the Arctic than globally, but most significantly so in case of black carbon and sulfur dioxide. Especially the wintertime emissions are net warming, and even more so in the Arctic, mostly due to black carbon. The snow albedo effect of the Finnish BC emissions is ~~expected~~

found to be large for Finland aand this phenomenon should be adequately included in the analyses. Since the atmospheric lifetime of SLCFs is relatively short, their climate impact is more dependent on the emission region than with GHGs. Our study demonstrated using the Finnish case that Future future studies and further development of the metrics should use more precisely the geographical location of Finland as the emission region in order to provide more precise temperature estimates for the Finnish emissions.

Author contribution

KJK and MS compiled the emission data with supporting contributions from NK and VP. BA prepared the climate metrics databases and applied them to the emission data. KJK, BA and MS were leading the preparation of the manuscript. NK and VP acted as contributing authors.

Acknowledgements

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Tables & figures

Table 1. Data sources of the historical emission data for 2000-2010

Pollutant	**Data source**
Black carbon (BC), organic carbon (OC)	FRES model
CO	GAINS model (http://gains.iiasa.ac.at)
CO_2, CH_4 and N_2O from combustion sources	FRES model

CO_2, CH_4 and N_2O from other sources than combustion	National inventory of greenhouse gases specified in the Kyoto Protocol to the Secretariat of the UNFCCC
NH_3 and VOC	National emission inventory to the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP)

Table 2. Primary energy consumption in Finland (TWh a^{-1}) (Ministry of Employment and the Economy, 2013)

	2010	2020 Baseline	2030 Baseline
Traffic fuels	50	48	42
Other oil fuels	48	43	32
Coal	52	50	22
Gas	41	37	31
Peat	26	16	13
Wood fuels,	89	98	101
-of which RWC	19	15	17
Nuclear power	66	106	171
Hydro power	13	14	15
Wind power	0.3	6	7
Others, including waste	10	16	19
Import of electricity	11	0	-3
Sum	407	433	459

Table 3. The climate metric values (°C/Tg) used in this study. Mean(ARTP(1-25yrs)) ~~and mean(AGTP(1-25yrs))~~ values for SLCF and GHG emissions. The Arctic response for the GHGs is based on the latitudinal pattern for CH_4. The annual average is based on emissions in 2010. Normalized values (CO_2-equivalents) are shown in Table A2.

	Mean(1-25yrs), global response in °C/Tg			Mean(1-25yrs), Arctic response in °C/Tg		
	Annual average	Summer	Winter	Annual average	Summer	Winter
CO_2 [CO_2]	5.7E-7	5.7E-7	5.7E-7	8.2E-7	8.2E-7	8.2E-7
CH_4 [CH_4]	4.8E-5	4.8E-5	4.8E-5	6.9E-5	6.9E-5	6.9E-5
N_2O [N_2O]	1.5E-4	1.5E-4	1.5E-4	2.1E-4	2.1E-4	2.1E-4

NO_X [NO_2]	-1.7E-5	-2.3E-5	-1.1E-5	-1.9E-5	-2.7E-5	-1.1E-5
VOC [VOC]	9.6E-6	1.4E-5	6.1E-6	1.6E-5	1.6E-5	1.6E-5
CO [CO]	4.1E-6	3.9E-6	4.3E-6	5.2E-6	5.0E-6	5.4E-6
BC [C]	2.7~~1.8~~E-3	1.5~~1.1~~E-3	3.4~~2.2~~E-3	2.2~~7.4~~E-~~3~~2	1.0~~3.5~~E-~~3~~2	2.9~~9.8~~E-~~3~~2
OC [C]	-4.7~~-4.0~~E-4	-6.7~~-5.6~~E-4	-3.5~~-3.0~~E-4	-1.9~~-8.1~~E-3~~4~~	-2.7~~-1.2~~E-3	-1.4~~-5.8~~E-3~~4~~
SO_2 [SO_2]	-2-2~~-2.0~~E-4	-3.5~~-3.1~~E-4	-1.0~~-9.1~~E-4~~5~~	-8.5~~-4.4~~E-4	-1.3~~-7.0~~E-3~~4~~	-3.7~~-1.9~~E-4
NH_3 [NH_3]	-4.3~~-3.7~~E-5	-5.2~~-4.5~~E-5	-3-3~~-2.9~~E-5	-1.4~~-6.2~~E-~~5~~4	-1.7~~-7.5~~E-~~5~~4	-1-1~~-4.8~~E-4~~5~~

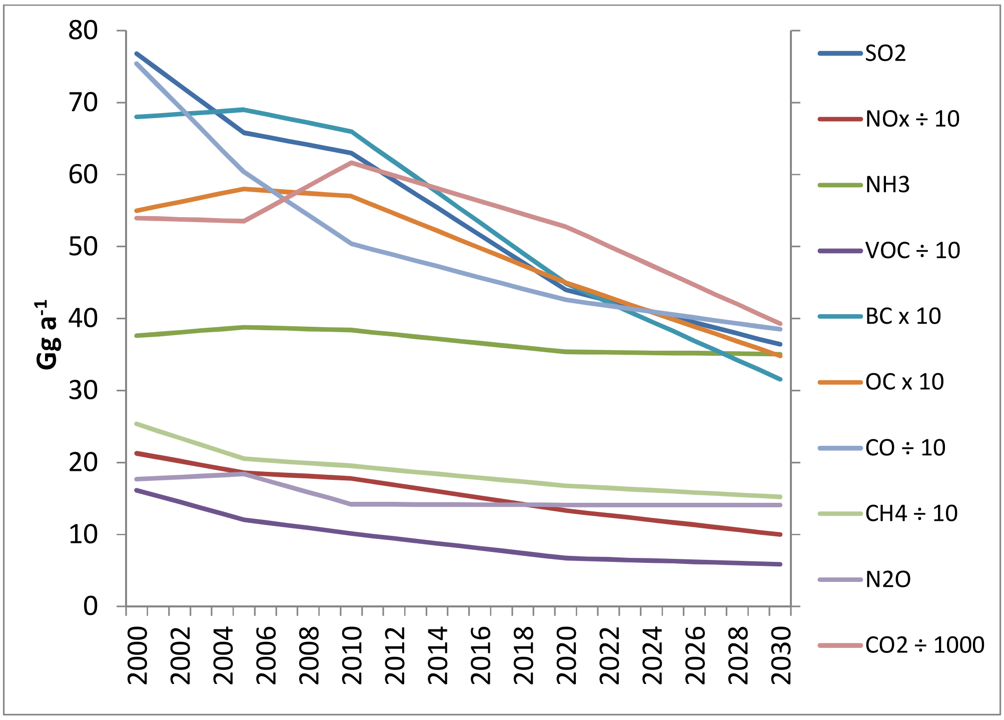


Figure 1. Finnish emissions (Gg a^{-1}) of air pollutants and greenhouse gases in the period 2000 to 2030 in the baseline scenario. Emissions by sector for 2000, 2010 and 2030 can be found in Table A1 of the Supporting material.

