United States Environmental Protection Agency

Methane and Black Carbon Impacts on the Arctic:
Communicating the Science

2016

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Preface

This document describes the scientific understanding of the impacts of methane[1] and black carbon emissions on the Arctic[2] climate. This information is provided to help facilitate communication of the evolving science, evaluate mitigation strategies, and inform decision-making.

Why focus on methane and black carbon emissions and their impacts on the Arctic?

- **Surface air temperatures in the Arctic region are increasing faster than anywhere else across the globe.** This results in a wide range of impacts, including sea ice loss, glacial retreat, and increasing boreal wildfires. These regional changes directly impact parts of the United States and also have global implications. For example, warming at high latitudes causes permafrost thaw, which can lead to increased emissions of soil carbon dioxide[3] and methane, which contribute to further warming.

- **Reductions in methane and black carbon emissions can reduce near-term Arctic warming.** Because methane and black carbon are short-lived in the atmosphere, mitigating emissions can reduce near-term climate warming. Methane and black carbon emissions mitigation complements strategies aimed at reducing the longer-term climate impacts of carbon dioxide emissions. Recent studies suggest that targeted reductions in emissions of methane and black carbon can reduce projected Arctic warming by 25% by 2050 (AMAP, 2015a).

- **A number of factors complicate analyses of the impacts of black carbon on Arctic climate.** For example, the same quantity of black carbon emitted from sources near or within the Arctic exerts a stronger Arctic temperature response than black carbon emitted from lower latitudes. Additionally, black carbon is emitted with other pollutants that have cooling effects on climate; these co-emitted pollutants could offset some of black carbon's warming, particularly in the near-term. Continued research to improve scientific knowledge about black carbon's impacts will better inform decision-making about strategies to reduce near-term climate warming.

1. Methane is often abbreviated by its chemical formula, CH_4.
2. The Arctic is commonly defined as the region north of the Arctic Circle, where the sun does not set below the horizon at the summer solstice or rise above it at the winter solstice. Other definitions are sometimes used and are based on the location of tree line, certain temperature thresholds, and permafrost and ice extent (ACIA, 2004). In this document, we refer to the Arctic more broadly to include the area north of the Arctic Circle and also the subarctic region, which lies just to the south. This region influences patterns and changes in the Arctic system and encompasses the boreal forest region.
3. Carbon dioxide is often abbreviated by its chemical formula, CO_2.

1

Arctic Climate Change

Temperatures in the Arctic are increasing faster than anywhere else across the globe, resulting in a range of regional and global impacts. This warming is caused by several pollutants. Understanding the ways in which these pollutants interact and influence Arctic climate is important for evaluating strategies to mitigate their impacts.

Climate change has distinct and significant impacts on the Arctic

Over the past century, Arctic climate has warmed at a rate almost double that of the global average. From 1950 to 2012, the region's mean annual surface temperature increased by about 1.6°C (AMAP, 2015c). It is projected that by 2050, the mean annual surface temperature will increase by about 2°C relative to present-day temperatures (AMAP, 2015a). This warming is contributing to several key impacts in the region:

- **Sea ice loss**. Part of the Arctic Ocean is covered by ice year-round. The area covered by ice is typically smallest in September, after the summer melting season; ice cover then expands throughout the winter. Due to warming temperatures, the extent of Arctic sea ice has decreased: more melting occurs in the summer and ice cover growth in the winter has diminished (see Figure 1). Arctic ice has also become thinner, which makes it more vulnerable to additional melting (EPA, 2016a). Reductions in sea ice cover also increase exposure of darker, underlying water, causing more sunlight to be absorbed. This leads to more warming, further acceleration of snow and ice melt, and further exposure of darker water.
- **Glacial retreat**. Glaciers in the United States and worldwide have generally shrunk since the 1960s, and the rate at which glaciers are melting has accelerated over the last decade. The loss of ice from glaciers, including those in Alaska and the Arctic, has contributed to the observed rise in sea levels (EPA, 2016a).
- **Increase in wildfires**. Over the 15-year period from 1984 to 1998, wildfires burned approximately 315,000 acres per year in Alaska, most of this being in the subarctic portion of the state. This figure more than quadrupled during the 15-year period from 1999 to 2013; over this period, wildfires burned approximately 1.3 million acres per year across the state (EPA, 2016a).
- **Other impacts**. Land surface snow and ice cover have diminished in duration and extent (IPCC, 2014). In many areas of the Arctic, the tree line has moved further north and the prevalence of tall shrubs and grasses is increasing. Climate change is also affecting bird and animal migratory patterns in and across the Arctic (ACIA, 2004; IPCC, 2014). Changes in Arctic climate also have implications for the region's social and economic systems (e.g., IPCC, 2014; National Research Council of the Academies, 2015).

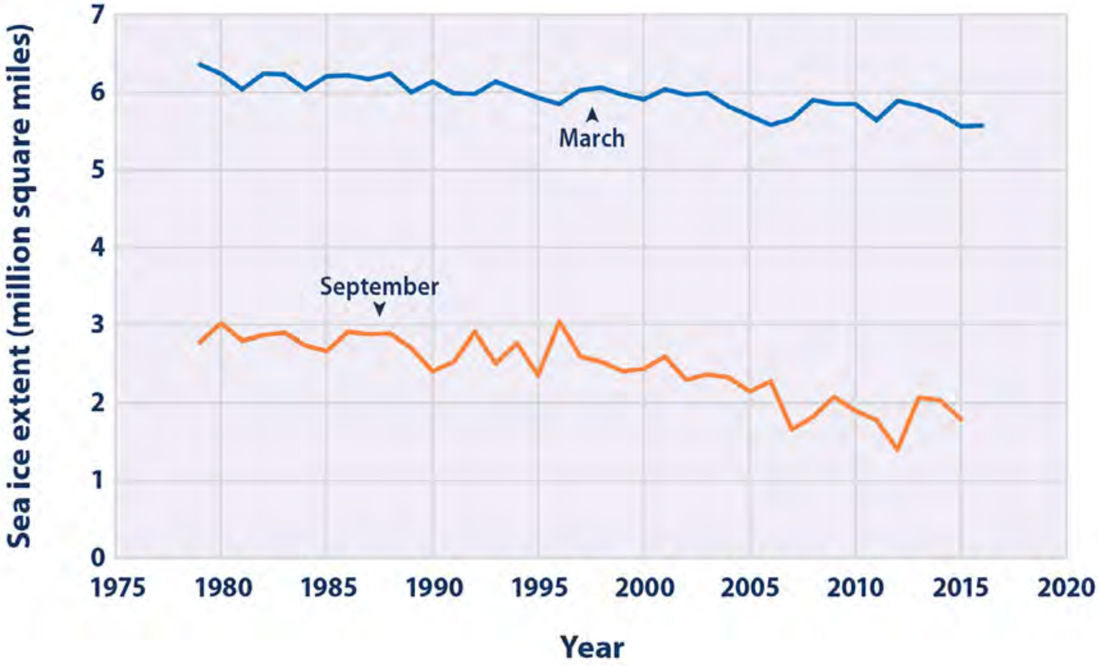


Figure 1. March and September monthly average Arctic sea ice extent, 1979–2016.
Source: EPA, 2016a.

