City Climate
Finance Gap Fund

GAP FUND TECHNICAL NOTES

GREENHOUSE GASES: A PRIMER FOR URBAN PRACTITIONERS

MARCH 2023

A multi-gas perspective on urban climate mitigation

- Cities contribute **70% of greenhouse gas (GHG)** emissions that are responsible for the majority of observed and anticipated global warming – Strong mitigation action is needed.

- Most of this warming is attributed to emission of **carbon dioxide or CO_2** associated with combustion of fossil fuels. As a result, most efforts have been directed at reducing this key and important gas.

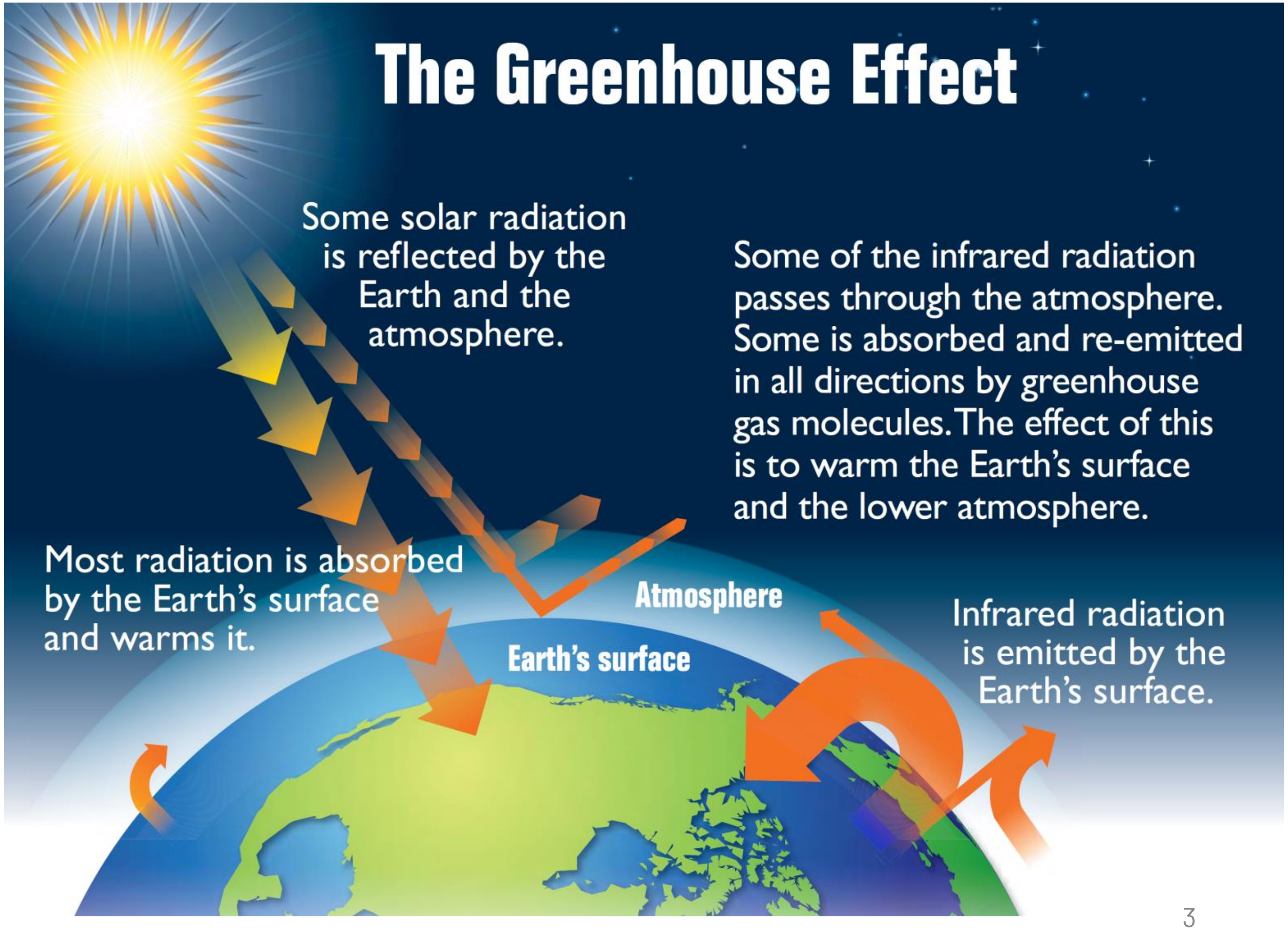
- However, the **non-CO_2 GHGs** emitted directly by human activities include methane (CH_4) and nitrous oxide (N_2O), and a group of industrial gases including perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6). When taken together with the already banned chlorofluorocarbons (CFCs), their climate significance over the past century is **roughly equivalent to that of CO_2**.

- The objective of this note is to discuss the varying sources and impacts of CO_2 and non-CO_2 gases, place their emissions into context, and discuss ways in which cities can address their contributions to global warming.

