

Global atmospheric impacts of residential fuels

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The impacts of increased pollutant concentration may affect the behavior of the Earth-atmosphere system. In particular, large-scale changes in atmospheric composition are associated with changes in the Earth's radiative balance and climatic change. In this paper, we describe the various substances that are important, and examine emissions of air pollutants from residential fuels in relation to emissions from other sources. Using a global simulation of pollutant transport, we also estimate atmospheric concentrations of one pollutant, carbon particles, and identify regions in which residential fuels contribute greatly to the atmospheric aerosol. Finally, we compare total emissions from a variety of residential end-use technologies and estimate their effect on the radiative balance, with the implication that improvements could lead to a cleaner atmosphere on scales that are much larger than typically considered.

1. Atmospheric chemistry on the grand scale

Increasingly, human activities are producing effects on global and regional scales in addition to the familiar indoor and urban scales. Although the globally averaged concentration of pollutants is small, changes in that concentration are of concern when they affect the Earth system. In this paper, we discuss the contribution of residential fuels – those used for heating and cooking – to atmospheric composition on very large scales. The impacts of increased concentration may affect the behavior of the Earth-atmosphere system, as discussed later in this section. This phenomenon is popularly called “global warming”, but is more properly called “climate change”. We discuss the chemical species (gases or different types of particles) that lead to these changes and some of the ways in which they affect the Earth's climate. In Section 2, we use recent emission inventories to examine emissions of air pollutants from residential fuels in relation to emissions from other sources. Simulation results show atmospheric concentrations of particles in Section 3, identifying regions where residential fuels have significant impacts on atmospheric composition. A comparison of total emissions from a variety of residential end-use technologies appears in Section 4, combining the effects of several pollutants to assess total impacts of different technologies.

1.1. Greenhouse gases

The best-known problem involving fuel consumption and the composition of the global atmosphere is that of carbon dioxide (CO₂). Because the Earth system (including plants, soil and the ocean) cannot absorb all the CO₂ that

is emitted, the atmospheric concentration of that gas is increasing. Human activities are also causing increases in the atmospheric concentration of other gases such as methane (CH₄) and nitrous oxide (N₂O). The Earth's energy balance will be affected because these so-called “greenhouse gases” (GHGs) act as a blanket, as shown in Figure 1a. This blanket hinders the escape of infrared energy to outer space.

The resulting behavior of the Earth system may include increased temperatures, but also changes in rainfall patterns or extreme weather events [IPCC, 2001, Ch. 9]. Scientists have higher confidence in some of these projected changes, such as higher temperatures, than in others. It is thought that these changes will become significant over several decades, because these gases stay in the atmosphere for decades to centuries, and emissions can result in significant accumulation over long periods even if the annual totals seem small. To address this long-term problem, governments and other organizations are discussing ways to limit GHG emissions, a consideration that has become a component of assessing sustainability.

Changes in residential solid fuels have not been considered a major part of a solution to the greenhouse-gas problem because most solid fuels (excluding coal) are considered “renewable”. When they grow by taking up CO₂ that is already in the atmosphere, the CO₂ produced when they are burned is not a net addition to the atmosphere. However, if the fuel burned is not replaced with new growth, then a net addition of CO₂ to the atmosphere does occur.

