

or a high percentile) as the sensitivity of peak values to meteorological conditions can be different from sensitivity of the median or mean (Porter et al., 2015). The AR5 assessed with *medium confidence* that uniformly higher temperatures in polluted environments will trigger regional feedbacks in chemistry and local emissions that will increase peak ozone and PM pollution, but assessed *low confidence* in projecting changes in meteorological blocking associated with these extreme episodes.

Meteorological conditions, such as heatwaves, temperature inversions and atmospheric stagnation episodes favour air quality extremes and are influenced by changing climate (Fiore et al., 2015). The body of literature on the connection between climate change and extreme anthropogenic pollution episodes is essentially based on correlation and regression applied to observation reanalysis but the metrics and methodologies differ making quantitative comparisons difficult. Many emission processes in the natural systems are sensitive to temperature, and bursts of emissions as a response to extreme weather, as in the case of wildfires in dry conditions (Bondur et al., 2020; Xie et al., 2020) can occur, which would then add to the risk of extreme air pollution but are not sufficiently constrained to be quantitatively assessed.

Since AR5, published studies provide augmented evidence for the connections between extreme ozone and PM pollution events and high temperatures, especially long-lasting heatwaves, whose frequency is increasing due to a warming climate (Lelieveld et al., 2014; Porter et al., 2015; Hou and Wu, 2016; Jing et al., 2017; Schnell and Prather, 2017; Sun et al., 2017; H. Zhang et al., 2017). However, the relationship between air pollution and individual meteorological parameters is exaggerated because of covariation on synoptic time scales (Fiore et al., 2015). For example, heatwaves are often associated with clear skies and stagnation, making clear attribution to specific meteorological variables complicated. In Asia, future changes in winter conditions have also been shown to favour more particulate pollution (Cai et al., 2017; Zou et al., 2017). The relationship between the occurrence of stagnation episodes and high concentrations of ozone and PM_{2.5} has been shown to be regionally and metric dependant (Oswald et al., 2015; Sun et al., 2017; Kerr and Waugh, 2018; Schnell et al., 2018; Garrido-Perez et al., 2019).

The increase of frequency, duration and intensity of heatwaves is *extremely likely* on all continents for different future warming levels (Section 11.3.5, Table 11.2). However, there is *low confidence* in projected changes in storm tracks, jets and blocking, and thus their influence on extreme temperatures in the mid-latitudes (Section 11.3.1).

In conclusion, there is still *medium confidence* that climate-driven changes in meteorological conditions, such as heatwaves or stagnations, will favour extreme air pollution episodes over highly polluted areas, however, the relationship between these meteorological conditions and high concentrations of ozone and PM_{2.5} have been shown to be regionally and metric dependant.

6.6 Air Quality and Climate Response to SLCF Mitigation

Long-lived greenhouse gas (LLGHG) emissions reductions are typically motivated by climate change mitigation policies, whereas SLCF reductions mostly result from air pollution control and climate policies (FAQ6.2), as well as policies focusing on achieving UN Sustainable Development Goals (SDGs; Box 6.2). The management of several SLCFs (BC, methane, tropospheric ozone and HFCs) is considered in the literature as a fast-response, near-term measure to curb climate change, while reduction of emissions of LLGHGs is an essential measure for mitigating long-term climate warming (Shindell et al., 2012, 2017b; Shoemaker et al., 2013; Rogelj et al., 2014b; Lelieveld et al., 2019). Note that the term short-lived climate pollutants (SLCPs), referring only to warming SLCFs, has been used within the policy arena. The SR1.5 report states that limiting warming to 1.5°C to achieve Paris Agreement goals, implies net-zero CO₂ emissions around 2050 and concurrent deep reductions in emissions of non-CO₂ forcers, particularly methane (Rogelj et al., 2018a). In addition, several SLCFs are key air pollutants or precursors of fine particulate matter (PM_{2.5}) and tropospheric ozone, and therefore subject to control driven by air-quality targets.

Policies addressing the reduction of either SLCFs or LLGHGs, often prioritize mitigation of emissions from specific anthropogenic sources, such as energy production, industry, transportation, agriculture, waste management and residential fuel use. The choice of the targetted sector and chosen measures will determine the ratios of emitted SLCFs and LLGHGs. These changes in emissions of co-emitted species will result in diverse responses driven by complex chemical and physical processes, and resulting climate perturbations. The understanding of the co-benefits through sectoral mitigation efforts (as well as potential negative impacts) is essential to inform policymaking.

The discussion of targeted SLCF policies and their role in climate change mitigation includes: critical evaluation of the climate co-benefits (Smith and Mizrahi, 2013; Pierrehumbert, 2014; Rogelj et al., 2014b; Strefler et al., 2014; M.R. Allen et al., 2016); modelling the potential of dedicated BC and methane reductions in association with or without climate policy (Harmsen et al., 2020a; Smith et al., 2020); quantifying individual or multi-component mitigation in relation to natural variability (Samset et al., 2020); warning about the risk of diversion of resources from targeted LLGHG policies, especially those targeting CO₂ (e.g., Shoemaker et al., 2013); and seeing it as an opportunity to strengthen commitment and accelerate action on LLGHGs (Victor et al., 2015; Aakre et al., 2018).

Over the last decade, research on air quality–climate interactions and feedbacks has brought new attention from policy communities to the possibility of win-win mitigation policies that could both improve air quality and mitigate climate change, possibly also reducing the cost of interventions (Anenberg et al., 2012; Shindell et al., 2012, 2017b; Schmale et al., 2014a, b; Sadiq et al., 2017; Fay et al., 2018; Harmsen et al., 2020b). Haines et al. (2017) and Shindell et al. (2017b) connect the measures to mitigate SLCFs with the achievements of some of the SDGs. Indeed, most studies on co-benefits to date focus on the

impacts of climate change mitigation strategies, in particular to meet Nationally Determined Contributions (NDCs) and/or to remain below specific global temperature targets, on air quality and human health (West et al., 2013; Rao et al., 2016; Shindell et al., 2016, 2017b; Zhang et al., 2016; Chang et al., 2017; Haines et al., 2017; Li et al., 2018; Markandya et al., 2018; Williams et al., 2018; Xie et al., 2018; Lelieveld et al., 2019). Such co-benefits of climate change mitigation for air quality and human health can offset the costs of the climate measures (Saari et al., 2015; Li et al., 2018). A growing number of studies analyse the co-benefits of current and planned air-quality policies on LLGHGs and global and regional climate change impacts (Lund et al., 2014; Akimoto et al., 2015; Lee et al., 2016; Maione et al., 2016; Peng et al., 2017).

This section assesses the effects of mitigating SLCFs, motivated by various objectives, discussing temperature response time, temperature and air-quality attribution of SLCFs sources, and chosen mitigation approach. The air quality and climate effects of the measures to contain the spread of COVID-19 in 2020 are discussed in Cross-Chapter Box 6.1 at the end of this section.

6.6.1 Implications of Lifetime on Temperature Response Time Horizon

The effect over time on GSAT following a mitigation effort affecting emissions of LLGHGs or SLCFs depends on the lifetimes of the LLGHGs and SLCFs, their radiative efficiencies, how fast the emissions are reduced, how long reductions last (limited time or sustained reduction), and the inertia of the climate system itself. Mitigation of SLCFs is often implemented through new legislation or technology standards for the different emissions sectors and components, implying that reductions are sustained over time.

It is often perceived that the full climatic response following mitigation of SLCFs will occur almost immediately. However, the inertia of the climate system strongly modifies the short-term and long-term response. SLCFs with lifetimes shorter than the time scales for inter-hemispheric mixing (1–2 years) can cause a more spatially heterogeneous forcing than LLGHGs and thus different regional patterns of the climate response (Section 6.4.3). The temporal response in GSAT to a radiative forcing can be quantified using linear impulse response functions (Cross-Chapter Box 7.1; Geoffroy et al., 2013; Oliv   and Peters, 2013; Smith et al., 2018). Figure 6.15 shows the GSAT response for sustained step reduction in emissions of idealised SLCFs with different lifetimes. The response is relative to a baseline with constant emissions, so effects of emissions before the step reduction is not shown. For SLCFs with lifetimes shorter than a few years, the concentrations quickly reach a new steady state and the response time is primarily governed by the thermal inertia and thus the time scales of the climate system. For compounds with lifetime on the order of 10 years (e.g., methane), there is about a 10-year delay in the response during the first decades, compared to compounds with lifetimes less than one year. However on longer time scales the response is determined solely by the time scales of the climate system itself. For CO₂ (dashed line in Figure 6.15) the temporal response is very different due to the long time scale for

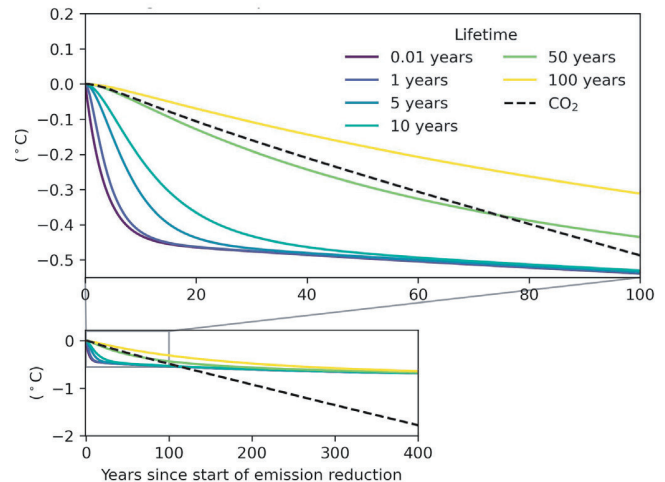


Figure 6.15 | Global mean surface air temperature (GSAT) response to an abrupt reduction in emissions (at time $t=0$) of idealized climate forcing agents with different lifetimes. All emissions are cut to give a radiative forcing of -1 W m^{-2} at a steady state (except for CO₂). In other words, if the yearly emissions are E_0 before the reduction, they will have a fixed lower value $E_{\text{year}>0} = (E_0 - \Delta E)$ for all succeeding years. For comparison, the GSAT response to a sustained reduction in CO₂ emissions resulting in an RF of -1 W m^{-2} in year 100 is included (dashed line). The temperature response is calculated using an impulse response function (Cross-Chapter Box 7.1) with a climate feedback parameter of $-1.31 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$. Further details on data sources and processing are available in the chapter data table (Table 6.SM.3).

mixing into the deep ocean and therefore a substantial fraction of atmospheric CO₂ is only removed on millenium time scales. This means that for SLCFs including methane, the rate of emissions drives the long-term stabilisation, as opposed to CO₂ where the long-term effect is controlled by cumulative emissions (Allen et al., 2018b). Methods to compare rates of SLCF emissions with cumulative CO₂ emissions are discussed in Chapter 7 (Section 7.6.1.4).

