CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

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ADDRESSING BLACK CARBON EMISSION INVENTORIES

A REPORT BY THE CLIMATE AND CLEAN AIR COALITION SCIENTIFIC ADVISORY PANEL

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Summary

- Black Carbon (BC) has a strong influence on radiative forcing, affecting the climate globally and regionally, and is responsible for a significant proportion of the global forcing to date. BC deposited on the cryosphere leads to enhanced melting rates and can affect the intensity and distribution of precipitation.
- Black carbon, and co-emitted substances from key sources, form a significant fraction of ambient fine particulate matter ($PM_{2.5}$), which is the most important global environmental health risk.
- The development of emission inventories of black carbon and co-emitted substances is important in estimating the net impacts of measures addressing BC on climate and human health. The rate of near-term global warming can be influenced by implementing key measures to limit the emission and formation of Short-Lived Climate Pollutants (SLCPs). The Climate and Clean Air Coalition (CCAC) has undertaken actions to promote mitigation action on SLCPs, including BC.
- The CCAC is promoting emission inventories of BC and co-emitted pollutants by countries that can provide a basis for evaluation of benefits across relevant sectors, to develop plans to reduce emissions. This is being implemented with partner countries of CCAC, within the initiative 'Supporting National Action and Planning on SLCPs' (SNAP) using the LEAP-IBC (Long-range Energy Alternatives Planning- Integrated Benefits Calculator) tool.
- The emission inventory approaches in LEAP-IBC are based to a large extent on European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) *Emissions Inventory Guidebook* for non-GHGs, and for GHGs, the Intergovernmental Panel on Climate Change (IPCC) *Guidelines for Greenhouse Gas Inventories*. A default emission factor dataset used by this tool is available on line.
- The IPCC has not yet undertaken development of emission inventory guidance on non-GHGs, including BC. The EMEP/EEA Guidebook has included default emission factors for BC since 2013 but tends to focus on sources of relevance to industrialised countries.
- There is a need for improved emission factors associated with sources more prevalent in the developing world, such as biomass cookstoves, traditional brick kilns, and open-burning of solid waste. There are large uncertainties in emission estimates of BC and other components of PM from such sources for a range of reasons, including poor characterisation of emissions from sources typical of developing countries.
- Issues around the definition and measurement of BC versus elemental carbon (EC) introduce additional uncertainty, although this is likely to small compared to the uncertainty around emission factors and activity data.
- Focussing on 'uncertainty' is a problem if important, though uncertain, information is ignored in public debate and policy-making. The uncertainties in BC emission estimation may be relatively large, but such uncertainties are also inherent in emissions estimates for nitrous oxide and methane, which has not prevented these substances from being included in the IPCC guidelines.

- The 2005 report of the IPCC Expert Meeting on Emission Estimation of Aerosols Relevant to Climate Change, stated that "it is not possible, at this stage, to reliably produce internationally comparable national emission estimates…". Since then, internationally comparable BC emission inventories for European countries have been compiled and reported under the auspices of the UN-ECE CLRTAP. Also, within the SNAP initiative of the CCAC, countries are producing emission inventories of pollutants (including BC) using the LEAP-IBC tool which provides a standardised approach and includes fully referenced default emission factors.
- There is an urgent need for the development of authoritative emission inventory guidance on short-lived climate forcers, including BC, to promote internal consistency between GHGs emission inventories and non-GHGs emission inventories, within and across the various assessments (including IPCC's).
- A comprehensive, transparent (fully referenced), on-line emission factor database (for BC, OC and other co-emitted substances, including CO_2) for use globally, is required to drive improvements in the quality of BC and co-emitted pollutant emission inventories and to reduce the uncertainty.

This briefing report provides a basis for feedback and discussion aimed to agree on a way forward for the development and improvement of national black carbon emissions inventories.

The Importance of Undertaking Emission Inventories for Sources of Black Carbon

Black carbon (BC) is emitted during the incomplete combustion of fossil fuels and biomass. It forms part of the ambient fine particulate matter, characterized as $PM_{2.5}$. The sources of BC are also sources of other components of $PM_{2.5}$, including other directly emitted particles – organic carbon and $PM_{2.5}$ of mineral origin – and the gases sulfur dioxide (SO_2), nitrogen oxides (NO_X) and ammonia (NH_3) which react in the atmosphere to form nitrate, sulphate and ammonium which constitute the secondary inorganic fraction of the $PM_{2.5}$ burden. The sources can be either natural or anthropogenic. The World Health Organization (WHO) has declared $PM_{2.5}$ concentrations the most important global environmental health risk and has issued recommendations to countries to lower ambient concentrations (WHO, 2016). Various studies have considered the health impact of BC in relation to other components of $PM_{2.5}$ and suggest that BC may have larger effects than undifferentiated $PM_{2.5}$ (e.g. Smith et al., 2009). In studies taking BC and $PM_{2.5}$ into account simultaneously, associations are robust for BC according to the assessment made by WHO/EU-REVIHAAP (2013). Black Carbon is carcinogenic and has other deleterious health effects, e.g. to the cardiovascular system, and is linked to premature deaths (Dominici et al., 2006; EPA, 2009; WHO/EU-REVIHAAP, 2013).