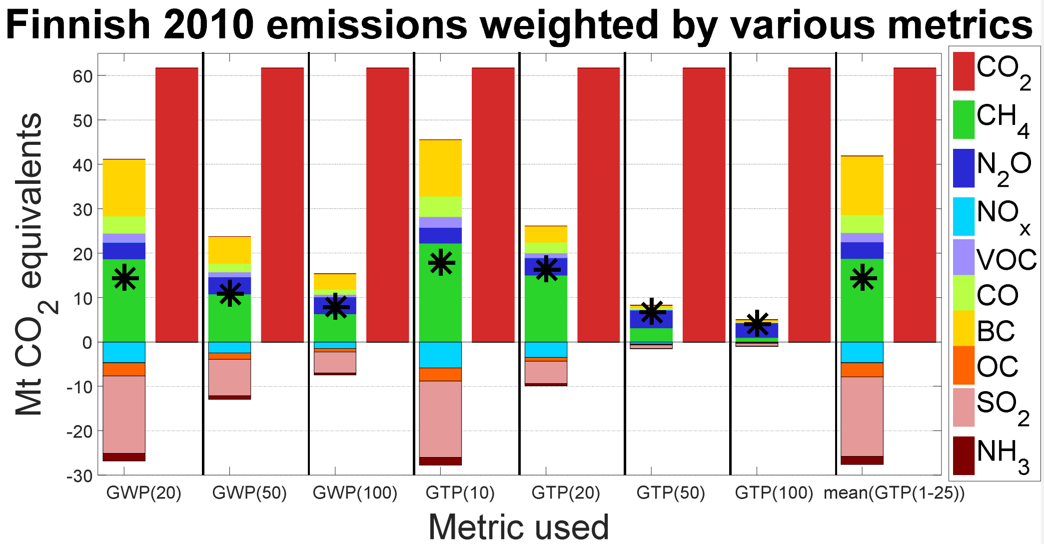
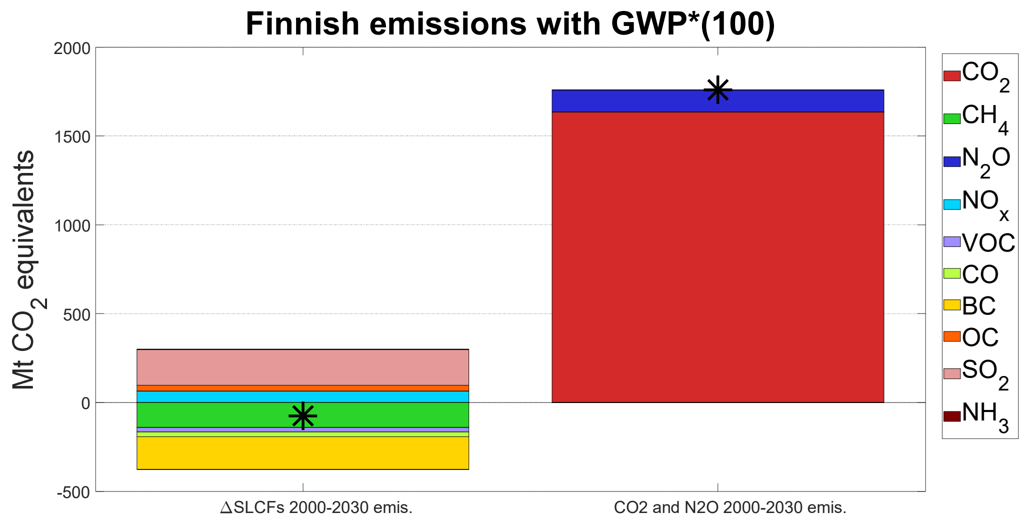


Figure 2. Finnish 2010 emission (Mt CO_2-eq) as a pulse emission weighted by various global metrics. CO_2 is separated out and the net impact of the non-CO_2 is given by the star.



~~New~~ **Figure 3. The CO2-equivalent emissions for the period 2000-2030 given the alternative metric GWP*(100). The net impact of SLCFs (left) and CO2 and N2O (right) is given by the star.**