As a consequence, in idealized ESM studies that assume an instantaneous removal of all anthropogenic or fossil fuel-related emissions, a rapid change in aerosol levels occurs leading to large increases in GSAT with the rate of warming lasting for several years. Similarly, the thermal inertia causes the pulse emissions (Figure 6.15) of SLCFs to have a significant effect on surface temperature even after 10 years.

In summary, for SLCFs with short lifetime (e.g., months), the response in surface temperature occurs strongly as soon as a sustained change in emissions is implemented and continues to grow for a few years, primarily due to thermal inertia in the climate system (*high confidence*). Near its maximum, the response slows down but will then take centuries to reach equilibrium (*high confidence*). For SLCFs with longer lifetimes (e.g., a decade), a delay equivalent to their lifetimes comes in addition to the delay due the thermal inertia (*high confidence*).

6.6.2 Attribution of Temperature and Air Pollution Changes to Emissions Sectors and Regions

Assessment of the temperature response to source emissions sectors is important for identifying priority mitigation measures and designing efficient mitigation strategies.

Temperature effects of emissions can be quantified for the historical contribution to the present temperature impact (Section 6.4.2), for idealized one-year pulses of emissions or for continued (sustained) emissions at present levels and for changes during a specific time period, for emissions from future scenarios with various hypotheses, giving complementary information to feed mitigation strategies. The AR5 assessed the net global temperature impact of source emissions sectors from a one-year pulse (a single year's worth) of year 2008 emissions and found that the largest contributors to warming on 50–100-year time scales are the energy, industrial and on-road transportation sectors. Sectors that emit large amounts of methane (agriculture and waste management) and black carbon (residential biofuel) are important contributors to warming over short time horizons up to 20 years. Below, we discuss the effect on ERFs, temperature and air pollution of selected key sectors estimated to have large non-CO₂ forcing, including agriculture, residential and commercial, and transport (aviation, shipping, land transportation).

6.6.2.1 Agriculture

According to the SRCCL assessment (Jia et al., 2019), agriculture, forestry and other land use (AFOLU) are a significant net source of GHG emissions (*high confidence*), with more than half of these emissions attributed to non-CO₂ GHGs from agriculture. With respect to SLCFs, agricultural activities are major global sources of methane and NH₃ (Section 6.2.1). The agriculture sector exerts strong near-term warming due to large methane emissions that is slightly offset by a small cooling from secondary inorganic aerosols formed notably from the NH₃ emissions (Heald and Geddes, 2016; Lund et al., 2020). For present-day emissions, agriculture is the second largest contributor to warming on short time scales but with a small persisting effect on surface temperature (+0.0012°C ± 0.00028°C) after a pulse of current emissions (Figure 6.16, see detailed description in Section 6.6.2.3.4; Lund et al., 2020). Aerosols produced from agricultural emissions, released after nitrogen fertilizer application and from animal husbandry, influence surface air quality and make an important contribution to surface PM_{2.5} in many densely populated areas (Figure 6.17; Lelieveld et al., 2015b; Bauer et al., 2016).

6.6.2.2 Residential and Commercial Cooking and Heating

The residential and commercial sector is associated with SLCF emissions of carbonaceous aerosols, CO and NMVOCs, SO₂ and NO_x, and can be split by fuel type (biofuel or fossil fuel) where residential fossil fuel is also associated with CO₂ and methane emissions (Section 6.2.1).

The net effect of residential CO and NMVOC emissions is warming and that of SO₂ and NO_x is cooling of the atmosphere. However, the

sign of the net global radiative effects of carbonaceous aerosols from the residential sector and solid-fuel cookstove emissions (warming or cooling) is not well constrained based on evidence from recent global atmospheric modelling studies. Estimates of direct aerosol–radiation and aerosol–cloud effects from the global residential sector range from –20 to +60 mW m⁻² (Kodros et al., 2015) and –66 to +21 mW m⁻² (Butt et al., 2016) and from –20 to +10 mW m⁻² (Kodros et al., 2015) and –52 to –16 mW m⁻² (Butt et al., 2016), respectively. Uncertainties are due to assumptions about the aerosol emissions masses, size distribution, aerosol optical properties and mixing states (Section 6.3.5.3). Allowing BC to act as an INP in a global model leads to a much larger global forcing estimate from –275 to +154 mW m⁻² with a large uncertainty range due to uncertainty in the plausible range of maximum freezing efficiency of BC (Huang et al., 2018). The residential biofuel sector is a major concern for indoor air quality (Bonjour et al., 2013). In addition, several atmospheric modelling studies find that this sector is also important for outdoor air quality and even a dominant source of population-weighted outdoor PM_{2.5} in India and China (Lelieveld et al., 2015b; Silva et al., 2016; Spracklen et al., 2018; Reddington et al., 2019).

The net climate effect of a one-year pulse of current emissions from the residential sector is warming in the near term of +0.0018°C ± 0.00084°C from fossil fuel use and +0.0014°C ± 0.0012°C from biofuel use. Over a 100-year time horizon, this warming is +0.0017°C ± 0.00017°C and +0.0001°C ± 0.000079°C, respectively (Lund et al., 2020). This is due to the effects of BC, methane, CO and NMVOCs, which add to that of CO₂, but the uncertainty in the sign of carbonaceous aerosol net effects challenges overall quantitative understanding of this sector and leads to *low confidence* in this assessment. Residential sector emissions are an important source of indoor and outdoor air pollution in Asia and globally (*high confidence*).

6.6.2.3 Transportation

6.6.2.3.1 Aviation

Aviation is associated with a range of SLCFs, in particular emissions of NO_x and aerosol particles, alongside emissions of water vapour and CO₂. The largest SLCF effects are those from the formation of persistent condensation trails (contrails) and NO_x emissions. Persistent contrails are ice-crystal clouds, formed around aircraft soot particles (and water vapour from the engine), injected in ambient cold and ice-supersaturated atmosphere, which can spread and form contrail cirrus clouds. The 'net NO_x' effect arises from the formation of tropospheric ozone, counterbalanced by the destruction of ambient methane and associated cooling effects of reductions in stratospheric water vapour and background ozone. The AR5 assessed the radiative forcing from persistent linear contrails to be +0.01 [+0.005 to +0.03] W m⁻² for the year 2011, with *medium confidence* (Boucher et al., 2013). The combined linear contrail and their subsequent evolution to contrail cirrus radiative forcing from aviation was assessed to be +0.05 [+0.02 to +0.15] W m⁻², with *low confidence*. An additional forcing of +0.003 W m⁻² due to emissions of water vapour in the stratosphere by aviation was also reported (Boucher et al., 2013). The aviation sector was also estimated to lead

to a net surface warming at 20- and 100-year horizons following a one-year pulse emission. This net temperature response was determined by similar contributions from contrails, contrail cirrus and CO₂ over a 20-year time horizon, and dominated by CO₂ in a 100-year perspective (Figure 8.34 in AR5, Myhre et al., 2013).

Our assessment is built upon Lee et al. (2021). Their study consists of an updated, comprehensive assessment of aviation climate forcing in terms of RF and ERF based on a large number of studies and the most recent air-traffic and fuel-use datasets available (for 2018), new calculations and the normalization of values from published modelling studies, and combining the resulting best estimates via a Monte-Carlo analysis. Lee et al. (2021) report a net aviation ERF for year-2018 emissions of +0.101 [0.055–0.145] W m⁻² with major contributions from contrail cirrus (0.057 W m⁻²), CO₂ (0.034 W m⁻²) and NO_x (0.017 W m⁻²). Contrails and aviation-induced cirrus yield the largest individual positive ERF followed by CO₂ and NO_x emissions (Lee et al. 2021). The *confidence* level in ERF due to contrails and aviation-induced cirrus is assessed to be *low* in Chapter 7 (Section 7.3.4.2) due to potential missing processes. The formation and emission of sulphate aerosols yield a negative (cooling) term. SLCF forcing terms contribute about eight times more than CO₂ to the uncertainty in the aviation net ERF in 2018 (Lee et al., 2021). The largest uncertainty in assessing aviation climate effects is on the interactions of BC and sulphate aerosols on cirrus and mixed-phase clouds, for which no best estimates of the ERFs were provided (Lee et al., 2021).

One of the most significant changes between AR5 and AR6 in terms of aviation SLCFs is the explicit calculation of a contrail cirrus ERF found to be 35% of the corresponding RF (Bickel et al., 2020), confirming the studies indicating smaller efficacy of linear contrails (Ponater et al., 2005; Rap et al., 2010). The net-NO_x term is generally agreed to be a positive RF in the present day, although attribution in a non-linear chemical system is problematic (Grewe et al., 2019), but Skowron et al. (2021) point out that the sign of net NO_x term is dependent on background conditions and could be negative under certain future scenarios.

The best estimate ERFs from aviation (Lee et al., 2021) have been used to calculate aviation-specific Absolute Global Temperature change Potential (AGTP) using the method described in Lund et al. (2020) and subsequently compute the effect of a one-year pulse of aviation emissions on global mean surface temperature on a 10- and 100-year time horizon (Section 6.6.2.3.4 and Figure 6.16). The effect of contrail-cirrus is most important for the estimated net-GSAT response after the first decade, followed by similar warming contributions from NO_x and CO₂ emissions. At a 20-year time horizon, the net contribution from aviation to GSAT has switched from a positive to a small negative effect (see Supplementary Material 6.SM.4). This is due to the combination of rapidly decaying contrail-cirrus warming and the complex time variation of the net temperature response to NO_x emissions, which changes sign between 10 and 20 years due to the balance between the positive short-lived ozone forcing and negative forcing from changes in methane and methane-induced changes in ozone and stratospheric water vapour. The net GSAT response to aviation emissions has previously been estimated to be

positive on a 20-year time horizon (AR5, Chapter 8; Lund et al., 2017). This difference in net GSAT after 20 years in AR5 compared to AR6, results primarily from a shorter time scale of the climate response in the underlying AGTP calculations in Lund et al. (2020), which means the initial, strong impacts of the most short-lived SLCFs, including the warming by contrail-cirrus decay faster, in turn giving the net NO_x effect a relatively higher importance after 20 years. On longer time horizons, the net GSAT response switches back to positive, as CO₂ becomes the dominating warming contribution.

