Estimating Arctic Temperature Impacts From Select European Residential Heating Appliances and Mitigation Strategies

Brannon Seay1, Anna Adetona1, Marcus Sarofim2, and Michael Kolian2

1Battelle Memorial Institute, Columbus, OH, USA, 2Office of Air and Radiation, United States Environmental Protection Agency, NW, Washington DC, USA

**Abstract** The use of residential heating devices is a key source of black carbon and other short-lived climate forcer emissions in Arctic and other high-latitude regions, with important impacts to the Arctic climate and human health. The types of combustion technologies and fuels used vary by region, which impacts the emission profiles of these pollutants and thus the magnitude of Arctic climate responses. Using emission inventory data from 14 European countries, we derive wood-fueled residential heating emissions of black carbon, organic carbon, and sulfate from six appliance types in 2016. Using previously derived equilibrium Arctic temperature responses, we estimate Arctic temperature influences from each appliance type. Using the 2016 appliance emission data as a baseline, we compute the emission mass and Arctic temperature mitigation potential from hypothetical stove conversion scenarios. A total of 43.2 gigagrams (Gg) of black carbon, 175.7 Gg of organic carbon, and 10.3 Gg of sulfate were emitted in 2016 from the six appliance types in the 14 countries. The combined emissions increased Arctic surface temperatures by +2.8 millikelvin. If each country converted its appliance fleet to the technologically advanced pellet stoves and boilers, the combined black carbon, organic carbon, and sulfate emissions from heating appliances could be reduced by 94% and the Arctic temperature response reduced by 85%. The specific source and originating region of emissions are important factors in resolving the magnitude of their impacts. Improved country-level accounting of specific appliances and their emission characteristics can lead to a better understanding of potential mitigation options.

**Plain Language Summary** Wood-burning household heating appliances can emit large amounts of pollutants into the atmosphere. Black carbon, a sooty and dark pollutant, is a major component of these emissions. Black carbon is known to contribute to the warming of the Earth and, when inhaled, lead to negative human health effects. Reducing heating appliance emissions of black carbon and other pollutants can yield positive impacts on human health and climate. Using data from 14 European countries, we estimated air quality and Arctic climate impacts based on black carbon, organic carbon, and sulfate emissions from six different wood-fueled home heating appliances. Results indicate that while newer, more advanced stoves help improve air quality through reduced emissions, the stove type effect on climate change impacts are variable. In investigating stove replacement programs, in which older and lower quality stoves are swapped out for newer and higher quality ones, we found that stove emissions of black carbon, organic carbon, and sulfate can be reduced by up to 94% and Arctic warming effects by 85%. Given the short amount of time that these pollutants remain aloft in the atmosphere, the positive human health and Arctic temperature impacts of implementing this strategy would be felt almost immediately.

1. Introduction

Arctic temperatures are increasing at a rate approximately double that of the global average largely due to anthropogenic emissions of greenhouse gases (GHGs) and radiation absorbing aerosols (AMAP, 2015b; Bekryaev et al., 2010; Christensen et al., 2013; Jeffries et al., 2013; Overland et al., 2011; Trenberth et al., 2007). Since 1950 Arctic temperatures have increased by approximately 1.6°C (AMAP, 2015b) and is expected to increase an additional 2°C by 2050 (AMAP, 2015c), which has both regional and global implications. Regional impacts include sea ice loss, glacial retreat, increased wildfire, northwardly moving tree line, animal migration changes, altered terrestrial and marine ecosystems, and changes to socioeconomic systems (AMAP, 2019; IPCC, 2014; Myhre et al., 2013). Global impacts include a feedback loop of further...
increases in warming due to lowered surface albedo from retreating ice and snow exposing darker surfaces as well as production of carbon dioxide (CO₂) and methane (CH₄) emissions from thawing permafrost, rising sea levels from ice melt, and possible changes in large-scale weather patterns and ocean currents (IPCC, 2014; Myhre et al., 2013).

Black carbon (BC) is a light-absorbing carbonaceous aerosol primarily formed from the combustion of carbon-based fuels (Bond et al., 2013). Main sources of BC emissions include open burning (forest and savanna fires), residential heating and cooking, industrial processes, and diesel engines (Bond et al., 2013). BC is the third largest contributor to anthropogenic radiative positive forcing (0.64 W/m² in 2011) behind only CO₂ and CH₄ (Myhre et al., 2013). However, when measuring the pollutant’s radiative efficiency, BC ranks ahead of both in terms of its net radiative forcing impact per amount emitted (Myhre et al., 2013). Multiple processes impact BC’s influence on the climate, including direct absorption of solar radiation, deposition on snow and ice, and interactions with clouds that alters their stability, reflectivity, and lifetime (Bond et al., 2013). BC is considered a short-lived climate forcer (SLCF) given its relatively short atmospheric lifetime (3–8 days; Wobus et al., 2016) compared to other GHGs. Given BC’s radiative efficiency and short lifetime, its near-term Arctic climate mitigation potential is large; therefore, it is a key area of interest for policy actions.

When assessing BC’s near-term climate impacts, other co-emitted SLCFs must also be considered. Organic carbon (OC) and sulfur compounds (SOₓ = sulfur dioxide [SO₂] + sulfate [SO₄]) are two commonly co-emitted SLCFs that are both cooling radiative forcers (Sand et al., 2015; Wobus et al., 2016). Emissions of BC, OC, and SOₓ all contribute to the climate impact from a given emission source. The ratio of warming to cooling aerosol agents, that is, BC:(OC + SOₓ), emitted from the specific source can provide a rough estimate of whether the net climate impact of that source is warming or cooling. Since the term SLCF often implies the inclusion of CH₄, which is not analyzed in this study, herein we use the term climate-active aerosols (CAAs) to describe BC, OC, and SOₓ.

Previous studies have investigated Arctic temperature impacts from various emission sectors and regions through climate modeling of CAAs (AMAP, 2015a; Sand et al., 2015; Wobus et al., 2016). The Arctic Monitoring and Assessment Programme (AMAP) defined seven emission source sectors and seven global regions in which radiative forcings from BC, OC, and SOₓ were used to estimate the equilibrium Arctic temperature changes through several climate and transport models (AMAP, 2015a). In AMAP’s assessment, BC’s direct radiative effect, snow/ice effect, and cloud indirect effects were considered individually. Also, a technique was derived in which the vertical resolution of BC forcing in the Arctic could be assessed following simulations from Flanner (2013), given that the temperature impact of BC in the Arctic is a function of altitude. Higher altitude Arctic BC exerts a cooling effect on the surface, whereas lower altitude BC’s impact is net warming (Flanner, 2013). The AMAP assessment was expanded upon by Sand et al. (2015), in which more detailed calculations were used and Arctic temperature responses were quantified. However, the indirect cloud interaction radiative forcing of BC was not considered in this study. Sand et al.’s (2015) research concluded that near-Arctic regions can have a major impact on Arctic warming and a few specific emission sources provide the major mitigation potential in the region. Using the equilibrium Arctic temperature response per unit of emission results from Sand et al. (2015), Wobus et al. (2016) analyzed present and future Arctic temperature impacts from seven different emissions scenarios and found that current residential and transportation sector emissions produce most of the Arctic warming from BC. Including the negative radiative forcing from OC and SOₓ, they found that the net temperature increase from the three CAAs was larger from the residential sector, defined as the use of small combustion appliances to provide thermal energy for heating domestic buildings and cooking food (EMEP, 2016), than any other sector investigated (i.e., energy + industry + waste, transportation, agricultural burning, and flaring) (Wobus et al., 2016). They determined that targeting specific short-term (i.e., SLCF) and long-term (i.e., CO₂) sector/region mitigation goals together can be used to avoid further near-term Arctic warming while also enabling long-term Arctic temperature reductions (Wobus et al., 2016). Their results showed that short-term mitigation scenarios focused on the residential sector offer a promising approach for minimizing near-term Arctic climate increases (Wobus et al., 2016). A recent study found that SLCF emissions from residential wood combustion increased Finland’s GHG emissions impact on Arctic climate by 170% (Savolahti et al., 2019). Given the substantial impact these SLCFs have on Arctic climate and that BC emissions from the residential sector have
been estimated to account for approximately 25% of all global emissions (Bond et al., 2013), the potential of these mitigation efforts is significant.