Photo: Kentaro Iemoto

Global warming via the greenhouse effect

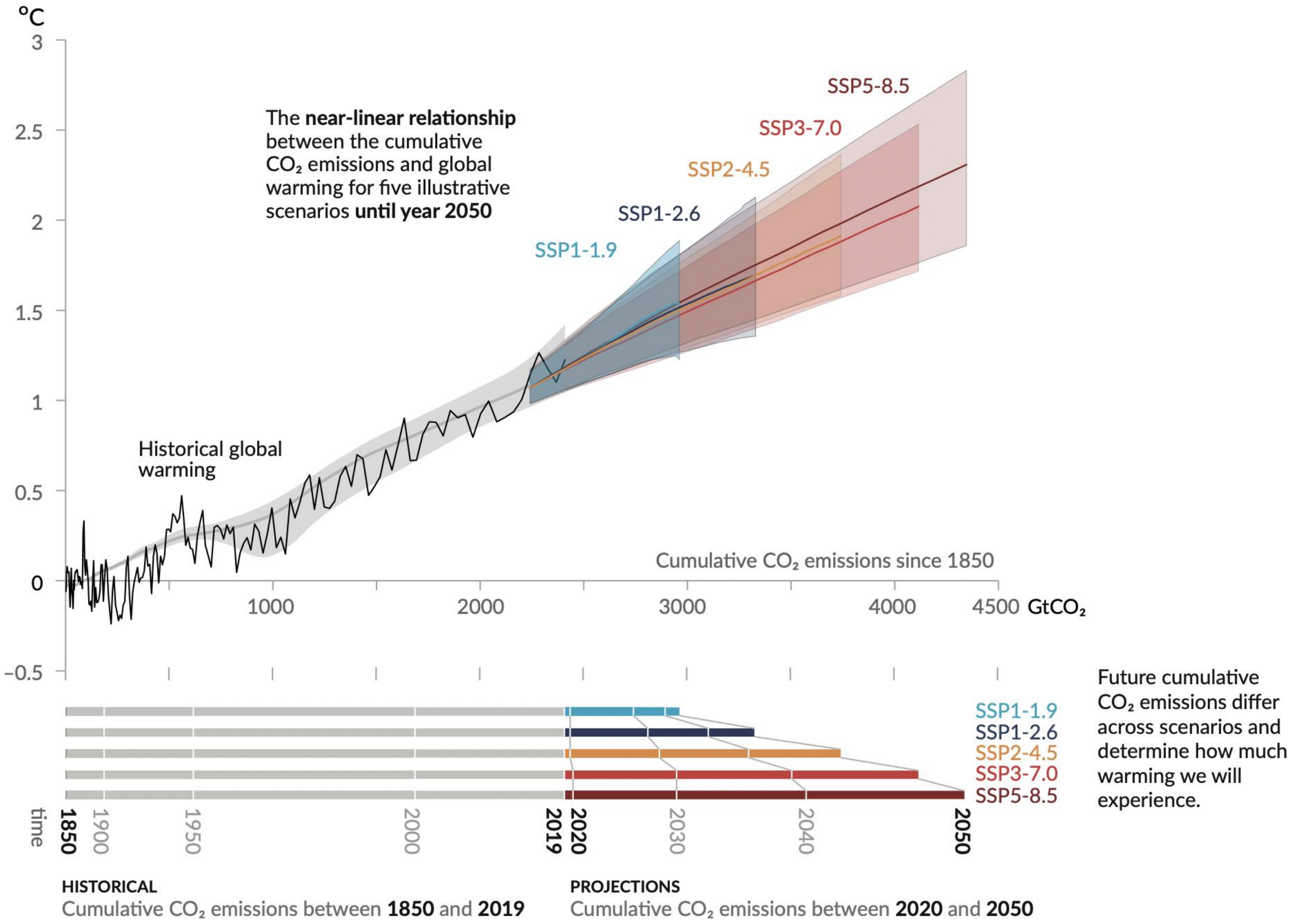
- Light from the sun heats the surface of the Earth.
- There is a natural balance of light that reflects to space or heats the atmosphere.
- Some heat from the surface of the earth is "captured" by the natural CO_2 and other gases in the atmosphere (water vapor, natural methane, etc.).
- The more we add CO_2, methane and other GHGs to the atmosphere, the more heat energy the atmosphere absorbs from the surface of the earth.
- Over time, the balance shifts to a warmer equilibrium.



Source: US EPA (2012)

Every tonne of CO_2 emissions adds to global warming

Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)



Source: IPCC WG1, 2021

The problem is cumulative!

Warming won't stop until we cease <u>all</u> carbon emissions.

What is CO_2-equivalence?

- Increased CO_2 emissions are the primary driver of human-made climate change and global warming; however other emissions also contribute.
- The 6 primary gases that contribute (often called the 'Kyoto gases' because they were called out in the Kyoto Protocol) include: Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulfur Hexafluoride (SF_6).
- Each gas has a factor that allows you to convert 1 ton of emissions of other gases into the equivalent contribution of 1 ton of CO_2.
- When expressed as a ton of CO_2, the contribution of other gases are said to be expressed as "CO_2-equivalent" or "CO_2e."
- The factor for converting other gases to CO_2e is called the "global warming potential" or GWP and is usually expressed as the GWP_{100} denoting that the accounting is done over a 100-year period.
- This accounting can be done for other time periods, such as 20 years, which is relevant for shorter-lived species, like methane.

Short-Lived Climate Pollutants (SLCPs)

- Some emissions are far more potent than CO_2 but may only last in the atmosphere for a few weeks or months. For these short-lived pollutants, a different GWP (like GWP_{20}) may provide better insight into their contribution to global warming over the near-term but can overestimate impact into the future.

- For example, kg for kg, **methane** warms much more than CO_2. However, methane has a lifetime of only 12 years, compared to CO_2's lifetime of more than 100 years. Thus, 1 ton of methane is 28 times more potent than CO_2 measured over 100 years (GWP_{100} = 28) because most of the methane will be gone after 10 or so years, but it is 86 times more potent than CO_2 when measured over a shorter period like 20 years (GWP_{20} = 86).