Changes in Arctic climate can have global implications

Changes in Arctic climate can have implications for the global climate (ACIA, 2004; IPCC, 2014; National Research Council of the Academies, 2015):

- Decreases in Arctic snow and sea ice cover reveal darker surfaces (both water and land), which can cause increased surface warming.
- Increases in Arctic snow and ice melt (including glacial melt) result in increased quantities of freshwater entering the ocean. This contributes to rising sea levels and affects ocean current circulation.
- Warming in the Arctic leads to permafrost thaw, which can increase soil carbon dioxide and methane emissions, thereby contributing to further warming.

Impacts of Climate Change on the Arctic

Section 5 provides lists of additional resources on the impacts of climate change on the Arctic.

2

Understanding How Methane and Black Carbon Emissions Affect Arctic Climate

Pollutants affect Arctic climate in multiple ways, depending on the properties of the emitted pollutant. Some pollutants, such as carbon dioxide and most other greenhouse gases (GHGs), have long atmospheric lifetimes (i.e., the amount of time it remains in the atmosphere before being removed by chemical reaction or deposition). These pollutants affect Arctic climate over very long time periods. Other pollutants have shorter atmospheric lifetimes, and mainly affect near-term Arctic climate. Understanding how these pollutants affect Arctic climate is important to inform decision-making about mitigation strategies.

Short-lived climate pollutants have unique properties that influence their contribution to changes in Arctic climate

Short-lived climate pollutants (SLCPs) are gases and particles that cause warming and have lifetimes in the atmosphere of a few days to a few decades, much shorter than that of carbon dioxide (see discussion below). The SLCPs with the greatest influence on Arctic climate are methane and black carbon.

Methane

Methane is a GHG that is emitted by both natural and anthropogenic sources. Methane is emitted during the production and transport of coal, natural gas, and oil; from livestock and other agricultural practices; and as a product of the decay of organic waste in municipal solid waste landfills. It has a global warming potential (GWP) of 28–36 (IPCC, 2014), meaning its pound-for-pound impact on climate is 28–36 times more potent than that of carbon dioxide on a 100-year timescale. Methane is generally well-mixed throughout the global atmosphere. Any gas with an atmospheric lifetime greater than one or two years is considered well-mixed, meaning that emissions from any given location have the same impacts on global climate as emissions from any other location, and that concentrations far from any sources or sinks will be very similar, although concentrations can be influenced by local emissions sources. Therefore, methane emissions from anywhere in the world can contribute to Arctic warming (AMAP, 2015a).

Black carbon

Black carbon is a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths, thereby warming the atmosphere. Black carbon is a component of particulate matter that is produced as a byproduct of incomplete combustion of fossil fuel, biofuel, and biomass. It is co-emitted, and interacts in the atmosphere, with various other pollutants.

Black carbon influences climate in several complex ways that differentiate its effects from GHGs like carbon dioxide and methane (as illustrated in Figure 2):

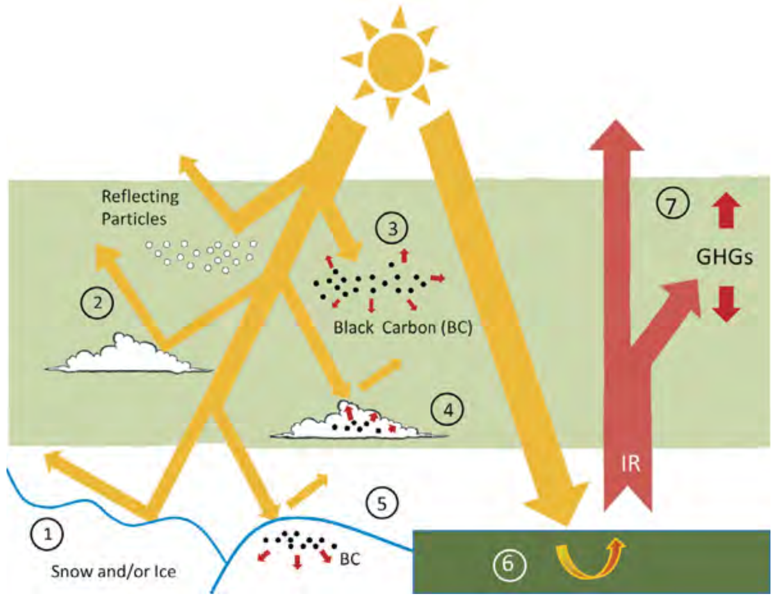
- Black carbon has the **direct effect** in the atmosphere of absorbing incoming and outgoing radiation. Absorbing incoming sunlight leads to dimming at the Earth's surface but warming in the atmosphere. Unlike black carbon, GHGs mainly trap outgoing infrared radiation from the Earth's surface (EPA, 2012).

  The net direct effect of black carbon in the Arctic atmosphere depends on the particles' altitude. Black carbon particles at high altitudes (i.e., far above the surface) in the Arctic lead to surface cooling – these particles are typically emitted from sources outside the Arctic and transported into the region. Black carbon that is lower in the atmosphere leads to surface warming – this black carbon tends to come from higher-latitude sources in and around the Arctic (AMAP, 2015a).

- Black carbon that is deposited on snow and ice darkens those surfaces and decreases their reflectivity (albedo). This is known as the **snow/ice albedo effect**. This effect results in the increased absorption of radiation that accelerates melting. GHGs do not directly affect surfaces' albedo (EPA, 2012).