Not only do the CAA emissions from the residential and other sectors influence climate, but studies also indicate associated adverse health effects from particulate matter (PM) exposure, of which BC and OC are primary components and to a lesser extent sulfate. It is well established that exposure to fine particulate matter (PM$_{2.5}$) is associated with various negative health effects such as cardiovascular and respiratory diseases (Brook et al., 2010; Burnett et al., 2014; Jansen et al., 2005; Pope & Dockery, 2006) and that ambient PM$_{2.5}$ is the most dangerous pollutant to human health worldwide (WHO, 2013). Approximately 3 billion people globally use wood and other solid fuels for residential cooking and heating (WHO, 2018). Cooking via these methods is most prominent in Africa and South-Southeast-East Asia (Bond et al., 2013). Indoor air pollution from inefficient cooking practices causes the premature death of nearly 4 million people annually (WHO, 2018). Residential heating using wood and other solid fuels is most prominent in Europe, Eastern Europe, the Caucasus, Central Asia, and North America (Bond et al., 2013). Globally, it is estimated that 110,000 deaths per year occur from ambient air pollution caused by residential heating, of which 61,000 (55% of total) occur in Europe (WHO, 2015). Lowering emissions from the residential sector and improving air quality will contribute to improved health outcomes.

Few studies inventory residential appliance emissions. There is also a relative lack of data on appliance usage and emissions in many regions of the world, making it difficult to estimate the impact of such appliances on climate and health. A wide variety of fuel types and appliance devices are used in this sector (Bond et al., 2013), and the use of residential appliances depends on local fuel supply, resources, and needs for renewable or sustainable energy sources. Given that emissions profiles can vary greatly by appliance type, wood fuel species, and combustion characteristics (Fachinger et al., 2017; Gonçalves et al., 2011), understanding the impact of these factors in a given region of interest is important to accurately estimate residential sector emissions. The majority of BC emissions from the residential sector come from the burning of wood, agricultural waste, dung, and coal (Bond et al., 2013). In Europe, the use of biomass/wood appliances for cooking can generally be considered negligible: the largest use is for residential heating. The Arctic Council Expert Group on Black Carbon and Methane has recommended the reduction of emissions from the residential heating sector by accelerating the replacement of legacy heating devices and the deployment of cleaner and more efficient ones, promoting user educational materials on appliance operations and fuel usage, and promoting advanced energy efficiency within households. Over the last few decades (1990–2010), Western Europe has already been updating to cleaner wood-fueled heating appliances as indicated by a roughly 40% and 20% reduction in emission factors (EFs), defined as average emission rate of a given pollutant from a specific source, for PM$_{2.5}$ and BC, respectively (Klimont et al., 2017). Given the recommendation of appliance replacement programs and the already noted progress in Western Europe, research is needed to better understand the emission characteristics of various wood-fueled heating appliances and how replacement programs will impact climate and health.

In this study we aim to estimate the wood-fueled residential heating emissions of BC, OC, and SO$_x$ from select Arctic and European countries using country level emission inventories from 2016. Each country’s emission estimate is disaggregated into six generalized appliance types of varying combustion capabilities. Given these emission estimates and utilizing the equilibrium temperature response results from Sand et al. (2015), the Arctic surface temperature impact for each country-appliance combination is derived. Lastly, emission mass and temperature response mitigation scenarios simulating appliance replacement programs are investigated for multiple heating appliance types.

2. Data and Methodology
2.1. Data Sources

Emission inventory data sets and information used in this study were extracted from the European Monitoring and Evaluation Programme (EMEP)/Centre on Emission Inventories and Projections (CEIP), which collects emissions and projections of various air pollutants from multiple sources for participating countries/parties. Specifically, information was extracted from the most current available data at the time of this analysis, 2016 EMEP/European Environment Agency (EEA) Air Pollutant Emissions Inventory Guidebook (EMEP, 2016) and country specific 2018 inventory submissions, which reported 2016 emission
inventory data (EMEP, 2018). In a few instances, selected countries referenced the 2013 EMEP/EEA Guidebook from which we extracted applicable information (EMEP, 2013). From these resources, calendar year 2016 emission inventory data were extracted for residential stationary combustion (Nomenclature For Reporting [NFR] code 1A4bi) from various selected European countries. Specifically, the emission data from various residential heating appliances using wood/biomass as fuel were investigated. Figure S1 of the supporting information displays a flow chart illustrating the data collection and analysis procedures conducted during this study. The “Data Collection” column highlights key pieces of data and information that were extracted from each country’s inventory.

Supplemental to country inventories, we also used the International Institute for Applied Systems Analysis (IIASA) Greenhouse gas-Air pollution Interactions and Synergies (GAINS) Integrated Assessment Model (Amann et al., 2011; GAINS, 2011). The GAINS model is currently used for negotiations under the Convention on Long-range Transboundary Air Pollution (CLRTAP), the organization that oversees EMEP. The model is used to analyze both air quality and temperature changes and can provide users the opportunity to run scenarios of air pollution reductions and assess impacts on human health and climate. Using the most recent baseline scenario, ECLIPSE V5a CLE base (Stohl et al., 2015), we used the GAINS model output of residential heating appliance fuel activity splits from selected European countries for the year 2015.

To derive the Arctic temperature impact from the residential heating appliances in each country, we utilized the equilibrium temperature responses based on emissions from the year 2010 and derived by Sand et al. (2015). These temperature responses were calculated based on six different forcing effects, including BC direct atmospheric radiative forcing, BC forcing from deposition on snow and ice, and both direct and indirect forcing from both OC and sulfate. The indirect forcing effect occurs from aerosols acting as cloud condensation nuclei, which influences cloud properties and lifetime (Peng-Ping & Zhi-Wei, 2011). The temperature responses were derived using radiative forcing as calculated by four different models, and regional climate sensitivities from four latitudinal bands (90°–28°S, 28°S–28°N, 28–60°N, 60–90°N), originally derived by Shindell and Faluvegi (2009) and extended further by Collins et al. (2013). The responses within each of the four latitudinal bands are a function of pollutant source region (United States, Canada, the Nordic countries, the rest of Europe, Russia, East and South Asia, and the rest of the world) and sector (domestic, energy/industry/waste, transport, agricultural fires, grass/forest fires, and gas flaring). The AMAP originally defined these seven regions and six sectors (AMAP, 2015a). We utilized the six model mean temperature responses for the latitudinal band between 60°N and 90°N (containing the Arctic region) from multiple source regions (varied based on country location) within the domestic sector (includes residential heating).

The regional temperature response approach developed by Sand et al. (2015) does have some limitations. In particular, the Arctic temperature responses were developed using very large emissions changes in order to create a signal, and recent research has suggested nonlinearities with the size of the emissions change (Sand et al., 2020; Yang et al., 2019), with Arctic temperature responses generally being larger per ton of emission change for smaller emission changes. However, it remains the best approach available for examining the Arctic temperature impacts of aerosol emissions perturbations, as direct modeling would be computationally prohibitive and not sufficiently sensitive for perturbations of the magnitude examined in this manuscript.

2.2. Methodology

The data analysis and methodological process conducted for every country assessed within this study followed four main steps: (1) querying and extracting data from inventories and supplemental data sets, (2) disaggregating national reported emissions and deriving per appliance type mass emissions, (3) translating emissions from each selected appliance type into Arctic temperature responses, and (4) estimating CAA emission and temperature response mitigation potentials provided hypothetical mitigation scenarios of 100% conversion to single stove types. Figure S1 of the supporting information illustrates a simplified flow chart of this process. The following subsections provide further detail on this methodological approach.