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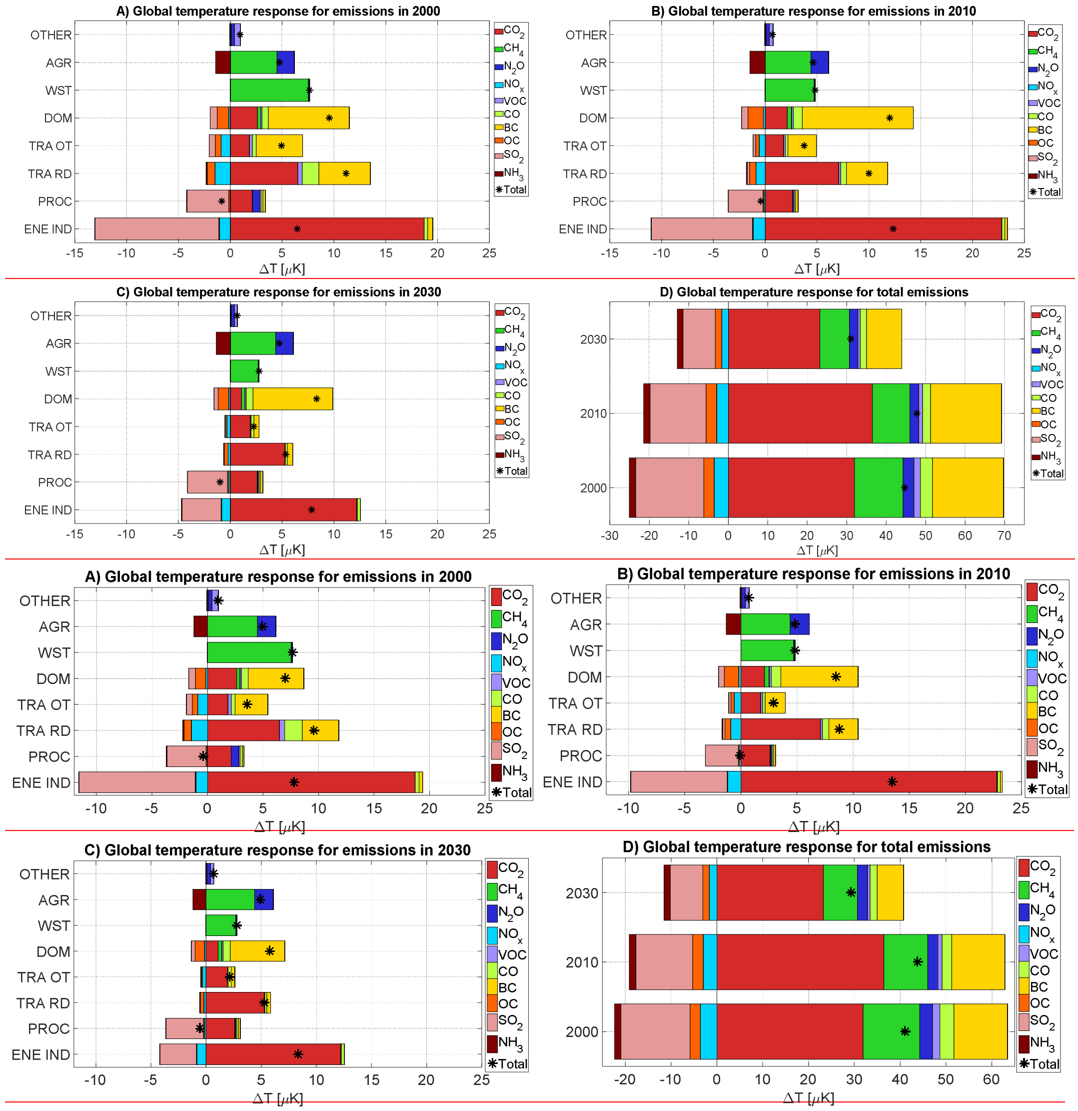
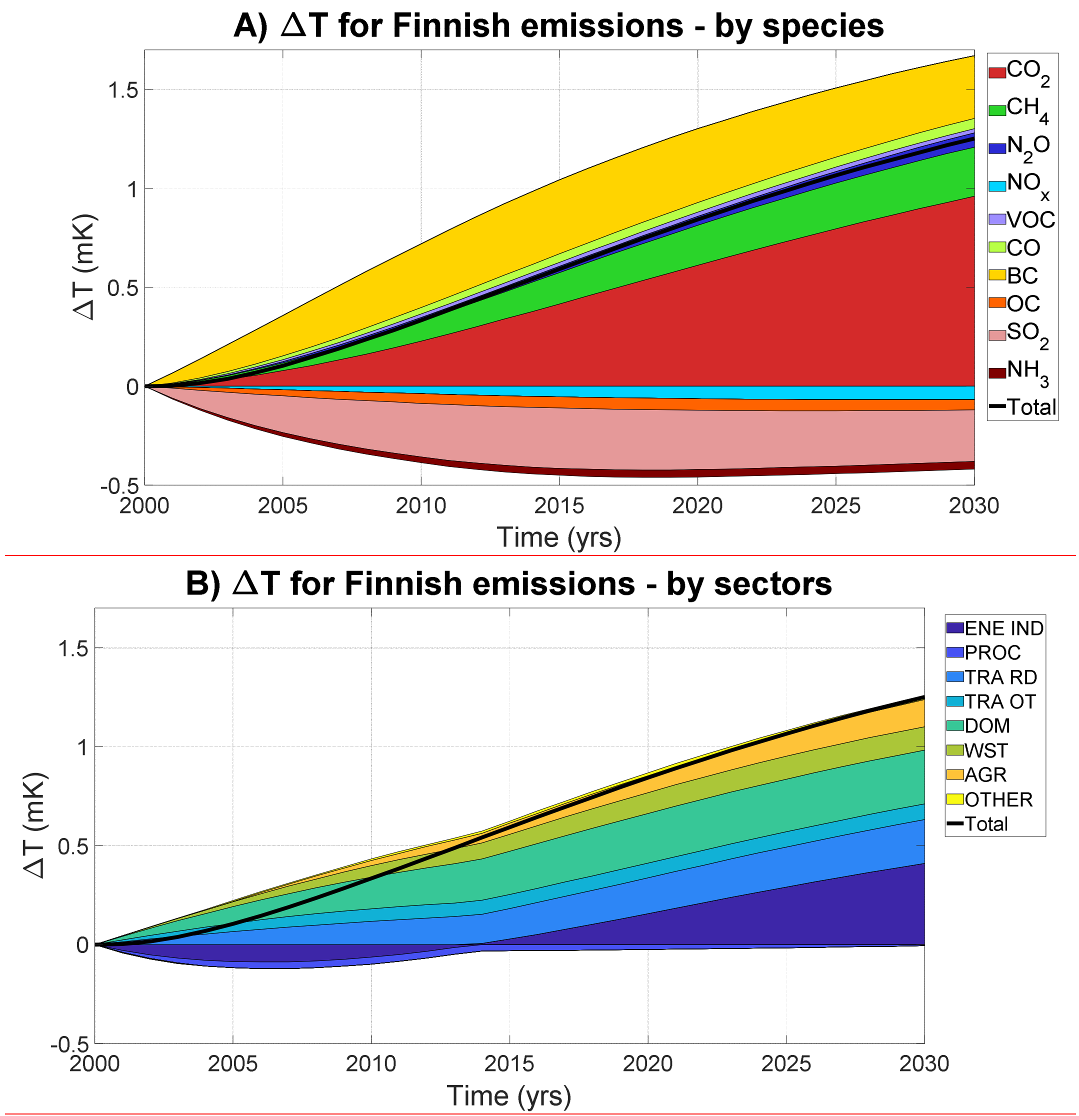


Figure 43. The temperature response (µK) due to emissions in 2000 (A), 2010 (B), and 2030 (C) from sectors energy and industry (ENE IND), industrial processes (PROC), transport road (TRA RD), off-road transport and machinery (TRA OT), domestic (DOM), waste (WST), agriculture (AGR), and other (OTHER). The sum of all sectors is shown in (D). The climate metric applied is the global mean(ARTP(1-25 yrs)) for pulse emissions.


A) ΔT for Finnish emissions - by species
ΔT (mK)
Time (yrs)
CO_2
CH_4
N_2O
NO_x
VOC
CO
BC
OC
SO_2
NH_3
Total
B) ΔT for Finnish emissions - by sectors
ΔT (mK)
Time (yrs)
ENE IND
PROC
TRA RD
TRA OT
DOM
WST
AGR
OTHER
Total