On average, BC-containing particles comprise around 10% of $PM_{2.5}$ mass in ambient air (Christoforou et al., 2000; Chow et al., 2002; Viidanoja et al., 2002; Baumgardner et al., 2007, Chow et al., 2011; Chen et al., 2014; Briggs and Long, 2016), but it can reach up to 30% depending on the location and dominant sources (e.g. residential heating/cooking with solid biomass fuel, Gramsch et al., 2014). Implementing specific measures to reduce BC emissions from key sources, both in the urban and rural environments is desirable to protect human health. This is achieved through the reduction in BC itself as well as the emissions giving rise to other components of $PM_{2.5}$. Understanding the impacts of any measure requires the estimation of emissions of BC and co-emitted pollutants.

Black carbon has a strong influence on radiative forcing, affecting the climate globally, as well as a strong regional signature and is responsible for a significant proportion of the forcing to date (Bond et al., 2013; IPCC, 2013). Many papers and reports highlight significant BC contribution to changes in surface temperature and the vertical structure of temperature in the atmosphere, leading to changes in weather patterns and affecting regional precipitation (Ramanathan and Carmichael, 2008; IPCC, 2013). Studies have also documented the impact of BC deposited on the cryosphere, leading to enhanced melting rates (IPCC, 2013).

Studies have indicated the potential to reduce the rate of near-term warming by implementing key measures to limiting the emission and formation of Short-Lived Climate Pollutants (SLCPs) (UNEP/WMO 2011; Shindell et al. 2012). The Climate and Clean Air Coalition (CCAC) has undertaken to promote mitigation action on SLCPs, including BC. The other SLCPs in focus are methane, tropospheric ozone and hydrofluorocarbons. Further, CCAC activities aim to promote a '*Multiple Benefits Pathway*' approach towards achieving the temperature targets. Such an approach will provide the greatest benefits to sustainable development, such as through avoided health and crop yield impacts, and at the same time reduce climate impacts due to the avoided cumulative warming that will result from implementing SLCP and greenhouse gas (GHG) mitigation strategies.

As part of these activities, CCAC is promoting the development of emission inventories of BC and co-emitted pollutants that can provide a basis for evaluation across countries and relevant sectors, from which actions can be planned to reduce emissions. This is being implemented with partner countries of CCAC, using the LEAP-IBC tool (see Section 6) within the SNAP Initiative – or 'Supporting National Action and Planning on SLCPs'. The emission inventory approaches in this tool are based to a large extent on European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) guidance for non-GHGs and Intergovernmental Panel on Climate Change (IPCC) guidance on GHGs. The IPCC has not yet undertaken development of emission inventory guidance on non-GHGs, including BC. Guidance covering all short-lived climate forcers is likely to improve the internal consistency between GHGs emission inventories and climate forcing-non-GHGs emission inventories, within and across the various assessments and mitigation strategies, and improve integration and comparability in terms of the emissions inputs into the various models.

Quantifying impacts of implementing emission reduction strategies on sources of BC, and for the *Multiple Benefits Pathway* approach to be mainstreamed into policies and action, requires that countries are provided with authoritative guidance on how to compile emission inventories for BC, and for the co-emitted pollutants that affect both air quality and climate.

Characterising Black Carbon Emissions

The term 'black carbon' is used to represent primary particles emitted during the incomplete combustion of fossil fuels and biomass from different source sectors. The black carbon particles are composed mainly of carbon, and are measured by using optical absorption measurement techniques. The term 'elemental carbon' (EC) is also used extensively, which is based on a thermal classification of particles containing carbon. The use of these different metrics in the Convention on Long-Range Transboundary Air Pollution's (CLRTAP) 'EMEP/EEA Emissions Inventory Guidebook' is explained in Section 5.[1] Black Carbon is never emitted alone, since other gases and aerosol components are also emitted during the combustion process. The co-emitted gases include carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOCs), and nitrogen oxides (NO_X made up of NO_2 & NO), all ozone (O_3) precursors, as well as other GHGs (CO_2, N_2O). Also, BC can be co-emitted with other primary carbonaceous particles (organic carbon (OC)) and inorganic gases precursors (SO_2, NOx and NH_3) of secondary $PM_{2.5}$. Some of these components warm the atmosphere (CO_2, CH_4, BC, nitrous oxide (N_2O), whereas others cool the atmosphere (SO_2, OC, NO_X, NH_3), and whilst CO_2 and N_2O are long lived, the remainder, including BC are relatively short-lived in the atmosphere. Understanding the emissions of each pollutant is needed to understand the net influence on temperature of combined emissions from a source, or of a mitigation measure applied to the source.

There have been several attempts to characterize BC emissions in different countries and globally (e.g. EPA, 2011; ECCC, 2017; Jacobson, 2001, 2002; Bond et al., 2004; Klimont et al., 2017; Evans et al., 2017; Hoesly et al., 2018, Zheng et al., 2018). The Convention on Long-range Transboundary Air Pollution encourages parties to the Convention to estimate BC emissions. These emission inventories show that the highest contributing sectors that emit BC can be broadly categorized as: transportation, industrial sources, residential cooking and heating and open burning (forest and savanna fires, agricultural residues and solid waste).