2.2.1. Mass Emission Assessment

Each selected country’s EMEP inventory included national mass emissions of approximately 25 pollutants, including BC and SO2, but excluding OC, for approximately 130 NFR source sectors. The sector of interest, residential heating (NFR code 1A4bi), is described as the use of small combustion appliances to provide thermal energy for heating. The fuel activity data for each sector were disaggregated by various fuel types,
including liquid, solid, gaseous, biomass, and other fuels (e.g., municipal, industrial, and oil wastes). This analysis focused only on emissions from the burning of biomass, which included wood, wood pellets, charcoal, and vegetable/agricultural waste, but consisted mostly of wood. For example, Latvia reported total biomass activity of 18,864 Terajoules Net Calorific Value (TJ NCV) for 2016, of which 18,799 TJ NCV (99.7%) were from wood, whereas the remaining 65 TJ NCV (0.3%) were from charcoal. While we aimed to focus solely on wood-fuel emissions, because not all selected countries provided wood specific activity data, we actually assess emissions based on the total biomass activity for all countries to remain consistent across each inventory.

The data analysis process per country was dependent on the tiered methodology each used to derive its residential heating BC mass. Countries assessed in this study used either a Tier 1 or Tier 2 approach. The Tier 1 approach has the lowest level of accuracy and highest level of uncertainty. A Tier 1 assessment applied default EFs from the 2016 EMEP/EEA Guidebook that were based on fuel type only and did not assess emissions by appliance type. The Tier 2 approach provided better pollution estimates by applying country specific EFs and further disaggregating fuel use and emissions by specific appliance types. EMEP provided EFs for six different wood burning appliance types for the Tier 2 methodology (Table S1).

For a Tier 2 assessment, countries used either their own country specific appliances or the six appliance types provided in the 2016 EMEP/EEA Guidebook. The EMEP appliance types are open fireplaces, conventional stoves, conventional boilers <50 kW, high-efficiency stoves, advanced/ecolabeled stoves and boilers, and pellet stoves and boilers. A brief description of each appliance type is provided in Table S1. For more detailed appliance information, see the 2016 EMEP/EEA Guidebook (EMEP, 2016). Here we aggregated country specific mass emissions and temperature responses based on the six EMEP appliance types. If a country's inventory defined its own appliance types, and these appliances were not defined extensively enough to decipher how best to appropriately aggregate them into the six EMEP appliance categories, the inventory was excluded from our analysis. Otherwise, country specific appliances were aggregated into one of the six EMEP appliances. As with the appliance types, countries implementing the Tier 2 methodology either used their own derived appliance EFs or used those provided in the 2016 EMEP/EEA Guidebook. In some cases, countries used the default EMEP appliance types but derived their own specific EFs based on internal research findings. For example, Italy used the six EMEP appliances but applied the minimum EF value of the range reported in the 2016 EMEP/EEA Guidebook for every appliance type excluding pellet stoves and boilers. Italy's IIR indicated that a study conducted by the research institute Stazione Sperimentale dei Combustibili determined that these lower-level EF values were more representative of the appliances and wood types typically used in the country. The EMEP default PM$_{2.5}$, BC, OC, and SO$_x$ EFs for each appliance type are listed in Table S1.

As previously stated, OC was not reported as one of the 25 pollutants listed in the national inventories. However, the 2016 EMEP/EEA Guidebook provided OC EFs for four of the six Tier 2 residential wood combustion appliances (this analysis estimated OC EFs as described below for the remaining two appliances), allowing for the calculation of OC mass for each type. Table S1 of the supporting information defines the six appliance types and lists the PM$_{2.5}$, BC, OC, and SO$_x$ EFs for each. The PM$_{2.5}$ EFs include both the solid/filterable particles and the gases that form particles upon cooling. For both BC and OC, the appliance specific EFs were provided as a percentage of PM$_{2.5}$. The remaining fraction of PM$_{2.5}$ from woodburning residential appliances is mostly comprised of ash compounds and the remaining components (excluding OC) of OM. The ash compounds provide a cooling impact to the climate, whereas the remaining non-OC components of OM can have both radiative warming and cooling impacts. In this study we assume this remaining fraction of PM$_{2.5}$ that is not BC or OC (i.e., ash and the remaining OM) has no net impact on climate and is not considered in this analysis.

Table S1 is listed in order of improved combustion technology; that is, the PM$_{2.5}$ EF decreases from the top to the bottom of the table. In general, as combustion technology improves, OC is reduced more than BC, and therefore the relative ratio of BC to OC increases. However, the BC percentage for pellet stoves and boilers is lower than that for advanced/ecolabeled stoves and boilers. The 2016 EMEP/EEA Guidebook did not provide OC EFs for conventional boilers <50 kW or high-efficiency stoves. Since the OC percentages decrease with improved technology, an average of the EFs of conventional stoves (less advanced) and...
advanced/ecolabeled stoves (more advanced) was used to derive conventional boiler and high-efficiency stove EFs.

For country inventories that implemented the Tier 1 methodology, the reported national residential heating biomass activity was divided among the six EMEP appliances (Table S1) based on 2015 GAINS fuel consumption splits. The GAINS model provided appliance splits for fireplaces, automatic feed single house boilers <50 kW, manual feed single house boilers <50 kW, and heating stoves in 5-year increments. The 2016 EMEP/EEA Guidebook associated manual feed boilers with conventional boilers and automatic feed boilers with pellet stoves and boilers. Heating stoves were associated with conventional stoves, high-efficiency stoves, and advanced/ecolabeled stoves. It was assumed that most European stoves are conventional due to their long lifetimes (EMEP, 2016); given that no country specific information was provided on splits between these three stove types from Tier 1 inventories, we applied all GAINS heating stove splits to conventional stoves (EMEP, 2016). Appliance splits were provided for most European countries in the GAINS model; however, it was not all inclusive. For countries in which no split information was provided, a reasonable approach (EMEP, 2016) is to select fuel split information from a country most resembling that country. Our analysis included only one country, Georgia, in which no GAINS splits were available. Therefore, appliance splits from the neighboring country, Turkey, were used to disaggregate Georgia’s biomass activity data.

For Tier 2 inventories, biomass activity data were split among the six EMEP appliances based on country specific split information. These data were generally provided in each country’s IIR but in many instances the split information was not included. For these cases the GAINS splits were applied as long as no conflicting information existed between the GAINS model and country IIR.

Given the appliance specific EFs and activity splits from either a Tier 1 or 2 inventory, the 2016 mass emission ($E_i$) for each appliance ($j$), pollutant ($i = BC, OC, or SO_x$), and country ($k$) was calculated by the following:

$$E_{j,i,k} = EF_{j,i,k} \times Act_k \times Split_{j,k}$$

(1)

Here $EF$ denotes the emission factor (country specific or EMEP default), $Act$ the country total activity data, and $Split$ the percentage of a country’s total fuel consumption (country’s IIR or GAINS derived) used by a given appliance type. EMEP default and country specific EFs are provided in Tables S1 and S2, respectively, whereas country specific biomass activity and appliance splits are provided in Table S3 of the supporting information.

As a quality control check, each country’s sum of BC mass across all six appliances was compared against the national reported BC mass from the residential heating sector (NFR code 1A4bi). Knowing that the national reported mass included emissions from all fuel types (liquid, solid, gaseous, biomass, and other) but that these emissions were dominated by biomass consumption, the ratio of the sum of the six biomass fueled appliances to national reported mass was expected to be close to but less than 1 and never greater than 1. Countries with ratios $\gg 1$ were excluded from this analysis.

### 2.2.2. Arctic Surface Temperature Response

After each country’s appliance specific mass emissions of BC, OC, and SO_x were derived, the Arctic temperature responses from each were calculated. We utilized model mean temperature responses based on emissions from the year 2010 (Sand et al., 2015) for the latitudinal band between 60°N and 90°N (containing the Arctic region) from multiple source regions (varied based on country location) within the domestic sector (includes residential heating). Assuming linearity between the climate response and emissions (Hodnebrog et al., 2014), we derived a model mean Arctic surface temperature forcer response ratio (Table S4 of the supporting information), calculated as the domestic sector’s Arctic equilibrium surface temperature responses divided by the 2010 emissions used by Sand et al. (2015) for each region and pollutant. Next, we calculated the six temperature responses, two each from BC, OC, and SO_x, caused by each country’s appliance by multiplying the country specific response ratio by the CAA mass emitted by each appliance type.