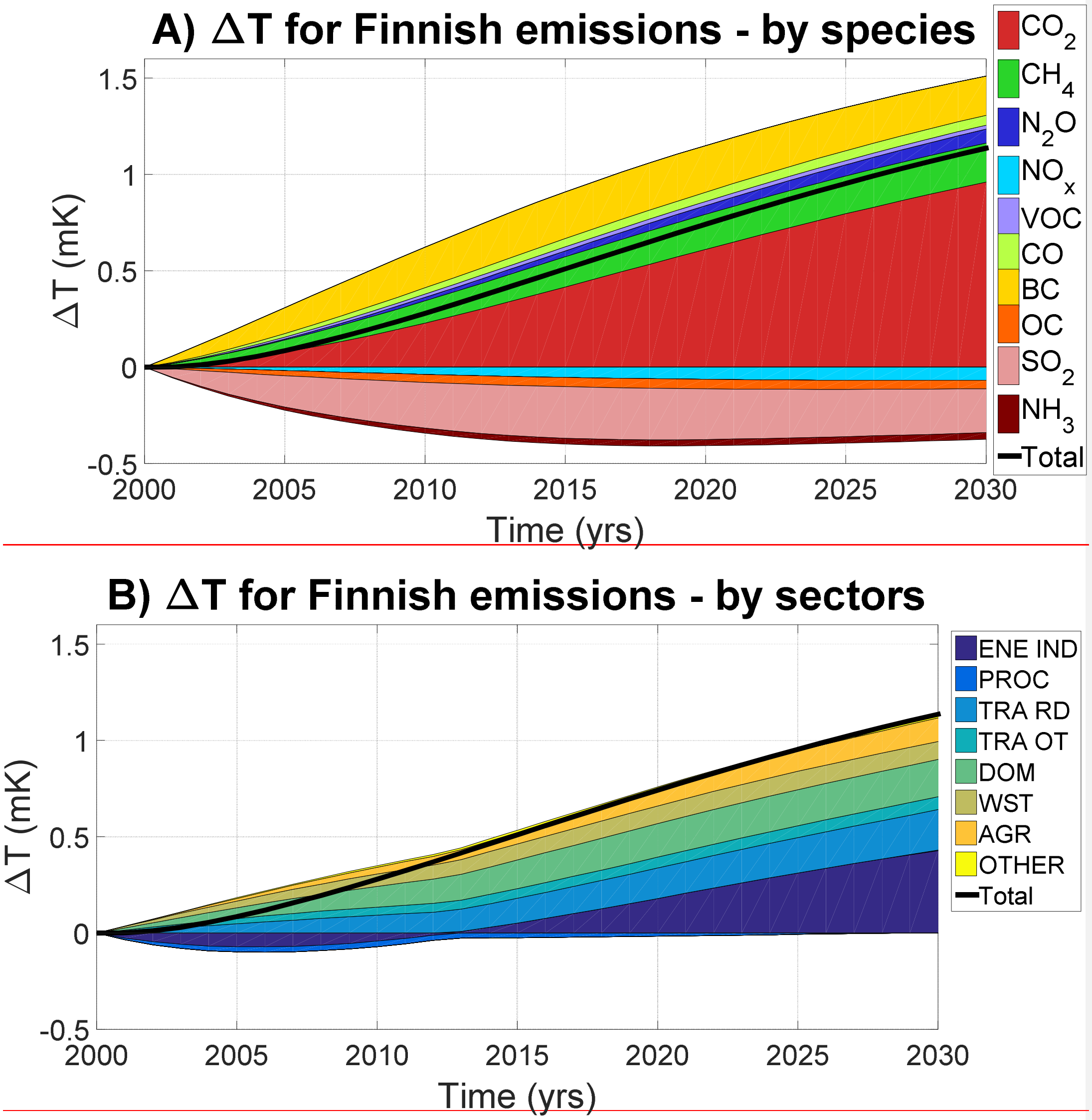
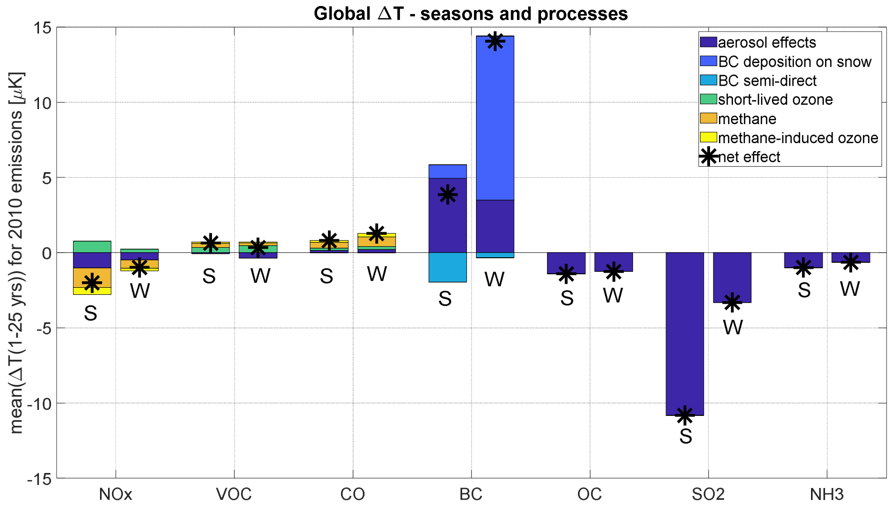


Figure 45: The global temperature development (mK) of Finnish emissions for the period 2000-2030. Temperature is given by pollutants in (A) and by sectors in (B). The global temperatures are estimated as a convolution of ARTP values and an emission scenario.



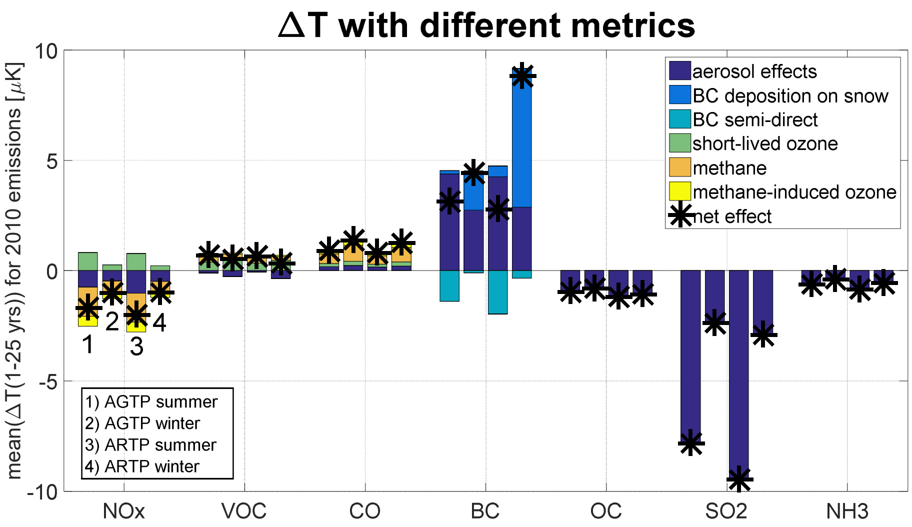
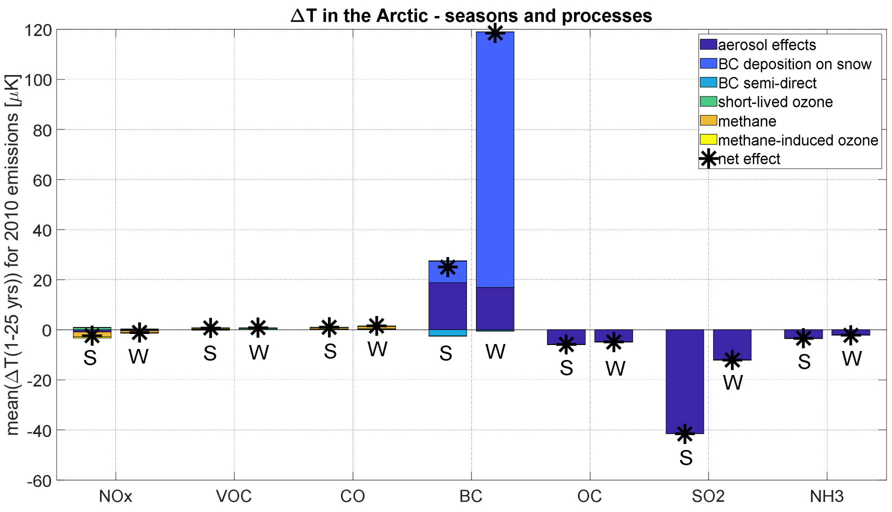


Figure 56: **The global temperature response (μK) of Finnish emissions in 2010 by applying the mean temperature 1-25 yrs after the pulse emission. This figure compares emissions occurring in summer vs. winter, as well as global temperature estimated by either AGTP (Aamaas et al., 2016) or ARTP (Aamaas et al., 2017). The emission region for the climate metrics is Europe for all cases. We present four cases for each pollutant from left to right: 1) summer emissions with AGTP, 2) winter emissions with AGTP, 3) summer emissions with ARTP, 4) winter emissions with ARTP. The responses are divided into six different**

processes. The global temperature response (µK) of Finnish emissions in 2010 by applying the mean temperature 1-25 yrs after the pulse emission. This figure compares emissions occurring in summer (S) vs. winter (W) by applying ARTP values (Aamaas et al., 2017; Sand et al., 2016). The responses are divided into six different processes.