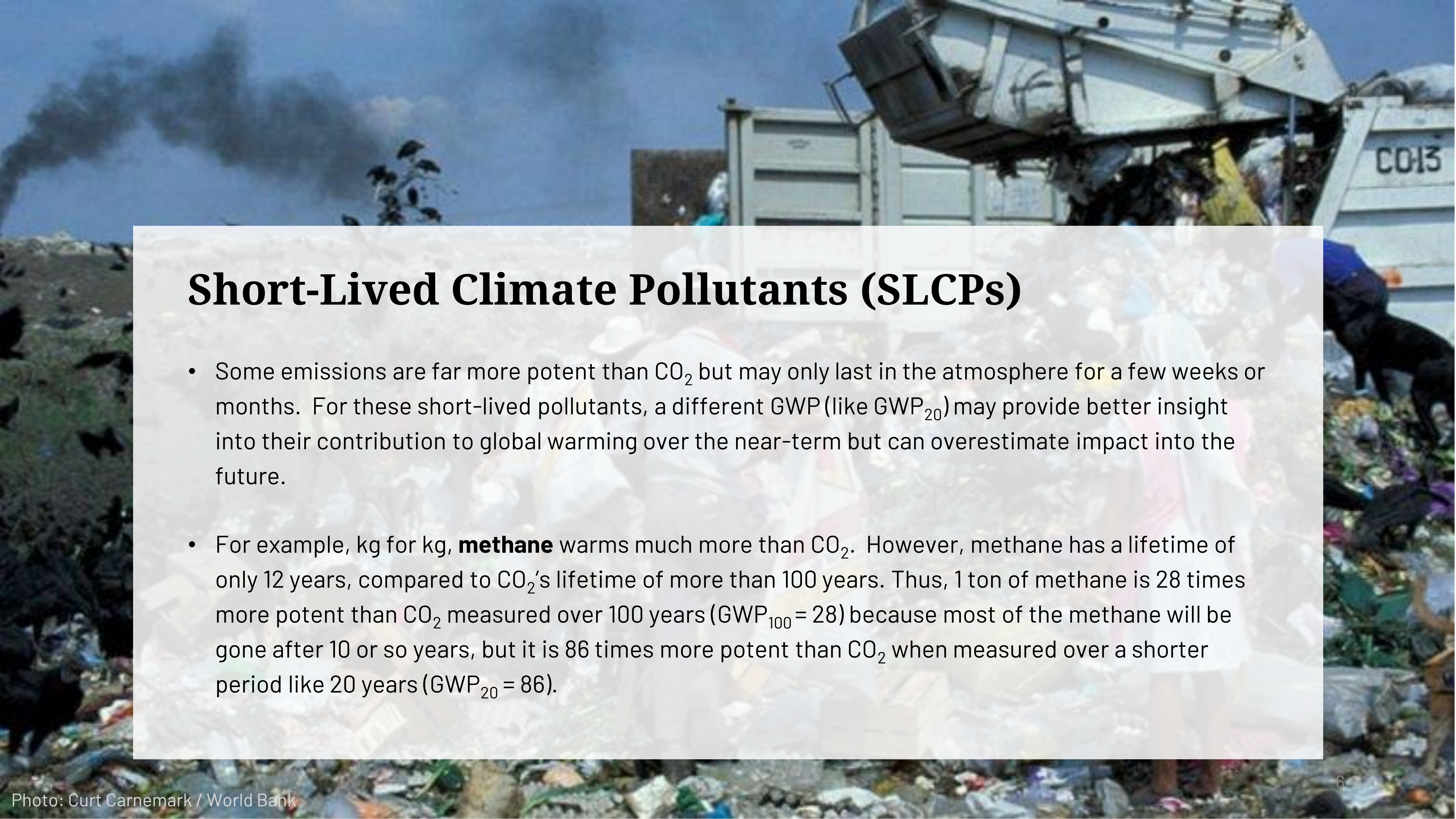


Photo: Curt Carnemark / World Bank

SLCPs (continued)

- **Black Carbon (BC),** or soot, is a solid component of air pollution (fine particles) that results from inefficient combustion and lasts for only a few weeks in the air; however, 1 ton of BC emissions still warms the atmosphere hundreds of times more than 1 ton of CO_2 even when measured over 100 years and thousands of times more than CO_2 when measured over 20 years.

- BC is also a component of fine **particulate matter ($PM_{2.5}$)**, the form of air pollution responsible for the greatest burden of air pollution-related disease, so reducing $PM_{2.5}$ (especially from BC-rich sources) saves lives and cools the planet simultaneously and quickly!

Each pollutant has a unique potential to warm the planet and will also warm over a unique timescale.

While we need to reduce all climate pollution, reducing SLCPs immediately and avoiding lock-in to long-lived GHG infrastructure can provide immediate relief while we decarbonize the broader economy!

Ambient Air Pollution (AAP)

- Many sources of GHG emissions or SLCP emissions are also sources of more traditional air pollutants (i.e., fine particulate matter or $PM_{2.5}$, BC and organic carbon or OC, nitrogen dioxide or NO_2, sulfur dioxide or SO_2 and toxic chemicals).

- Reductions of GHGs that have common sources with ambient air pollution can result in multiple development benefits including cooling the planet, protecting public health associated with reduced air pollution exposure, increased food and energy security, reduced traffic fatalities and congestion, enhanced economic activity through alternative patterns of investment and quality-of-life benefits.

- By including the multiple benefits of emission reduction in GHG planning assessments, you can improve cost-benefit assessments and engage a broader array of stakeholders to support climate action plans with multiple benefits.