### 2.2.3. CAA Emissions and Arctic Temperature Mitigation Scenarios

We next assessed a mass emission and Arctic temperature mitigation scenario that included only the activity data and mass emissions from the four stove type appliances (conventional stoves, high-efficiency stoves, etc.).
advanced/ecolabeled stoves and boilers, and pellet stoves and boilers) and excluded open fireplaces and conventional boilers <50 kW from the analysis. We estimated mass emissions and Arctic temperature responses of BC, OC, and SOx in which we assumed 100% of the four stove’s usable heat energy output were from a single stove type appliance. These results illustrate the potential emissions and Arctic temperature responses given a hypothetical scenario of 100% conversion in a country to a single appliance type. While a 100% stove conversion in any country is not expected to ever occur, these results provide an upper bound on the mitigation potential provided a conversion to each selected appliance type.

Given the vast differences between appliance types, it is presumable that open fireplaces and conventional boilers are unlikely to be replaced by, or be replacements for, the four stove appliances within a given household. Open fireplaces are typically a part of the overall construction of a property, and while they could be retained as a supplemental heating source in residences where other heating appliances are used, they are unlikely to ever fully replace. The mechanics and functionality between boilers and stoves are dissimilar and therefore we assumed that conversion is limited to the four stove appliance types (conventional, high-efficiency, advanced/ecolabeled stoves and boilers, and pellet stoves and boilers). For the mitigation scenarios, we do not consider fuel switching among the appliances such as from wood products to natural gas. While the advanced/ecolabeled and pellet categories both include a subcategory of boilers based on similarities in emission profiles, we assume that the majority of these appliances are stoves and therefore group them as such.

In this assessment the mass emission and Arctic temperature response mitigation potentials are analyzed solely between and based on the activity data, EFs, and efficiencies of the four stove appliances. Here we define stove efficiency as the ratio of output heat energy produced by the stove to the total energy introduced to the stove from the fuel (EMEP, 2016). For more efficient stoves, a larger quantity of the fuel burned is converted into heat energy and a lower quantity of the produced heat energy is lost as compared to less efficient stoves. Therefore, a more efficient stove burns less wood to warm a home as compared to a less efficient stove and a given stove type’s efficiency must be considered when applying the activity data from one stove type to another. The following equation was used to estimate the hypothetical mass emission \((E)\) for a given stove \((A)\), pollutant \((i = \text{BC, OC, or SO}_{x})\), and country \((k)\) assuming 100% of the usable heat energy output from the 2016 stove mix were instead produced by a single stove \((A)\):

$$E_{A,i,k} = \sum_{j=1}^{4} \text{Eff}_{A} \times \text{Act}_{j,k} \times \text{EF}_{A,i,k}.$$  \hspace{1cm} (2)

Here the subscript \(j\) denotes the stove type, \(\text{Eff}\) the stove efficiency, \(\text{Act}\) the activity data, and \(\text{EF}\) the emission factor. The stove specific EFs and efficiencies used in this study are listed in Table S1. Given the results from Equation 2, updated temperature responses were derived as described in section 2.2.2 above. We then compared the emissions and temperature responses from the reported 2016 appliance mix (section 3.2 results) to the results assuming country-wide stove conversions (section 3.3 results) as described here. This difference (section 3.4 results) illustrates the emission and temperature mitigation potential of a full conversion to each of the four residential heating stove types.

### 3. Results

#### 3.1. Country Analysis and Selection

We assessed mass emission and Arctic temperature mitigation potentials for European countries with EMEP inventories; however, countries selected for inclusion in this assessment were based on those that demonstrated large emission mitigation potential, and quality and availability of emissions inventory data.

To illustrate mitigation potential, we provide a three-dimensional plot (Figure 1) of the wood-burning residential heating “average appliance dirtiness” (y axis), the “average usage rate” (x axis), and the total emissions (shape and color of markers) of BC for various countries based on their 2016 EMEP inventories. Specifically, the apparent average appliance dirtiness was estimated by dividing the nationally reported residential heating BC mass (NFR code 1A4bi) by its biomass fuel activity, whereas the average usage rate was calculated by dividing a country’s biomass fuel activity by its population. The highest residential heating BC mitigation potentials were from countries with larger circles in the upper-right region of the scatterplot,
whereas lower mitigation potential existed for smaller circles in the lower-left. Preference for data mining of country IIRs was given for larger circles in the upper-right region of Figure 1.

As illustrated in Figure 1, Ireland’s apparent average appliance dirtiness is approximately four times greater than the next closest country (Azerbaijan). However, the parameter plotted on the y axis considers all residential BC mass (biomass plus all other fuel types) in the numerator of the equation. For most countries, a majority of the total BC mass emissions were due to residential biomass combustion (e.g., 2.28 Gg of Bulgaria’s total 2.51 Gg), and therefore this parameter was a reasonable initial estimate (prior to deriving...
emissions from only biomass) of wood-burning appliance dirtiness. For Ireland, however, further analysis revealed that only 0.09 Gg of the country’s total 0.48 Gg of BC emissions were from biomass. Ireland’s emission inventory included various other fuel types (e.g., anthracite and ovoids, lignite, sod peat, and peat briquettes) that accounted for a larger ratio of the total BC mass. Accounting for only biomass emissions, Ireland’s average appliance dirtiness decreases from 357 to 69 g/GJ.

We investigated inventory submissions from 23 countries based primarily on those demonstrating large emission mitigation potentials including higher latitude countries important for Arctic climate as illustrated in Figure 1. Of these 23, four (Estonia, Finland, Sweden, and Norway) were excluded because the country-defined appliance types were not aggregable into the six EMEP appliance categories with the information provided. Another three countries (France, Ukraine, and Iceland) were excluded because not all necessary data to complete this analysis were reported or accessible in the countries’ IIR. Two other countries (United Kingdom [UK] and Poland) were excluded due to not meeting quality control checks. The UK’s inventory data sets included conflicting information between the GAINS output and IIR. The UK used their own country-derived splits but did not include the values in their IIR. The IIR did state that pellet stoves made up only a small portion of appliances used in the UK, as most residential combustion occurred in open fireplaces and closed stoves. This qualitative statement contradicts the quantitative data from GAINS, which had pellet stoves at approximately 50% of all wood activity in the UK, open fireplaces ~12%, and heating stoves ~22%. Given this discrepancy and no exact split values included in the IIR, the UK inventory was excluded from the analysis. For Poland, the ratio of the sum of the six biomass fueled appliances to national reported mass was >>1 and therefore excluded from further analysis. Poland’s IIR reported national BC mass emissions from residential heating to be 4.53 Gg, but when splitting their activity data based on the GAINS model and applying EMEP default EFs, the sum of the BC mass from the six appliances equaled 8.01 Gg. Given this high ratio (1.8), Poland’s inventory was excluded from this analysis. Poland used a Tier 1 approach but utilized its own country-derived EF value based on internal research rather than the EMEP default EF, which led to the noted discrepancy. Figure 2 provides a map of the 14 countries, meeting the above criteria, that are included in the following sections.

3.2. The 2016 Mass Emissions and Arctic Temperature Responses

Figure 3 illustrates the total 2016 mass emissions of BC, OC, and SOx for each of the six appliance types within each of the 14 European countries (Figure 3a), as well as the appliance total emissions across all selected countries for the year (Figure 3b). For the CAAs, 77% (175.7 Gg) of the total mass emissions were OC, 19% (43.2 Gg) BC, and 4% for SOx (10.3 Gg).