Transportation has been a rapidly increasing sector for BC emissions due to economic development in many regions of the world and is expected to continue growing over the next decades (Yan et al, 2014). Black carbon emissions in this sector arise primarily from diesel engines in on- and off-road vehicles, ships and generators. Improvements in control technologies and fuel quality (Cofala et al., 2007; Klimont et al., 2009) have gradually led to reductions in the emissions intensity.

Industrial sources include artisanal brick production using different types of kilns that can range broadly in emissions, depending on their structure and on the fuel used. Artisanal brick kilns and coke ovens are used primarily in the developing world (Rajarathnam et al., 2014). Also flaring of waste gas during extraction and processing of crude oil and natural gas are key sources of BC.

Residential heating and cooking using solid fuel, such as coal and biomass, including dung, are important sources of BC emissions in the developing world. Further sources include forest and

[1] https://www.eea.europa.eu/publications/emep-eea-guidebook-2016

savannah fires, burning of agricultural residues in fields and burning of solid municipal waste at waste dumps or dispersed across cities.

Emission inventories for BC and co-emitted substances have been undertaken at different scales from global to urban. Bond et al. (2004, 2007) produced some of the earliest BC emission estimates and the publication of the 'Bounding Black Carbon' review updated these in 2013 (Bond et al., 2013). The International Institute for Applied Systems Analysis (IIASA) has used the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model to develop global emissions of BC and all co-emitted air pollutants. The current emission inventory version is ECLIPSE V5a (Klimont et al, 2017), which estimates emissions for 172 countries. This emission dataset includes particulate matter emissions as mass-based size distribution (PM_1, $PM_{2.5}$ and PM_{10}), as well as primary carbonaceous aerosols (BC and organic carbon, OC). The IIASA GAINS model was used to provide the emission scenarios used in the UNEP-WMO (United Nations Environment Programme – World Meteorological Organization) assessment of black carbon and tropospheric ozone (UNEP/WMO, 2011), and has since been used globally in an OECD (Organisation for Economic Co-operation and Development) study of the economic impacts of air pollution (OECD, 2016), and in regional assessments in Latin America (CCAC-LAC, 2018). The IIASA GAINS is currently supporting a regional assessment in Asia. Another widely used global database is EDGAR (*Emission Database for Global Atmospheric Research)* developed by the Joint Research Centre of the European Commission and Netherlands Environmental Assessment Agency. The most recent EDGAR v4.3.2 dataset covers, in addition to GHGs, emissions of all gaseous and particulate air pollutants, including BC and OC, over the period 1970–2012 (Crippa et al., In review, 2018). All human activities, except large-scale biomass burning and land use, land-use change and forestry, are included in the emissions calculation. The bottom-up compilation methodology of sector-specific emissions was applied consistently for all world countries, providing methodological transparency and comparability between countries. The Peking University (PKU) inventory is another example of a global, bottom-up emissions inventory. It covers 11 pollutants including BC, OC, and most other SLCFs other than CH_4, from 1960-2014 and spans 64 individual source categories including great detail in the residential sector.[2]

[2] http://inventory.pku.edu.cn/download/download.html

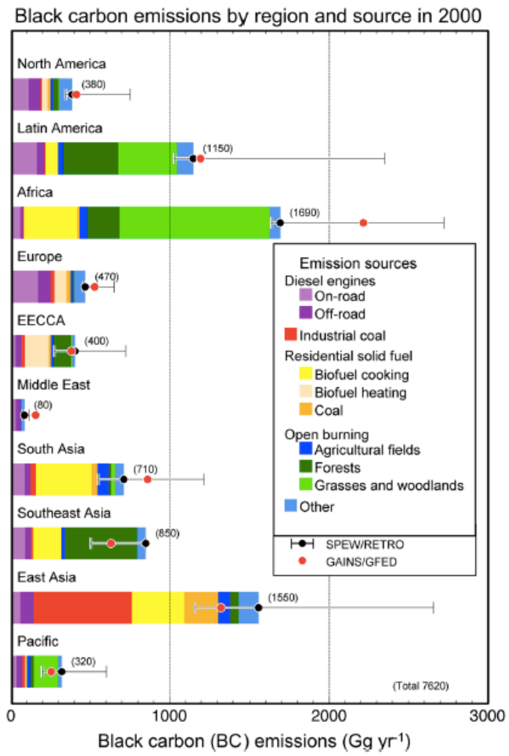

Figure 1 above, taken from Bond et al (2013), illustrates BC emission sources for different regions of the world and it highlights the differences is emission estimates by various models: SPEW, GAINS and RETRO.

In addition, national scale BC emission inventories are being undertaken in the UN Economic Commission for Europe (UNECE) countries which are parties to CLRTAP (see Sections 3, 4 and 5 below), and within the Commission for Environmental Cooperation (CEC) countries of North America. Developing countries engaged with the CCAC are also compiling BC inventories as part of their national SLCP planning (See Section 6). The only internationally recognized guidance for BC emissions inventories, outside of North America, is the EMEP/EEA Emissions Inventory Guidebook, focusing on sources typical of industrialised UNECE countries. The IPCC Guidelines (IPCC, 2006) refer to this in relation to characterizing emissions of BC and other air pollutants. The Long Range Energy Alternatives Planning system-Integrated Benefits Calculator (LEAP-IBC) tool uses default emission factors from these two guidance document, but also adds factors from the peer-reviewed literature for emission sources not specifically included in the EMEP/EEA Emissions Inventory Guidebook, and for pollutants not extensively covered - especially organic carbon (OC).