In summary, the net aviation ERF is assessed to be +0.1 W m⁻² (±0.045) for the year 2018 (*low confidence*). This confidence level is largely a result of the fact that the SLCF-related terms, which account for more than half (66%) of the net aviation ERF, are the most uncertain terms. The climate response to SLCF-related aviation terms exhibits substantial spatio-temporal heterogeneity in characteristics (*high confidence*). Overall, cirrus and contrail cirrus warming, as well as NO_x-induced ozone increase, induce strong but short-lived warming contributions to the GSAT response 10 years after a one-year pulse of present-day aviation emissions (*medium confidence*), while CO₂ both gives a warming effect in the near term and dominates the long-term warming impact (*high confidence*).

6.6.2.3.2 Shipping

Quantifying the effects of shipping on climate is particularly challenging because (i) the sulphate cooling impact is dominated by aerosol–cloud interactions and (ii) ship emissions contain NO_x, SO_x and BC, which lead to mixed particles. Previous estimates of the sulphate radiative effects from present-day shipping span the range –47 to –8 mW m⁻² (direct radiative effect) and –600 to –38 mW m⁻² (indirect radiative effects) (Lauer et al., 2007; Balkanski et al., 2010; Eyring et al., 2010; Lund et al., 2012). Partanen et al. (2013) reported a global mean ERF for year-2010 shipping aerosol emissions of –390 mW m⁻². The temperature change has been shown to be highly sensitive to the choice of aerosol–cloud parametrization (Lund et al., 2012). One year of global present-day shipping emissions, not considering the impact of recent low sulphur fuel regulation (IMO, 2016), are estimated to cause net cooling in the near term (–0.0024°C ± 0.0025°C) and slight warming (+0.00033°C ± 0.00015°C) on a 100-year horizon (Lund et al., 2020).

Shipping is also of importance for air pollution in coastal areas along the major trade routes, especially in Europe and Asia (Corbett et al., 2007; H. Liu et al., 2016, Figure 6.17; Jonson et al., 2020). Jonson et al. (2020) estimated that shipping is responsible for 10% or more of the controllable PM_{2.5} concentrations and depositions of oxidised nitrogen and sulphur for many coastal countries. Widespread introduction of low-sulphur fuels in shipping from 2020 (IMO, 2016) will lead to improved air quality and reduction in premature mortality and morbidity (Sofiev et al., 2018).

In summary, a year's worth of present-day global shipping emissions (i.e., without the implementation of the 2020 clean fuel standards) cause a net global cooling (–0.0024 ± 0.0025°C) on 10–20 year time horizons (*high confidence*) but its magnitude is of *low confidence*.

6.6.2.3.3 Land transportation

The on-road and off-road transportation sectors have a net warming impact on climate over all time scales (Berntsen and Fuglestvedt, 2008; Fuglestvedt et al., 2008; Unger et al., 2010; Lund et al., 2020). A one-year pulse of present-day emissions has a small net global temperature effect on short time scales ($+0.0011^{\circ}\text{C} \pm 0.0045^{\circ}\text{C}$), predominantly driven by CO_2 and BC warming offset by NO_x -induced cooling through methane lifetime reductions (Lund et al., 2020).

The vehicle tailpipe emissions profiles of diesel and gasoline are distinctly different. Diesel air pollutant emissions are dominated by BC and NO_x , whereas gasoline air pollutant emissions are dominated by CO and NMVOCs, especially when distribution and upstream losses are considered. Thus, the net radiative effect of the on-road vehicle fleets depends upon the share of different fuels used, in particular gasoline and diesel (Lund et al., 2014; Huang et al., 2020). The net SLCF for year-2010 emissions from the global diesel vehicle fleet have been estimated to be $+28 \text{ mW m}^{-2}$ (Lund et al., 2014). Huang et al. (2020) estimated net global radiative effects of SLCFs (including aerosols, ozone, and methane) from the gasoline and diesel vehicle fleets in the year 2015 to be $+13.6$ and $+9.4 \text{ mW m}^{-2}$, respectively, with similar fractional contributions of SLCFs to the total global climate impact including CO_2 on the 20-year time scale (14–15%).

There is consensus that on-road transportation sector emissions, including gasoline and diesel, are important anthropogenic contributors to elevated surface ozone and $\text{PM}_{2.5}$ concentrations (Chambliss et al., 2014; Lelieveld et al., 2015b; Silva et al., 2016; Anenberg et al., 2019). At a global scale, land transportation has been estimated to be the dominant contributor to surface ozone concentrations in populated areas (Silva et al., 2016) and ozone-induced vegetation damages (Section 6.4.4; Unger et al., 2020). Furthermore, it is now well established that real-world diesel NO_x emissions rates are substantially higher, the so-called ‘excess NO_x ’, in all regional markets than in laboratory tests, worsening air quality (Anenberg et al., 2017; Jonson et al., 2017; Chossière et al., 2018) and contributing to slightly larger warming on the scale of years and smaller warming at the decadal scale (Tanaka et al., 2018). Excess NO_x emissions from key global diesel markets are estimated at 4.6 Tg yr^{-1} in 2015, with annual mean ozone and $\text{PM}_{2.5}$ increases of 1 ppb and $1 \mu\text{g m}^{-3}$ across large regions of Europe, India and China (Anenberg et al., 2017).

In summary, the present-day global land-based transport pulse emissions cause a net global warming on all time scales (*high confidence*) and are detrimental to air quality (*high confidence*).

6.6.2.4 GSAT Response to Emissions Pulse of Current Emissions

Figure 6.16 presents the GSAT response to an idealized pulse of year-2014 emissions of individual SLCF and LLGHG. The GSAT response is calculated for 11 sectors and 10 regions accounting for best available knowledge and geographical dependence of the forcing efficacy of different SLCFs (Lund et al., 2020). Two time horizons are shown (of 10 and 100 years) to represent near- and long-

term effects (and a 20-year horizon is presented in Supplementary Material Figure 6.SM.3). Other time-horizon choices may affect the relative importance, and even sign in the case of the NO_x effect, of the temperature response from some of the SLCFs, or be more relevant for certain applications. GSAT response is calculated using the concept of AGTP (Section 7.6.2.2). Further details of the AGTP emulator applied in Figure 6.16 are provided in Lund et al. (2020) and Supplementary Material 6.SM.4 (Section 7.6.1.2, Cross-Chapter Box 7.1 and Supplementary Material 7.SM.7.2). As discussed by Lund et al. (2020), the AGTP framework is primarily designed to study the relative importance of individual emissions and sources, but the absolute magnitude of temperature responses should be interpreted with care due to the linearity of the AGTP, which does not necessarily capture all the non-linear effects of SLCFs emissions on temperature.

Differences in the mix of emissions result in net effects on GSAT that vary substantially, in both magnitude and sign, between sectors and regions. SLCFs contribute substantially to the GSAT effects of sectors on short time horizons (10–20 years) but CO_2 dominates on longer time horizons (Figure 6.16). As the effect of the SLCFs decays rapidly over the first few decades after emission, the net long-term temperature effect is predominantly determined by CO_2 . N_2O adds a small contribution to the long-term effect of agriculture. CO_2 emissions cause an important contribution to near-term warming that is not always fully acknowledged in discussions of LLGHGs and SLCFs (Lund et al., 2020).

The global sectoral ranking for near- and long-term global temperature effects is similar to the AR5 assessment despite regional reductions in aerosol precursor emissions between 2008 and 2014. This report has applied updated climate policy metrics for SLCFs and treatment of aerosol–cloud interactions for SO_2 , BC and OC (Lund et al., 2020). By far the largest 10-year GSAT effects are from the energy production (fossil fuel mining and distribution), agriculture and waste management sectors (*high confidence*). Methane is the dominant contributor in the energy production, agriculture and waste management sectors. On the 10-year time horizon, other net warming sectors are residential fossil fuel and energy combustion (dominated by CO_2) and aviation and residential biofuel (dominated by SLCFs and cloud) (*medium confidence*). The total residential and commercial sector, including biofuel and fossil fuels, is the fourth largest contributor to warming globally on short time horizons of 10–20 years. The energy combustion sector has considerable cooling from high emissions of SO_2 that result in a relatively small net GSAT temperature effect on short time horizons, despite the high CO_2 emissions from this activity. On the 10-year time horizon, global emissions from industry and shipping cause a net cooling effect despite a considerable warming from CO_2 emissions. On the 100-year time horizon, the net effects of agriculture and waste management are small, while energy combustion is the largest individual contributor to warming due to its high CO_2 emissions. The second largest driver of long-term temperature change is industry, demonstrating the importance of non- CO_2 emissions for shaping relative weight over different time frames. Transport contributes a small net warming on the 10-year time horizon that increases by a factor of three on the 100-year time horizon. In contrast, the aviation sector contribution to warming shrinks by about a factor of three between the 10- and 100-

year time horizons. Results for the 20-year time horizon are provided in the Supplementary Material 6.SM.4. Compared to the 10-year time horizon, there are some changes in ranking, especially of sectors and regions with a strong SO₂ contribution, which decays substantially between 10 and 20 years. Aviation is the sector with the most distinct difference between 10- and 20-year time horizons, such that the net GSAT effect after 20 years becomes small but negative. This is due to a switch in sign for the NO_x AGTP for this sector and the stronger effect of short-lived ozone response over these two short-term horizons in the case of aviation compared with other sectors.

In terms of source regions, the largest contributions to net short-term warming are caused by emissions in Eastern Asia, Latin America and North America, followed by Africa, Eastern Europe, West-Central Asia and South East Asia (*medium confidence*). However, the relative contributions from individual species vary. In Eastern Asia, North America, Europe and Southern Asia, the effect of current emissions of cooling and warming SLCFs approximately balance in the near term and these regions cause comparable net warming effects on 10- and 100-year time horizons (Figure 6.16). In Latin America, Africa, and South East Asia and Developing Pacific, methane and BC emissions are currently high while emissions of CO₂ and cooling aerosols are low compared to other regions, resulting in a net warming effect after 10 years that is substantially higher than that of CO₂ alone.