Conventional stoves were the most common and dirtiest emitting appliance type and were by far the highest emitting within most of the countries. We define an appliance’s “dirtiness ratio” as the ratio of total CAA (BC + OC + SOx) emitted to total biomass activity. The dirtiness ratio is normalized in Figure 3b (gray bars) to the pellet stove value (the cleanest burning appliance) to better illustrate the comparisons among the appliance types. This shows that conventional stoves emit approximately 15 times more CAA mass per unit of wood fuel burned as compared to pellet stoves. Given the higher usage rate and dirtiness ratio, conventional stoves accounted for the majority of the CAA mass emissions (154.6 Gg, or 67% of the total), in which 122.2 Gg of OC (70% of the total), 27.2 Gg of BC (63% of the total), and 5.2 Gg of SOx (50% of the total) were emitted. Note that if no information was provided on the activity splits between conventional, high-efficiency, and advanced/ecolabeled stoves, we applied all heating stave activity data from the GAINS model to conventional stoves following EMEP recommendations (EMEP, 2016). Considering that half of the countries selected in this assessment did not provide information for these splits, the results presented here likely represent an upper bound on conventional stoves emissions and, conversely, a lower bound on emissions from high-efficiency stoves and advanced/ecolabeled stoves and boilers. After conventional stoves, the highest CAA emissions were from open fireplaces (34.9 Gg), followed by conventional boilers (28.2 Gg), high-efficiency stoves (7.2 Gg), advanced/ecolabeled stoves (2.9 Gg), and pellet stoves and boilers (1.4 Gg).

Because we utilized the GAINS model data to supplement some country inventories, we chose to compare the BC mass, OC mass, and biomass activity results using the EMEP data against those from the GAINS Europe model (GAINS, 2011) (Figure S2 of the supporting information). It is important to note, however, that SOx emissions are not provided for the residential sector in GAINS and therefore are not included in this comparison. Georgia results are also excluded for this comparison, as the GAINS Europe model does not
provide these data. Also, GAINS results are for the year 2015 (as opposed to 2016), GAINS activity data consider fuelwood only (as opposed to total biomass), and GAINS outputs a single heating stove emission mass (as opposed to separate emissions from conventional, high-efficiency, and advanced/ecolabeled stoves). For comparison, conventional, high-efficiency, and advanced/ecolabeled stove results from this study are summed in the heating stove comparison in Figure S2. These results illustrate variability at the individual country level but good overall agreement in activity data and BC mass emissions. Total activity data from the current study are 10.1 petajoule (PJ)/year (16.8%) greater than GAINS. Some of this difference may be due to the fact that our study included all biomass activity data as compared to only fuelwood by GAINS. The current study measured 3.9 Gg (9.3%) less BC mass as compared to that from GAINS. Larger differences exist for OC mass emissions, however, with the current study measuring 79.0 Gg (46.2%) more OC mass as compared to GAINS. This difference can be attributed to differences in OC EFs, in which GAINS considers various levels of emission control for each appliance type. The GAINS OC EFs decrease drastically with increased emission controls, whereas the BC EFs remain relatively the same. Where large OC mass differences are seen, the GAINS model assumes a larger ratio for the given appliance type contains some emission controls, whereas the EFs used in this study more closely align with the appliance EFs assuming no emission controls. Advantages of using this study’s methodological approach involving utilization of the EMEP database include (1) the ability to estimate SOx emission from the residential heating sector and (2) EMEP data provide annually updated country-specific data allowing for timely and accurate emission and temperature estimates.

Figure 4 plots the model mean Arctic surface temperature responses of the six model forcers based on the 2016 CAA mass emissions for each appliance type within each country (Figure 4a), as well as the per-appliance temperature responses summed across all selected countries (Figure 4b). The 43.2 Gg of BC emissions were responsible for 5.8 millikelvin (mK) of Arctic warming (13.4 mK of warming per 100 Gg)}
Figure 3. Mass emissions by CAA and wood-burning appliance types for 14 European countries. (a) Total mass emissions of BC (blue), OC (green), and SO$_x$ (red) from each appliance type (stacked bars) for each country during 2016. The appliance type for each country are (in order from left to right) open fireplace, conventional stove, high-efficiency stove, advanced/ecolabeled stove and boiler, pellet stove and boiler, and conventional boilers <50 kW. Country total emissions per pollutant are illustrated by horizontal dashes. (b) Total mass emissions and dirtiness ratio relative to pellet stoves (gray) per appliance type across all 14 countries.
Figure 4. Arctic surface temperature response of CAA emissions from wood-burning appliance types for 14 European countries. Model mean Arctic surface temperature response of BC direct (dark blue), BC snow/ice (light blue), OC direct (dark green), OC indirect (light green), SOx direct (dark red), and SOx indirect (pink) for each country (a) and appliance type (b). The appliance type for each country are (in order from left to right) open fireplace, conventional stove, high-efficiency stove, advanced/ecolabeled stove and boiler, pellet stove and boiler, and conventional boilers <50 kW. The black crosses represent the total temperature response for a given appliance type (i.e., the sum of the six model forcers), whereas the black horizontal dashes (panel (a) only) are the total temperature responses for a country (i.e., the sum of the country’s six crosses).
emitted). This result is comparable to that from Sand et al. (2020), in which 10 mK of warming per 100 Gg emitted was modeled in a scenario where baseline European BC emissions were perturbed by a factor of 10. Snow and ice deposition were responsible for 64% of warming influence from BC. The 175.7 Gg of OC (1.6 mK of cooling per 100 Gg emitted) and 10.3 Gg of SOx emissions (0.9 mK of cooling per 100 Gg emitted) were responsible for 2.9 and 0.088 mK of Arctic cooling, respectively. Indirect forcing from OC accounts for the majority (96%) of the total negative Arctic temperature response. Combining the three CAAs, the total net Arctic temperature response resulted in surface warming of 2.8 mK in 2016.

The net Arctic temperature impact of every combination of country and appliance type was positive, indicating a warming effect (black crosses; Figure 4a). Romania’s conventional stoves produced the largest single temperature impact from a given country/appliance combination, in which 0.47 mK of warming occurred. Of the six appliance types, conventional stoves had the largest temperature impact, in which 1.5 mK of warming occurred, which accounted for 55% of the total temperature increase. Conventional stoves also had the largest pollution impact, as shown above, emitting 67% of the total CAA mass emissions. The large impacts noted from conventional stoves are due to both the high usage rate and dirtiness ratio attributed to the appliance type. Pellet stoves and boilers, on the other hand, were the least impactful in terms of both climate and air quality based on its low usage rate and dirtiness ratio, accounting for only 2% of the Arctic temperature increase and 1% of CAA emissions. It should be noted, however, that an appliance’s effect on total CAA emissions is not a direct correlation to its effect on climate. For example, while open fireplaces were the second largest CAA emitting appliance, its net Arctic temperature warming impact was the second smallest, due primarily to a high ratio of negative forcing to positive forcing aerosol emissions, that is, (OC + SOx):BC.

The larger the mass of OC and SOx emissions as compared to BC, the greater the warming forcers are canceled out by the cooling forcers, minimizing the climate impact.

### 3.3. Estimated Results Assuming 100% Usage From a Single Stove Type Appliance

Figure 5 illustrates the estimated mass emissions of BC, OC, and SOx in which 100% of the usable heat energy output from each country’s 2016 stove mix were instead produced by a single stove type as calculated by Equation 2. It also illustrates the relative ranking of selected appliances in terms of dirtiest to cleanest per country and overall for each CAA.

Figure 5a illustrates the total estimated CAA mass emission from each stove type and by pollutant (stacked bars). It shows that for each country, conventional stoves (represented by the first bar for each country) were responsible for the largest mass emissions, followed by high-efficiency stoves. Pellet stoves and boilers were responsible for the least emissions in every country excluding Italy. Italy’s results differed from those of the other countries because their EMEP inventory applied the minimum EF value of the range reported in the 2016 EMEP Guidebook, as previously discussed. In applying these lower EFs, Italy reported lower total emissions in 2016 than Romania, even though their residential heating activity was more than double that of Romania. See Table S2 of the supporting information for appliance specific EFs applied for each country.