There are uncertainties in emission inventories for all pollutants, (See Section 5). Uncertainties are greater for BC and organic carbon (OC) compared with other pollutants, and the characterisation of emissions from sources typical in developing countries of Asia, Latin America and Africa is not widespread, leading to higher uncertainty of emissions from these sources. Data and limited guidance are currently available to allow initial emission estimates to be determined. However, globally, there is a need for an authoritative and systematic appraisal of emission and activity data to give the best advice to countries, regions, cities and sectors that wish to develop quantitative assessments of BC and co-emitted pollutants, particularly if the emissions inventory is to be used to underpin policy development and implementation.

Compiling Emission Inventories

Emission inventories are generally estimated by multiplying emission factors by activity data. An 'emission factor' represents the mass of pollutant emitted per unit of activity, as opposed to total emissions. The term 'activity data' indicates a quantitative measure of an event that leads to emission, such as the quantity of fuel burned, product manufactured, or kilometres driven. In practice, the calculations may be more complex, for example, a range of factors may have to be considered to derive the final emission factor (such as different appliance types used in the residential sector, emissions control equipment used in industry etc.

There are two main internationally-recognized sources of information on emission inventory preparation methods and emission factors:

- The IPCC *Guidelines for Greenhouse Gas Inventories* (IPCC, 2006) provides methods for estimating emissions of the major GHGs including CO_2, CH_4 and N_2O. However, the IPCC Guidelines do not provide methodologies for estimating emissions of non-GHGs, e.g. BC that has an impact on climate. The IPCC refers the inventory compiler to the EMEP/EEA *Emissions Inventory Guidebook* (see below) as the best source of information for estimating emissions of non-GHGs.
- The 'EMEP/EEA *Emissions Inventory Guidebook*' is produced under the European Monitoring and Evaluation Programme[3] (EMEP) within the CLRTAP. The Guidebook includes information on the emission of air pollutants, which are associated with a range of adverse impacts, such as: acidification, eutrophication, ozone formation, and human and ecosystem exposure to hazardous substances. It therefore includes emission factors for primary particulate matter (TSP, PM_{10} and $PM_{2.5}$) and BC (currently expressed as a percentage of the $PM_{2.5}$). The current version of the EMEP/EEA Emissions Inventory Guidebook does not include a complete set of emission factors for OC, although some of the sectoral chapters contain information on carbon speciation as an annex. The EMEP/EEA Emissions Inventory Guidebook cross-refers to the IPCC Guidelines for estimating emissions of GHGs.

The level of detail with which an inventory can be complied depends on the level of disaggregation of the available activity data as well as the availability of suitable emission factors. For example, for fuel

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[3] EMEP is the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe. It is a scientifically based and policy driven programme under the UN Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (CLRTAP).

combustion in the Public electricity generation sector, the EMEP/EEA Emissions Inventory Guidebook provides a simple Tier 1 approach in which the default emission factors assume an average, or typical technology and abatement implementation in the sector. Where data on fuel combustion in the sector are available, disaggregated by specific combustion technology and abatement techniques, then a more detailed Tier 2 method may be applied using the technology-specific default emission factors. Where facility-level emissions data of sufficient quality are available, the EMEP/EEA Emissions Inventory Guidebook also describes a more detailed Tier 3 approach. Where the appropriate and reliable data exist, it can be assumed that the higher Tier methods will give the more accurate emissions estimates.

The EMEP/EEA Emissions Inventory Guidebook has been compiled to meet the needs of Parties to the CLRTAP, and consequently there is a focus on sources commonly found in industrialized countries. The methodologies within the EMEP/EEA Emissions Inventory Guidebook therefore have important limitations when being used for compiling inventories for developing countries - where technologies and practices may differ radically from those used in industrialized countries. Sources that are common in developing countries that are either not well characterised or not included in the Guidebook include:

- Domestic biomass combustion (especially in traditional cookstoves)
- Open-burning of municipal solid waste
- Crop residue open-burning in the field
- Traditional brick kilns
- Forest fires and savanna burning
- Traditional coke ovens
- Charcoal making
- Flaring from oil gas production

Inventory compilers for countries outside the UNECE region (comprising primarily North America and Europe) must therefore look to other sources, e.g. from local research and in the literature, for extracting the relevant emission factors.

Another limitation of the EMEP/EEA Emissions Inventory Guidebook is its limited provision of emission factors for OC. As pointed out earlier, emissions of the co-emitted pollutants, *including OC*, must also be quantified if the net impact of BC sources on climate and air quality is to be assessed. In Section 6 the emission calculations using LEAP-IBC are explained, and there is an on-line appendix to this report showing default emission factors used by LEAP-IBC that can be applied to different sources. This tool heavily relies on the EMEP/EEA Emissions Inventory Guidebook and IPCC Guidelines, but also on other reference sources, such as for OC emission factors.