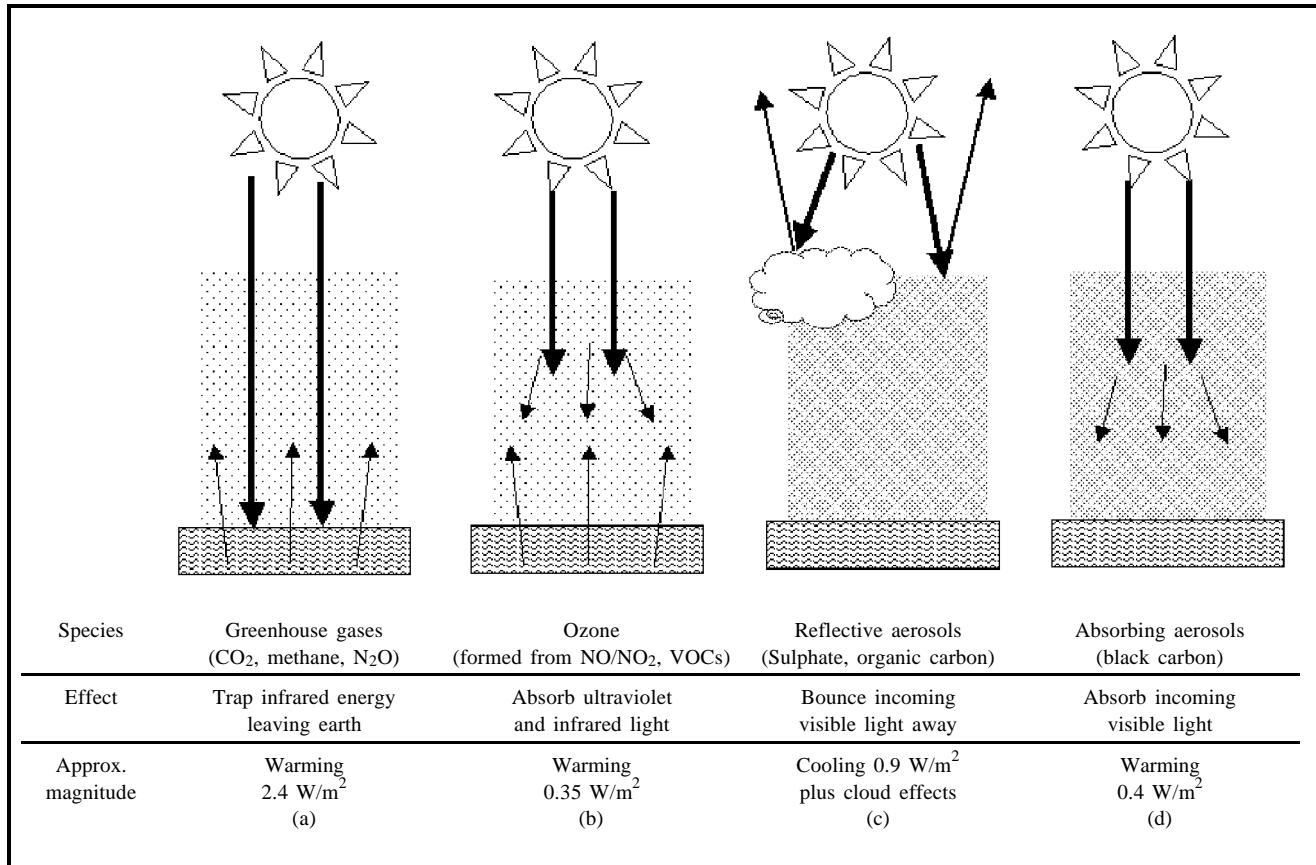


Figure 1. Impacts of combustion products on the Earth's radiative balance

1.2. Short-lived species

Greenhouse gases with long lifetimes are not the only species that change the Earth's radiative balance. Two other substances that have significant effects are ozone and aerosols, both found in polluted areas, and both with typical atmospheric residence times of less than two weeks. Concern about ozone and aerosols usually focuses on their effects on health or local air quality; such short-lived species aren't considered in the long-term problem of climate change.

Ozone is a gas that absorbs both ultraviolet light and infrared radiation, adding energy to the Earth system as shown in Figure 1b. It is formed through a complex series of reactions that involve nitrogen species (NO and NO₂), organic (carbon-containing) gases, and sunlight. Any process that produces NO, NO₂, or volatile organic compounds (VOCs) can contribute to ozone formation. Some VOCs are better at forming ozone than others, but we will not address that fine detail in our discussion here.

Aerosols are tiny suspended particles, with diameters about 50-100 times smaller than a human hair. Diameters range from 0.01 to 20 μm, with the most numerous being in the range 0.05-0.5 μm. Aerosols come from many processes, including burning fuels and formation from gases emitted to the atmosphere. The effects of aerosols on the Earth's energy balance are more difficult to determine than those of greenhouse gases, because there are two general classes of particles. One type reflects sunlight away from the Earth (Figure 1c), so that less energy is

added to the Earth system. Another type both absorbs and reflects light (Figure 1d), with the net result usually being an increase in energy added to the atmosphere. The major component of the absorptive type is sometimes called "black carbon" or "soot". Reflective aerosols include a range of compounds such as sulfates, nitrates, and "organic" (non-black) carbon. A piece of burning wood demonstrates the difference between black carbon (BC) and organic carbon (OC). The fire may emit black smoke (mostly BC) when the flaming is vigorous, and white smoke (mainly non-black, OC) when there is little flame. How the wood – or any fuel – is burned can determine whether the resulting particles add energy to or remove it from the system.

1.3. What's important?

With so many species affecting the Earth's energy balance, how does one determine which are most important? To compare impacts, we introduce two terms. The first, "radiative forcing", is the *change in the amount of energy* entering the lower atmosphere (troposphere). Although most people are interested in how that energy change will affect their lives directly – for example, altering temperature, rainfall, or growing seasons – determining these more immediate impacts is difficult, and the results of computer simulations do not always agree. It is easier to obtain agreement on estimated changes in the energy balance.

All species are removed from the atmosphere, some more quickly than others. A species that stays in the

Table 1. Global warming potentials (GWP) of various combustion products, relative to CO₂. The GWP is presented on a mass basis, showing the impact of 1 kg of each product versus 1 kg of CO₂. The definition of GWP is the total amount of radiative forcing during the period of interest after 1 kg of the species is emitted, divided by the total amount of radiative forcing by 1 kg of CO₂ emitted at the same time.

Species	Lifetime	Global warming potential			Additional concerns
		20-yr	100-yr	500-yr	
Traditional greenhouse gases					
Carbon dioxide (CO ₂) ^[1]	~100 yrs	1	1	1	None
Methane (CH ₄) ^[1]	12 yrs	62	23	7	Ozone production
Nitrous oxide (N ₂ O) ^[1]	114 yrs	275	296	156	None
Other climate-active species					
Carbon monoxide (CO) ^[1]	~1 month	10	3	1	Ozone production
Volatile organic compounds (VOCs) ^[2,3]	A few days	4.9	1.7	0.9	Ozone production
Black carbon aerosol (BC) ^[4]	A few days	2000	650	170	Health effects
Organic carbon aerosol (OC) ^[5]	A few days	-250	-75	-20	Health effects

Notes

1. From IPCC, 2001
2. From IPCC, 1990
3. Non-methane VOCs only (because methane is counted separately as a greenhouse gas)
4. From Bond and Sun [2004]
5. See discussion in Appendix A.

atmosphere longer contributes to global change for a long time after emission. To compare species with different atmospheric residence times, we introduce the “global warming potential” (GWP), or the total amount of radiative forcing experienced during some period of interest after emission (usually 20-100 years) [IPCC, 2001, Ch. 6]. The value of GWP for various species is listed in Table 1, along with the lifetimes of those species. Although greenhouse gases have far longer lifetimes than the other climate-active species listed, the GWPs of the other species are still significant, even over long periods. A large GWP means that trace amounts of a species are relatively powerful, but it does not mean that the species is responsible for most of the radiative forcing. For example, both nitrous oxide and black carbon have large GWPs, but because their atmospheric concentrations are far lower than those of CO₂, their total forcing is lower than that of CO₂.