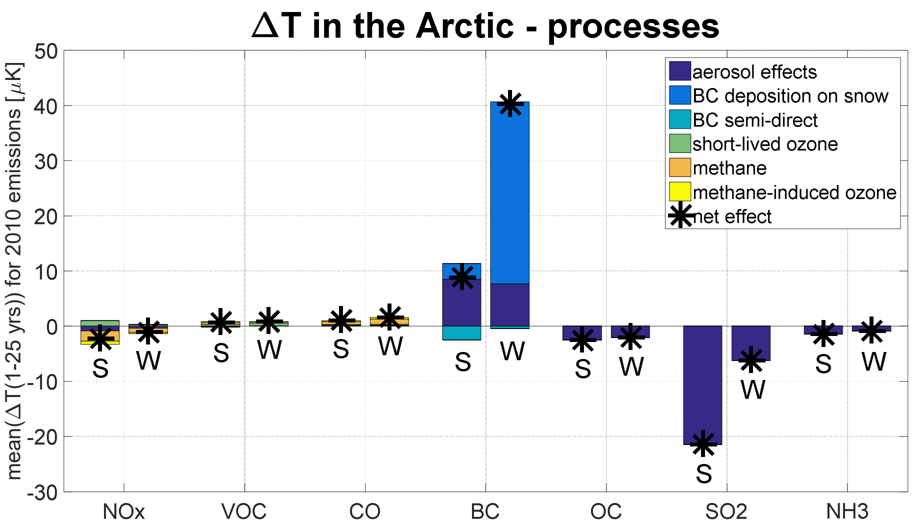


Figure 67: The temperature response (µK) in the Arctic of Finnish emissions in 2010, by applying the mean temperature 1-25 yrs after the pulse emission. This figure compares emissions occurring in summer (S) vs. winter (W) by applying ARTP values (Aamaas et al., 2017; Sand et al., 2016). The emission region for the climate metrics is Europe for all cases.

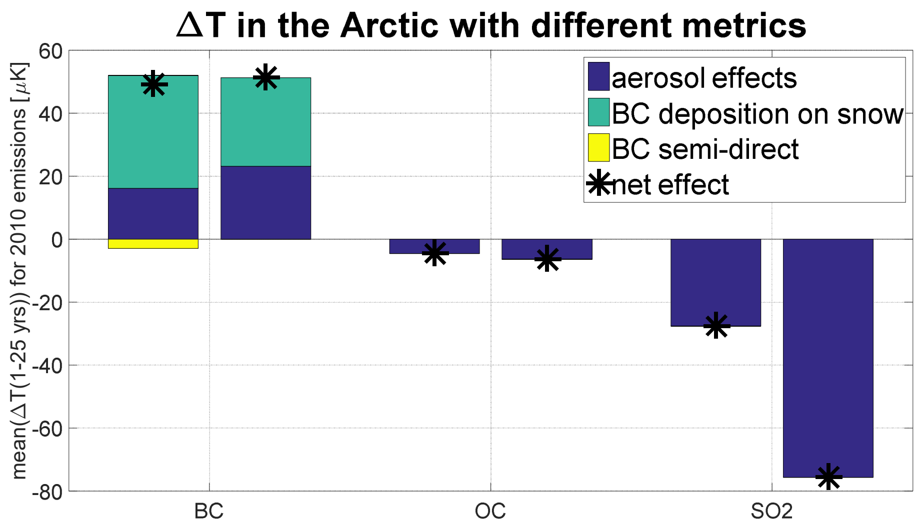
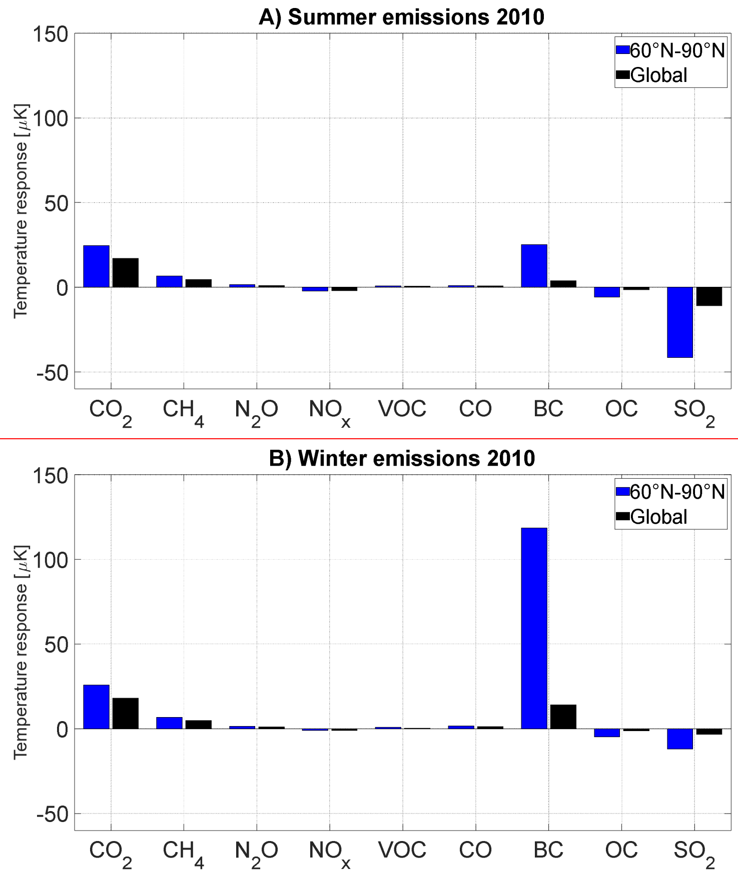
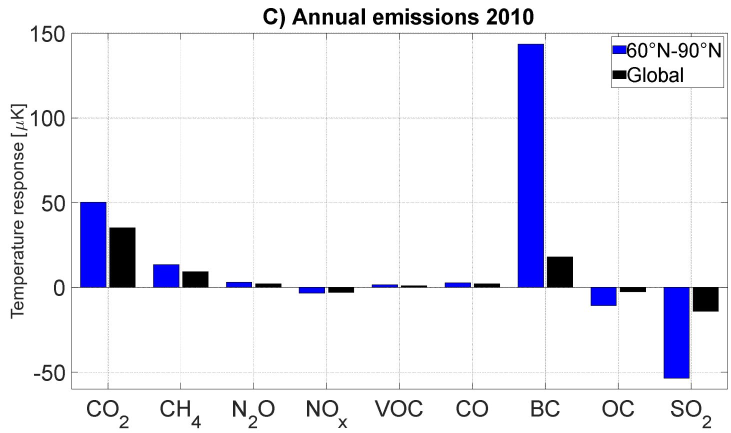
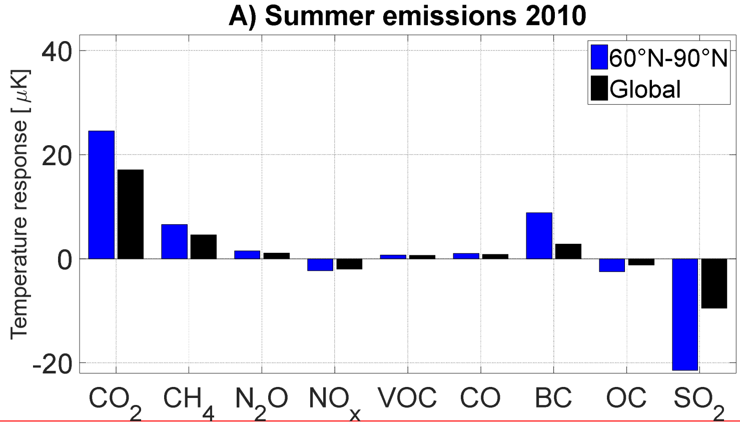