The Commission for Environmental Cooperation (CEC, 2015) has published guidelines to estimate BC emission inventories across Canada, the United States and Mexico. These guidelines provide a consistent set of methods to improve the accuracy of North American BC emission inventories, to establish baselines and to determine mitigation strategies. These guidelines follow the format of IPCC (2006) and EMEP/EEA (2013) guideline documents. For nearly all emission sectors, BC emission inventories are derived from underlying $PM_{2.5}$ emission inventories. The methods and data sources used for $PM_{2.5}$ and a speciation factor form the basis of the recommended BC emission inventory guidelines. The guidelines incorporate emission factors for sources that are important for developing countries such as open fires, agricultural burning, residential cooking (for a variety of fuel types) and burning of solid waste. The CEC report acknowledges the need for continuous improvement of speciation factors for BC accounting for light-absorbing properties and aligning these factors with the level of detail found in underlying PM emission factors.

Uncertainties in Emission Inventories

Uncertainty estimates are an essential element of a complete emission inventory. Although the statistical methods described below are intended to estimate uncertainties in the final inventory, it is important to recognize that uncertainties that are not addressed by these approaches may also exist (IPCC, 2006). This includes uncertainties arising from omissions (e.g. an important emission source was missed), double-counting (e.g. industrial fuel combustion emissions counted under both energy consumption and process emissions), other conceptual errors, or incomplete understanding of the emission processes. Simple mistakes such as transcription errors or using the wrong units can introduce further uncertainty - although quality assurance and quality control (QA/QC) procedures should minimize these.

The IPCC (2006) Guidelines draw attention to eight broad causes of uncertainty that the inventory developer should recognize:

- *Lack of completeness*: Measurement or other data are not available because the process is either not yet recognized or a measurement method does not yet exist.
- *Model*: Models can be as simple as a constant multiplier (e.g. an emission factor) and increase in complexity, such as for complicated process models. These can introduce uncertainty if the form of bias or random error for a wide range of reasons.
- *Lack of data*: In some situations, there may not yet be data available to characterise a particular emission and so proxy (or surrogate) data for analogous or similar categories may have to be used.
- *Lack of representativeness of data*: This source of uncertainty is associated with lack of complete correspondence between conditions associated with the available data and the conditions associated with real-world emissions or activity. For example, emissions factors developed in one country/region are applied to a different country/region where the technology is very different. Lack of representativeness typically leads to bias.

- *Statistical random sampling error*: This source of uncertainty is associated with data that are a random sample of finite size and typically depends on the variance of the population from which the sample is extracted and the size of the sample itself (number of data points).
- *Measurement error*: May be random or systematic and results from errors in measuring, recording and transmitting information.
- *Misreporting or misclassification*: Uncertainty here may be due to incomplete, unclear, or faulty definition of an emission. This cause of uncertainty typically leads to bias. It can be reduced by QA/QC procedures.
- *Missing data*: Uncertainties may result when measurements were attempted but no value was available, such as when measurements are below the detection limit. This cause of uncertainty can lead to both bias and random error.

Another possible source of uncertainty, specific to BC, relates to technical definitions and terminology of BC derived from various measurement techniques. Black carbon has been used for many years as a catch-all term to describe a variety of types of carbonaceous particles (Lack et al., 2014). Petzold (2013) clarified definitions of carbonaceous particles including BC, elemental carbon (EC) and recommends using 'BC' as a descriptive term referring to light-absorbing carbonaceous particles whilst EC refers to particles that are measured using evolved gas analyzers. In practice, BC and EC are mostly treated as equal.

'Black Carbon' was selected as the term identified within the CLRTAP Gothenburg Protocol, with the requirement that Parties develop emission inventories and projections for BC. However, the majority of BC emission factors (EFs) reported in the EMEP/EEA Emissions Inventory Guidebook are EC EFs, which introduces further uncertainty.

Both the EMEP/EEA Emissions Inventory Guidebook and IPCC Guidelines recommend that uncertainty should be expressed as the 95% confidence interval - which is specified by the confidence limits defined by the 2.5 percentile and 97.5 percentile of the cumulative distribution function of the estimated quantity. Both guidelines provide advice on the use of standard mathematical tools (error propagation and Monte-Carlo analysis) to quantify uncertainties associated with emissions totals.

Activity data are usually derived from reasonably well characterised datasets, such as national energy statistics and balances, economic production rates, population data, etc. They are often accompanied by information on uncertainty levels. Where this is not the case, indicative ranges are available from the EMEP/EEA Emissions Inventory Guidebook (EMEP/EEA, 2016; Part A, Chapter 5 'Uncertainties', Table 3-1). Both the IPCC Guidelines and the EMEP/EEA Emissions Inventory Guidebook offer default EFs together with the upper and lower values of their associated 95% confidence ranges to allow uncertainties to be determined.

Currently, BC EFs are presented in the EMEP/EEA Emissions Inventory Guidebook as a percentage of the $PM_{2.5}$ EF (see Section 5). Theoretically, the uncertainty of the BC EF can then be determined by combining the uncertainty of the $PM_{2.5}$ EF with the uncertainty of the BC percentage of $PM_{2.5}$.

However, the underlying data for BC are not well characterised, and the confidence intervals accompanying the BC EFs are not known with any certainty. It is important to recognise this when using a detailed mathematical approach to quantifying uncertainty for BC.