Overall, the global sectors that contribute the largest warming on short time scales are the methane-dominated sources, that is energy production (fossil fuel mining and distribution), and agriculture and waste management (*high confidence*). On short time scales, other net warming sectors are residential fossil fuel and energy combustion (dominated by CO₂), and aviation and residential biofuel (dominated by SLCFs) (*medium confidence*). On short time scales, global emissions from industry and shipping cause a net cooling effect despite a considerable warming from CO₂ emissions (*high confidence*). On longer time horizons, the sectors that contribute the largest warming are energy combustion and industry due to the large CO₂ emissions (*high confidence*).

6.6.2.5 Source attribution of regional air pollution

The attribution of present-day surface PM_{2.5} and ozone concentrations to sectors and regions (Figure 6.17) is based on 2014 CMIP6 emissions used in the TM5-FASST model (Van Dingenen et al., 2018) that has been widely applied to analyse air quality in regional and global scenarios (e.g., Van Dingenen et al., 2009; Rao et al., 2016, 2017; Vandyck et al., 2018; Harmsen et al., 2020b). Regions with the largest year-2014 population-weighted annual average surface PM_{2.5} concentrations are Southern Asia, Eastern Asia and the Middle East. The dominant anthropogenic source of ambient PM_{2.5} in Southern Asia are the residential and commercial sectors (biomass and coal fuel-based cooking and heating) with secondary contributions from energy and industry. In Eastern Asia, the main anthropogenic sources of ambient PM_{2.5} are energy, industry and residential sources. Natural sources, predominantly dust, are the most important PM_{2.5} source in the Middle East, Africa and Eurasia, contributing about 40–70% of ambient annual average concentrations (Figure 6.17). Agriculture

is an important contributor to ambient PM_{2.5} in Europe and North America, while open biomass burning is a major contributor in South East Asia and Developing Pacific, North America as well as Latin America. These results are consistent with several global and regional studies, where contribution of emissions sources to ambient PM_{2.5} or premature mortality was estimated at different scales (e.g., Guttikunda et al., 2014; Lelieveld et al., 2015b; Amann et al., 2017; Qiao et al., 2018; Venkataraman et al., 2018; Wu et al., 2018).

Natural sources contribute more than 50% to surface ozone in all regions except Southern Asia and South East Asia. Southern Asia, Eastern Asia and the Middle East experience the highest surface ozone levels of all regions. For ozone, the anthropogenic sectoral attribution is more uniform across regions than for PM_{2.5}, except for Southern and South East Asia, where land transportation plays a larger role, and Eastern Asia, where the most significant contribution is from energy and industry. Land transportation and energy are the most important contributors to ozone across many of the regions, with smaller contributions from agriculture, biomass burning, waste management and industry. Open biomass burning is not a major contributor to surface ozone, except for in Africa, Latin America and South East Asia where its contribution is estimated at about 5–10% of anthropogenic sources. The relative importance of natural and anthropogenic emissions sources on surface ozone has been assessed in several studies (Uherek et al., 2010; Zare et al., 2014; Mertens et al., 2020; Unger et al., 2020) and the results are comparable with the estimates of the TM5-FASST used here.

Residential and commercial cooking and heating are among the most important anthropogenic sources of ambient PM_{2.5}, except in the Middle East and Asia-Pacific Developed (*high confidence*) and agriculture is the dominant source in Europe and North America (*medium confidence*). Energy and industry are important PM_{2.5} contributors in most regions, except Africa (*high confidence*). Energy and land transportation are the major anthropogenic sources of ozone across many world regions (*medium to high confidence*).

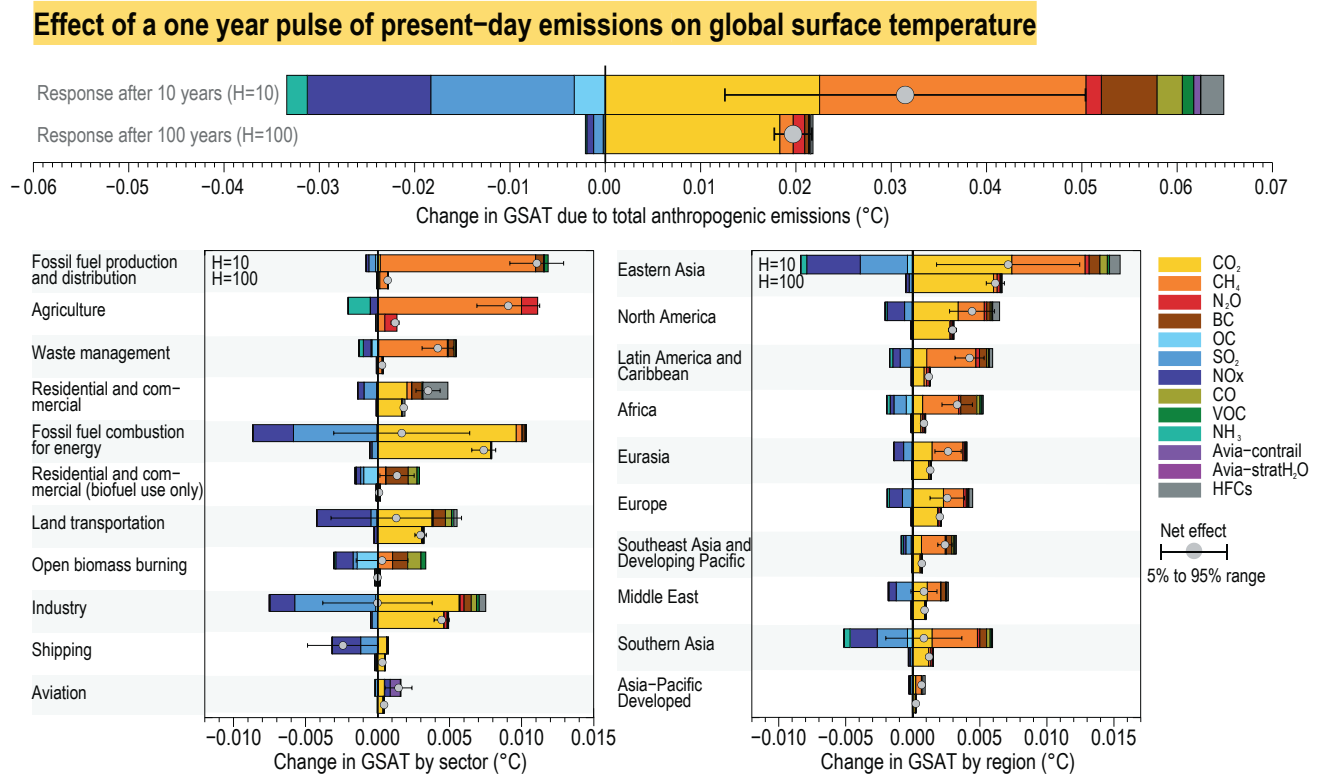


Figure 6.16 | Global mean temperature response 10 and 100 years following one year of present-day (year 2014) emissions. The temperature response is broken down by individual species and shown for total anthropogenic emissions (top), sectoral emissions (left) and regional emissions (right). Sectors and regions are sorted by (high-to-low) net temperature effect on the 10-year time scale. Error bars in the top panel show uncertainty (5–95% interval) in net temperature effect due to uncertainty in radiative forcing *only* (calculated using a Monte Carlo approach and best estimate uncertainties from the literature – see Lund et al. (2020) for details). CO₂ emissions are excluded from open biomass burning and residential biofuel use due to their unavailability in the Community Emissions Data System (CEDS) and uncertainties around non-sustainable emission fraction. Emissions for 2014 originate from the CEDS (Hoesly et al., 2018), except for HFCs which are from Purohit et al. (2020), open biomass burning from van Marle et al. (2017), and aviation H₂O which is from Lee et al. (2021). The split of fossil fuel production and distribution and combustion for energy and residential and commercial fuel use into fossil fuel and biofuel components is obtained from the GAINS model (ECLIPSE version 6b dataset). Open biomass burning emissions are not included for the regions. Emissions are aggregated into fossil fuel production and distribution (coal mining, oil and gas production, upstream gas flaring and gas distribution networks), agriculture (livestock and crop production), fossil fuel combustion for energy (power plants), industry (combustion and production processes, solvent-use losses from production and end use), residential and commercial (fossil fuel use for cooking and heating as well as HFCs leakage from A/C and refrigeration), waste management (solid waste, including landfills and open trash burning, residential and industrial waste water), transport (road and off-road vehicles, and HFC leakage from A/C and refrigeration equipment), residential and commercial (biofuels use for cooking and heating), open biomass burning (forest, grassland, savanna fires and agricultural waste burning), shipping (including international shipping), and aviation (including international aviation). Further details on data sources and processing are available in the chapter data table (Table 6. SM.3).