Figure 7: The temperature response (µK) in the Arctic (60-90° N) due to Finnish emissions of BC, OC, and SO_2. The column to the left for each pollutant is based on ARTPs for Europe by Aamaas et al. (2017) and to the right ARTPs for Nordic countries by Sand et al. (2016).



A) Summer emissions 2010
Temperature response [μK]
150
100
50
0
-50
60°N-90°N
Global
CO2
CH4
N2O
NOx
VOC
CO
BC
OC
SO2
B) Winter emissions 2010
Temperature response [μK]
150
100
50
0
-50
60°N-90°N
Global
CO2
CH4
N2O
NOx
VOC
CO
BC
OC
SO2


C) Annual emissions 2010
Temperature response [μK]
150
100
50
0
-50
60°N-90°N
Global
CO2
CH4
N2O
NOx
VOC
CO
BC
OC
SO2


A) Summer emissions 2010
Temperature response [μK]
40
20
0
-20
60°N-90°N
Global
CO2
CH4
N2O
NOx
VOC
CO
BC
OC
SO2

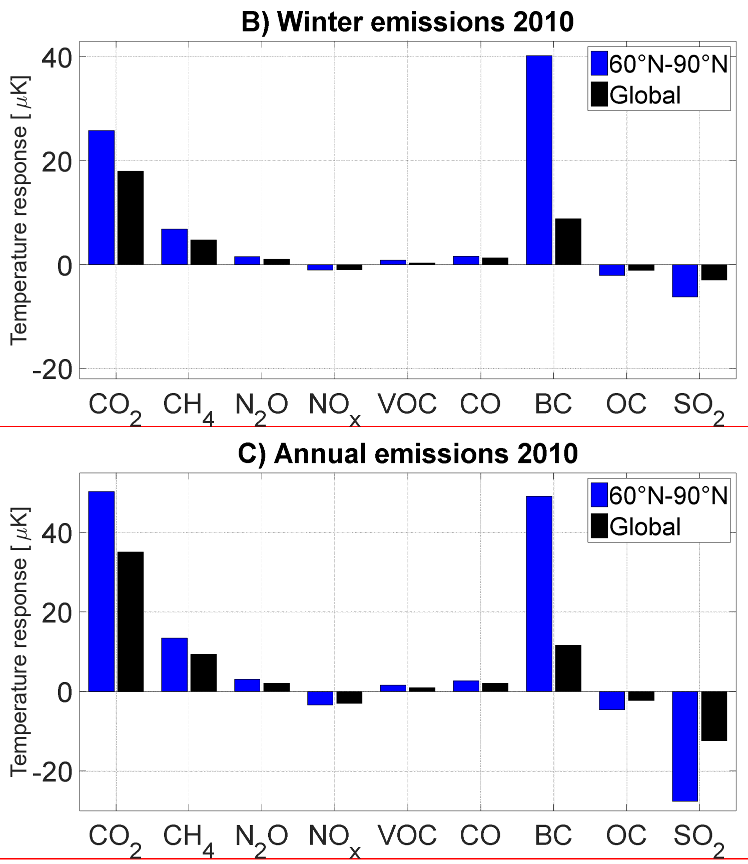


Figure 8: Global and Arctic (60-90° N) temperature responses (µK) to Finnish emissions based on ARTP values in Aamaas et al. (2017; Sand et al. (2016)). As for most of the figures, the temperature response is the mean response 1 to 25 years after a pulse emission.

Climate Impact of Finnish Air Pollutants and Greenhouse Gases using Multiple Emission Metrics

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Supporting Information

Table A1. Emissions in 2000, 2010 and 2030 from sectors energy and industry (ENE IND), industrial processes (PROC), transport road (TRA RD), off-road transport and machinery (TRA OT), domestic (DOM), waste (WST), agriculture (AGR), and other (OTHER). Unit: Gg a^{-1}

Pollutant	Year	DOM	ENE_IN	PROC	TRA_RD	TRA_OT	WST	AGR	OTHER
BC	2000	2.7	0.2	0.1	2.0	1.8	0.0	0.0	0.0
BC	2010	3.7	0.1	0.1	1.6	1.1	0.0	0.0	0.0
BC	2030	2.7	0.0	0.1	0.2	0.2	0.0	0.0	0.0
OC	2000	2.5	0.1	0.2	1.5	1.1	0.0	0.0	0.1
OC	2010	3.4	0.1	0.2	1.2	0.7	0.0	0.0	0.1
OC	2030	2.3	0.1	0.2	0.7	0.2	0.0	0.0	0.0
CO	2000	147.0	80.2	45.0	390.2	87.0	4.2	0.6	0.0
CO	2010	209.0	66.9	32.0	134.2	57.2	4.3	0.2	0.0
CO	2030	154.8	76.3	35.3	45.7	68.3	4.4	0.2	0.0
NO_X	2000	11.0	62.0	2.3	85.9	51.7	0.0	0.0	0.0
NO_X	2010	13.0	69.7	7.4	53.3	34.5	0.0	0.0	0.0
NO_X	2030	10.3	49.1	9.2	12.8	18.6	0.0	0.0	0.0
VOC	2000	14.3	0.5	11.7	45.3	28.3	2.0	0.0	59.3
VOC	2010	19.2	2.2	8.5	18.5	17.2	0.6	0.0	35.2
VOC	2030	13.1	2.0	7.4	3.2	4.9	0.4	0.0	27.6
SO_2	2000	3.9	52.5	17.7	0.1	2.6	0.0	0.0	0.0
SO_2	2010	3.4	42.9	14.7	1.0	1.0	0.0	0.0	0.0
SO_2	2030	2.3	16.6	17.0	0.1	0.4	0.0	0.0	0.0