Studies of emission inventories show that, of the major pollutants, the lowest uncertainties are associated with CO_2 and SO_2, which depend primarily on the quality of fossil fuel statistical data and fuel properties. Studies estimate globally an 8% uncertainty (90% confidence interval) for emissions of CO_2 (Andres et al., 2012; IPCC, 2014) and 8–14% uncertainty for SO_2, for a roughly 5–95% confidence interval (Smith et al., 2011). However, uncertainty for certain sectors can be much larger, for example 50% for global estimates of CO_2 emissions from the combined Agriculture, Forestry and Other Land Use sector (IPCC, 2014). Similarly, uncertainty can be larger in certain regions (e.g. China) due to uncertainties in the level of coal consumption, emission factor for coal and the actual implementation and efficiency of control technology (Guan et al., 2012; Liu et al., 2015; Olivier et al., 2015; Xu et al., 2009; Zhang et al., 2012). Uncertainties for global inventories of GHGs other than CO_2 are much higher, being estimated by IPCC (2014) at ±20% for CH_4 and ±60% for N_2O (both expressed as the 90% confidence interval). Again, uncertainties for some sectors are much higher, for example, for CH_4 emissions from rice paddy fields, livestock enteric fermentation and landfill.

Emissions of PM, including BC and primary OC, are more uncertain, as these pollutants usually form under poor combustion conditions in small, inefficient installations burning poor-quality fuels, which are difficult to account for, resulting in large emission variability (Bond et al., 2004; Klimont et al., 2017; Hoesly et al., 2018). Considering local data and knowledge about emission sources and their emission factors could significantly reduce these uncertainties (Zhang et al., 2009). Inconsistencies in measurements of PM emissions (e.g. in-stack or directly after stack for industry; laboratory versus real-world measurements for cookstoves) in different countries contribute to overall global inventory uncertainties. Uncertainty can also be large for activity data of relevance to PM emissions - such as poor-quality fuels (e.g. biomass) in cook stoves or brick kilns (Klimont et al 2017) or even size and composition of local vehicle fleets.

Bond et al. (2004) estimated total uncertainties of about a factor of 2 (i.e. -50% to +100%) in their global estimates of BC and OC emissions for 1996 from contained combustion (excluding open-burning of vegetation and crop residues). More recent work (Bond et al., 2013) estimated larger uncertainties for a global BC inventory for the year 2000; of around a factor of 3 for energy-related emissions and >3 when open-burning is included. Advances in emission characterization for small residential, industrial, and mobile sources will be required to reduce the scale of these uncertainties. Uncertainties in national scale BC emission estimates are likely to be less than for the global inventories described above. For example, emission uncertainties are considered to be in the order of 1.5 to 2-fold for national BC inventories recently prepared by EU countries for CLRTAP.

There are ways to reduce the uncertainties:

- Uncertainties in emissions from open-burning of vegetation and crop residues, a significant BC source, can be reduced using satellite-derived data to characterize the magnitude and spatial distributions of biomass burning.

- The large uncertainties associated with estimates of emissions from open-burning of solid municipal waste, an activity widespread in the developing world, could be reduced by improving data on waste collection and disposal.
- The analysis combining field measurements and atmospheric transport modelling with iterative inventory development can also be undertaken to reduce uncertainties.

The everyday use of the word 'uncertainty' has negative connotations, which is a problem if important, though uncertain, information is consequently ignored in public debate and policy-making (Milne et al, 2015). It is therefore imperative that the current uncertainty in BC inventories does not dissuade policy-makers from considering this important short-lived climate forcer and air pollutant.

Progress Made Under The Convention on Long-Range Transboundary Air Pollution

The Gothenburg Protocol of the CLRTAP includes the voluntary reporting of BC emissions, and encourages countries to support the development of BC emissions inventories. In order to allow countries to make BC emission estimates, information was added to the 2013 version of the EMEP/EEA Emissions Inventory Guidebook, and updates were made for the 2016 version.

It was decided that the initial focus should be on ensuring completeness of BC emissions estimates, and consequently EFs were assigned to all relevant sources by drawing on the available literature. The literature was dominated by EC EFs rather than BC EFs, and it was decided that, within the levels of uncertainty associated with the data, *EC EFs were suitably representative of BC*. The current emissions reporting from countries is labelled as BC, but, more closely represents emissions of EC.

Furthermore, it was decided to present the BC EFs as a percentage of the $PM_{2.5}$ EF. This approach was chosen to ensure that BC emissions could not be reported as exceeding $PM_{2.5}$. However, since the BC EFs have been included in the EMEP/EEA Guidebook, it has become apparent that this causes added complexity when quantifying the uncertainties of BC emissions. There are currently discussions about updating the EMEP/EEA Emissions Inventory Guidebook to change the way the BC EFs are presented.