Photo: Mark Danielson

Example conversion factors (GWPs) to estimate GHGs as CO_2e

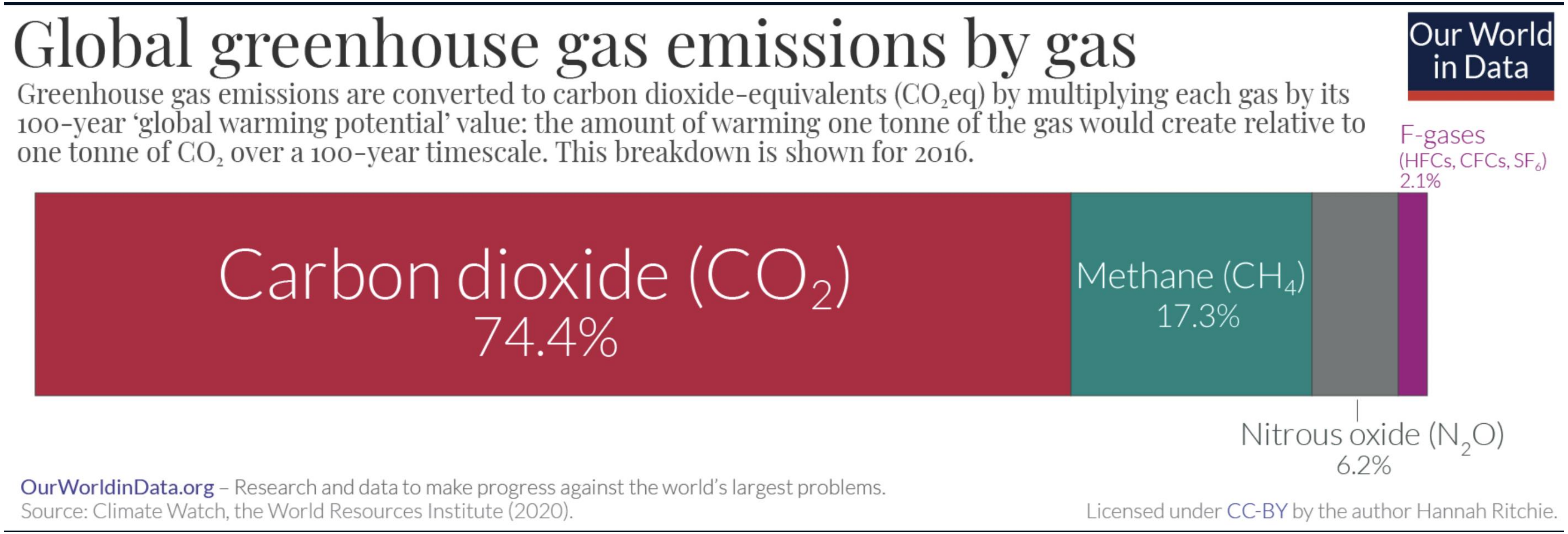
Species	CO_2	CH_4	N_2O	HFCs (e.g., HFC_{23}, HFC_{134a})	PFCs (e.g., NF_3, PFC_{14})	SF_6	Black carbon	Organic carbon
Lifetime (Years)	120	12	109	228/ 14	569/ 50,000	3,200	Days-weeks	Days-weeks
GWP_{100}	1	28	273	14,600/1,530	17,400/7,380	25,200	460	-69
GWP_{20}	1	81	273	12,400/4,140	13,400/5,300	18,300	1600	-240

Its true! Emitting one ton of SF_6 (sulfur hexafluoride, used in electrical switching equipment) will warm the planet over the next century as much as 25,000 tons of CO_2!

However, we emit far, far more CO_2 than SF_6, so it remains less of a problem.

Source: *IPCC AR6, Chapter 7 supplementary material, Table 7.SM.7 BC and OC estimates are the Fuglestvedt et al. (2010) values from IPCC AR5, Ch. 8, negative value indicates cooling.*

CO_2 dominates warming on an annual average basis…

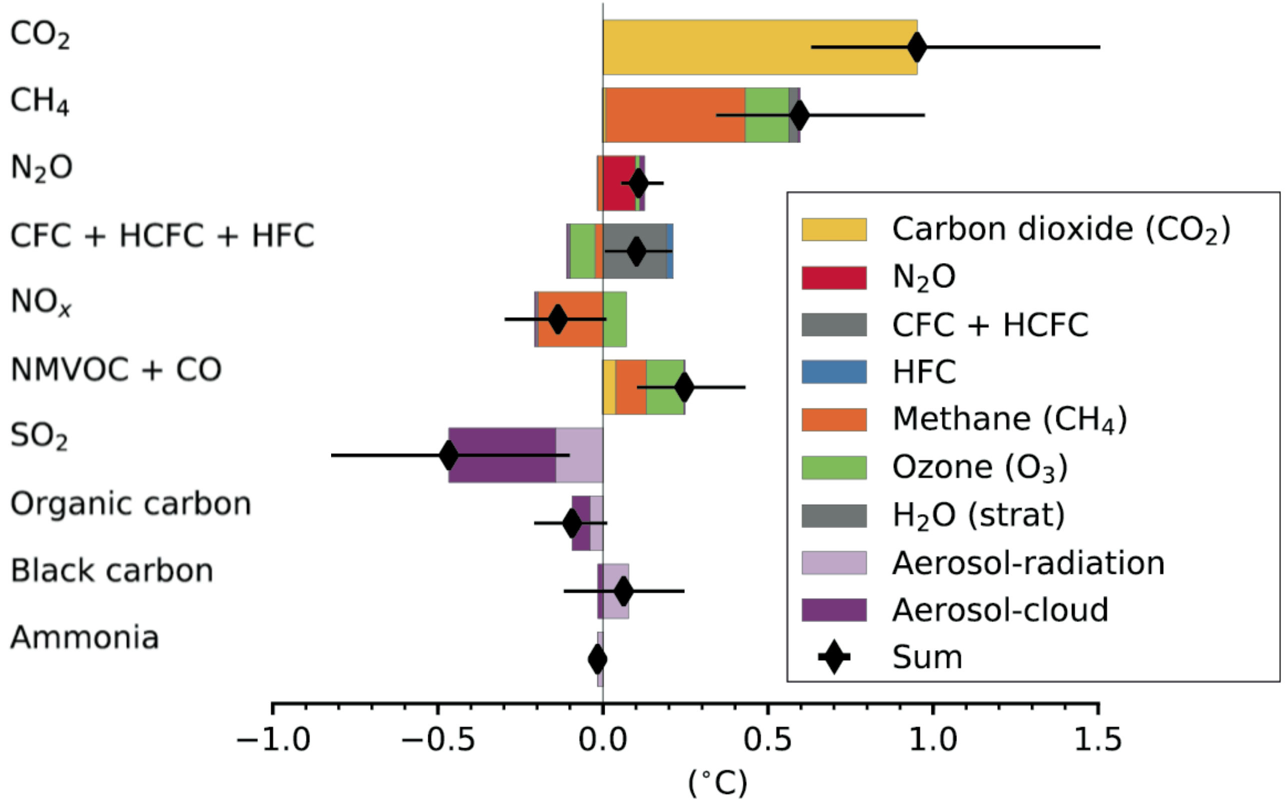


In the chart we see the breakdown of global emissions **in 2016**, measured on the basis of carbon dioxide-equivalents (CO_2e).