Attribution of regional, population-weighted PM_{2.5} and ozone to sectors

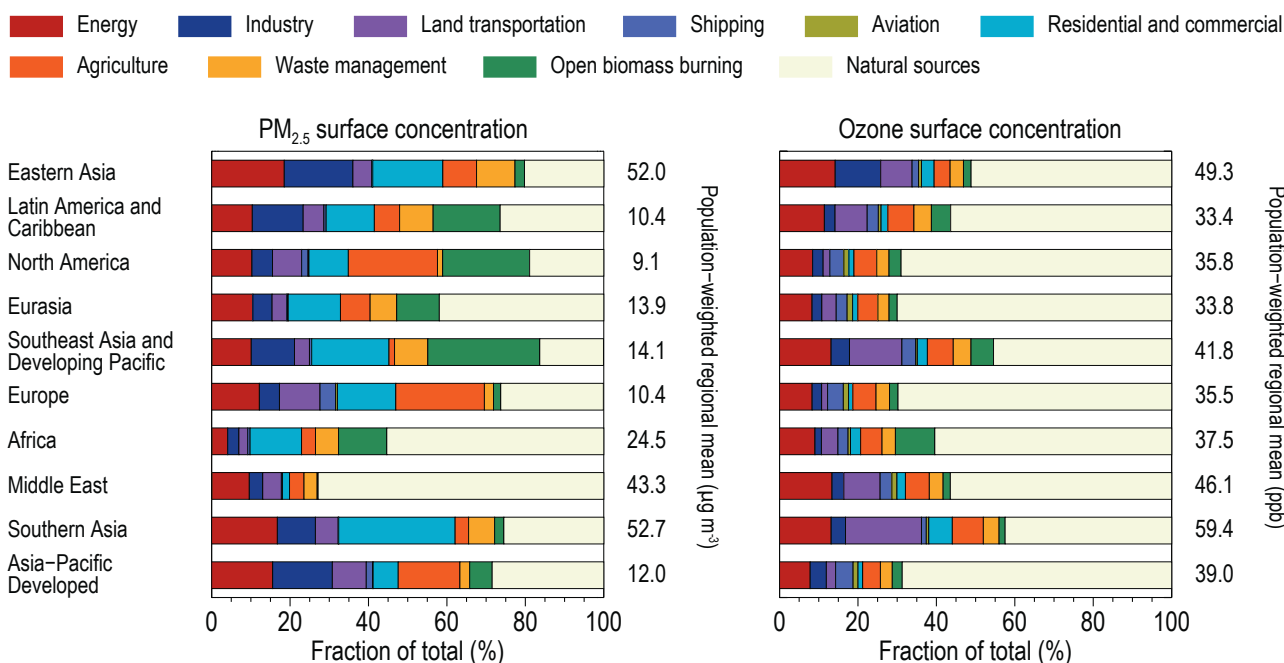


Figure 6.17 | Emissions source-sector attribution of regional population-weighted mean concentrations of PM_{2.5} and ozone for present-day emissions (year 2014). Regional concentrations and source apportionment are calculated with the TM5-FASST model (Van Dingenen et al., 2018) for the 2014 emissions data from the Community Emissions Data System (CEDS) (Hoesly et al., 2018) and van Marle et al. (2017) for open-biomass burning. Dust and sea salt contributions to PM_{2.5} are monthly mean climatological averages over 2010–2018 from CAMS global reanalysis (EAC4) (Inness et al., 2019), generated using Copernicus Climate Change Service information (January 2020). Anthropogenic sectors are similar to those in Figures 6.2 and 6.16, except the grouping of fossil fuel production, distribution and combustion for energy under ‘Energy’ and the grouping of use of fossil fuel and biofuel use for cooking and heating under ‘Residential and Commercial’. Further details on data sources and processing are available in the chapter data table (Table 6.SM.3).

6.6.3 Past and Current SLCF Reduction Policies and Future Mitigation Opportunities

Several SLCF-emissions reduction strategies have been explored in the literature or are already pursued as part of environmental and development policies, including air quality, waste management, energy poverty and climate change. The effects of various policies and strategies have been addressed in a limited number of modelling studies with different objectives that range from assessment of specific policies and their regional effects (UNEP and WMO, 2011; Shindell et al., 2012, 2017b; AMAP, 2015a, b; Haines et al., 2017; UNEP and CCAC, 2018; UNEP, 2019; Harmsen et al., 2020a) to large-scale global-scenario studies with varying levels of SLCF control (e.g., Sand et al., 2016; Rogelj et al., 2018b; Shindell and Smith, 2019). They could be grouped into:

- Projections of future SLCF emissions compatible with the climate change mitigation trajectories investigated in the climate model intercomparison projects (respective RCP or SSP scenarios): in such scenarios, when climate change mitigation is considered, it is associated with a strong decrease of CO₂ emissions, largely relying on fossil fuel-use reduction, along with proportional reductions in the co-emitted SLCFs from combustion and methane from the production and distribution of fossil fuels. Depending on

the carbon price and climate change mitigation target, further reduction of methane from waste and agriculture will also be part of such scenarios. The limitations of RCP scenarios (where continuous strengthening of air-quality legislation was assumed resulting in lack of futures where global and regional air quality deteriorates) for the analysis of air quality and potential for mitigation of SLCFs have been discussed in literature (e.g., Amann et al., 2013; von Schneidmesser et al., 2015). SSP scenarios consider various levels of air pollution control, in accordance with their socio-economic narrative, and thus cover a wider span of SLCF trajectories (Section 6.7). The economic cost of the implementation of these scenarios and their co-benefits on air quality and SDGs are assessed in the AR6 WGIII Report (Chapter 3).

- Projections of SLCF emissions assuming strong reduction of all air pollutants in the absence of climate change mitigation (e.g., the SSP3-lowSLCF scenario): the latter is an idealized simulation of a very ambitious air-quality policy where the maximum technical potential of existing end-of-pipe technologies is explored in the SSP3-7.0 scenario. Methane reduction can also be part of such sensitivity analysis, although methane reductions have not historically been motivated by air pollution concerns.
- Projection of emissions targeting air quality or other development priorities: anthropogenic emissions’ source-structure and the

level of exposure to pollution and subsequent effects varies significantly from one region to another. Therefore, air-quality policies, regional climate impact concerns and development priorities, as well as the consequent level of mitigation of particular SLCF species, will differ regionally and source-wise with respect to the emissions sources, influence of inter-continental transport of pollution, and spatial physical heterogeneities (Lund et al., 2014; AMAP, 2015a; Sand et al., 2016; Turnock et al., 2016; Sofiev et al., 2018; WMO, 2018). This is also the case at a finer local and regional scale where priorities and scope for SLCF mitigation will differ (e.g., Amann et al., 2017; UNEP, 2019).

- Projections exploring mitigation potential for a particular source or SLCF: These studies focus on the assessment of SLCF reduction potential that can be realised with either existing and proven technologies or extend the scope to include transformational changes needed to achieve further reduction (e.g., UNEP and WMO, 2011; Stohl et al., 2015; Velders et al., 2015; Purohit and Höglund-Isaksson, 2017; Gómez-Sanabria et al., 2018; UNEP, 2019; Höglund-Isaksson et al., 2020; Purohit et al., 2020) – several of these studies are subsequently used for parametrization of the models used to develop emissions scenarios (e.g., IAM models used in the IPCC process).

In the following subsections, we assess the SLCF mitigation and its effects as identified in regional and global studies evaluating past and current air quality and other SLCF regulations (Sections 6.6.3.1, 6.6.3.2 and 6.6.3.3). Development policies, independent from the CMIP6 assessment framework, including peer-reviewed studies and initiatives like the United Nations Environment Programme (UNEP), analysing win-win climate, air-quality and SDG-motivated strategies are discussed in Section 6.6.3.4. Note that sensitivity studies where impacts of complete removal of particular species are analysed (e.g., Samset et al., 2018) are used sparingly in this assessment. While such analysis can be useful for assessing the effect of a zero-emissions commitment (Chapter 4.7.1.1), they do not correspond to a realistic SLCF-mitigation strategy with plausible pace of implementation and removal of co-emitted species (Shindell and Smith, 2019). Discussion of climate and air-quality implications of SLCF reductions in SSP scenarios is provided in Section 6.7.

6.6.3.1 Climate Response to Past AQ Policies

Air-quality policies emerged several decades ago focusing on emissions mitigation, first driven by local- then by regional-scale air-quality and ecosystem-damage concerns, that is, health impacts, acidification and eutrophication. They have made it possible to reduce or limit pollution exposure in many megacities or highly populated regions, for example, in Los Angeles, Mexico City and Houston in North America (Parrish et al., 2011), Santiago in Chile (Gallardo et al., 2018), São Paulo in Brazil (Andrade et al., 2017), Europe (Reis et al., 2012; Crippa et al., 2016; Serrano et al., 2019), and over Eastern Asia during the last decade (Silver et al., 2018; Zheng et al., 2018b). However, very few studies have quantified the impact of these policies on climate. The AR5 concluded that air-quality control will have consequences on climate including strong regional variability, however, no estimates of impacts of specific air-quality policy were available. Since AR5, few studies have provided estimates of climate-relevant indicators

affected by significant air pollutant burden changes due to air-quality policy in selected regions. Turnock et al. (2016) estimated that the strong decrease in NO_x , SO_2 and $\text{PM}_{2.5}$ emissions in Europe, induced by air-quality policies resulting in implementation of abatement measures since the 1970s, have caused a surface warming of $+0.45^\circ\text{C} \pm 0.11^\circ\text{C}$ and increase of precipitation $+13 \pm 0.8 \text{ mm yr}^{-1}$ over Europe, compared to the scenario without such policies. While the temperature increase is likely overestimated since the impact of the increase in ammonium nitrate was not considered in this study, the simulated European all-sky TOA radiative effect of the European air pollutant mitigation over the period 1970–2009 is 2.5 times the change in global mean CO_2 radiative forcing over the same period (Myhre et al., 2013). Other studies found that the recent measures to reduce pollution over China have induced a decrease of aerosols and increase of ozone over east China (K. Li et al., 2019, 2020), resulting in an overall warming effect mainly due to the dominant effect of sulphate reductions in the period 2012–2017 (Dang and Liao, 2019).

6.6.3.2 Recently Decided SLCF-relevant Global Legislation

International shipping emissions regulation: from January 2020, a new global standard, proposed by the International Maritime Organisation, limits the sulphur content in marine fuels to 0.5% against the previous 3.5% (IMO, 2016). This legislation is considered in the SSP5 and SSP2-4.5 and with a delay of few years in SSP3-lowSLCF, SSP1-1.9, and SSP1-2.6, and in other SSP-emissions scenarios achieved by the mid-21st century. This global measure aims to reduce the formation of sulphate (and consequently $\text{PM}_{2.5}$) and largely reduce the health exposure to $\text{PM}_{2.5}$, especially over India, east China and coastal areas of Africa, and the Middle East (Sofiev et al., 2018). Sofiev et al. (2018) used a high spatial-and-temporal resolution chemistry climate model and estimated a net total ERF of $+71 \text{ mW m}^{-2}$ associated with this measure and due to lower direct aerosol cooling ($+3.9 \text{ mW m}^{-2}$) and lower cloud albedo ($+67 \text{ mW m}^{-2}$). This value, which corresponds to an 80% decrease of the cooling effect of shipping induced by about 8 Tg of SO_2 of avoided emissions, is consistent with older estimates which considered similar reduction of emitted sulphur. However, there is considerable uncertainty in the indirect forcing since small changes in aerosols, acting as CCNs in a clean environment, can have disproportionately large effects on the radiative balance. Since sulphate is by far the largest component of the radiative forcing (Fuglestad et al., 2008) and of surface temperature effect (Figure 6.16) due to ship emissions over a short time scale, limiting the co-emitted SLCFs can not offset the warming by sulphur reductions. The reduction of sulphur emissions from shipping is assessed to lead to a slight warming mainly due to aerosol–cloud interactions (*medium evidence, medium agreement*).