The concept of the GWP is well accepted for greenhouse gases that are well mixed in the atmosphere, and has been evaluated for other gases such as carbon monoxide [IPCC, 2001] and volatile organic compounds [IPCC, 1990] that are not evenly mixed. The use of GWP for aerosols is rather controversial. Appendix A gives some technical details describing how the GWPs for black and organic carbon were derived, although the full derivation will appear in another paper. GWPs for volatile organic compounds and for aerosols are very uncertain; we estimate that the GWP for black carbon is only known within a factor of three.

Aerosols also have several impacts that cannot be reflected in the GWP. These include changes in the vertical energy structure of the atmosphere, the quantity or loca-

tion of rainfall [Rotstayn and Lohmann, 2002; Menon et al., 2002], and changes in cloud properties that affect their interaction with sunlight and their ability to produce rain [Twomey et al., 1984; Albrecht, 1989; Rosenfeld, 2000]. While it is easy to find arguments that the GWP is not a perfect way of comparing relative impacts, it is more difficult to come up with a better comparison. In the following discussion, we will use the GWP to compare the atmospheric impacts of different species.

When a fuel is burned, the carbon it contains forms a number of products. If the combustion is complete, it forms only CO₂. If the combustion is not complete, it emits other gases such as carbon monoxide (CO) or VOCs, as well as particles. Particles emitted from solid-fuel combustion contain mostly black and organic carbon, and a small amount of other substances such as potassium. An important point is that most carbon-containing products of incomplete combustion have *greater* effects on the energy balance (as measured by their GWP) than the CO₂ from complete combustion, for two reasons. First, some of these compounds absorb radiation much more strongly than does CO₂. Second, CO₂ is a final combustion product and does not participate in further chemical reactions. In other words, CO₂ might be considered an undesirable product in terms of Earth’s energy balance, but any *other* combustion product is probably worse. The combined effects of incomplete combustion on the energy balance are discussed further in Section 5.

2. Sources of climate-active species

2.1. New attention to residential fuels

Both modeling and measurement results have been leading

toward the conclusion that residential fuels could have important impacts on large-scale atmospheric chemistry. Over a decade ago, scientists had estimated that impacts of aerosols on the Earth's radiative balance could rival those of greenhouse gases. Most of the simulations examined particles containing sulfate, which mainly comes from coal-fired power plants [e.g., Charlson et al., 1991; Kiehl and Briegleb, 1993]. Other models examined impacts of black carbon and organic carbon aerosols from open field- and forest-burning [Penner et al., 1992]. The contribution of residential biofuels to atmospheric aerosols was lumped into this open-burning calculation in the "scientific consensus" reports on global change [IPCC, 2001].

Large visibility reductions attributable to aerosols over the Indian subcontinent have been reported for years [Moorthy et al., 1993, 1999; Husar et al., 2000], and similar observations were reported from several other world regions [Husar et al., 2000]. However, the climatic impacts of the haze around India appear to have been ignored until a large experiment involving dozens of scientists, called the Indian Ocean Experiment (INDOEX), "re-discovered" it in 1999 [Lelieveld et al., 2001]. The darkness of the haze was of particular surprise to INDOEX scientists. Measurements showed that its impact on the regional radiative balance was approximately 10 times greater than that of greenhouse gases [Satheesh and Ramanathan, 2000], and computer simulations suggested that it could cause changes in rainfall as well [Ramanathan et al., 2001]. The haze was originally nicknamed the "Asian Brown Cloud", a name that was changed to "Atmospheric Brown Cloud" when comparisons showed comparable aerosol concentrations in other world regions [Quinn and Bates, 2003].

The discovery of the "brown cloud" led to much speculation among scientists who had little knowledge of the combustion practices in these countries. Where did the cloud come from? Some named burning of biomass, either for energy use or open burning, as the culprit [Guazzotti et al., 2001]. Others pointed at fossil fuels on the basis of limited chemical information [Novakov et al., 2000]. Results from other experiments near the east coast of Asia [Huebert et al., 2003] also implied that residential fuels might contribute to the atmospheric aerosol [Carmichael et al., 2003]. These recent experiments have highlighted the importance of aerosols from residential use of fuel, but those fuels may also be significant sources of ozone-forming species [Tsai et al., 2003] and other pollutants [Ludwig et al., 2003].

Along with the experimental results, additional work on emissions [Reddy and Venkataraman, 2002a; Streets et al., 2003; Bond et al., 2004], combined with improvements in biofuel consumption data [Hall et al., 1994; Marufu et al., 1997; Sinha et al., 1998; Amous, 1999; Kituyi et al., 2001; Yevich and Logan, 2003], meant that models of the atmosphere could better represent the contribution of residential fuels. Although residential fuels are an age-old challenge, the scientific focus and the computational tools needed for atmospheric scientists to examine their contribution have only recently become available.

2.2. Building emission inventories

All models of atmospheric chemistry, whether global, regional, or urban, begin with "emission inventories". An inventory is a tabulation of the quantity and location of emissions, estimated by combining data on *activities* – the actions that produce the emissions – and *emission factors* – how much of the species is produced by the activity. Activity data include fuel consumption, energy used, products produced, or hectares burned. As an example, aerosol emissions from a family's cooking might be calculated as follows: the family burns 5 kg of wood per day (activity); 3 g of particulate matter are emitted per kg of wood burned (emission factor). The particulate matter emitted from the family's home is $(5 \text{ kg/day}) \times (3 \text{ g/kg}) = 15 \text{ g/day}$, assuming that the family engages in no other activities that emit aerosols and that all the particles escape to the outdoors.