Carbon dioxide was the largest contributor , accounting for around three-quarters (74.4%) of total emissions. Methane contributed 17.3%; nitrous oxide, 6.2%; and other emissions (HFCs, CFCs, SF_6), 2.1%.

… but integrated over time, other gases add up.

Change in Global Mean Surface Air Temperature, 1750 to 2019



Integrated over the historical record, and accounting for shifts in key economic sectors and their contributing emissions, we see that CO_2 is still the largest contributor to overall temperature increase, but when accounting for the indirect, knock-on effects of the emission of some gases – like CH_4 – which leads to formation of other climate pollutants – like ozone (O_3) – the combined contribution of other GHGs is about equal to that of CO_2.

This is especially true for some non-GHG pollution like SO_2 and organic carbon that form aerosols (purple) which cool the planet. As air pollution is reduced, we stop masking the warming of GHGs.

Contribution to global mean air temperature between 1750 and 2019

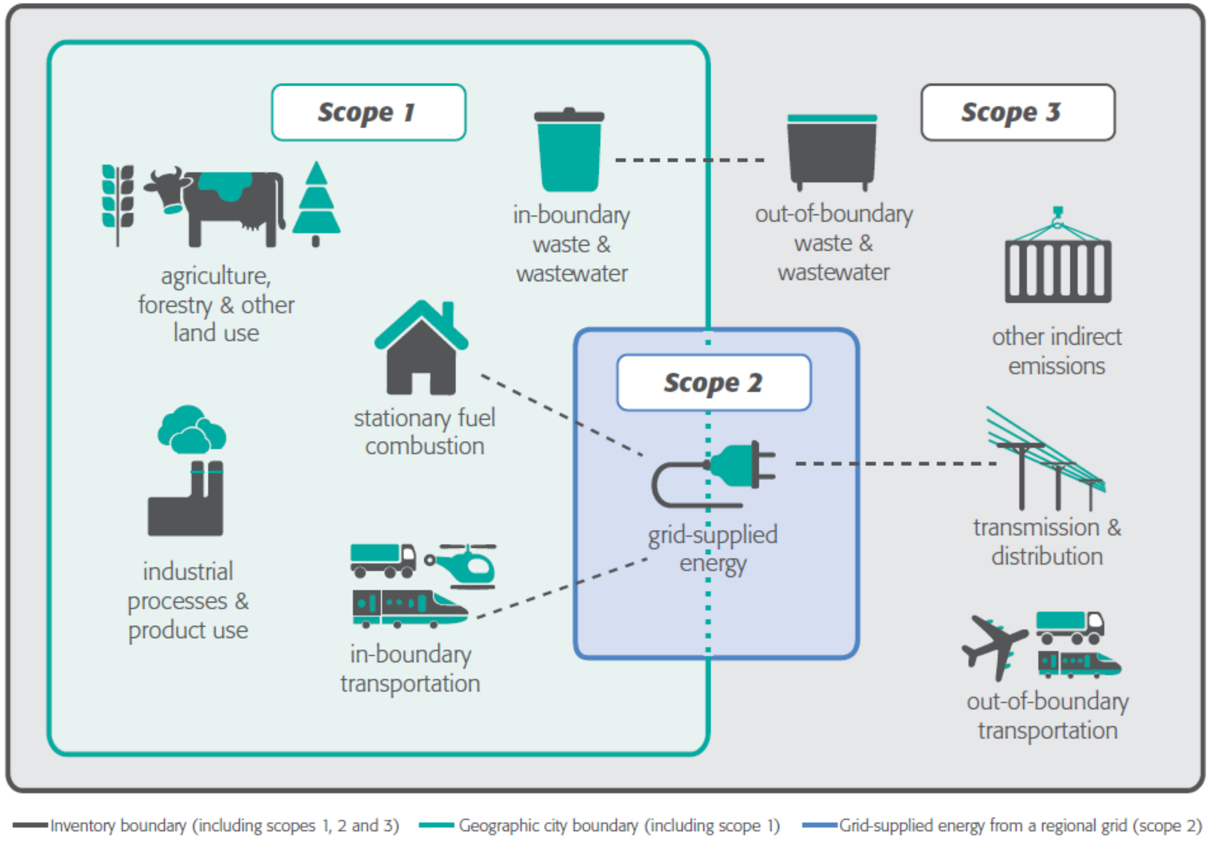
Source: IPCC WGI, 2021, Fig 6.12

A city's emissions include different scopes.

"Scope" refers to where emissions physically occur:

- Scope 1 - emissions within administrative boundaries
- Scope 2 - emissions associated with imported electricity
- Scope 3 - transboundary life-cycle supply-chain emissions

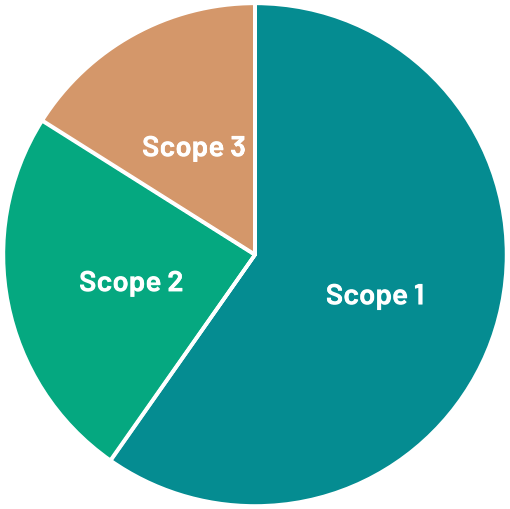
These designations lead to so-called "production"-based accounting (scope 1 emissions) or "consumption"-based accounting that includes the community-wide life-cycle (global) footprint of residents and businesses of a city (scope 1+2+3).