The Kigali Amendment (UNEP, 2016): with the adoption of the Kigali Amendment to the Montreal Protocol (UN, 1989) in 2016, parties agreed to the phase-down of HFCs, substances that are not ozone depleting but are climate-forcing agents (Papanastasiou et al., 2018). Baseline scenarios, in the absence of controls or only pre-Kigali national legislation, projected increased use and emissions of HFCs. All recent baseline projections are significantly higher than those used in the Representative Concentration Pathways (RCP) scenarios (Figure 6.18; Meinshausen et al., 2011). There is *low*

confidence that the high baseline (assuming absence of controls, lack of technical progress and high growth) as developed by Velders et al. (2009), resulting in additional warming of about 0.5°C by 2100 (Xu et al., 2013; WMO, 2018), is plausible. Evolution of HFC emissions along the baselines consistent with Velders et al. (2009) and Velders et al. (2015) would result in a global average warming, due to HFCs, relative to 2000, of about 0.1°C–0.12°C by 2050 and 0.35°C–0.5°C and 0.28°C–0.44°C by 2100, respectively (Xu et al., 2013). The baseline implementation considered in SSP5-8.5 (Section 6.7.1.1) is comparable to the lower bound of projections by Velders et al. (2015; Figure 6.18) and several other studies (Gschrey et al., 2011; Purohit and Höglund-Isaksson, 2017; EPA, 2019; Purohit et al., 2020) and result in additional warming of 0.15°C–0.3°C by 2100 (*medium confidence*) (Figure 6.22).

Efficient implementation of the Kigali Amendment and national and regional regulations has been projected to reduce global average warming in 2050 by 0.05°C–0.07°C (Klimont et al., 2017b; WMO, 2018) and by 0.2°C–0.4°C in 2100 compared with the baseline (see Figure 2.20 of WMO, 2018). Analysis of SSP scenarios based on an emulator (Section 6.7.3) shows a comparable mitigation potential of about 0.02°C–0.07°C in 2050 and about 0.1°C–0.3°C in 2100 (Figure 6.22, SSP5-8.5 versus SSP1-2.6). Furthermore, the energy efficiency improvements of cooling equipment alongside the transition to low-global-warming potential alternative refrigerants for refrigeration and air-conditioning equipment could potentially increase the climate benefits from the HFC phasedown under the Kigali Amendment (Shah et al., 2015; Höglund-Isaksson et al., 2017; Purohit and Höglund-Isaksson, 2017; WMO, 2018). Purohit et al. (2020) estimated that depending on the expected rate of technological development, improving the energy efficiency of stationary cooling technologies and compliance with the Kigali Amendment could bring future global electricity savings of more than 20% of the world's expected electricity consumption beyond 2050 or cumulative reduction of about 75–275 Gt CO_{2,eq} over the period 2018–2100 (*medium confidence*). This could potentially double the climate benefits of the HFC phase-down of the Kigali Amendment as well as result in small air-quality improvements due to reduced air pollutant emissions from the power sector (i.e., 8–16% reduction of PM_{2.5}, SO₂ and NO_x; Purohit et al., 2020).

6.6.3.3 Assessment of SLCF Mitigation Strategies and Opportunities

There is a consensus in the literature that mitigation of SLCF emissions plays a central role in simultaneous mitigation of climate change, air quality and other development goals including SDG targets (UNEP and WMO, 2011; Shindell et al., 2012, 2017b; Rogelj et al., 2014b, 2018b; AMAP, 2015a; Haines et al., 2017; Klimont et al., 2017b; McCollum et al., 2018; Rafaj et al., 2018; UNEP and CCAC, 2018; UNEP, 2019). There is less agreement in the literature with respect to the actual mitigation potential (or its potential rate of implementation), necessary policies to trigger successful implementation, and resulting climate impacts. Most studies agree that climate policies, especially those aiming to keep warming below 1.5°C or 2°C, trigger large SLCF mitigation co-benefits, (e.g., Rogelj et al., 2014b, 2018b), however, discussion of practical implementation of respective policies and

SDGs has only started (Haines et al., 2017). Note that mitigation scenarios outside of the SSP framework are assessed here while those within the SSPs are assessed in Section 6.7.3.

Focusing on air quality, specifically addressing aerosols, by introducing the best available technology reducing PM_{2.5}, SO₂ and NO_x in most Asian countries within the 2030–2050 time frame (a strategy that has indeed shown reduction in PM_{2.5} exposure in China) comes, in many regions, short of national regulatory PM_{2.5} concentration standards (often set at 35 µg m⁻³ for annual mean; UNEP, 2019). Similarly, global studies (Rafaj et al., 2018; Amann et al., 2020) show that strengthening current air-quality policies, that address primarily aerosols and their precursors, will not enable the achievement of WHO air quality guidelines (annual average concentration of PM_{2.5} below 10 µg m⁻³) in many regions.

A multi-model study (four ESMs and six CTMs) found a consistent response to the removal of SO₂ emissions that resulted in a global mean surface temperature increase of 0.69°C (0.4°C–0.84°C). However, results are mixed for a global BC-focused deep SLCF reduction without SO₂ and methane mitigation which remain as in the baseline (see ECLIPSE in Figure 6.18). BC contributed about –0.022°C temperature reduction for the decade 2041–2050 based on the assumption that mitigation of the non-methane species contributed only about 10% of the global temperature reduction for the strategy where methane mitigation was also included (–0.22°C ± 0.07°C; Stohl et al., 2015). These results are consistent with studies analysing similar strategies using emulators (e.g., Smith and Mizrahi, 2013; Rogelj et al., 2014b). Stohl et al. (2015) also analysed the impact of BC-focused mitigation on air quality, estimating large-scale regional reduction in PM_{2.5} mean concentration from about 2% in Europe to 20% over India for the decade 2041–2050.

Local response to global reduction can be higher than the global temperature response, particularly for regions subjected to rapid changes. Hence, mitigation of rapid warming in the Arctic has been subject to an increasing number of studies (Sand et al., 2013b, 2016; Jiao et al., 2014; AMAP, 2015a, b; Mahmood et al., 2016; Christensen et al., 2019). Considering maximum technically feasible reductions (MTFR) for methane globally and an idealized strategy reducing key global anthropogenic sources of BC (about 80% reduction by 2030 and sustained thereafter) and precursors of ozone was estimated to jointly bring a reduction of Arctic warming, averaged over the 2041–2050 period, between 0.2°C and 0.6°C (AMAP, 2015a; Sand et al., 2016). Stohl et al. (2015) have estimated that a global SLCF mitigation strategy (excluding further reduction of SO₂) would lead to about twice as high a temperature reduction (–0.44 (–0.39 to –0.49) °C) in the Arctic than the global response to such mitigation.

While there is *robust evidence* that air-quality policies resulting in reductions of aerosols and ozone can be beneficial for human health but can lead to 'disbenefits' for near-term climate change, the existence of such trade-offs in response to climate change mitigation policies is less certain (Shindell and Smith, 2019). Recent studies show that very ambitious but plausible gradual phasing out of fossil fuels in 1.5°C-compatible pathways with little or no overshoot, lead to a near-term future warming of less than 0.1°C, when considering

associated emissions reduction of both warming and cooling species. This suggests that there may not be a strong conflict, at least at the global scale, between climate and air-quality benefits in the case of a worldwide transition to clean energy (Shindell and Smith, 2019; Smith et al., 2019). However, at the regional scale, the changes in spatially variable emissions and abundance changes might result in different responses, including implications for precipitation and monsoons (Chapter 8), especially over Southern Asia (e.g., Wilcox et al., 2020).

Decarbonization of energy supply and end-use sectors is among key pillars of any ambitious climate change mitigation strategy and it would result in improved air quality owing to associated reduction of co-emitted SLCF emissions (e.g., McCollum et al., 2013; Rogelj et al., 2014b; Braspenning Radu et al., 2016; Rao et al., 2016; Stechow et al., 2016; Lelieveld et al., 2019; Shindell and Smith, 2019). Regional studies (Lee et al., 2016; Shindell et al., 2016; Chen et al., 2018; Li et al., 2018), where significant CO₂ reductions were assumed for 2030 and 2050, show consistently reduced PM_{2.5} and ozone concentrations resulting in important health benefits. However, these improvements are not sufficient to bring PM_{2.5} levels in agreement with the WHO air-quality guidelines in several regions. Amann et al. (2020) and UNEP (2019) highlight that only the combination of strong air-quality, development and climate policies, including societal transformations, could pave the way towards the achievement of such a target at a regional and global level.

At a global level, Rao et al. (2016) showed that climate policies, compatible with Copenhagen pledges and a long-term CO₂ target of 450 ppm, result in important air-quality benefits, reducing the share of the global population exposed to PM_{2.5} levels above the WHO Tier 1 standard (35 µg m⁻³) in 2030 from 21% to 5%. The impacts are similar to a strong air-quality policy but still leave large parts of population, especially in Asia and Africa, exposed to levels well above the WHO air quality guideline level of 10 µg m⁻³. The latter can be partly alleviated by combining such climate policy with strong air-quality policy. Shindell et al. (2018) analysed more ambitious climate change mitigation scenarios than Rao et al. (2016) and highlighted the opportunities to improve air quality and avert societal effects associated with warmer climate by accelerated decarbonization strategies. Most climate change mitigation strategies compatible with limiting global warming to well below 2°C rely on future negative CO₂ emissions postponing immediate reduction. Alternatively, a faster decarbonization could allow the achievement of a 2°C goal without

negative CO₂ emissions and, with currently known and effectively applied emissions-control technologies, this would also have immediate and significant air-quality benefits, reducing premature deaths worldwide (Shindell et al., 2018). For a 2°C-compatible pathway, Vandyck et al. (2018) estimated 5% and 15% reduction in premature mortality due to PM_{2.5} in 2030 and 2050, respectively, compared to reference scenarios.

There is *robust evidence* that reducing atmospheric methane will benefit climate and improve air quality through near-surface ozone reduction (Fiore et al., 2015; Shindell et al., 2017a) and wide agreement that strategies reducing methane offer larger (and less uncertain) climate benefits than policies addressing BC (e.g., Smith and Mizrahi, 2013; Rogelj et al., 2014b, 2018b; Stohl et al., 2015; Christensen et al., 2019; Shindell and Smith, 2019). SR1.5 (Rogelj et al., 2018b) highlighted the importance of methane mitigation in limiting warming to 1.5°C in addition to net zero CO₂ emissions by 2050. Implementation of the identified maximum technically feasible reductions (MTFR) potential for methane globally, estimated at nearly 50% reduction (or 205 Tg CH₄ in 2050) of anthropogenic emissions from the baseline, would lead to a reduction in warming, calculated as the differences between the baseline and MTRF scenario, for the 2036–2050 period of about 0.20°C ± 0.02°C globally (AMAP, 2015b). Plausible levels of methane mitigation, achieved with proven technologies, can increase the feasibility of achieving the Paris Agreement goal through slightly slowing down the pace of CO₂ reductions (but not changing the final CO₂ reduction goal) while this benefit is enhanced by the indirect effects of methane mitigation on ozone levels (Collins et al., 2018). Addressing methane mitigation appears even more important in view of recently observed growth in atmospheric concentrations that is linked to increasing anthropogenic emissions (Section 5.2.2).