- Black carbon alters the properties and distribution of clouds, which affect their reflectivity and lifetime – these are called the **indirect effects** of black carbon. Black carbon also affects the stability of clouds, an effect called the **semi-direct effect**. Because these cloud effects can be both warming and cooling, black carbon's indirect and semi-direct effects have uncertain net influences on climate. GHGs do not have these effects (EPA, 2012).

These effects are further complicated by a number of factors, including the location from which the black carbon is emitted (these factors are addressed in Section 4). Overall, uncertainties regarding the atmospheric effects of black carbon (and associated climate impacts) are much larger than for methane (AMAP, 2015a).



1. Sunlight that penetrates to the Earth's surface reflects off bright surfaces, especially snow and ice.
2. Clean clouds and non-light-absorbing (transparent) particles scatter or reflect sunlight, reducing the amount of solar energy that is absorbed by the surface.
3. BC suspended in the atmosphere absorbs some incoming solar radiation, heating the atmosphere.
4. Clouds containing BC inclusions in drops and BC between drops can absorb some incoming solar radiation, reducing the quantity that is reflected. Clouds warmed by the absorbed energy have shorter atmospheric lifetimes and may be less likely to precipitate compared to clean clouds.
5. BC deposited on snow and/or ice absorbs some of the sunlight that would ordinarily be reflected by clean snow/ice, and increases the rate of melting.
6. Most solar radiation is absorbed by the Earth's surface and warms it. Part of the absorbed energy is converted into infrared radiation that is emitted into the atmosphere and back into space.
7. Most of this infrared radiation passes through the atmosphere, but some is absorbed by GHG molecules like CO_2, methane, ozone and others. These gases re-emit the absorbed radiation, with half returning to the Earth's surface. This GHG effect warms the Earth's surface and the lower atmosphere.

Figure 2. Effects of black carbon on climate. Source: EPA, 2012.

Other SLCPs

Other SLCPs impact climate, but are not the focus of this document. These include tropospheric ozone[4] and some hydrofluorocarbons (HFCs). Tropospheric ozone, which is a GHG and an SLCP, is not emitted directly; rather, it is formed as a byproduct of chemical reactions involving other substances, including methane. Tropospheric ozone remains in the atmosphere for weeks to months, which is not long enough for it to become well-mixed (as methane does) (AMAP, 2015a). The net climate effects of other pollutants that contribute to the formation of tropospheric ozone are not as well-understood as those for methane and black carbon. Additional information can be found in AMAP (2015b, 2015c) reports (see Section 5).

HFCs are GHGs that are often used as substitutes for ozone-depleting substances. Some HFCs are also SLCPs, having atmospheric lifetimes of less than 15 years. Although their current contribution to climate change is much smaller than that of methane or black carbon, global HFC use is increasing, leading to concern about their future impacts on climate.[5]

4. Tropospheric ozone is found in the lower atmosphere, in contrast to the ozone layer, which is found in the stratosphere, higher in the atmosphere.
5. See https://www.epa.gov/snap/reducing-hydrofluorocarbon-hfc-use-and-emissions-federal-sector.

There are three important considerations when evaluating pollutants' influence on climate

Radiative forcing is a measure of the influence of a particular pollutant on the net change in the Earth's energy balance. Pollutants such as GHGs and some aerosols can contribute to positive radiative forcing (which leads to surface warming) and, in the case of other aerosols, negative radiative forcing (which leads to surface cooling). Some pollutants affect radiative forcing in multiple ways that partially offset each other; in such cases, it is useful to consider the pollutants' net radiative forcing effects.

Understanding how, and to what degree, pollutants influence radiative forcing is important for determining appropriate Arctic climate change mitigation strategies. As discussed below, there are multiple ways to evaluate pollutants' radiative forcing effects.

1. Carbon dioxide contributes more radiative forcing than any other pollutant

The total amount of global anthropogenic (i.e., caused by humans) radiative forcing in 2011 relative to 1750 was 2.29 W/m^2. Carbon dioxide is by far the largest contributor to this radiative forcing (1.68 W/m^2). Global action to reduce carbon dioxide emissions is therefore an essential component of any Arctic climate change mitigation strategy (IPCC, 2014; AMAP, 2015a). Methane and black carbon are the second- and third-largest contributors to global anthropogenic radiative forcing (0.97 W/m^2 and 0.64 W/m^2 in 2011 relative to 1750, respectively) (IPCC, 2014).[6]

2. For every additional metric ton in the atmosphere, methane and black carbon contribute more radiative forcing than carbon dioxide

Radiative efficiency is a measure of a pollutant's net effect on radiative forcing for a given amount that is emitted. Pollutants' radiative efficiencies can be compared to better understand their relative effects on radiative forcing, and thus warming. For example, although carbon dioxide emissions considerably outweigh total global emissions of methane and black carbon (Figure 3, Panel A)[7] and carbon dioxide is the largest contributor to total anthropogenic radiative forcing (Figure 3, Panel B), methane and black carbon have higher radiative efficiencies than carbon dioxide (Figure 3, Panel C). In fact, when measured in terms of $W/m^2/Gt$, the radiative efficiencies of methane[8] and black carbon are approximately 120 and 360,000 times greater than the radiative efficiency of carbon dioxide, respectively.

3. Methane and black carbon have shorter atmospheric lifetimes than carbon dioxide and their impacts on climate diminish faster

A pollutant's atmospheric lifetime determines the timeframe during which its effects on radiative forcing and temperature are felt. The shorter the lifetime, the more quickly atmospheric concentrations (and thus impacts) can be reduced through emissions mitigation.

While some carbon dioxide will remain in the atmosphere for thousands of years,[9] methane and black carbon have relatively short atmospheric lifetimes of approximately 12 years and 1 week, respectively (AMAP, 2015a, 2015b). GWP, the most commonly used metric for comparing the impacts of different pollutants on climate, takes into account both the radiative efficiency and the lifetime of a given pollutant.

Policy actions addressing SLCPs can provide temperature reduction benefits in the short-term, slowing the rate of warming and its consequent impacts over the next decades. Reductions of these SLCPs can therefore be an important complement to the mitigation of carbon dioxide emissions (AMAP, 2015a). Figure 4 illustrates the temperature responses resulting from one-year emissions pulses for carbon dioxide, methane, black carbon, and organic carbon (a net-cooling pollutant that is co-emitted with black carbon), in proportion to their global emissions. This figure shows how the short atmospheric lifetimes of methane and black carbon result in strong influences on temperature in the short-term, and how those impacts diminish relatively quickly compared to carbon dioxide, which has prolonged effects on climate.