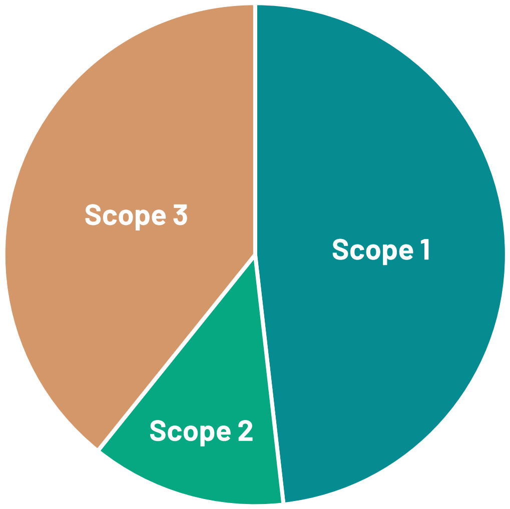
Source: WRI et al (2019) - Global Protocol for Community-Scale Greenhouse Gas Inventories

Examples of emissions categorized by scope:

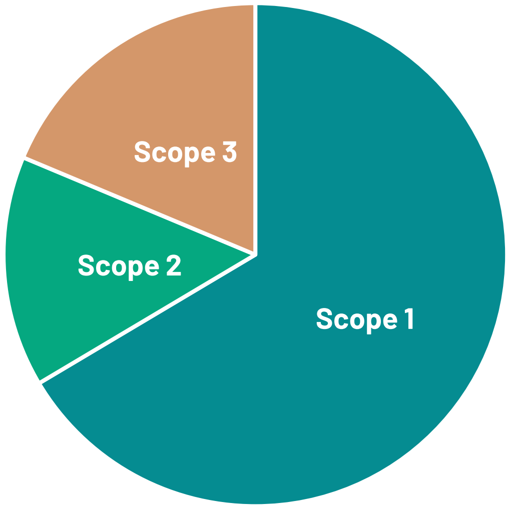
London (2018)



Mexico City (2018)



Medellin (2019)



Carbon Dioxide

CO_2

Lifetime	GWP_{100}	GWP_{20}
~120 years	1	1

GWP for CO2 is 1 for both 20 and 100 years, by definition, since GWP is defined relative to CO2.

Key facts

- CO_2 results from combustion of carbon-containing fossil (and biogenic) fuels which are oxidized in the atmosphere through chemical processes that break combustion products up into this very stable and ubiquitous molecule.
- Some CO_2 is taken up by plants, but not nearly as much as we produce.

Key urban sources of CO_2

(Figures in parentheses are CO2 emissions from Paris in Mt CO2/yr)

Scope 1:

- Residential buildings *(2.1)*
- Commercial buildings *(2.0)*
- Transportation *(1.3)*
- Solid waste *(0.4)*
- Industry *(0.1)*

Scope 2: Upstream energy *(1.3)*

Scope 3:

- Air transport *(8.7)*
- Food consumption *(4.8)*
- Road transport (supply-chain) *(3.4)*
- Materials/construction *(1.5)*

Key urban solutions – Paris Climate Action Plan, 2018

The lifetime of CO_2 is hundreds of years, so eliminating the use of carbon fuels now will only correct the imbalance sometime later this century, so it is critical to decarbonize quickly, avoid long-term infrastructure CO_2 lock-in and reduce SLCPs:

- Renewable Energy
- Circular economy/energy & waste recovery
- Shared, active and clean transportation*
- Low-emission zones/Smart transit
- Thermal improvement to buildings
- Financing energy renovation and energy management
- Flexible/reversible construction
- Local/low-carbon food production

*Mixed use, compact growth can also reduce distances traveled and enable low-carbon transport.

Methane

CH_4

Lifetime	GWP_{100}	GWP_{20}
10-12 years	**28** 28x more warming than CO_2 over 100 years	**81** 81x more warming than CO_2 over 20 years

Key facts

- CH_4 results from oil/gas extraction and distribution leakage as well as from bacterial decay of organic material in absence of oxygen (i.e., in a landfill or under water).
- Methane is considered both a GHG and an SLCP.
- When methane does break down, it contributes to the formation of ground-level ozone, another SLCP that is also a threat to health.
- Some of the biggest sources of methane globally take place outside of cities but remain attributable to cities (i.e., scope 3 emissions).

Key urban sources of CH_4

- Scope 1: Municipal solid waste decay
- Scope 1: Wastewater decay
- Scope 2: fossil fuel extraction
- Scope 2: fossil fuel distribution
- Scope 3: Livestock Agriculture

Key urban solutions

- Expand integrated solid waste management
- Circular economy/energy & waste recovery
- Expand/improve wastewater treatment or fecal sludge management
- Source local food
- Reduce fossil-fuel use
- Reduce meat consumption

Nitrous Oxide

N_2O

Lifetime	GWP_{100}	GWP_{20}
109 years	**273** 273x more warming than CO_2 over 100 years	**273** 273x more warming than CO_2 over 20 years

Key facts

- N_2O is produced as a by-product during the remineralization of organic matter via the primary processes of nitrification and denitrification.
- N_2O is also released in combustion of fuels.
- Nitrous oxide emissions have been increasing due to increased use of synthetic fertilizer and manure (adding nitrogen to the soils). Land-based agriculture and fossil fuel burning have been the largest driver of the observed increase through 2019.
- Since N_2O has a very similar lifetime to CO_2, the GWP_{100} is very close to the GWP_{20}, 273x more warming over both 100 and 20 years.

Key urban sources of N_2O

- Scope 1: Wastewater processing
- Scope 1: Industrial chemical processing (nitric and adipic acid production)
- Scope 1: Combustion of fossil fuels
- Scope 1: Residential solid biofuels
- Scope 3: Synthetic fertilizers/manure
- Scope 3: aquaculture
- Scope 3: manure management

Key urban solutions

- Certify food stocks as fertilizer friendly/organic
- Practice regenerative/sustainable agriculture
- Expand/improve tertiary wastewater treatment
- Regulate chemical industry
- Reduce fossil-fuel and biofuel use
- Enhance modern energy access

Hydrofluorocarbons

HFCs

Lifetime	GWP_{100}	GWP_{20}
10s-100s of years	1000s	1000s
	1000s of times more warming than CO_2 over varied lifetimes	

Key facts

- HFCs were introduced as replacements for ozone-depleting CFCs.
- While they break down more readily than CFCs, it is not before they warm the planet significantly with very high GWPs.
- Emissions of HFCs are growing at a rate of 10-15% per year. The global stock of air conditioners in buildings are projected to grow to 5.6 billion by 2050, or 10 new units sold every second for the next 30 years.