Figure 5b shows the estimated total mass emissions from each stove type assuming each of the 14 countries converted to full usage of a given stove. For each of the three CAAs, the dirtiest emitting stove was conventional, followed by high-efficiency, advanced/ecolabeled, and pellet. Combining the emissions from each of the three CAAs, total emissions would be 237.0 Gg from conventional, 89.5 Gg from high-efficiency, 23.4 Gg from advanced/ecolabeled, and 9.5 Gg from pellet stoves.

Conventional stoves emit more than three times as much OC (187.2 Gg) as that from high-efficiency stoves (59.0 Gg) in these hypothetical scenarios. For BC, however, the emissions are more comparable (approximately 1.5 to 1 ratio), with conventional stoves emitting 41.6 Gg compared to 24.8 Gg from high-efficiency stoves. In the reviewed EMEP inventories, the cleaner burning and more advanced stove types have smaller OC:BC ratios (conventional: 4.5 to 1, high efficiency: 2.4 to 1, advanced/ecolabeled: 1.1 to 1, and pellet stoves: 0.9 to 1). This phenomenon is pertinent for net Arctic temperature impacts, which are discussed in the following section.

Figure 6 illustrates the estimated model mean Arctic surface temperature responses of the six model forcers based on the hypothetical CAA emissions from the four stove appliances as presented in Figure 5. This analysis provides an estimate of what a selected country’s Arctic temperature impact would be if switching to
Figure 5. CAA mass emissions assuming 100% of the four stove’s usable heat energy output were produced by each individual stove type. (a) Estimated emissions of BC (blue), OC (green), and SO\(_x\) (red) for each of the four stove types (stacked bars) when applying the sum of the four stove’s residential heating activity to each individual stove type. The stove types for each country are (in order from left to right) conventional, high-efficiency, advanced/ecolabeled, and pellet. (b) Per stove type estimated mass emission totals summed across all 14 countries assuming all residential heating usage is applied to a single stove type.
Figure 6. Arctic temperature responses assuming 100% of the four stove's usable heat energy output were produced by each individual stove. Estimated model mean Arctic equilibrium surface temperature response assuming all residential heating usage from the four stove types is applied to each individual stove for BC direct (dark blue), BC snow/ice (light blue), OC direct (dark green), OC indirect (light green), SOx direct (dark red), and SOx indirect (pink) for each country (a) and stove type (b). The stove types for each country are (in order from left to right) conventional, high-efficiency, advanced/ecolabeled, and pellet. The black crosses represent the estimated total temperature response for a given stove type (i.e., the sum of the six model forcers) assuming all activity is from that appliance, whereas the black horizontal dashes (panel (a) only) illustrate each country's total temperature response from the four stove types based on the actual 2016 stove mix.
100% usage of a single stove type instead of the original 2016 mix between the four types. It also illustrates the selected appliances with the largest potential Arctic climate influence per each country and model forcer. The net positive forcing from BC is greater than the combined net negative forcing from OC and SO\textsubscript{x} for every stove type from each selected country, indicating a warming influence in the Arctic from each. This is illustrated by the black crosses in Figure 6a, which represent the net sum of the six model forcers for each stove type in each country. For each country excluding Italy, the hypothetical temperature response is largest for conventional stoves, followed by high-efficiency, advanced/ecolabeled, and pellet stoves. For Italy, high-efficiency stoves produced the largest and advanced/ecolabeled stoves the smallest temperature response.

While conventional stoves generate 2.6 times the PM emissions as high-efficiency stoves, the two stove types lead to approximately the same net increase in Arctic temperature (black crosses in Figure 6b), as the ratio of negative to positive temperature forcing is greater for conventional stoves. Advanced/ecolabeled and pellet stoves, however, have a warming impact about 2.5 and 8.5 times less than conventional stoves, respectively. Pellet stoves were found to be both the cleanest option and have the least climate impact of the categories analyzed.

### 3.4. Mitigation Potential From Wood-Burning Stove Conversions

In section 3.3, the absolute emission and temperature response impact of conversions to each stove type was presented. Here we apply a similar analysis, but using the current mix of appliance usage (section 3.2) as a baseline in order to assess the impact of conversion from the current mix to a new mix. Figure 7 illustrates the CAA emission mass mitigation potential based on this analysis for each selected country (Figure 7a) and summed across all 14 countries (Figure 7b). Individual countries that show a large mass increase (Croatia, Denmark, Italy, and Spain), based on conversion to the dirtier burning conventional stoves, indicate that its 2016 stove mix included a greater percentage of the cleaner burning stove types. Conversely, countries showing little to no mass change for a specific stove indicate that they were already heavily reliant on that specific stove for its 2016 residential heating. For example, 98% of the biomass burned by the four stove-type appliances in Romania came from conventional stoves. Therefore, conversion to 100% conventional stove usage only minimally impacts CAA emissions. However, this allows for a much larger emission reduction if the country converted to one of the cleaner stove types, as indicated by the 7.8, 37.3, and 0.6 Gg decrease of BC, OC, and SO\textsubscript{x}, respectively, if Romania switched to pellet stoves.

At the country level, high-efficiency stove emissions from Italy and Slovenia were the only two cases where the mitigation scenario saw an increase in some pollutants (BC) and a decrease in others (OC and SO\textsubscript{x}). In all other country stove type mitigation scenarios, either all three CAAs increased or decreased. Applied across all 14 countries (Figure 7b), a 100% conversion to conventional stoves would increase emissions for all three CAAs, whereas a decrease in emissions would occur for each CAA given a conversion to each of the other three stove types. The absolute mass mitigation among the technologically advanced stoves is much greater for OC as compared to BC. This result is expected given the total OC mass (128.5 Gg) emitted in 2016 was much higher than BC (30.6 Gg) and therefore a greater absolute mitigation potential existed for OC. However, there was also a greater percent decrease of OC compared to BC. For example, a 100% conversion to advanced/ecolabeled stoves reduced OC by 119.0 Gg, which is a 92.6% mass decrease, whereas BC is reduced by 22.0 Gg, only a 71.9% decrease. This occurs because, in general, the BC fraction of PM\textsubscript{2.5} increases with improved combustion technology, whereas the OC fraction decreases (EMEP, 2016). In other words, as combustion technology improves and the total PM\textsubscript{2.5} emissions decrease, the percentage of the PM\textsubscript{2.5} comprised of BC increases, whereas it decreases for OC.

Figure 8 illustrates the temperature response mitigation potential for each of the 14 countries (Figure 8a) and summed across all countries (Figure 8b) for each stove type. This analysis shows that even though the net Arctic climate impact of every stove type is warming (black crosses in Figure 6b), conversion from the 2016 mix of stoves to advanced/ecolabeled stoves and boilers or pellet stoves and boilers could contribute to slowing the rate of Arctic warming by 0.89 or 1.6 mK for the year, respectively. While this reduction would only reverse a fraction of the percent of the approximately 1 K total human-induced global temperature increase since preindustrial levels (Allen et al., 2018), the magnitude of this reduction is meaningful given these emissions are from a single sector in only 14 countries. Conversely, Arctic warming would be
Figure 7. Per stove CAA mass emission mitigation potential. Estimated BC (blue), OC (green), and SO$_x$ (red) emission mitigation potential per country (a) and stove type (b) calculated as the emission mass considering each individual stove conversion scenario minus the actual country total emissions given the 2016 stove mix. The stove types for each country are (in order from left to right) conventional stove, high-efficiency stove, advanced/ecolabeled stove and boiler, and pellet stove and boiler. Negative values indicate the country's emission would decrease if switching to 100% usage of the given stove, whereas positive values indicate increasing emissions.
Figure 8. Per stove Arctic temperature mitigation potential. Estimated Arctic equilibrium temperature response mitigation potential for each country (a) and appliance type (b) calculated as the temperature response considering each individual stove conversion scenario minus the actual country temperature response given the 2016 stove mix. The stove types for each country are (in order from left to right) conventional stove, high-efficiency stove, advanced/ecolabeled stove and boiler, and pellet stove and boiler. Negative values (blue bars) indicate that the Arctic temperature increase would be reduced if switching to 100% usage of the given stove, whereas positive values (red bars) indicate an increase in the warming.
increased relative to the 2016 mix given a full conversion to either conventional stoves or high-efficiency stoves.