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6. The global anthropogenic radiative forcing estimates in this section account for both warming and cooling influences. As a result, the sum of the estimates for carbon dioxide, methane, and black carbon is greater than the estimated total for all pollutants of 2.29 W/m^2.
7. The estimated emissions for black carbon (103 Gg) appear as zero in Figure 3, Panel A, due to the figure scale.
8. Including methane's impact on ozone and other atmospheric compounds with radiative forcing effects.
9. Carbon dioxide's lifetime is poorly defined because the gas is not destroyed over time, but instead moves among different parts of the ocean, the atmosphere, and the land system (EPA, 2016b).

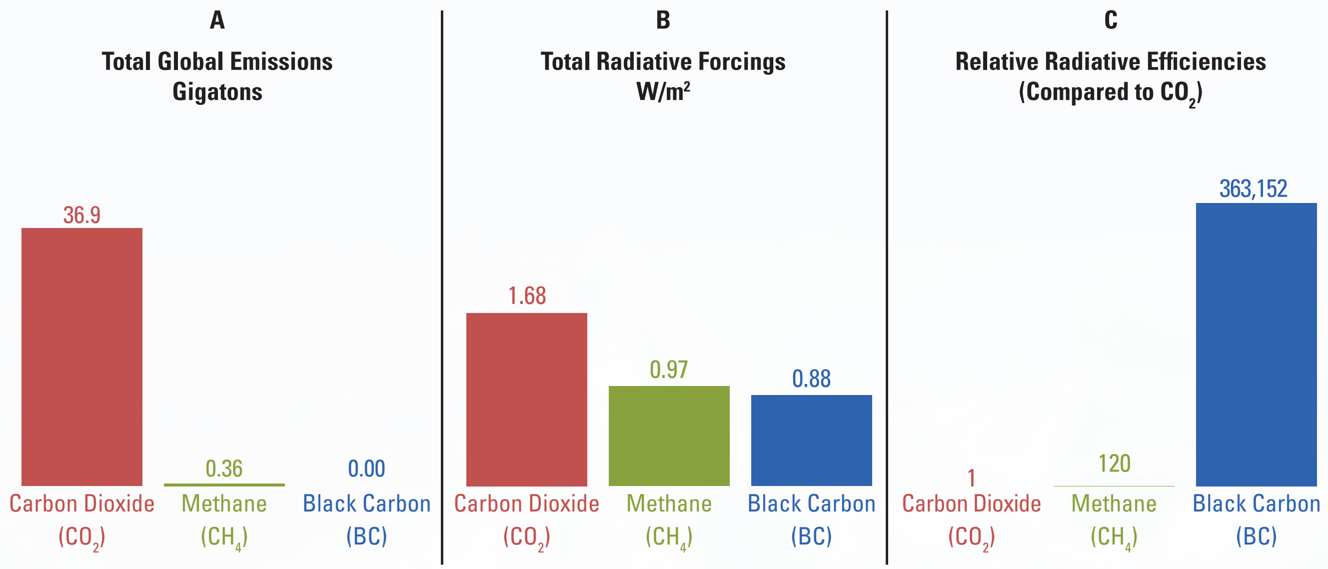

Figure 3. Comparison of carbon dioxide, methane, and black carbon's total global emissions (A), total radiative forcings (B), and relative radiative efficiencies (C). Sources: Bond et al., 2013; IPCC, 2014.

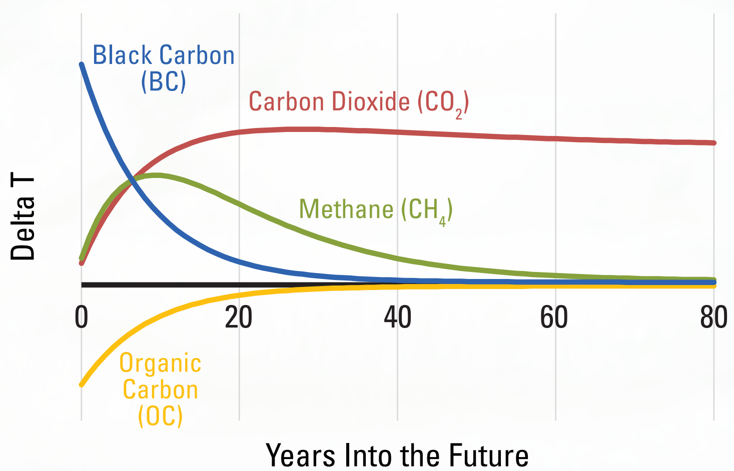

Figure 4. Temperature responses by pollutant for total anthropogenic emissions for one-year emissions pulses. Derived from: IPCC, 2014.

3

Assessing the Impacts of Methane and Black Carbon Emissions and Benefits of Mitigation

Recent studies, such as those conducted by the Arctic Council's[10] Arctic Monitoring and Assessment Programme (AMAP), have contributed to improved understanding of the influences and regional climate impacts of methane and black carbon on the Arctic. The analyses described in these reports used new observational data and modeling results to provide an up-to-date evaluation of the current understanding of these SLCP climate impacts.

AMAP created two expert groups to evaluate the specific processes by which SLCPs influence Arctic climate, the amount of warming for which they are responsible, and the potential benefits of mitigating emissions. This work resulted in two technical reports: *AMAP Assessment 2015: Methane as an Arctic Climate Forcer* (AMAP, 2015c) and *AMAP Assessment 2015: Black Carbon and Ozone as Arctic Climate Forcers* (AMAP, 2015b). As noted in the AMAP (2015a) summary for policymakers, the findings from the two assessment reports (AMAP, 2015b, 2015c) suggest that the global implementation of maximum, technologically feasible mitigation measures for methane, black carbon, and other tropospheric ozone precursors could reduce projected Arctic warming by at least 0.5°C by 2050. This estimate accounts for the direct effects of co-emitted cooling pollutants, but not indirect cloud effects.