Obtaining accurate activity data for residential fuels is quite difficult. Even in fossil-fuel energy statistics, the allocation of fuel to residential, commercial, or agricultural uses is not always broken down. In contrast to fossil fuels, many solid biomass fuels are traded or gathered by the users and do not form part of a formal economic network, so that the official recording associated with fossil-fuel use does not occur. Biofuel consumption estimates are often based on survey data. Because these surveys are not available for all regions or years, they may be extrapolated on the basis of population surveys, per-capita consumption, or economic data. A recent study has reduced the uncertainties in estimates of biofuel for cooking by producing estimates based on food consumption [Habib et al., 2004]. However, uncertainties of 50-100 % in activity data are common [Yevich and Logan, 2003; Bond et al., 2004; Habib et al., 2004].

Most of the carbon in fuel becomes CO₂ during combustion, so it is not difficult to predict CO₂ emission factors. In contrast, the emission factors for particles and VOCs depend very much on the burning process, with poor combustion generally resulting in higher emissions. Figure 2 shows the range of black carbon emission factors from burning 1 kg of coal in different ways. The figure shows why residential fuels might be important sources of aerosols even if fuel quantities are small. Large, well-designed, expensive burners use a combination of air-fuel mixing and high temperatures to reduce emissions. Low-technology combustion does not have those advantages and produces emissions that are orders of magnitude higher. With the exception of a few studies (tabulated by [Reddy and Venkataraman, 2002a; Bhattacharya and Salam, 2002; Bond et al., 2004]), measurements that characterize emission factors have not concentrated on such small sources. Few emission factors have been measured, and lack of relevant emission factors is a major uncertainty when developing emission inventories. (Because biofuel is so widely used, it might be more interesting for Figure 2 to show the range of emissions that occur from burning wood different ways, but there are not enough available measurements to do so!)

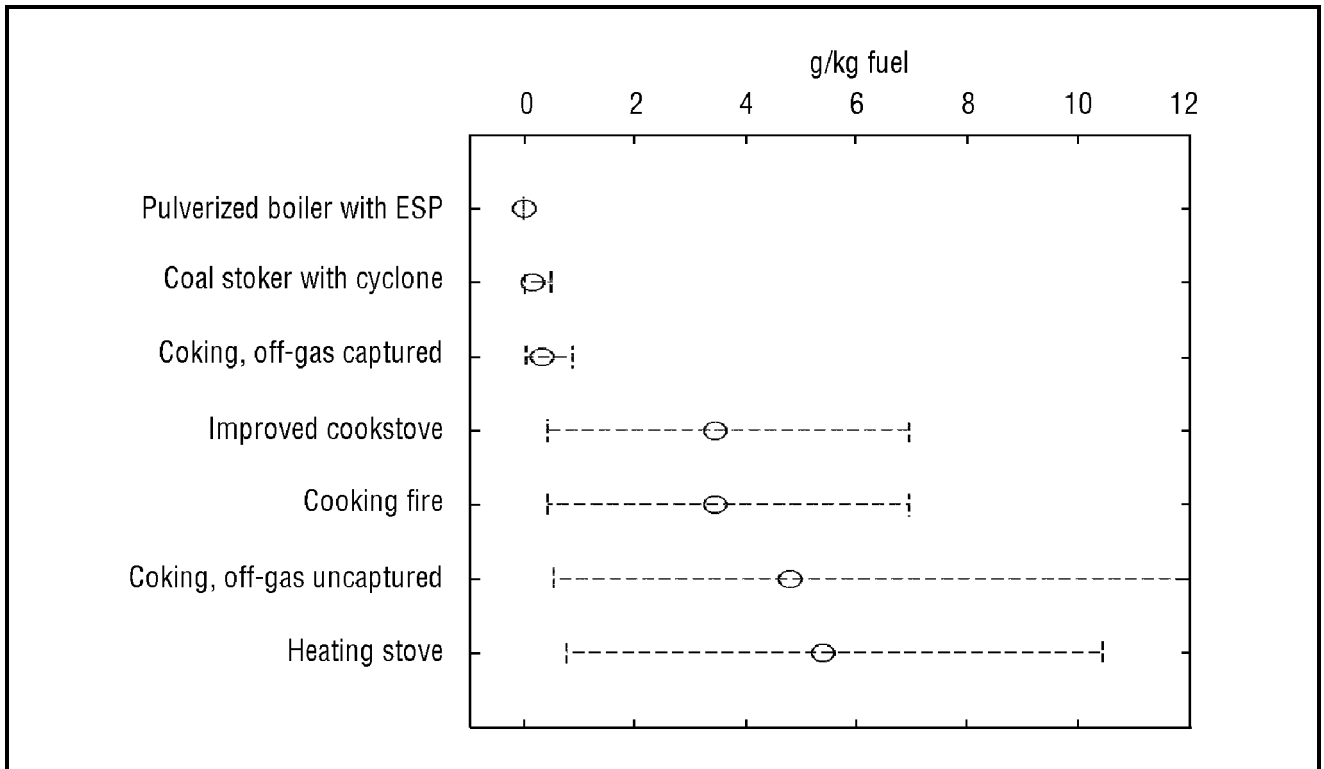


Figure 2. Emission factors of "black carbon" from different kinds of coal-burning, from tabulation in Bond et al. [2004]. The dashed lines indicate uncertainties in emission factors. "ESP" means electrostatic precipitator, a type of emission control device installed on most modern coal-boilers.

2.3. Inventory results

Many of the emission estimates used in global modeling can be accessed via the Internet. This include the EDGAR database (<http://arch.rivm.nl/env/int/coredata/edgar/>) and the Global Emission Inventory Activity collection (GEIA, <http://geiacenter.org>). Some recent inventories are also described in the peer-reviewed literature, especially for Asia [Bhattacharya et al., 2000; Reddy and Venkataraman, 2002a, 2002b; Streets et al., 2003; Bond et al., 2004]. To produce Figure 3, we combined data from the EDGAR database [Olivier et al., 2001] on gaseous species and from Bond et al. [2004] on aerosol emissions. Uncertainties in both databases are high.