NH_3	2000	0.0	0.9	1.1	2.4	0.0	0.1	32.9	0.2
NH_3	2010	0.0	0.9	0.6	1.6	0.0	0.1	35.0	0.2
NH_3	2030	0.0	1.0	0.5	1.3	0.0	0.1	32.0	0.2
CH_4	2000	6.0	0.0	0.5	0.0	0.0	154.6	92.5	0.0
CH_4	2010	8.2	0.0	0.4	0.0	0.0	96.5	90.1	0.0
CH_4	2030	6.7	0.0	0.4	0.0	0.0	55.0	90.1	0.0
CO_2	2000	4467	31600	3600	10990	3143	0	0	170
CO_2	2010	3572	38540	4400	11988	3005	0	0	150
CO_2	2030	1852	20636	4400	8948	3299	0	0	150
N_2O	2000	0.1	0.1	4.4	0.0	0.0	0.5	10.6	2.0
N_2O	2010	0.2	0.1	0.5	0.0	0.0	0.5	10.9	2.0
N_2O	2030	0.1	0.1	0.5	0.0	0.0	0.5	10.9	2.0

Table A2: Mean(RTP(1-25yrs)) ~~and mean(GTP(1-25yrs))~~ values (°C/Tg) for SLCF and GHG emissions. The normalized values of Table 3. The Arctic response for the GHGs is based on the latitudinal pattern for CH_4. The annual average is based on emissions in 2010.

	Mean(1-25yrs), global response			Mean(1-25yrs), Arctic response		
	Annual average	Summer	Winter	Annual average	Summer	Winter
CO_2 [CO_2]	1	1	1	1	1	1
CH_4 [CH_4]	84	84	84	84	84	84
N_2O [N_2O]	262	262	262	262	262	262
NO_X [NO_2]	-30	-41	-19	-23	-33	-14
VOC [VOC]	17	24	11	19	19	19
CO [CO]	7	7	8	6	6	7
BC [C]	4770~~3085~~	2710~~1950~~	6030~~3779~~	26700~~9111~~	12300~~4328~~	35500~~12036~~
OC [C]	-824 ~~-699~~	-1170 ~~-986~~	-619 ~~-529~~	-2290 ~~-989~~	-3360 ~~-1450~~	-1660 ~~-715~~
SO_2 [SO_2]	-394 ~~-346~~	-618 ~~-541~~	-181 ~~-159~~	-1040 ~~-537~~	-1650 ~~-853~~	-457 ~~-236~~
NH_3 [NH_3]	-74 ~~-65~~	-90 ~~-79~~	-58 ~~-51~~	-176 ~~-76~~	-214 ~~-92~~	-137 ~~-59~~

~~Table A3: Temperature response (°C/Tg) in the Arctic with ARTPs from Sand et al. (2016). The climate sensitivity is adjusted making the estimates comparable to the other metric studies in our study. The sectors are those given by Sand et al. (2016), which deviate somewhat to the sectors in our study and a perfect match is not possible. The sectors ENE IND,~~

~~PROC, WST, and OTHER take the values from energy/industry/waste. The sectors TRA RD and TRA OT use transport. DOM is linked to domestic. AGR takes the values from agricultural waste burning. The climate metric values vary between the different emission sectors due to differences in spatial and temporal patterns of emissions.~~

~~Mean(ARTP(1-25 yrs)), Arctic response in °C/Tg~~	~~Domestic~~	~~Energy/industry/waste~~	~~Transport~~	~~Agricultural waste burning~~	~~Grass/forest fires~~	~~Flaring~~
~~BC~~	~~1.1E-2~~	~~9.6E-3~~	~~1.0E-2~~	~~4.6E-3~~	~~1.8E-2~~	~~1.3E-2~~
~~OC~~	~~-1.5E-3~~	~~-1.4E-3~~	~~-1.5E-3~~	~~-6.5E-4~~	~~-2.9E-3~~	~~-1.7E-3~~
~~SO_2~~	~~-6.4E-4~~	~~-1.2E-3~~	~~-1.6E-3~~	~~-4.7E-4~~	~~-4.4E-3~~	~~-6.6E-3~~