The voluntary reporting of BC within the CLRTAP has proved to be successful, with more than 30 countries providing emissions estimates. Figure 2 below presents the source apportionment for selected countries. It illustrates that Road Transport and Residential & Commercial Combustion are major sources in all displayed countries. However, there is considerable variation in the source apportionment across the countries. Some of this variability is expected to reflect the real-world emissions, such that relatively high or low use of coal and wood in the residential sector. However, it is also expected that some sources are not being captured consistently in emission inventories across the countries. For example, in Spain a large contribution from the open burning of waste - shown in Figure 2 is included in the source labelled "Other" (including Solvents, Agriculture, Waste). It is particularly difficult to estimate emissions from waste burning, and it may be that other countries are using methodologies, which do not capture the emissions in the same way, or under the same source in their inventories.

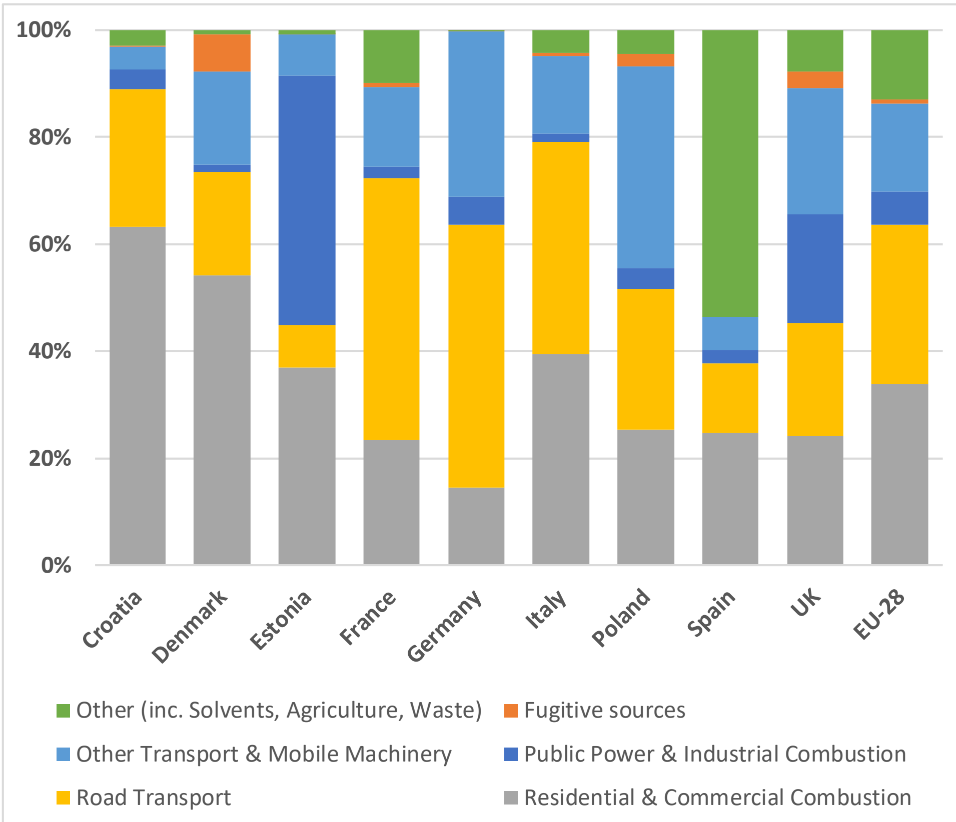

Figure 2. CLRTAP emissions of BC for 2015 from selected countries[4]

As can be seen, overall completeness of reporting is good, with the majority of countries reporting BC emission estimates from most sources. Attention can now be given to improving the contents of the EMEP/EEA Emissions Inventory Guidebook, and hence the accuracy of the existing emissions inventories. The maintenance and improvement of the EMEP/EEA Emissions Inventory Guidebook is completely reliant on voluntary contributions from Parties to the Convention, and international organisations such as the EEA and the European Commission. Consequently, whilst improvements to the guidance are the key step in delivering better quality BC emissions estimates, this can only be achieved if resources can be secured.

[4] Taken from CLRTAP Parties' 2017 submissions.

Estimating Black Carbon and Co-Emissions Using LEAP-IBC

The CCAC has developed an initiative Supporting National Action and Planning (SNAP) to reduce SLCPs, which is helping countries to set priorities for action to reduce SLCP-related emissions. Part of this activity is the development of emission inventories and emission scenarios to quantify emissions of BC and co-emitted pollutants necessary to quantify benefits of mitigation scenarios from all sectors. This includes all the substances affecting climate (GHGs and SLCPs) as well as all emissions influencing $PM_{2.5}$ concentrations and tropospheric ozone formation.

The Long-range Energy Alternatives Planning (LEAP, www.energycommunity.org) system is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed over 25 years by the Stockholm Environment Institute (SEI). LEAP is an integrated scenario-based modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. In addition, it can account for both energy and non-energy sector GHGs emission sources and sinks.

Since 2012, additional functionality has been added to the core LEAP software in form of the LEAP-Integrated Benefits Calculator (LEAP-IBC). The purpose of the LEAP-IBC tool is to enable estimates of emissions produced in LEAP to be used to quantify impacts of air pollutants on human health and agricultural crop yield loss, and the impacts of both GHGs and SLCPs on global temperature change. The IBC module therefore extends the scenario analysis capabilities of LEAP by allowing for the rapid evaluation of the estimated benefits that could result from the implementation of particular measures and policies, in terms of reductions in premature deaths associated with air pollution exposure, less crop loss due to ozone pollution exposure, and reduced global warming.