The figure shows the major sources of three species, each representing one pathway to radiative impact: CO₂, a traditional greenhouse gas; VOCs, which lead to atmospheric ozone; and black carbon, the fraction of the aerosol that causes warming. For all species, vehicles are a large source. Power generation contributes strongly to CO₂ and little to aerosol impacts. Residential fuels are a large source of aerosols and a small source of greenhouse gases. Characteristic sources and source magnitudes vary between regions. For example, aerosol emissions appear dominated by transport in North America, by open burning in Africa, and by residential solid fuels in Asia.

Figure 4 is similar to Figure 3, but it focuses on the residential sector, showing emissions of black (light-absorbing) carbon from different fuels. (Available inventories of other species do not provide enough detail to include them in this treatment.) The figure also shows comparative per-capita emissions in different regions. As we shall see in the next section, high populations in Asia

result in large *total* emissions, but examining per-capita emissions is also instructive. Although there are large uncertainties in these values, it is easy to see that solid fuels are the largest sources of aerosols in this sector, even in industrialized countries where alternatives are available. In Africa, estimated per capita emissions of aerosols are higher than they are in Asia because of the relatively greater use of animal waste (dung); although emissions from burning 1 kg of dung are only slightly greater than those from 1 kg of wood, dung is an inefficient fuel, requiring more fuel to achieve the same tasks.

3. Atmospheric impact

Emission inventories may suggest the sources and locations responsible for pollutants. However, the highest concentrations and the highest emissions do not necessarily occur in the same locations. For example, winds carry pollutants away from sources and reduce local concentrations, but spread them over a larger region, so that even areas with no emissions can be affected. Determining the locations that are most greatly affected requires a computer model. While these models are not perfect, they do consider many of the physical processes that govern atmospheric concentrations.

Figure 5 shows the results of a global transport model (MATCH, run at the National Center for Atmospheric Research in Boulder, Colorado, USA; description available at http://www.cgd.ucar.edu/cms/match/new_website/index.html). The top panel shows the calculated average annual distribution of carbon particles (both black and organic) that are emitted from biofuel-burning. Total emissions of biofuel-related aerosols differ somewhat

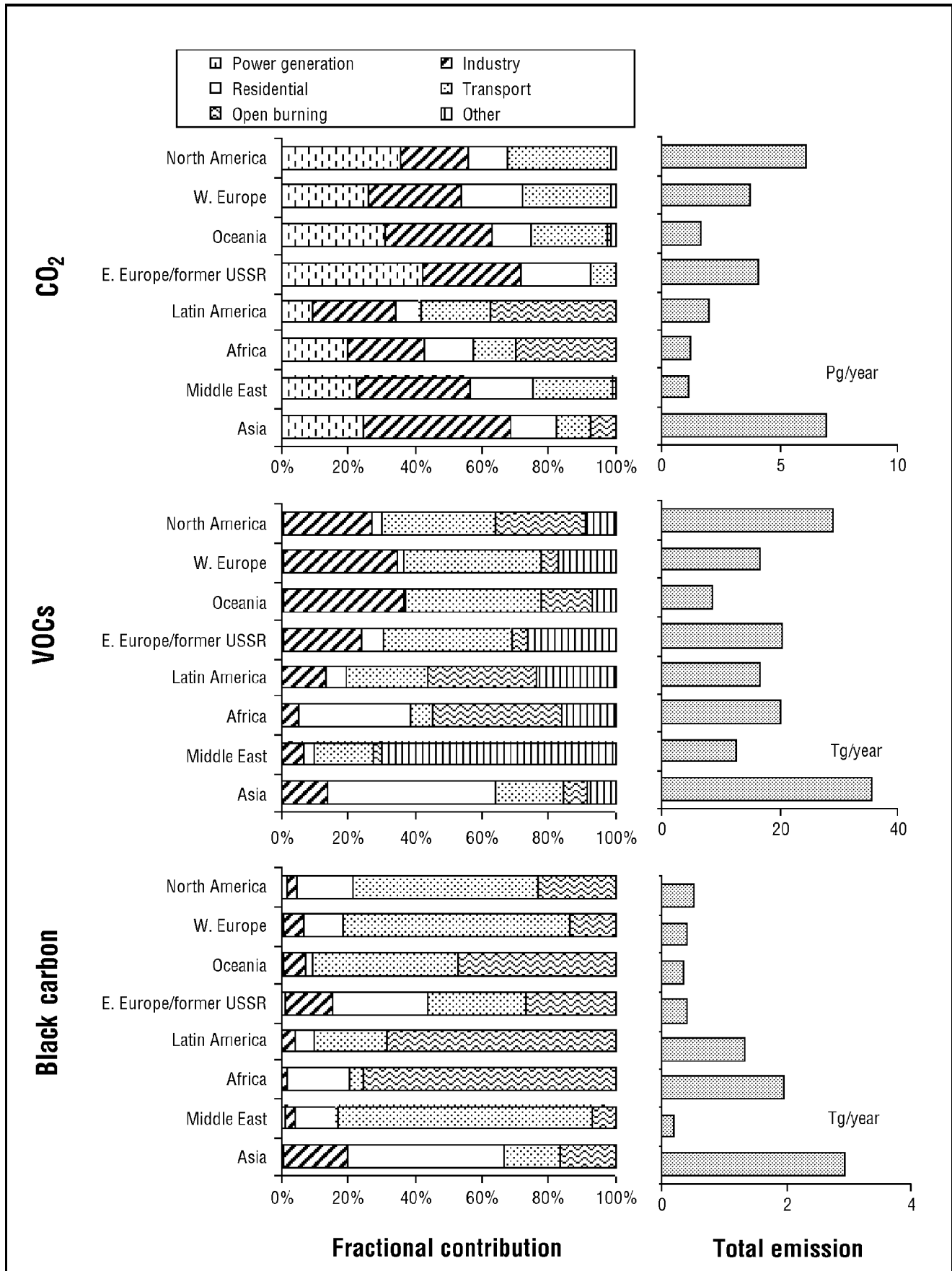


Figure 3. Sources of radiative forcing: (a) carbon dioxide, a greenhouse gas; (b) non-methane volatile organic compounds, an ozone precursor; (c) black carbon, an aerosol. CO₂ emissions from open burning include only deforestation. They exclude cyclic open burning such as field-clearing and residential or industrial biomass where replacement growth occurred. (Pg = 10¹⁵ g; Tg = 10¹² g)

Sources: CO₂ and non-methane VOCs: EDGAR 3.2 by RIVM/TNO, Olivier et al. [2001]; BC: Bond et al. [2004].