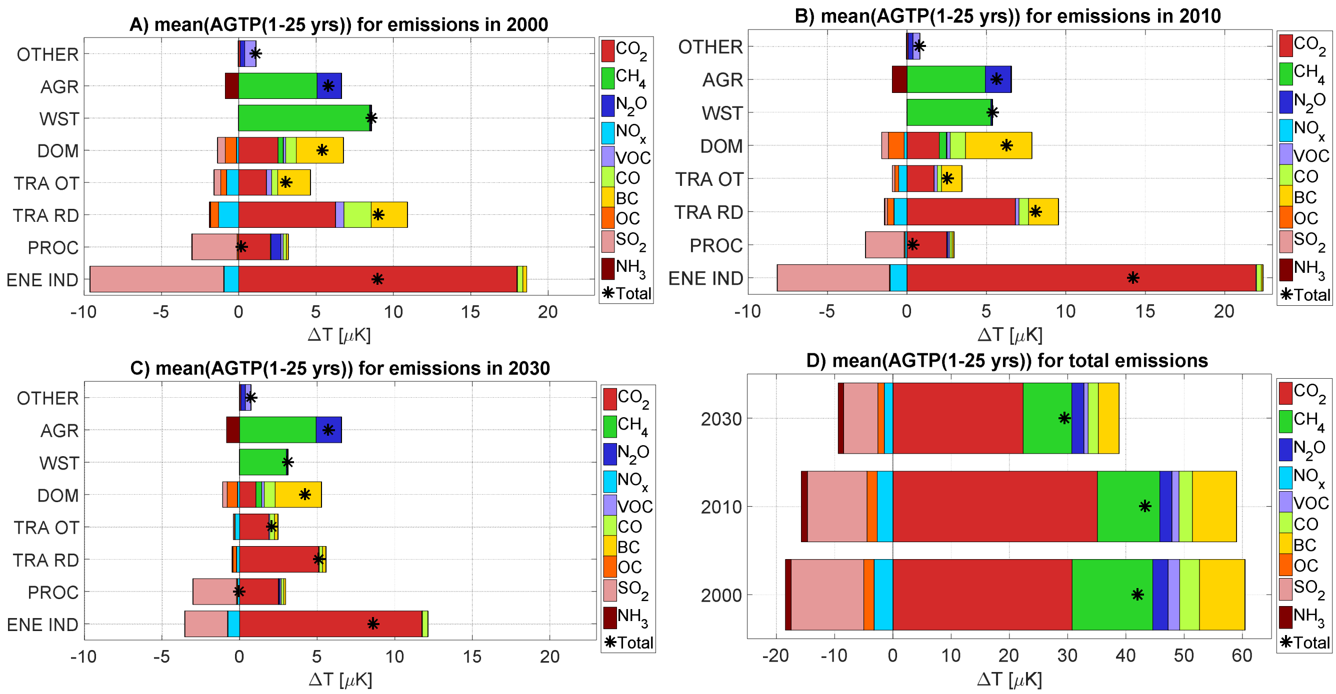
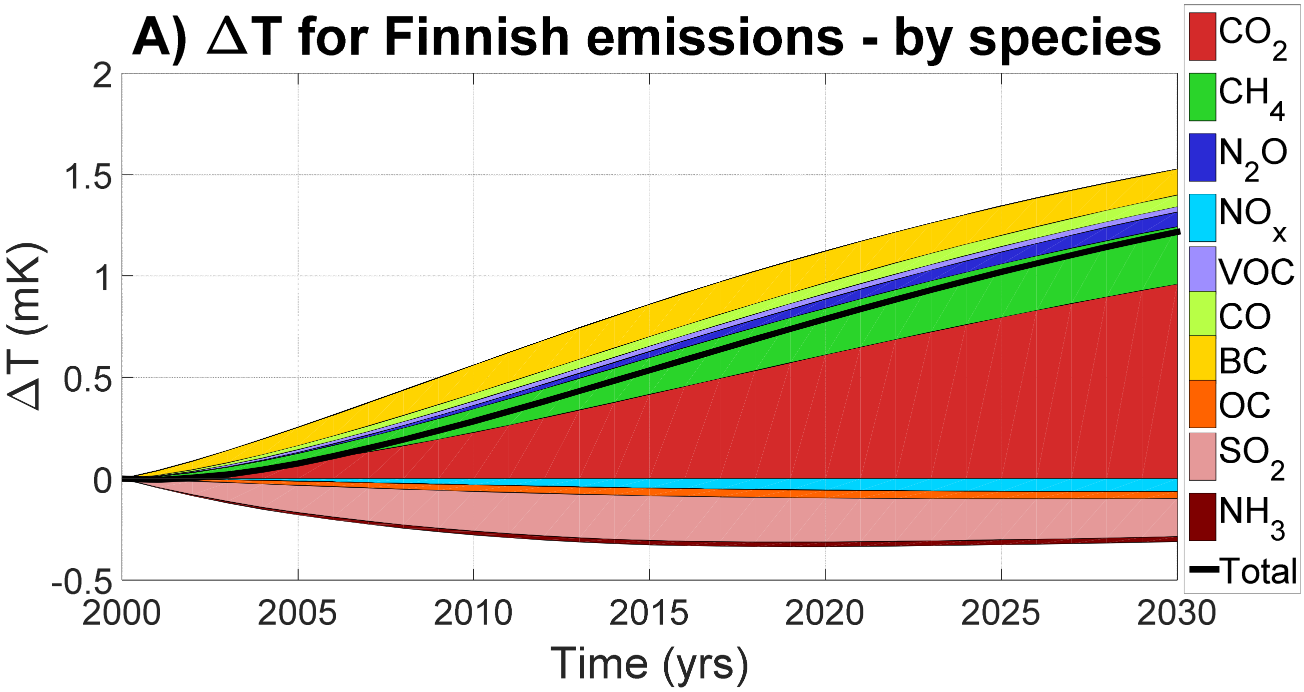


Figure A1: The same as Figure 3, but based on AGTPs in Aamaas et al. (2016), and not ARTPs. The temperature response (μK) due to emissions in 2000 (A), 2010 (B), and 2030 (C) from sectors energy and industry (ENE IND), industrial processes (PROC), transport road (TRA RD), off-road transport and machinery (TRA OT), domestic (DOM), waste (WST), agriculture (AGR), and other (OTHER). The sum of all sectors is shown in (D). The climate metric applied is mean(AGTP(1-25 yrs)) for pulse emissions.



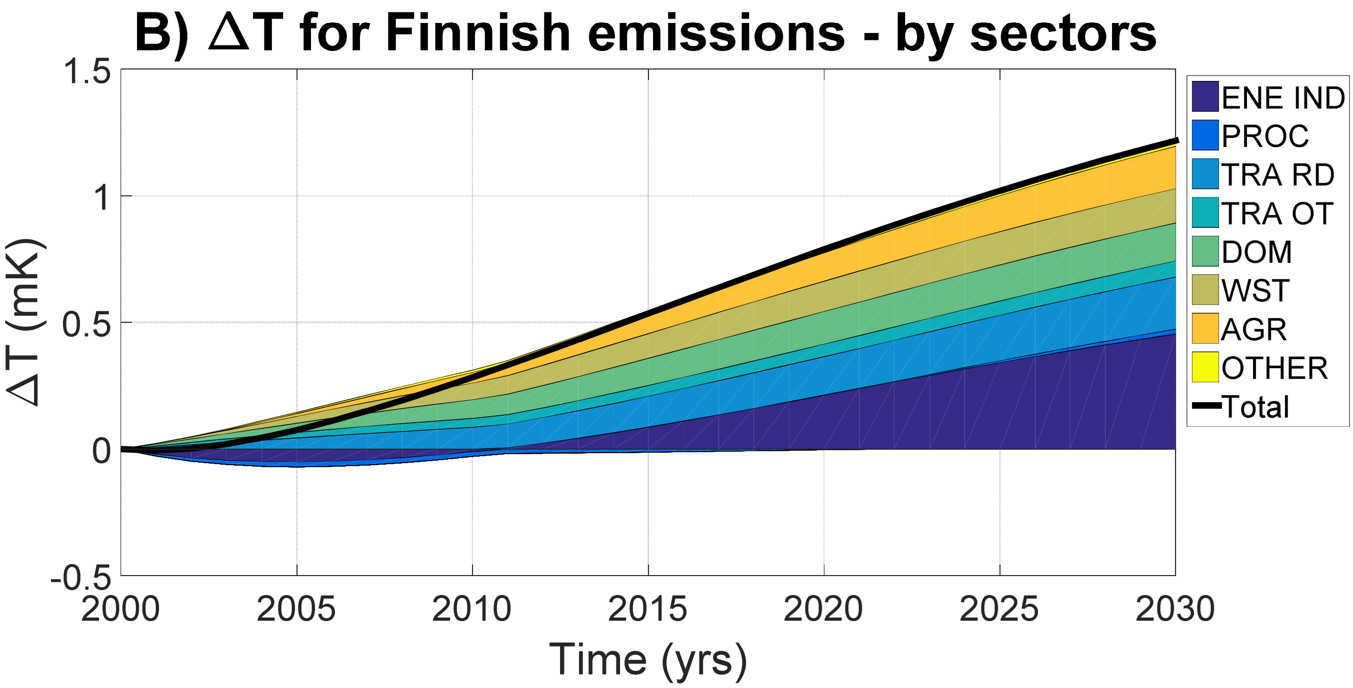


Figure A2: The same as Figure 4, but based on AGTPs in Aamaas et al. (2016), and not ARTPs. The global temperature development (mK) of Finnish emissions for the period 2000-2030. Temperature is given by pollutants in (A) and by sectors in (B).

35