Key urban sources of HFCs (All scope 1)

- A/C, refrigeration
- Foam agents
- Aerosols
- Fire retardants

Key urban solutions

- Adopt/enforce Kigali Amendment to the Montreal Protocol
- Substitute low- or zero-GWP alternatives, combined with improvements in lifecycle energy efficiency
- Improved insulation/building designs to reduce A/C

Perfluorocarbons

PFCs

Lifetime	GWPs
100s-1000s of years	**1,000s-10,000s** 1000x-10,000x more warming than CO2 over varied lifetimes

Key facts

- PFC gases do not exist naturally in the atmosphere but are produced synthetically.
- PFCs - like HFCs - replace chlorofluorocarbons (CFCs) but are used in the manufacture of semiconductors and have several other uses.
- Not technically a perfluorocarbon, nitrogen tri-fluoride, or NF_3, is a greenhouse gas, with a global warming potential (GWP_{100}) 18,500 times greater than that of CO_2. Its GWP places it second only to SF_6 in the Kyoto gases.

Key urban sources of PFCs

- Scope 1: By-product during aluminum production
- Scope 1: Solvent in electronics industry
- Scope 1: Specialized refrigeration
- Scope 1: (NF_3) Manufacture of flat panel displays, photovoltaics, LEDs and other electronics
- Scope 3: imported products using PFCs in their manufacture

Key urban solutions

- Strict inventory reporting for PFCs and NF3
- Materials efficiency, circular material flows and emerging primary processes
- Fluorine gas (F2, diatomic fluorine) is a climate neutral - but highly toxic - replacement for nitrogen trifluoride in some manufacturing applications; however, it requires more stringent handling and safety precautions, especially to protect manufacturing personnel.

Sulfur Hexafluoride

SF_6

Lifetime	GWP_{100}	GWP_{20}
3,200 years	**25,200** 25,200x more warming than CO_2 over 100 years	**18,300** 18,300x more warming than CO_2 over 20 years

Key facts

- SF_6 is an inorganic compound that is a colorless, odorless, non-flammable, and non-toxic gas.
- Its observed increase over the last 40 years was driven in large part by the expanding electric power sector, including fugitive emissions from banks of SF_6 gas contained in medium- and high-voltage switchgear.

Key urban sources of SF_6 (All scope 1)

- Electrical switches
- Etchant in semiconductor industry
- Casting for magnesium (mostly in China, Canada, Russia and USA)

Key urban solutions

- Strict inventory reporting for SF_6 to ID local sources
- Regulate semiconductor etchants
- Alternative melt-protection for magnesium manufacture (e.g., fluorinated ketone with N_2/CO_2)