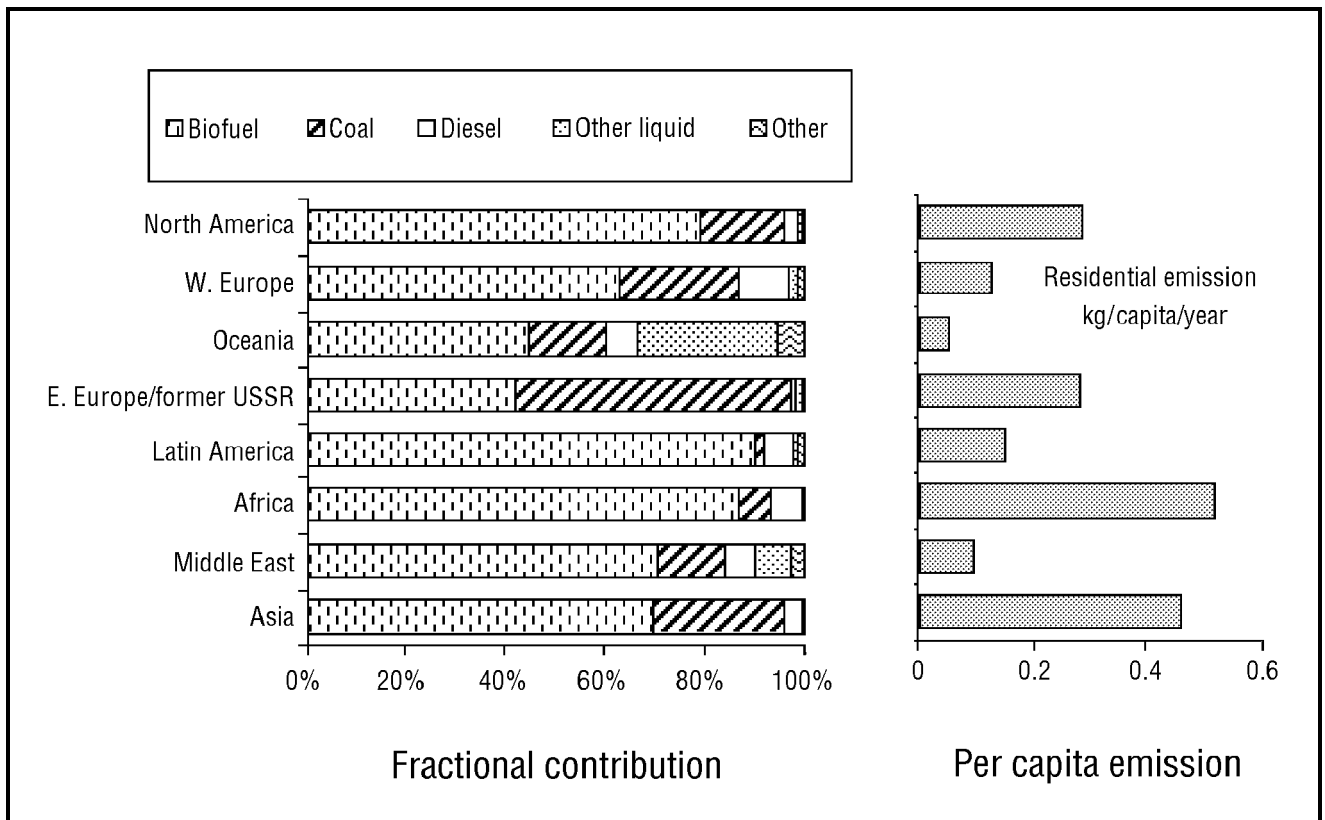


Figure 4. Sources of black carbon emission from residential fuel consumption

from total residential emissions because the former include biofuel used in industry and power generation, and do not include coal-burning. However, to our knowledge, this is the first published global simulation where the emissions from biofuel-burning have been separated from those from open biomass combustion.

The largest concentrations appear around Asia, where large populations rely on biofuels. There are also large concentrations around sub-Saharan Africa, resulting from biofuel for cooking, and the north-eastern United States, resulting from heating with wood. The lower portion of Figure 5 shows the fraction of total carbon aerosol that comes from biofuel use. Other sources are fossil-fuel use, open field- and forest-burning, and emissions from trees. The biofuel fraction is also largest around Asia, especially South Asia, where other sources are few. The fraction is slightly lower in East Asia because of greater use of fossil fuel there, especially coal. The fraction is also low over North America and Europe because of greater use of and emissions from fossil fuel, and because of large biogenic (tree) emissions at far northern locations. Although the top panel shows that biofuel use does result in significant atmospheric concentrations in the Southern Hemisphere, the fractional contribution is low because of the very large contribution of open burning (see Figure 3). Thus, aerosol from biofuel-burning does cause significant concentrations, which dominate the concentration of carbon particles around Asia but not in other regions. Cleaning up residential biofuel consumption will help to reduce concentrations of these particles, but other sources will need to be addressed as well, and the same is true for pollutants other than aerosols.