Methane

Key findings from the methane assessment (AMAP, 2015c) include:

- **Impacts on Arctic climate.** In the Arctic, the average atmospheric concentration of methane is currently about 1,895 ppb. This concentration, higher than the global average (1,820 ppb), is a reflection of the strength of the region's methane emissions sources relative to its sinks (e.g., uptake in soils). From 1950 to 2005, increases in the atmospheric concentration of methane contributed 0.5°C to Arctic warming. For comparison, these increases contributed to an average of 0.3°C in warming across the globe.
- **Emissions sources.** Natural sources of methane emissions in the Arctic include marine systems (e.g., ocean floor sediments) and terrestrial systems (e.g., wetlands, thawing permafrost); these sources account for 1–17 Tg and 10–30 Tg of methane per year, respectively. The key sources of anthropogenic emissions in the Arctic are (in descending order): fossil fuel production, transmission, and distribution; agriculture; and the waste and wastewater sectors.
- **Significance of Arctic Council nations' contributions.** In total, anthropogenic activities in Arctic Council nations contribute approximately 66 Tg of methane each year (one-fifth of global

10. The Arctic Council is an intergovernmental forum established to promote cooperation, coordination, and interaction among the Arctic States and their inhabitants, with a particular focus on issues of sustainable development and environmental protection in the Arctic. Arctic Council member states include Canada, Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, Sweden, the Russian Federation, and the United States. The Arctic Council includes several working committees, such as the AMAP, which is dedicated to researching and informing decisions about the Arctic environment (Arctic Council, 2016).

anthropogenic emissions), although not all of these activities occur in the Arctic. The AMAP methane assessment did not evaluate the specific contribution of Arctic Council nations' methane emissions to Arctic warming because, as noted above, methane becomes well-mixed throughout the global atmosphere; therefore, emissions from anywhere in the world can contribute to Arctic warming.

- **Feedback mechanisms.** Increased warming in the Arctic contributes to increases in methane emissions from natural sources. The region contains large carbon reservoirs in frozen soils (i.e., permafrost) and oceans. Warming temperatures allows for previously frozen organic material to decompose, thus producing methane (alongside carbon dioxide). In addition, rising ocean temperatures can cause methane hydrates (i.e., quantities of methane that exist in a solid, frozen state) that are trapped in ocean sediments to melt and release methane to the atmosphere. These emissions increase atmospheric methane concentrations, feeding back to further warming.
- **Mitigation potential.** Global implementation of maximum technically feasible approaches to reduce anthropogenic methane emissions could reduce annual mean warming in the Arctic by 0.26–0.40°C by 2050.

Black carbon

Key findings from the black carbon and ozone assessment (AMAP, 2015b) include:

- **Impacts on Arctic climate.** AMAP's best estimate of total Arctic surface temperature response due to the direct effect of current global combustion-derived black carbon, organic carbon, and sulfate is +0.35°C. This does not account for indirect effects of aerosols, however, which would lower the temperature response. Section 4 provides information on recent studies that explore these effects and their implications for the net temperature response due to black carbon and co-emitted pollutants.
- **Emissions sources.** Black carbon emissions from Arctic Council nations come from both natural and anthropogenic sources. Open biomass burning (e.g., wildfires) is the key source of natural black carbon emissions, but estimates of these emissions are highly uncertain. Key sources of anthropogenic black carbon emissions from Arctic Council nations include the surface transportation and residential/commercial[11] sectors: these sectors collectively account for approximately 70% of black carbon emissions from these countries. The energy sector[12] accounts for approximately one-fifth of the Arctic Council nations' black carbon emissions; 75% of this amount comes from flaring in the oil and gas industry. Emissions from East/South Asia and Russia are the largest contributors to black carbon in the Arctic (according to AMAP's analyses, 43% and 21% of the total black carbon in the Arctic atmosphere comes from these two regions).
- **Significance of Arctic Council nations' contributions.** In total, black carbon emissions from Arctic Council nations represent approximately 10% of global black carbon emissions. Black carbon emissions from Arctic Council nations contribute to approximately 32% of total Arctic warming from that pollutant. The relative strength of Arctic Council nations' contribution to Arctic warming from black carbon, compared to their contribution to global black carbon emissions, reflects the significance of location on black carbon's impacts on climate, a feature that distinguishes it from methane.
- **Mitigation potential.** Emissions mitigation case studies suggest that global black carbon emissions could be reduced substantially through focused mitigation policies, in addition to the reductions that are projected as a result of existing policies. One study cited by AMAP estimated that 70–80% of black carbon emissions could be reduced by 2030. Overall, global implementation of maximum technologically feasible mitigation strategies for black carbon and co-emitted pollutants could reduce Arctic warming by 2050 by about 0.25°C, excluding the indirect cloud effects of particles.

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11. Examples of sources in the residential/commercial sector include household heating and cooking, and heating of commercial buildings.
12. Examples of sources in the energy sector include power plants, and energy conversion and extraction equipment.

Methane and black carbon emissions contribute to other, non-climate impacts

In addition to their effects on climate, methane and black carbon have negative impacts on air quality and human health:

- Methane contributes to the formation of ground-level ozone, an air pollutant that can trigger a variety of health problems (e.g., chest pain, coughing, throat irritation, airway inflammation), and reduce lung function and harm lung tissue. Ozone can also reduce agricultural productivity.

- Black carbon is a component of particulate matter (PM), another air pollutant that can affect the heart and lungs and cause serious health effects. Pollutants that are co-emitted with black carbon are also constituents of PM that impact air quality and health.

Reducing emissions of methane and black carbon can therefore have significant benefits that extend beyond mitigating impacts on climate.

Advancements in Quantifying the Health Benefits of Methane Emissions Mitigation

A recent study found that reducing 1 million metric tons of methane emissions will prevent approximately 240 premature mortalities from short-term exposure to ozone worldwide, or approximately 600 premature mortalities from long-term exposure worldwide. These mortality reduction benefits are valued at approximately $790 and $1,775 per metric ton of methane, respectively.

Source: Sarofim et al., 2015.

4

Important Considerations for Evaluating Methane and Black Carbon Emissions Mitigation Strategies

The previous section described the significant contributions of methane and black carbon to Arctic warming, and the potential benefits of mitigating those emissions in general. However, understanding the specific benefits of mitigating emissions is complicated by several factors that should be taken into consideration when evaluating emissions mitigation strategies.

Black carbon's indirect effects have uncertain impacts on climate

As noted in Section 2, black carbon's indirect effects on clouds (e.g., effects on cloud reflectivity and lifetime) have uncertain influences on climate (EPA, 2012). Whether these effects have been accounted for when assessing black carbon's net impact on climate is important for understanding the potential benefits of emissions mitigation strategies. The AMAP (2015b) assessment did not account for the indirect effects of particles on clouds; therefore, the projected benefits of black carbon emissions reductions discussed in the report (and discussed in Section 3) may be high. More recent work, including research by Sand et al. (2015) and Wobus et al. (2016), does account for some of those indirect effects (as described later in this section. This is an evolving and growing area of research.