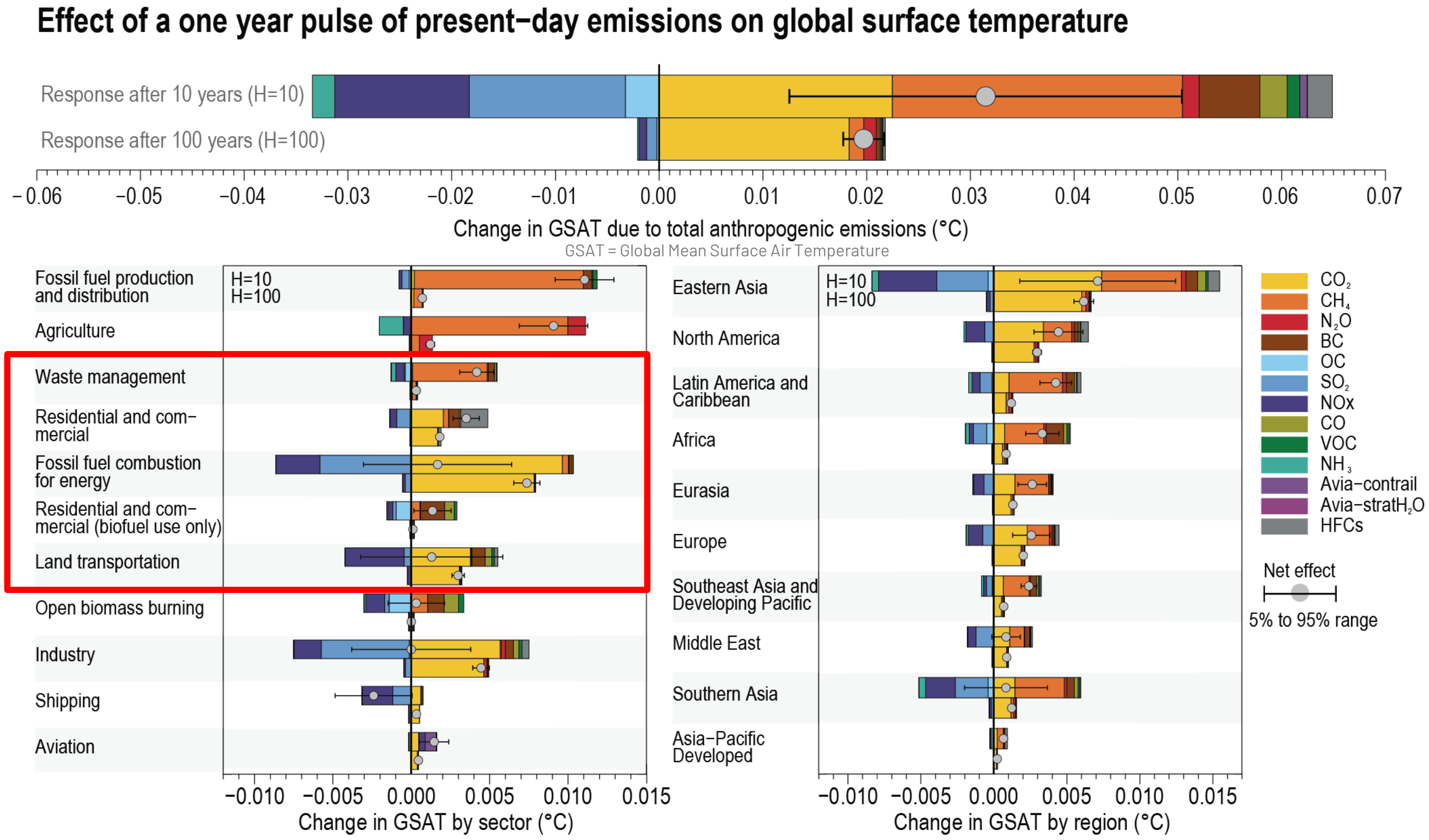
Emission Inventory Comparison

	London (2018)	Mexico City (2018)	Medellin (2019)
Population	3.9 Million	9 Million	2.5 Million
Per Capita GDP	$182,000	$21,000	$7,000
CO_2e (all GHGs at BASIC+*)	37.5 Mt	46.6 Mt	3.4 Mt
% from CO_2	80%	89%	78%
% from CH_4	14%	10%	20%
% from N_2O	1%	1%	2%
% from HFCs	4.7%	0.2%	NE
% from PFCs (mostly NF_3)	0.2%	NE	NE
% from SF_6	0.0001%	NE	NE

*Basic+ is an inventory reporting level that covers all scope 1 and scope 2 sources except from imported waste as well as scope 3 emissions from the stationary energy and transportation sectors.

Source: GHG Interactive Dashboard Data. 2020. London, UK: C40 Cities Climate Leadership Group. Available at: https://www.c40knowledgehub.org/s/article/C40-cities-greenhouse-gas-emissions-interactive-dashboard?language=en_US

All sources contain a mix of GHGs, SLCPs and other climate-impactful air pollutants.



Global Mean Temperature Response 10 and 100 years following one year of 2014-level emissions

Source: IPCC WGI, 2021, Fig 6.16 (see references)

Red box identifies sectors most relevant for urban Scope 1 and 2 emissions

Urbanization and income affect urban GHG emissions.

Urbanization has historically increased GHG emissions.

- The urbanization and adjustment of industrial structure has historically driven energy consumption and carbon emissions.

The transition from lower-income to higher-income urban structure affects the mix of pollutants.

- The shift from **agricultural economies** (with more methane from waste and wastewater and N_2O emissions from agriculture) to **industrial economy** (more CO_2, HFC/PFC/SF_6 emissions from industries and buildings) will shift the main contributing gases.

The scope of emission sources will also change as cities become denser, industrialize and outsource energy and food supply.

- Increasing wealth enables enhanced treatment of waste/wastewater, reducing Scope 1 methane emissions.
- The magnitude of upstream emissions will vary as a function of upstream energy sources, transportation patterns and agricultural/food supply chains (Stronger consumer demand for energy and meat may increase Scope 3).

As cities develop an increase in carbon footprint is not inevitable.

- Local regulation can reduce Scope 1 emissions.
- Local and national regulation can impact Scope 3.

Urban mitigation summary

Sector	Key pollutants	Mitigation options	Potential impacts of urban planning
Transportation	CO_2, Diesel particulate, HFCs (auto air conditioning)	Electrify light duty, DPFs/clean fuels for heavy duty, low-carbon public transit options and Transit-oriented development	Planning for mixed-use and compact development that is coordinated with public and non-motorized transportation options, as well as the provision of public electric vehicle charging infrastructure, can reduce transportation emissions.
Power	CO_2, CH_4 (upstream fossil fuel production), SF6 (electrical switches)	EE/RE w grid optimization, solar microgrids	Building regulations can enable the adoption of distributed renewable energy.
Industrial Point Sources	CO_2, PFCs (Aluminum and electronics manufacture), SF_6 (magnesium casting), HFCs (fire retardants, aerosols, foams), N_2O (nitric and adipic acid production)	EE & materials efficiency, circular material flows and adopt emerging primary processes for PFCs, Alternative materials for switches and alternative processes for electronics/ magnesium manufacture for SF6, Careful use of F_2.	Compact and coordinated development, as well as updated regulations, can reduce the quantity of construction materials required for buildings and infrastructure (primarily cement and steel), which reduces embodied emissions associated with manufacturing these materials.
Waste/Wastewater	CH_4	ISWM, expand/tertiary WW treatment	Cities can reduce methane from waste by increasing waste collection, minimizing open dumping and uncontrolled landfilling, managing landfill gas, and diverting organic waste from landfills.
Buildings	CO_2 (combustion of fossil-fuels), BC/OC (combustion of residential solid biofuels); HFCs (A/C)	RE/EE w/modern energy services for residential cooking & heating, materials efficiency for construction, low-GWP alternatives for A/C	Density, building height and building design impact the energy efficiency of buildings.
Food systems	CH_4 (livestock), N_2O (fertilizer application), HFCs (refrigeration), BC/OC (Open burning of crop residue)	Local/sustainable agriculture; shift food preferences	Planning that enables farmer's markets and urban farming can support local agriculture and reduce emissions associated with food packaging and transport.

To explore the GHG benefit of various options, see tools for modeling future scenarios at the city level here.

Source: Authors

Key takeaways

- CO_2 constitutes the majority of city emissions.
- The mix of non-CO_2 GHGs can vary. Contributions from methane and nitrous oxide depend on the degree of upstream fossil fuel production/extraction, agricultural practices, and the volume of waste produced and how it is disposed.
- HFCs, PFCs and SF_6 are smaller contributors, often not estimated at the municipal level, and may require global action and regulation.
- Key city actions include reducing fossil fuel use through renewable energy, energy efficiency, integrated solid waste management, enhanced wastewater treatment, electrification of transportation, compact and coordinated urban growth, and local food production/food choice.
- Key sources emit a mix of pollutants. This means that reducing emissions can yield not only climate benefits, but also public health, agriculture, energy and economic benefits, as eliminating key sources can eliminate a wide range of pollutants simultaneously.

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