4. Toward a holistic view of technology choice

It is generally accepted that sustainability considerations include minimizing long-term changes in atmospheric chemistry. We now know that greenhouse gases are an important part of the atmospheric chemistry picture, but not the only part. Technology choice affects emissions of many species that alter the Earth's energy balance on both short and long time-scales.

4.1. Previous studies

Few studies have considered the simultaneous radiative effects of CO_2 and short-lived species. Most of these studies use some variant of the global warming commitment (GWC) introduced by Smith et al. [2000]. This measure represents the total GWP of the emissions from producing a fixed amount of useful energy, so it accounts for inefficiencies in the cooking or heating as well as the emissions. Bhattacharya and Salam [2002] compared options for cooking based on a comparison of long-lived greenhouse gases only. Smith et al. [2000] compared the total GWP from both long-lived and short-lived greenhouse gases and found that biofuel emissions had a higher GWC than fossil-fuel emissions owing to the poor burning and low efficiencies. By combining the impacts of CO_2 and particles, Jacobson [2002] suggested that diesel vehicles warmed climate more than gasoline vehicles on short time-scales, even though diesels emit less CO_2 . Bailis et al. [2003] found that charcoal and wood had similar CO_2 emissions, but charcoal had much higher emissions of greenhouse gases even though it had lower health effects. These studies highlight the impacts of incomplete combustion on the Earth's radiative balance, and they send a

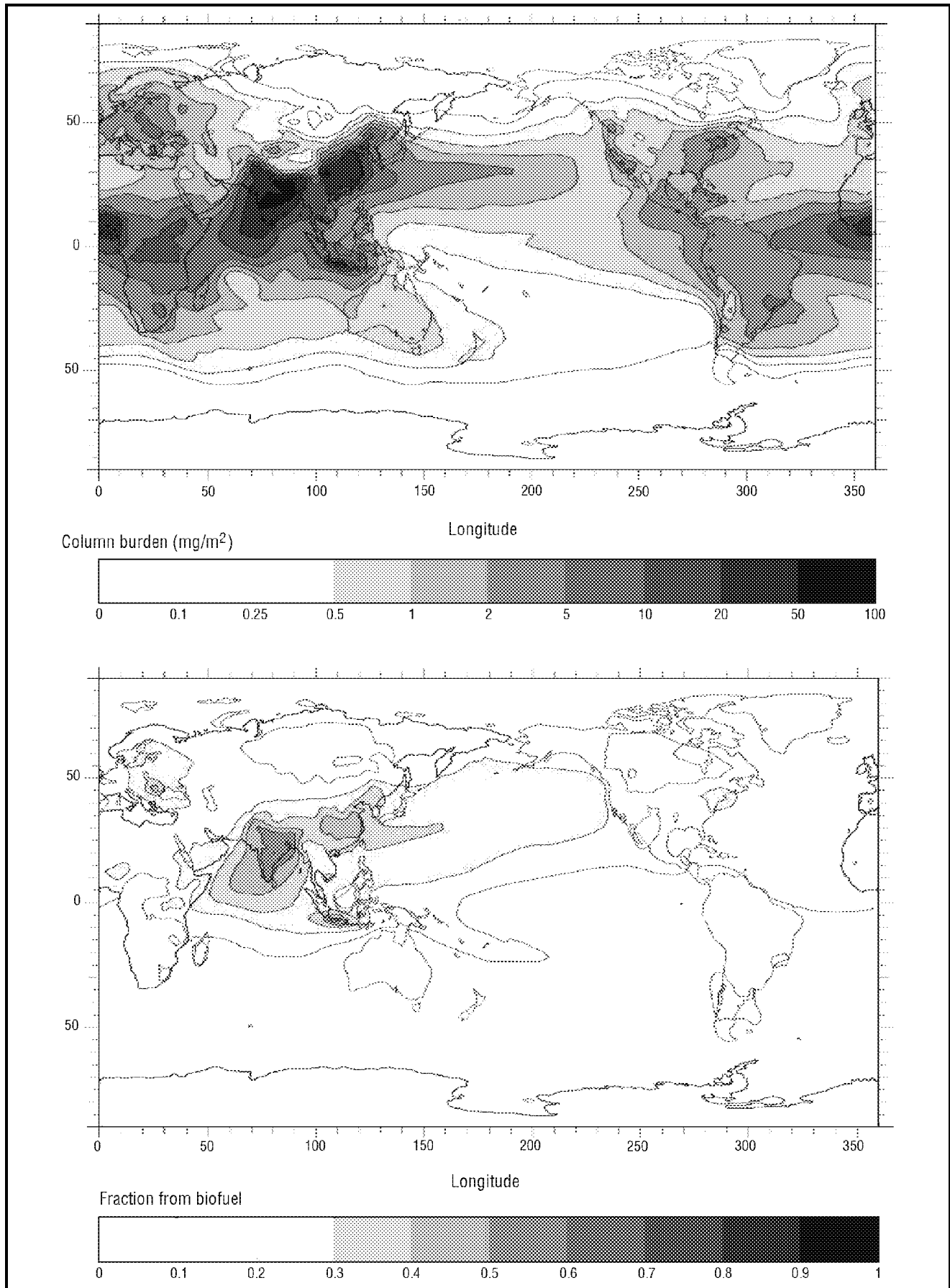


Figure 5. Atmospheric aerosol produced by biofuel burning, from computer simulations. Top: Column burden of carbon particles from biofuels ("column burden" means the total emissions of carbon particles from biofuels at a given point). Bottom: Fraction of total carbon particles that come from biofuels. Simulation: NCAR-MATCH with meteorological data for 2001.