Black carbon is emitted with other pollutants that can have cooling effects on climate

As noted in Section 2, black carbon is always emitted with other pollutants that interact in the atmosphere. Some of these co-emitted pollutants, such as organic carbon and sulfate, exert a cooling effect on climate that can offset black carbon's warming effects, particularly in the short-term. The net effect of an emissions source on climate depends in part on

Key Considerations for Evaluating Methane and Black Carbon Emissions Mitigation Strategies

- Indirect effects on clouds
- Co-emitted pollutants
- Location of emissions source
- Emissions scenario uncertainties
- Impacts of existing policies on emissions

the ratio of warming pollutants (e.g., black carbon) to cooling pollutants (e.g., organic carbon) in the emissions plume (EPA, 2012). For this reason, the net Arctic temperature response to mitigation strategies that target black carbon and co-emitted pollutants will depend on the emissions source. In addition, emissions sources of a particular type may have different net influences on climate across regions, depending on a range of factors (e.g., the influence on climate of emissions from wildfires may vary depending on the type of biomass burned) (Wobus et al., 2016). Studies indicate that some organic carbon, called "brown carbon," can have a warming effect on climate. However, the climate effects of brown carbon are less well understood.

Black carbon's effects on climate depend on the location of its source

Black carbon emitted from higher-latitude sources near the Arctic is more likely to be transported to or within the region and then deposited on snow and ice. In addition, black carbon emitted from sources near or within the Arctic is often found at low altitudes in the atmosphere, where it exerts a stronger warming influence on surface temperatures than black carbon at higher altitudes. Therefore, black carbon emitted from near or within the Arctic exerts a stronger Arctic temperature response per metric ton of emissions than black carbon emitted from farther away (Flanner, 2013; Sand et al., 2013a, 2013b; AMAP, 2015b).

Methane and black carbon emissions inventories and projections vary by sector and region

Emissions inventories inform decisions about appropriate emissions reduction goals and can serve as tools for evaluating the progress toward achieving them. Under the Enhanced Black Carbon and Methane Emissions Arctic Council Framework for Action, the eight Arctic Nations – including the United States – agreed to submit biennial national reports to the Arctic Council for the first time in 2015. These reports provide inventories of methane and black carbon emissions and describe emissions reduction actions (U.S. Department of State, 2015).

The United States has additional international obligations that can inform mitigation decisions on methane and black carbon in the Arctic:

- Under the United Nations Framework Convention on Climate Change (UNFCCC), EPA develops an annual inventory of U.S. GHG emissions and sinks that reports national emissions by source, sector, and gas (including methane). This report is submitted to the UNFCCC each year (EPA, 2016c).
- Under the 1979 Geneva Convention on Long-Range Transboundary Air Pollution, the United States maintains and reports an inventory of black carbon emissions.

Figure 5 presents a high-level overview of U.S. methane and black carbon emissions by source sector. The black carbon emissions figures are from the 2015 U.S. report to the Arctic Council (U.S. Department of State, 2015), while the methane emissions figures are from the 2016 submission of the inventory of U.S. GHG emissions and sinks (EPA, 2016c).

Both AMAP (2015b, 2015c) assessment reports illustrate how the selection of emissions inventories and projections for estimating the impacts of methane and black carbon on Arctic climate can influence the outcome. For example, in the methane assessment report, AMAP (2015c) found that most model estimates of total global methane emissions were in agreement, but sector-specific estimates varied considerably. For black carbon, AMAP (2015b) reported

Sector	Methane emissions (kt)
Energy	13,132
Agriculture	9,506
Waste	6,589
Land use, land use change, and forestry	294
Industrial	6
Total	29,527

Sector	Black carbon emissions (kt)
Fires	214
Mobile sources	211
Fuel combustion	58
Miscellaneous other	21
Industrial processes	9
Total	513

Figure 5. U.S. emissions of methane and black carbon. Sources: U.S. EPA, 2016c; U.S. Department of State, 2015.

increasing uncertainties among inventories in total emissions from each latitudinal band for northern latitudes, especially in the Arctic. These uncertainties introduce additional complexities when evaluating emissions mitigation strategies, and are a motivating factor behind efforts to improve inventories and projections through the Arctic Council (e.g., U.S. Department of State, 2015) and other venues.

Existing policies are already resulting in methane and black carbon emissions reductions

Existing policies adopted by several countries are already contributing to methane and black carbon emissions reductions. For example, in the United States, EPA is working to reduce methane emissions from landfills, coal mines, agriculture, and the oil and gas industry in support of goals described in the President's Climate Action Plan – Strategy to Reduce Methane Emissions (White House, 2014). In addition, black carbon emissions from the United States and other countries are declining due to the adoption and implementation of PM emissions standards for vehicles (EPA, 2012; U.S. Department of State, 2015).

Ongoing improvements in the understanding of methane and black carbon impacts on Arctic climate, and potential mitigation benefits

Activities aimed at understanding the impacts of methane and black carbon on Arctic climate, and potential strategies for mitigating them, are of high interest to the U.S. government and Arctic nations. When evaluating methane and black carbon emissions mitigation strategies, it is important to first consider the findings and recommendations from major assessment reports that describe the state of the science regarding their impacts. The AMAP assessments (AMAP, 2015, 2015b) represent a particularly valuable contribution to this understanding. In particular, the black carbon assessment (AMAP, 2015b) reflects advancements in efforts to quantify the potential for black carbon mitigation to slow Arctic warming in the short-term, as a complement to long-term efforts to reduce carbon dioxide emissions. However, the assessment included a caveat that the underlying analyses did not account for the interaction of aerosols and clouds, thus potentially overestimating the Arctic temperature response from black carbon emissions.

More recent research (e.g., Sand et al., 2015; Wobus et al., 2016) builds on the findings from the AMAP (2015b) assessment on black carbon by incorporating the effects of pollutants' interactions between aerosols and clouds. Wobus et al. (2016), for example, provide improved estimates of the net impacts of aerosol emissions by sector on Arctic temperatures. The findings from this research suggest that the domestic and transportation sectors are the only sectors in which Arctic warming from black carbon is not projected to be offset by cooling from co-emitted pollutants, primarily organic carbon and sulfur dioxide (see Figure 6).[13] Therefore, this research indicates that emissions mitigation approaches that target black carbon-rich emissions from the transportation sector globally, as well as the domestic sector (e.g., heating, cooking) in key regions, could help to reduce short-term Arctic warming.