At the individual country level, because Denmark already relies heavily on pellet stoves, conversion to advanced/ecolabeled stoves would actually lead to an increase in Arctic temperature. A temperature reduction would occur if only conventional stoves and high-efficiency stoves were converted to advanced/ecolabeled, and pellet stoves were not converted. For each of the other 13 countries, a conversion to advanced/ecolabeled stoves leads to a reduction in warming impact due to total stove emissions.

Table 1 summarizes the total mitigation potentials of each stove type, and includes both the BC, OC, and SO$_x$ mass as well as temperature response changes. Pellet stoves provide the best mitigation potential for each of the four parameters, that is, BC mass, OC mass, SO$_x$ mass, and temperature response mitigation potentials are larger given a pellet stove conversion as compared to the other stove types. A pellet stove conversion would reduce 2016 BC emissions from 30.6 to 2.8 Gg, a 91% reduction. Similarly, OC emissions would drop from 128.5 to 2.4 Gg, a reduction of 98%, and SO$_x$ emissions would reduce from 7.0 to 4.3 Gg, a 38% reduction. This CAA mass mitigation would result in an Arctic temperature increase of only 0.29 mK, an 85% reduction in warming from the current 1.9 mK increase given the 2016 stove mix.

4. Conclusions

In 14 select European countries, we estimated total BC (43.2 Gg), OC (175.7 Gg), and SO$_x$ (10.3 Gg) emissions in 2016 from six wood-fueled residential heating appliance types. Romania and Italy were the highest emitting of the selected countries, accounting for approximately 43% of all residential heating appliance CAA emissions. Of the six appliance categories studied, emissions were dominated by conventional stoves given this appliance type’s higher relative usage and emission rates. Much lower activity data and emissions were recorded for the more technologically advanced appliance types. The total CAA emissions from all six appliances combined to increase the Arctic surface temperature by 2.8 mK in 2016. Romania, Italy, and Spain were the largest contributing of the selected countries to the temperature increase, accounting for approximately 48% of the total warming.

To reduce emissions from the residential wood heating sector, it has been recommended that countries implement policies that accelerate the replacement of legacy heating devices with the deployment of cleaner and more efficient ones as well as promote the proper operation and maintenance of these devices (EGBCM, 2019). From our results we estimate that a wood-fueled residential heating mitigation strategy, in which all conventional, high-efficiency, and advanced/ecolabeled stoves are replaced with pellet stoves, can reduce CAA emissions from stoves by up to 94% and reduce the Arctic temperature response by 85% within all 14 European countries. At the country level, emissions can be reduced between 88% (Italy) and 96% (Hungary) and temperature responses by 74% (Italy) and 97% (Latvia). Given the short atmospheric lifetimes of these pollutants, results would be realized as quickly as phase-out mitigation programs of this strategy are implemented.

Given the differences in emission profiles for each selected appliance type, the impacts on climate and air quality varied for each. Both pellet and advanced/ecolabeled stoves provide a “win/win” scenario in terms of both improving air quality and reducing Arctic warming. Pellet stoves provide the best mitigation potential for each of the four parameters, that is, the decrease in BC mass, OC mass, SO$_x$ mass, and Arctic temperature response is greater for pellet stoves than any other stove type. An advanced/ecolabeled stove conversion scenario would realize approximately 91% of the air quality benefit and 56% of the temperature benefit compared with that from pellet stoves. While high-efficiency stoves produce less total CAA emissions than conventional stoves, the ratio of cooling to warming aerosol, that is, (OC + SO$_x$):BC, is such that the net effect of a full conversion from the current stove mix would lead to a net increase in Arctic warming. This occurs because a high-efficiency stove conversion more greatly reduces emissions from the cooling CAAs (OC and SO$_x$ reduced by 54.1% and 19.2%, respectively) as compared to the warming CAA (BC reduced by 18.9%). Therefore, high-efficiency stoves provide a “win/lose” mitigation scenario in that air quality is improved but Arctic temperature is increased. Note, however, that this result includes conversion from advanced/ecolabeled and pellet stoves to high-efficiency stoves as well. If only considering converting the less technologically advanced conventional stoves to high-efficiency stoves, the warming impact would be...
slightly reduced. The biomass burned by conventional stoves in 2016 resulted in 1.5 mK of warming, whereas, if applying that biomass activity to high-efficiency stoves, the warming would be reduced to 1.4 mK. Lastly, conversion to conventional stoves provide a “lose/lose” scenario, both reducing air quality and increasing Arctic temperature.

Potential economic pressures, financial and natural resources, local infrastructure, government incentive programs, and other societal factors influence the efficacy and feasibility of a given mitigation policy as well as an individual's willingness or ability to participate in the program. To implement an effective mitigation program particularly in remote areas of developing countries may require additional infrastructure for implementation on a large scale (Bond et al., 2013). For these reasons, a mitigation policy scenario that works effectively for a given region or country may not be feasible for another. For example, pellets are the most expensive wood fuel available to Serbian consumers and recent surveys have shown that cost is the most prominent reason Serbians have not replaced old and outdated residential appliances (E4tech et al., 2017). Many users in Serbia and other countries use a specific heating appliance because of the access to free fuelwood. Therefore, it is unlikely that a mitigation scenario in which conversions to pellet stoves would be successful in Serbia without the implementation of a strong government incentive and subsidy program.

This present study showcases the usefulness of the EMEP database, where timely, country specific, nationally validated data can be used to explore sector specific emissions, in this case climate impacts of emissions from the residential sector that utilizes wood-fueled heating appliances. Results from this study can be used to inform policymakers and researchers as to how EMEP data can be utilized to answer important questions surrounding climate, air pollution, and environmental/public health challenges that our society faces in the Anthropocene. Historically, there has been a general lack of information regarding speciation of residential stove emissions. Incorporating more country specific data would improve the evaluation of air quality impacts from different sectors and elucidate the best mitigation policy options for various countries.

### 4.1. Future Research Opportunities

A major source of emission uncertainty when inventorying residential heating combustion comes from uncertainty and variability in EFs. For both BC and OC, EFs are strongly dependent on the combustion process, which includes fuel composition, fire temperature, exhaust treatment (e.g., use of catalytic converters and/or scrubbers), and mix of fuel and air (Bond et al., 2013). These combustion processes are influenced by the appliance type, wood species and state (i.e., moisture content), and user operating practices. For SOx, while the combustion technology can influence its EF based on the retention of sulfur in ash (EMEP, 2016), the EF is mainly a function of the fuel’s sulfur content. We assumed good burning practices in this analysis; however, we are aware that best burning practices are not always used nor adopted by everyone. Inefficient burning practices may be due in part to the use of nonwood materials for fuel, wet fuel, improper fuel loading, insufficient stove appliance maintenance, and other factors (USEPA, 2019). As with the use of any heating appliance type, proper installation and operation, regular maintenance, and best

---

**Table 1**

| Parameter (2016 stove mix results) | Conventional stoves | High-efficiency stoves | Advanced/ecolabeled stoves and boilers | Pellet stoves and boilers |
|------------------------------------|---------------------|------------------------|----------------------------------------|--------------------------|
|                                    | Mit. | Diff. | PD (%) | Mit. | Diff. | PD (%) | Mit. | Diff. | PD (%) |
| BC (30.6 Gg)                       | 41.6 | 11    | 35.8   | 24.8 | -5.8  | -18.9  | 8.6  | -22   | -71.9   | 2.8  | -27.9  | -91    |
| OC (128.5 Gg)                      | 187.2 | 58.7  | 45.7   | 59   | -69.5 | -54.1  | 9.5  | -119  | -92.6   | 2.4  | -126.1 | -98.1  |
| SOx (7.0 Gg)                       | 8.1  | 1.2   | 16.7   | 5.6  | -1.3  | -19.2  | 5.2  | -1.7  | -25     | 4.3  | -2.7   | -38.2  |
| BC + OC + SOx (166.1 Gg)           | 237  | 70.9  | 42.7   | 89.5 | -76.6 | -46.1  | 23.4 | -142.7| -85.9   | 9.5  | -156.6 | -94.3  |
| Temp. Resp. (1.9 mK)               | 2.5  | 0.61  | 31.9   | 2.4  | 0.51  | 26.7   | 1.0  | -0.89 | -46.6   | 0.29 | -1.6   | -84.7  |