Neither ambitious climate change policy nor air-quality abatement policy can automatically yield co-benefits without integrated policies aimed at co-beneficial solutions (Zusman et al., 2013; Schmale et al., 2014a; Melamed et al., 2016), particularly in the energy generation and transport sectors (Rao et al., 2013; Thompson et al., 2016; Shindell et al., 2018; Vandyck et al., 2018). Integrated policies are necessary to yield multiple benefits of mitigating climate change, improving air quality, protecting human health and achieving several SDGs.

Box 6.2 | SLCF Mitigation and Sustainable Development Goals (SDG) Opportunities

Striving to achieve air-quality and climate targets will bring significant SLCF reductions. These reductions contribute first and foremost to the attainment of SDGs targeting improved human health and sustainable cities (SDGs 3 and 11), specifically related to PM exposure (goals 3.9 and 11.6; Lelieveld, 2017; Amann et al., 2020), but also access to affordable and clean energy, responsible consumption and production, and climate, as well as reducing nutrient losses and consequently protecting biodiversity (SDG 7, 12, 13, 14 and 15; UNEP, 2019; Amann et al., 2020). Furthermore, declining SLCF emissions will result in reduced crop losses (SDG 2; zero hunger) due to decrease of ozone exposure (Feng and Kobayashi, 2009; Ainsworth et al., 2012; Emberson et al., 2018).

However, the design of suitable policies addressing these SDGs can be difficult because of the complexity of linking emissions to impacts on human health, ecosystems, equity, infrastructure and costs. Beyond the fact that several species are co-emitted, interlinkage

Box 6.2 (continued)

between species, such as through atmospheric chemistry, can weaken the benefit of emissions reduction efforts. An illustration lies in the recent (2013–2017) reduction of aerosols over China (Silver et al., 2018; Zheng et al., 2018b) resulting from the strategy to improve air quality ('Clean Air Action'); this has successfully reduced the level of PM_{2.5} but has led to a concurrent increase in surface ozone, partly due to declining heterogeneous interactions of ozone precursors with aerosols (K. Li et al., 2019; Yu et al., 2019). This side effect on ozone has been addressed since then by amending the legislation to target NMVOC sources, especially solvent use. Complex interactions between anthropogenic and biogenic volatile compounds are also at play and reduction of certain SLCFs could possibly promote new particle formation from organic vapours (e.g., Lehtipalo et al., 2018). Finally, a recent example of this complexity is the mixed effects on ozone pollution induced by NO_x decrease during the COVID-19 pandemic (Cross-Chapter Box 6.1). Thus, the climate and air pollution effects of policies depend strongly on the choice of regulated compounds and the degree of reduction. Such policies have to be informed by strong science support, including for example multi-model analyses such as HTAP (UNECE, 2010) and AMAP (AMAP, 2015a, b), based on global and regional CCMs. This is essential to capture the complexity and inform the policy development process.

In addition, pursuing SDG objectives, apparently decoupled from air pollution, such as improved waste management, access to clean energy, or improved agricultural practices, would also stimulate and lead to mitigation of SLCFs. Amann et al. (2020) show that a global strategy to achieve the WHO air quality guidelines, cannot only rely on air pollution control but also on a combination of SDG-aligned policies. Such actions would include energy efficiency improvements, increased use of renewables, reduction of methane from waste management and agriculture, and CO₂ and methane due to lower fossil fuel consumption, resulting in climate co-benefits. Consideration of SDGs including local air-quality co-benefits, creates an opportunity to support and gain acceptance for ambitious climate change mitigation (Jakob and Steckel, 2016; Stechow et al., 2016; Vandyck et al., 2018). Such near-term policies targeting SDGs and air quality would enable longer-term transformations necessary to achieve climate goals (Chapter 17, WGIII).

In summary, there is *high confidence* that effective decarbonization strategies could lead to air-quality improvements but are not sufficient to achieve, in the near term, air-quality WHO guideline values set for fine particulate matter, especially in parts of Asia and in some highly polluted regions. Additional policies (e.g., access to clean energy, waste management) envisaged to attain SDGs bring complementary

SLCF reduction (*high confidence*). Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to an air pollution benefit by reducing ozone levels globally (*high confidence*).

Cross-Chapter Box 6.1 | Implications of COVID-19 Restrictions for Emissions, Air Quality and Climate

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In response to the outbreak of COVID-19 (officially the severe acute respiratory syndrome–coronavirus 2 or SARS-CoV-2), which was declared a pandemic on March 11 2020 by the World Health Organization (WHO), regulations were imposed by many countries to contain the spread of COVID-19. Restrictions were implemented on the movement of people, such as closing borders or requiring the majority of population to stay at home, for periods of several months. This Cross-Chapter Box assesses the influence of the COVID-19 containment on short-lived climate forcers (SLCFs) and long-lived greenhouse gases (LLGHGs), and related implications for the climate. Note that this assessment was developed late in the AR6 WGI process and is based on the available emerging literature.

Emissions

Global fossil CO₂ emissions are estimated to have declined by 7% (*medium confidence*) in 2020 compared to 2019 emissions, with estimates ranging from 5.8% to 13.0% based on various combinations of data on energy production and consumption, economic activity and proxy activity data for emissions and their drivers (Forster et al., 2020; Friedlingstein et al., 2020; Le Quéré et al., 2020; Liu et al., 2020). However, the concentration of atmospheric CO₂ continued to grow in 2020 compared to previous years (Dlugokencky and Tans, 2021). Given the large natural interannual variability

Cross-Chapter Box 6.1 (continued)

of CO₂ (Section 5.2.1), and the small expected impact of emissions in the CO₂ growth rate, there were no observed changes in CO₂ concentration that could be attributed to COVID-19 containment (*medium confidence*) (Chevallier et al., 2020; Tohjima et al., 2020).

Global daily CO₂ emissions from fossil fuel sources had a maximum decline of 17% in early April, compared with the mean 2019 levels, and coinciding with the global peak pandemic lockdown (Le Quéré et al., 2020). The reductions in CO₂ emissions in 2020 were dominated by the drop in emissions from surface transport followed, in order of absolute emissions reductions, by industry, power and aviation (Le Quéré et al., 2020; Liu et al., 2020). Residential emissions showed little change (Liu et al., 2020) or rose slightly (Forster et al., 2020; Le Quéré et al., 2020). Aviation had the biggest relative drop in activity. CO₂ emissions due to land use (based on early and uncertain evidence on deforestation and forest fires) were higher than average in 2020 (Amador-Jiménez et al., 2020).

Using similar methodologies, Forster et al. (2020) assembled activity data and emissions estimates for other greenhouse gases and aerosols and their precursors. Anthropogenic NO_x emissions, which are largely from the transport sector, are estimated to have decreased by a maximum of 35% in April (*medium confidence*). Species whose emissions are dominated by other sectors, such as methane and NH₃ from agriculture, saw smaller reductions.

Abundances and air quality

Owing to the short atmospheric lifetimes of SLCFs relevant to air quality, changes in their concentrations were detected within a few days after lockdowns had been implemented (e.g., Bauwens et al., 2020; Venter et al., 2020; Gkatzelis et al., 2021; Shi et al., 2021). The COVID-19-driven economic slowdown has illustrated how complex the relationship is between emissions and air pollutant concentrations due to non-linearity in the atmospheric chemistry leading to secondary compound formation (Section 6.1, Box 6.1; Kroll et al., 2020).

Several studies have examined the effect of COVID-19 containment on air quality, showing that multi-year datasets with proper statistical/modelling analysis are required to discriminate the effects of meteorology from that of emissions reduction (Dhaka et al., 2020; L. Li et al., 2020; Wang et al., 2020; Zhao et al., 2020b). Accounting for meteorological influences and with an increasing stringency index, the median observed change in NO₂ decreased from –13% to –48%, and in PM_{2.5} decreased from –10% to –33%, whereas the median change in ozone increased from 0% to 4% (Gkatzelis et al., 2021). The latter can be explained by the decrease of NO emissions that titrate ozone in specific highly polluted areas, leading to the observed increase in surface ozone concentration in cities (Le et al., 2020; Sicard et al., 2020; Huang et al., 2021).

The temporary decrease of PM_{2.5} concentrations should be put in perspective of the sustained reduction (estimated at 30–70%), which could be achieved by implementing policies addressing air quality and climate change (Section 6.6.3). Such sustained reductions can lead to multiple benefits and simultaneously achieve several SDGs (Section 6.6.3). These policies would also result in reduction of ground-level ozone by up to 20% (Section 6.7.1.3).

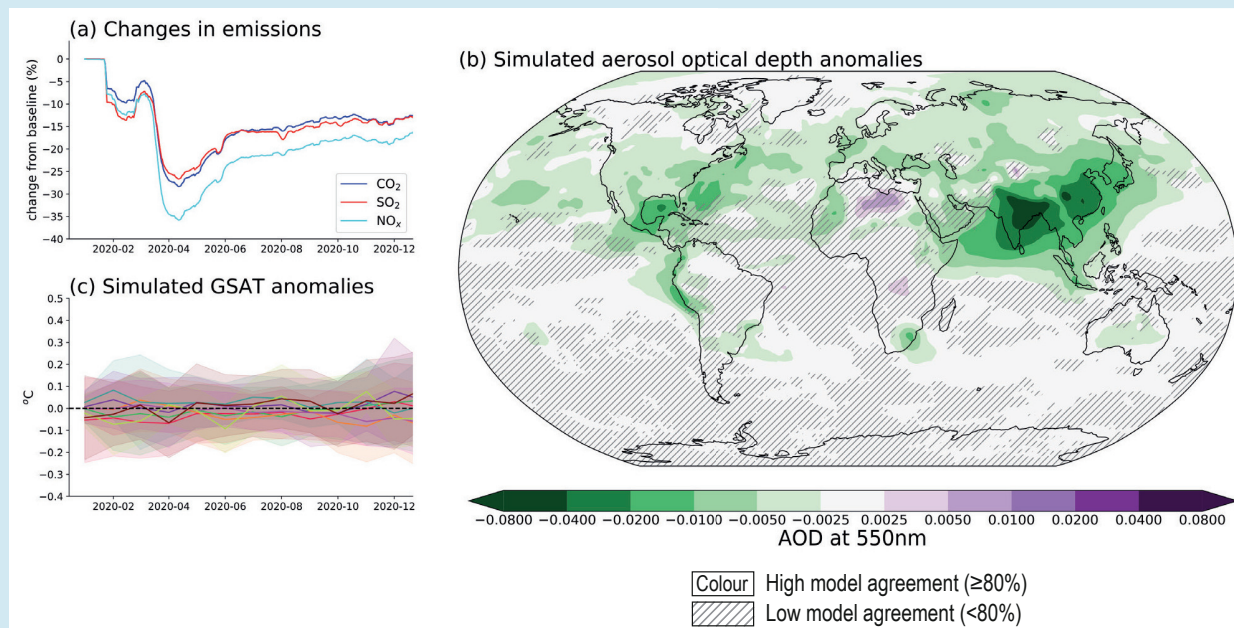
Except for ozone, temporary improvement of air quality during lockdown periods was observed in most regions of the world (*high confidence*), resulting from a combination of interannual meteorological variability and the impact of COVID-19 containment measures (*high confidence*). Estimated air pollution reductions associated with lockdown periods are lower than what can be expected from integrated mitigation policy leading to lasting reductions (*medium confidence*).