Further research on these issues is underway to address remaining important uncertainties. Within the U.S. government, the Interagency Arctic Research Policy Committee serves a coordinating role.[14] Engagement with international partners through the Arctic Council further contributes to improved understanding.

Evaluating the Benefits of EPA's Actions to Reduce Methane Emissions

A recent study analyzed the climate and economic benefits of EPA domestic programs and policies that reduced methane emissions from 1993 to 2013. The authors found that EPA's domestic efforts to reduce methane emissions alone resulted in an avoided temperature rise of 0.006°C by 2013, and yielded $255 billion in benefits (e.g., from avoided climate and health impacts).

Sources: EPA, 2016d; Melvin et al., 2016.

13. Individual sources within specific sectors might have higher proportions of black carbon emissions to co-emitted pollutants; these sources would have different net Arctic temperature impacts than the sector as a whole.
14. More information is available at: www.iarpccollaborations.org.

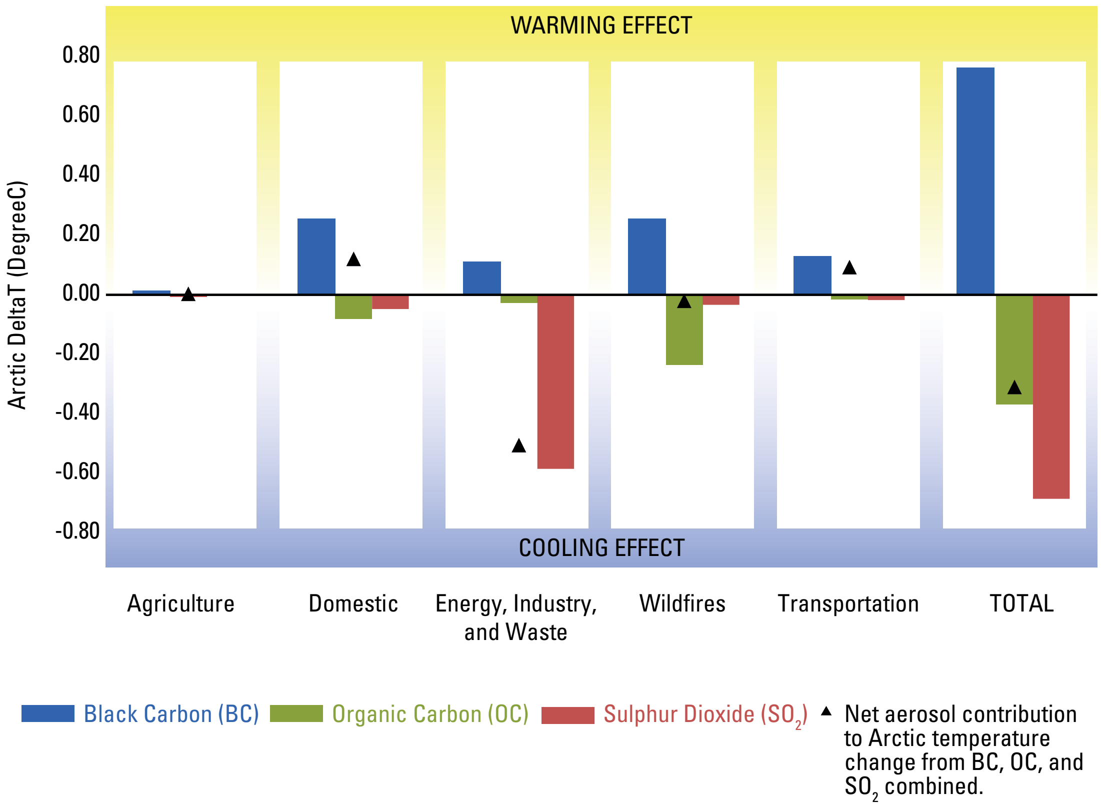

Figure 6. Arctic temperature change resulting from 2010 emissions of black carbon and co-emitted pollutants by sector. Derived from: Wobus et al., 2016.

5

Additional Resources

This section identifies a number of resources that provide additional information on topics related to climate change in the Arctic, and methane and black carbon emissions. These include citations for resources cited in the main body of this document.

Reports and assessments on black carbon, methane, and arctic impacts

Report to Congress on Black Carbon
EPA. 2012. Report to Congress on Black Carbon. Department of the Interior, Environment, and Related Agencies Appropriations Act, 2010. EPA-450/12-001. U.S. Environmental Protection Agency. March. Available: https://www3.epa.gov/blackcarbon/.

Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment
Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren, and C.S. Zender. 2013. Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment. *Journal of Geophysical Research: Atmospheres* 118(11):5380–5552. doi:10.1002/jgrd.50171. Abstract available: http://dx.doi.org/10.1002/jgrd.50171.

Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change
IPCC. 2014. Fifth Assessment Report (AR5). Intergovernmental Panel on Climate Change. Available: https://www.ipcc.ch/report/ar5/.

Arctic Matters: The Global Connection to Changes in the Arctic
National Research Council of the Academies. 2015. Arctic Matters: The Global Connection to Changes in the Arctic. Available: http://nas-sites.org/americasclimatechoices/files/2015/04/Arctic_Matters-booklet_final-web.pdf.

Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers
United Nations Environment Programme and World Meteorological Organization. 2011. Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers. Available: http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_SDM.pdf.

Climate Change Indicators in the United States
EPA. 2016a. Climate Change Indicators in the United States. U.S. Environmental Protection Agency. Available: https://www3.epa.gov/climatechange/science/indicators.

Arctic Council reports and materials

Impacts of a Warming Arctic: Arctic Climate Impact Assessment
ACIA. 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press, UK. Available: http://www.amap.no/arctic-climate-impact-assessment-acia.

An Assessment of Emissions and Mitigation Options for Black Carbon for the Arctic Council
Arctic Council. 2011. An Assessment of Emissions and Mitigation Options for Black Carbon for the Arctic Council. Technical Report of the Arctic Council Task Force on Short-Lived Climate Forcers. April. Available: https://oaarchive.arctic-council.org/handle/11374/1612.