*Note. Estimates are provided for each stove type aggregated across all 14 countries. Cells italicized indicate a mass or temperature increase provided a given stove conversion scenario, whereas bolded cells indicate a decrease. Values in parentheses provide the 2016 mass and temperature results given the 2016 stove mix. aMit. columns provide hypothetical mitigation scenario results assuming 100% usage from the given stove types. bDiff. columns provide the absolute difference (stove conversion – stove mix). cPD (%) columns provide the percent difference (absolute difference/stove mix * 100)."
burning practices are key in achieving optimal stove efficiency and reduced emissions (USEPA, 2019). The automated functionality of pellet stoves likely limits some of these human influenced impacts, meaning pellet stove mitigation potentials could be even greater than estimated in this study.

The combustion technologies within the residential heating sector are very diverse and strongly dependent on country and regional factors. This study utilized EFs for six generalized appliance types, which were derived as an aggregation of available referenced values and were assumed to represent an average of the wood species and conditions available. However, individual stove brands will have emission profiles that differ from the aggregate type, and therefore specific stove emission profiles could better inform specific replacement decisions. While a few of the selected countries analyzed here provided country specific EFs based on internal research, the majority utilized these default values. Therefore, within a given country these aggregated EFs may be biased high or low, and ideally each country’s inventory would utilize EFs based on appliances, wood species and conditions, and operating practices applicable to that country. It would be an improvement for appliance fuel consumption split information to be extracted from national statistics or national studies, reflecting the specific situation in the country. However, in the case of most countries investigated, this information was not available and default information, that is, GAINS model outputs, on how to split the activity data over the different appliance types were used. Similarly, the availability and use of different wood species will vary regionally, yet the default EFs assume an average over all wood types. A relatively small number of studies have been completed on emission measurements from the residential heating sector (Bond et al., 2013) and this is an area for the community to perform further research.

Other limitations to this research include the reliance on a single temperature-relationship (Sand et al., 2015), and the lack of data on other climate forcers such as CO₂ and CH₄ emissions from these selected residential heating appliances. Also, the Arctic surface temperature forcer response ratios derived here for SO₂ are based on climate model results (Sand et al., 2015) that considered emissions of SO₂ and the climate impacts from the atmospheric oxidation of these SO₂ emissions into SO₄. For wood-fueled residential heating appliance emissions, however, the majority of SO₂ are directly released as SO₄. It is unclear what impact direct SO₂ (as opposed to SO₄) emission inputs would have on the climate model results. However, given SO₂ accounted for only 4% of total CAA emissions and 1% of the total Arctic temperature impact measured here, this uncertainty likely minimally impacts these results. Other mitigation strategies not considered here include conversion from wood-fueled combustion to cleaner fuel alternatives. Natural gas and liquid fuels (e.g., kerosene, gas oil) could offer even greater air quality mitigation potentials. Because this study did not account for CH₄ or CO₂ contributions to warming, and these emissions are more significant for these alternative fuels as compared to wood, these pollutants’ impacts would need to be considered to capture the full climate effects. For future research, a more comprehensive country analysis within Europe as well as other global regions is warranted.

Acknowledgments
Support for this study was provided by the U.S. Environmental Protection Agency (EPA) grant 83617201. The authors would like to acknowledge Natasha Sadoff for her project management of the study, James Hicks (GIS Analyst) for developing the geospatial map presented in the manuscript, as well as Amara Holder and Larry Brockman for their insight as they helped us with the understanding of this topic. The data supporting the conclusions in this work are available in the supporting information package associated with this manuscript and at EPA’s data repository (https://doi.org/10.23719/1518754). Emission inventory data sets used in this study were extracted from EMEP's CEIP: 2016 EMEP/European Environment Agency (EEA) Air Pollutant Emissions Inventory Guidebook (EMEP, 2016), 2013 EMEP/EEA Guidebook (EMEP, 2013), and country specific 2018 inventory submissions (2016 emission inventory data) (EMEP, 2018).

The authors declare no conflict of interest. Disclaimer: The views expressed in this paper are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.

References
Allen, M. R., Dube, O. P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S., et al. (2018). Framing and context. In V. Masson-Delmotte et al. (Eds.), 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. Intergovernmental Panel on Climate Change (49–91). Geneva, Switzerland: World Meteorological Organization. Retrieved from https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter1_Low_Res.pdf

Aman, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., et al. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environmental Modelling & Software, 20(12), 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012

AMAP (2015a). AMAP assessment 2015: Black carbon and ozone as Arctic climate forcers. Oslo, Norway: Arctic Monitoring and Assessment Programme. Available at http://www.amap.no/documents/doc/amapassessment-2015-black-carbon-and-ozone-as-arcticclimate-forcers/1299

AMAP (2015b). AMAP assessment 2015: Methane as an Arctic climate forcer. Oslo, Norway: Arctic Monitoring and Assessment Programme. Available at http://www.amap.no/documents/doc/amapassessment-2015-methane-as-an-arcticclimateforcer/1285

AMAP (2015c). Summary for policy-makers: Arctic climate issues 2015: Short-lived climate pollutants. Oslo, Norway: Arctic Monitoring and Assessment Programme. Available at http://www.amap.no/documents/doc/summary-for-policy-makers-arctic-climateissues-2015/1196

AMAP (2019). Arctic climate change update 2019: An update to key findings of Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Tromsø, Norway: Arctic Monitoring and Assessment Programme. Available at https://www.amap.no/documents/download/3295/inline

Bekryaev, R. V., Polyakov, I. V., & Alexeev, V. A. (2010). Role of polar amplification in long-term surface air temperature variations and modern Arctic warming. Journal of Climate, 23(14), 3888–3906. https://doi.org/10.1175/2010jcli3297.1
Stohl, A., Aasmaas, B., Amann, M., Baker, L. H., Bellouin, N., Berntsen, T. K., et al. (2015). Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, 15(18), 10529–10566. https://doi.org/10.5194/acp-15-10529-2015

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., et al. (2007). Observations: Surface and atmospheric climate change. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (237–336). Cambridge, UK, and New York, NY: Cambridge University Press.

USEPA (2019). Energy efficiency and your wood-burning appliance. Research Triangle Park, NC: USEPA, Burn Wise. Available: https://www.epa.gov/burnwise/energy-efficiency-and-your-wood-burning-appliance

WHO (2013). *Health effects of particulate matter: Policy implications for countries in eastern Europe, Caucasus and central Asia* (1–15). Copenhagen, Denmark: World Health Organization. Available: http://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf

WHO (2015). *Residential heating with wood and coal: Health impacts and policy options in Europe and North America* (1–49). Copenhagen, Denmark: World Health Organization.

WHO (2018). *Household air pollution and health*. Copenhagen, Denmark: World Health Organization. Retrieved from https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

Wobus, C., Flanner, M., Sarofim, M. C., Moura, M. C. P., & Smith, S. J. (2016). Future Arctic temperature change resulting from a range of aerosol emissions scenarios. *Earth's Future*, 4(6), 270–281. https://doi.org/10.1002/2016ef000361

Yang, Y., Smith, S. J., Wang, H., Mills, C. M., & Rasch, P. J. (2019). Variability, timescales, and nonlinearity in climate responses to black carbon emissions. *Atmospheric Chemistry and Physics*, 19(4), 2405–2420. https://doi.org/10.5194/acp-19-2,405-2019