Radiative forcings

COVID-19-related emissions changes primarily exerted effective radiative forcing (ERF) through reduced emissions rates of CO₂ and methane, altered abundance of SLCFs, notably ozone, NO₂ and aerosols, and through other changes in anthropogenic activities, notably a reduction in the formation of aviation-induced cirrus clouds.

Forster et al. (2020) combined the FalR emulator (Cross-Chapter Box 7.1) with emissions changes for a range of species, relative to a continuation of Nationally Determined Contributions (Rogelj et al., 2017). They found a negative ERF from avoided CO₂ emissions that strengthens through 2020 to –0.01 W m^{–2}. During the spring lockdown, they found a peak positive ERF of 0.1 W m^{–2} from loss of aerosol-induced cooling, and a peak negative ERF of –0.04 W m^{–2} from reductions in tropospheric ozone (from reduced photochemical production via NO_x). Overall, they estimated a net ERF of +0.05 W m^{–2} for spring 2020, declining to +0.025 W m^{–2} by the end of the year.

Cross-Chapter Box 6.1 (continued)



Cross-Chapter Box 6.1, Figure 1 | Emissions reductions and their effect on aerosols and climate in response to COVID-19. Estimated reductions in emissions of CO₂, SO₂ and NO_x are shown in panel (a) based on reconstructions using activity data (updated from Forster et al., 2020). Eight Earth system models (ESMs) performed multiple ensemble simulations of the response to COVID-19 emissions reductions forced with these assumed emissions reductions up until August 2020 followed by a constant continuation near the August value to the end of 2020. Emissions reductions were applied relative to the SSP2-4.5 scenario. Panel (b) shows ESM-simulated AOD at 550nm (only seven models reported this variable). Panel (c) shows ESM-simulated GSAT anomalies during 2020; curves denote the ensemble mean result for each model with shading used for ± 1 standard deviation for each model. ESM data from these simulations ('ssp245-covid') is archived on the Earth System Grid CMIP6 database. Uncertainty is represented using the simple approach: no overlay indicates regions with high model agreement, where $\geq 80\%$ of models agree on sign of change; diagonal lines indicate regions with low model agreement, where $< 80\%$ of models agree on sign of change. For more information on the simple approach, please refer to the Cross-Chapter Box Atlas. 1.

Gettelman et al. (2021) extended Forster et al.'s (2020) results using two ESMs, and found a spring peak aerosol-induced ERF ranging from 0.12 to 0.3 W m⁻², depending on the aerosol parametrization. They also estimated an ERF of -0.04 W m⁻² from loss of contrail warming. Overall, they report a peak ERF of 0.04 to 0.2 W m⁻², and a subsequent decline to around half the peak value. Two independent ESM studies Weber et al. (2020) and Yang et al. (2020) found consistent results in time evolution and component contributions but included fewer forcing components.

The available studies are in broad agreement on the sign and magnitude of contributions to ERF from COVID-19-related emissions changes during 2020. The range in peak global mean ERF in spring 2020 was [0.025 to 0.2] W m⁻² (*medium confidence*), composed of a positive forcing from aerosol-climate interactions of [0.1 to 0.3] W m⁻², and negative forcings from CO₂ (-0.01 W m⁻²), NO_x (-0.04 W m⁻²) and contrail cirrus (-0.04 W m⁻²) (*limited evidence, medium agreement*). By the end of 2020, the ERF was at half the peak value (*medium confidence*).

Climate responses

Changes in atmospheric composition due to COVID-19 emissions reductions are not thought to have caused a detectable change in global temperature or rainfall in 2020 (*high confidence*). A large ensemble of Earth system model (ESM) simulations show an ensemble average reduction in Aerosol Optical Depth (AOD) in some regions, notably Eastern and Southern Asia (Fyfe et al., 2021). This result is supported by observational studies finding decreases in optical depth in 2020 (Gkatzelis et al., 2021; Ming et al., 2021; van Heerwaarden et al., 2021), which may have contributed to observed increases in solar irradiance (van Heerwaarden et al., 2021) or solar clear-sky reflection (Ming et al., 2021).

Cross-Chapter Box 6.1 (continued)

Model simulations of the response to COVID-19 emissions reductions indicate a small warming of global surface air temperature (GSAT) due to a decrease in sulphate aerosols (Forster et al., 2020; Fyfe et al., 2021), balanced by cooling due to an ozone decrease (Forster et al., 2020; Weber et al., 2020), black carbon decrease (Weber et al., 2020) and CO₂ decrease. It is noted that observational studies report little SO₂ change, at least locally near the surface (Shi et al., 2021), and do not correlate with emissions inventory-based changes (Gkatzelis et al., 2021). One study suggests a small net warming while another using idealized simulations suggests a small cooling (Weber et al., 2020). Simulated GSAT and rainfall changes are unlikely to be detectable in observations (*high confidence*) (Samset et al., 2020; Fyfe et al., 2021). Multi-model ESM simulations based on a realistic COVID-19 containment forcing scenario (Forster et al., 2020) indicate a model mean reduction in regional AOD but no discernible response in GSAT (Figure 1, Cross-Chapter Box 6.1).

6.7 Future Projections of Atmospheric Composition and Climate Response in SSP Scenarios

This section assesses the 21st-century projections of SLCF emissions, abundances and responses in terms of climate and air quality following the SSPs (Chapter 1, Section 1.6.1.3 and Cross-Chapter Box 1.5; Riahi et al., 2017; Gidden et al., 2019). The future evolution of atmospheric abundances and the resulting climate and AQ responses is driven mainly by anthropogenic emissions and by natural emissions modulated by chemical, physical and biological processes as discussed in Sections 6.2 and 6.3. Like the RCP scenarios used in AR5, the SSP emissions scenarios consider only direct anthropogenic (including biomass burning) emissions and do not project natural emissions changes due to climate or land-use changes; ESMs intrinsically consider these biogeochemical feedbacks to varying degrees (Section 6.4.5). We rely on future projections based on CMIP6 ESMs with comprehensive representation of chemistry, aerosol microphysics and biospheric processes that participated in the ScenarioMIP (O'Neill et al., 2016) and AerChemMIP (Collins et al., 2017). However, due to the high computational costs of running coupled ESMs, they cannot be used for quantifying the contributions from individual species, regions and sectors, and across the scenarios. Therefore, reduced complexity models (Box 1.3 and Cross-Chapter Box 7.1), which represent chemistry and complex ESM interactions in parametrized forms updated since the AR5, are also applied here.

6.7.1 Projections of Emissions and Atmospheric Abundances

6.7.1.1 SLCF Emissions and atmospheric abundances

The trajectory of future SLCF emissions is driven by the evolution of socio-economic drivers described in Section 1.6.1.1 but dedicated, SSP-specific, air pollution policy storylines can change the regional and global trends (Rao et al., 2017). Additionally, assumptions about urbanization (Jiang and O'Neill, 2017) will affect the spatial distribution of emissions and consequently air quality.

Growing urbanization worldwide has strongly modified the spatial distribution and intensity of SLCF emissions. The effect and extent of urbanization on air pollution and other emissions species are captured within Integrated Assessment Models (IAMs) at varying levels of complexity. In most cases, models use a combination of proxies and assumptions of end-use efficiency and technological improvement assumptions to estimate emissions arising from rural-to-urban migration and population growth within cities, utilizing quantifications of urbanization for the SSPs (Jiang and O'Neill, 2017). In addition, spatial patterns of future rural and urban population growth, migration, and decline have been quantified for the SSPs using a gravity model (Jiang and O'Neill, 2017). However, linking these spatial patterns with IAM regional emissions pathways is still an ongoing area of study and has not yet been represented in spatial emissions estimates provided by IAMs (Riahi et al., 2017; Gidden et al., 2019; Feng et al., 2020). As described in Feng et al. (2020), spatial emissions estimates derived from CMIP6 are largely a product of existing spatial patterns of population, but do not vary dynamically in future patterns. To the extent urbanization is accounted for in gridded emissions, IAM native region resolution (varying, for example, from 11 world regions to more than 30, depending on the model) provides urbanization-based dynamics. Despite the interest of studying the effect of well-planned, densely populated urban centres, which can help to maximize the benefits of agglomeration, by providing proximity to infrastructure and services, the opportunity for energy saving, and providing a frame for air-quality control, IAM realizations of SSPs are not sufficient to assess this effect. The opportunities and risks associated with this rapid urbanization for SLCF emissions and air quality are analysed in the Chapter 6 of the WGII report and Chapter 8 of the WGIII report.

All the RCP trajectories started in 2005 and relied on the assumption that economic growth will bring rapid strengthening of air pollution legislation, effectively reducing emissions of non-methane SLCFs (e.g., Chuwah et al., 2013). While in the long-term such trends are expected if more ambitious air pollution control goes on par with economic growth. The near-term developments, however, might be much more diverse across regions and species, as has been observed in the last three decades (Amann et al., 2013; Rafaj et al., 2014; Rafaj and Amann, 2018; Ru et al., 2018), especially in several fast-growing economies, leading to the difference between CMIP6 historical