LEAP-IBC includes a default template that can be used to estimate emissions of air pollutants (including BC) and GHGs from all major source sectors, including those sectors of relevance to SLCP mitigation. To estimate $PM_{2.5}$ and ozone (O_3) concentrations in a country, and to estimate the effect of a country's emissions on global temperature, it is necessary to estimate emissions of all pollutants that contribute to $PM_{2.5}$, O_3 or temperature change. To this end, the tool contains default emission factors for 11 pollutants, including BC and OC, other short-lived climate forcers, as well as the major GHGs. Many of the default emission factors are taken from the EMEP/EEA (2016) Emission Inventory Guidebook and the IPCC (2006) Guidelines. However, as pointed out earlier, these are not always appropriate for developing countries or for sources of specific relevance to SLCP mitigation. Additionally, therefore, many default emission factors offered in the tool have been derived from the literature and are fully referenced for transparency. The tool is flexible, allowing users to replace the default emission factors with locally-determined factors, if they wish. The database of default emission factors currently used in LEAP-IBC is available on-line.

The CCAC SNAP initiative is currently supporting 12 countries to estimate emissions, scenarios and impacts (Bangladesh, Ghana, Mexico, Colombia, Chile, Mexico, Cote d'Ivoire, Togo, Nigeria, Philippines, Morocco, Maldives) and SEI has additionally supported Tribhuvan University to undertake an analysis for Nepal. This is then an input to national planning, identifying action that can be taken by countries to reduce emissions.

Developments Since the IPCC's 2005 Expert Meeting on Emission Estimation of Aerosols Relevant to Climate Change

In the 2005 report of the IPCC Expert Meeting on Emission Estimation of Aerosols Relevant to Climate Change, is was stated that: "*it is not possible, at this stage, to reliably produce internationally comparable national emission estimates…"* Since then, internationally comparable BC emission inventories for European countries have been compiled and reported under the auspices of the UN-ECE CLRTAP. This has been facilitated by developments in the EMEP/EEA Emissions Inventory Guidebook which, since 2013, has included default emission factors for BC (with uncertainty ranges). Also, within the SNAP initiative of the CCAC, countries are producing emission inventories of pollutants (including BC) using the LEAP-IBC tool which provides a standardised approach and includes fully referenced default emission factors.

The 2005 IPCC report also stated that: *"There are no universally accepted unique definitions of Black Carbon, Organic Carbon or Elemental Carbon. Existing approaches work in the current state of models but for the development of comparable inventories clearer less ambiguous measurement methods would be needed."* Since then, Petzold (2013) and others have clarified definitions of carbonaceous particles, including BC and elemental carbon (EC), which related to how the particles are measured using either optical (BC) or thermal (EC) techniques. In deriving BC emission factors used in the EMEP/EEA Guidebook, it was found that within the levels of uncertainty associated with the data, EC EFs were suitably representative of BC.

It was also stated in the IPCC report that: *"To improve the quality of data used in global and regional inventories there needs to be consideration of the different measurement methods of each of Black Carbon, Elemental Carbon and Organic Carbon."* There has been progress since 2005 with for example, Lack et al. (2014) having reviewed and clarified the measurement methods that correspond to the terminology descriptions of Petzold et al. (2013).

Proposed Developments and Activities

Development of emission inventory guidance on short-lived climate forcers, including BC. Authoritative guidance on short-lived climate forcers is likely to improve integration and the internal consistency between GHGs emission inventories and non-GHGs emission inventories, within and across the various assessments (including IPCC's) and mitigation strategies at global to local levels, and across sectors. Such guidance would also improve comparability in terms of the emissions inputs into the various models used to inform policies.

Emission Factor database: A comprehensive, transparent (fully referenced), on-line emission factor database (for BC, OC and other co-emitted substances, including CO_2) for use globally, is required to drive quality improvement of the BC emission inventories and to reduce the uncertainty. Focus can be put on those emission sources of importance for SLCP mitigation, especially those relevant to sources that are currently not well-characterised in the EMEP/EEA Emission Inventory Guidebook and IPCC Guidelines. It should also include uncertainty ranges for each emission factor.

Voluntary development and exchange of emission inventories: Countries are encouraged to compile emission inventories of BC and co-emitted substances and share the information to promote mutual learning. The inventories should include uncertainty estimates to help identify the major sources of uncertainty on which future efforts to improve the inventory might be focused.

Support to, and co-ordination of, regional inventory guidelines: The EMEP/EEA Emissions Inventory Guidebook is formally updated every three years, and contributions to this process would be constructive (particularly because updating the BC emissions methodologies are not assigned a high priority). In addition, separate guidance and methodologies that may be developed for global regions other than the UN/ECE should be done so in a way that provides as much consistency and alignment as possible with the EMEP/EEA Emissions Inventory Guidebook.

Promotion of further research: Uncertainties in BC emissions can be reduced by promoting further research, as needed, to improve the quality of activity data and emission factors, especially for sources in developing countries.

Advisory service and guidance: Emission Inventory developers and users need to be advised on the choice of suitable emissions factors (for BC and co-emitted substances). They also need guidance on how to estimate emission inventory uncertainties.

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