Recommendations to Reduce Black Carbon and Methane Emissions to Slow Arctic Climate Change
Arctic Council. 2013. Recommendations to Reduce Black Carbon and Methane Emissions to Slow Arctic Climate Change. Artic Council Task Force on Short-Lived Climate Forcers. Available: https://oaarchive.arctic-council.org/handle/11374/80.

The Impact of Short-Lived Pollutants on Arctic Climate
AMAP. 2008. The Impact of Short-Lived Pollutants on Arctic Climate. AMAP Technical Report No. 1. By: P.K. Quinn, T.S. Bates, E. Baum, T. Bond, J.F. Burkhart, A.M. Fiore, M. Flanner, T.J. Garrett, D. Koch, J. McConnell, D. Shindell, and A. Stohl. Arctic Monitoring and Assessment Programme, Oslo, Norway. Available: http://www.amap.no/documents/download/974.

The Impact of Black Carbon on Arctic Climate
AMAP. 2011. The Impact of Black Carbon on Arctic Climate. AMAP Technical Report No. 4. By: P.K. Quinn, A. Stohl, A. Arneth, T. Berntsen, J.F. Burkhart, J. Christensen, M. Flanner, K. Kupiainen, H. Lihavainen, M. Shepherd, V. Shevchenko, H. Skov, and V. Vestreng. Arctic Monitoring and Assessment Programme, Oslo, Norway. Available: http://www.amap.no/documents/doc/the-impact-of-black-carbon-on-arctic-climate/746.

Summary for Policy-Makers: Arctic Climate Issues 2015, Short-Lived Climate Pollutants
AMAP. 2015a. Summary for Policy-Makers: Arctic Climate Issues 2015, Short-Lived Climate Pollutants. Arctic Monitoring and Assessment Programme, Oslo, Norway. Available: http://www.amap.no/documents/doc/summary-for-policy-makers-arctic-climate-issues-2015/1196.

AMAP Assessment 2015: Black Carbon and Ozone as Arctic Climate Forcers
AMAP. 2015b. AMAP Assessment 2015: Black Carbon and Ozone as Arctic Climate Forcers. Arctic Monitoring and Assessment Programme, Oslo, Norway. Available: http://www.amap.no/documents/doc/amap-assessment-2015-black-carbon-and-ozone-as-arctic-climate-forcers/1299.

AMAP Assessment 2015: Methane as an Arctic Climate Forcer
AMAP. 2015c. AMAP Assessment 2015: Methane as an Arctic Climate Forcer. Arctic Monitoring and Assessment Programme, Oslo, Norway. Available: http://www.amap.no/documents/doc/amap-assessment-2015-methane-as-an-arctic-climate-forcer/1285.

Arctic Council Website
Arctic Council. 2016. Arctic Council website. Available: http://www.arctic-council.org/index.php/en/.

U.S. National Black Carbon and Methane Emissions: A Report to the Arctic Council
U.S. Department of State. 2015. U.S. National Black Carbon and Methane Emissions: A Report to the Arctic Council. August. Available: http://www.ccacoalition.org/es/node/454.

Examples of recent studies on SLCPs and the Arctic

Future Arctic Temperature Change Resulting from a Range of Aerosol Emissions Scenarios
Wobus, C., M. Flanner, M.C. Sarofim, M.C.P. Moura, and S.J. Smith. 2016. Future Arctic Temperature Change Resulting from a Range of Aerosol Emissions Scenarios. *Earth's Future* 4(6):270–281. Available: http://onlinelibrary.wiley.com/doi/10.1002/2016EF000361/full.

Arctic Climate Sensitivity to Local Black Carbon
Flanner, M.G. 2013. Arctic Climate Sensitivity to Local Black Carbon. *Journal of Geophysical Research*: Atmospheres 118(4):1840–1851. doi:10.1002/jgrd.50176.

Arctic Surface Temperature Change to Emissions of Black Carbon within Arctic or Midlatitudes
Sand, M., T.K. Berntsen, Ø. Seland, and J.E. Kristjánsson. 2013a. Arctic Surface Temperature Change to Emissions of Black Carbon within Arctic or Midlatitudes. *Journal of Geophysical Research: Atmospheres* 118(14):7788–7798.

The Arctic Response to Remote and Local Forcing of Black Carbon
Sand, M., T.K. Berntsen, J.E. Kay, J.F. Lamarque, Ø. Seland, and A. Kirkevåg. 2013b. The Arctic Response to Remote and Local Forcing of Black Carbon. *Atmospheric Chemistry and Physics* 13:211–224.

Response of Arctic Temperature to Changes in Emissions of Short-Lived Climate Forcers
Sand, M., T.K. Berntsen, K. von Salzen, M.G. Flanner, J. Langner, and D.G. Victor. 2015. Response of Arctic Temperature to Changes in Emissions of Short-Lived Climate Forcers. *Nature Climate Change* 6:286–289. doi:10.1038/nclimate2880.

Valuing the Ozone-Related Health Benefits of Methane Emission Controls
Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg. 2015. Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics* pp. 1–19. doi:10.1007/s10640-015-9937-6. Available: http://link.springer.com/article/10.1007/s10640-015-9937-6.

Climate Benefits of EPA Programs and Policies that Reduced Methane Emissions 1993–2013
Melvin, A.M., M.C. Sarofim, and A.R. Crimmins. 2016. Climate Benefits of U.S. EPA Programs and Policies that Reduced Methane Emissions 1993–2013. *Environmental Science & Technology* 50(13):6873–6881. Abstract available: http://pubs.acs.org/doi/pdf/10.1021/acs.est.6b00367.

Efforts to address climate change in the United States

Regulatory Initiatives to Address Climate Change
EPA. 2016d. Regulatory Initiatives website. U.S. Environmental Protection Agency. Available: https://www3.epa.gov/climatechange/EPAactivities/regulatory-initiatives.html.

Climate Action Plan – Strategy to Reduce Methane Emissions
White House. 2014. Climate Action Plan – Strategy to Reduce Methane Emissions. The White House, Washington, DC. March. Available: https://www.whitehouse.gov/sites/default/files/strategy_to_reduce_methane_emissions_2014-03-28_final.pdf.

Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014 (April 2016)
EPA. 2016c. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014 (April 2016). U.S. Environmental Protection Agency. Available: https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

Overview of Greenhouse Gases
EPA. 2016b. Overview of Greenhouse Gases website. U.S. Environmental Protection Agency. Available: https://www3.epa.gov/climatechange/ghgemissions/gases.html.