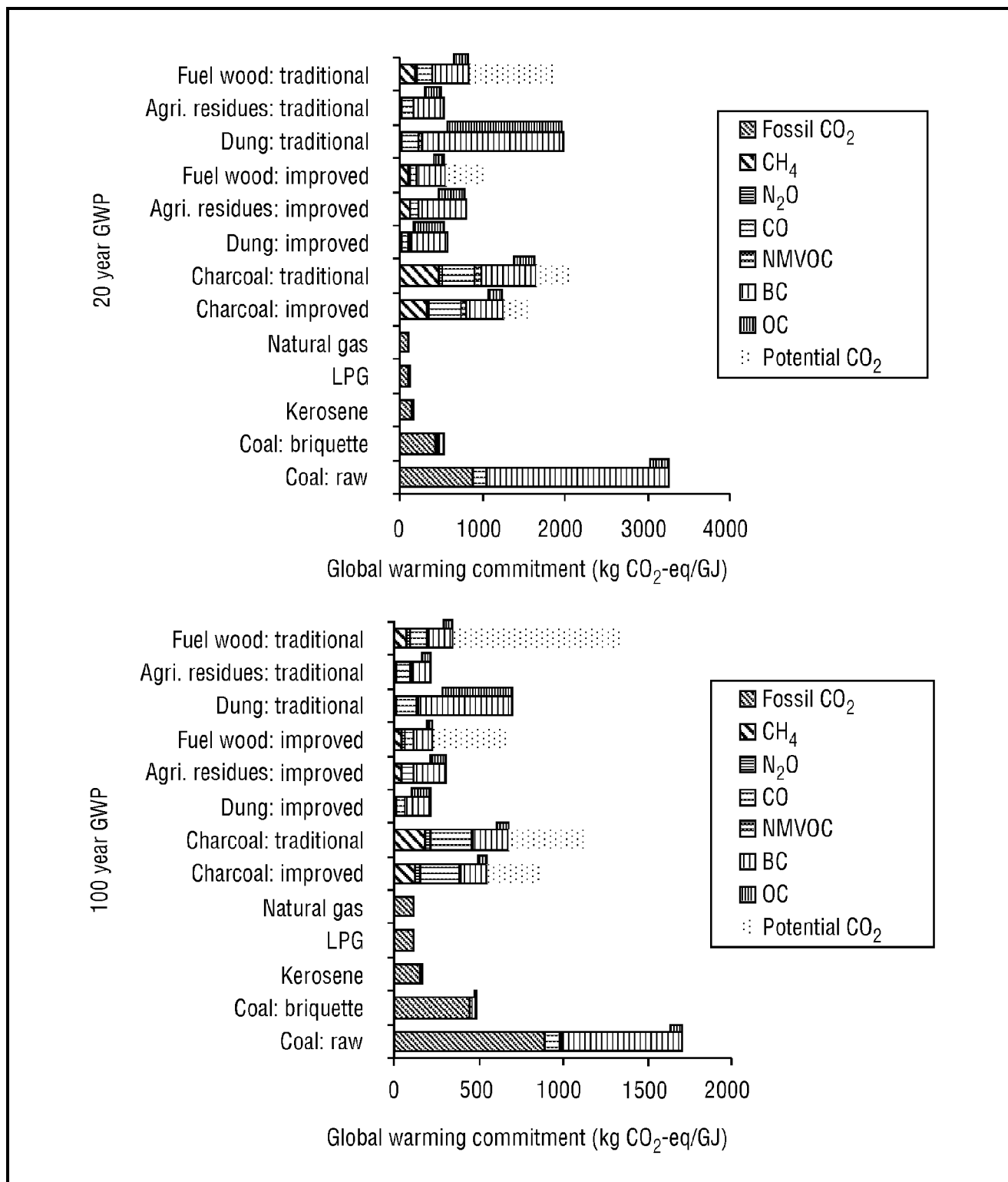


Figure 6. Global warming commitment (GWC) by 1 GJ of energy delivered to a cooking pot, for 20-year and 100-year GWP. Diagonal fill: traditional greenhouse gases; horizontal fill: non-traditional greenhouse gases; vertical fill: aerosols; dotted fill: CO₂ from biofuel. CO₂ from biofuel is a net emission only if the harvested material is not regrown and so is called “potential CO₂” in the figure. See the text for an explanation of the offsetting bars between BC and OC. Sulfate from coal-burning has not been included here and would also offset warming.

common message despite the different sources and species examined. Considering the total effect of individual technologies may give different answers from comparing just the CO₂. Often, the presence of incomplete combustion indicates greater impacts on global climate despite low CO₂ emissions.

Although poor combustion is definitely a concern for the people in the immediate vicinity, it also presents some large-scale challenges. People who cook and heat with solid fuels may experience many immediate problems, including but not limited to high exposures to pollutants, and may not be concerned with atmospheric chemistry on

Table 2. Change in radiative impact compared with traditional fuels and stoves when different species and time-frames are considered. In the table, all CO₂ from biomass is considered renewably harvested and does not contribute to radiative impact. The column headed "Total gases" is rather uncertain, and the columns headed "Gases + BC" and "Gases + all particles" are very uncertain. All of the values underlying the analysis are uncertain: emission rates of ozone-forming gases and aerosols could be uncertain by a factor of two or more, and GWPs could be uncertain by factors of three or more.

	Traditional GHG	Total gases	Gases + BC	Gases + all particles
20-year				
Traditional stoves	0 %	0 %	0 %	0 %
Improved stoves	0 %	- 30 %	-40 %	-30 %
Charcoal	+430 %	+250 %	+90 %	+170 %
Clean fossil fuels	+70 %	-30 %	-70 %	-50 %
100-year GWP				
Traditional stoves	0 %	0 %	0 %	0 %
Improved stoves	10 %	-40 %	-40 %	-30 %
Charcoal	+410 %	+190 %	+50 %	+120 %
Clean fossil fuels	+300 %	+0 %	-70 %	-40 %

the grand scale. However, the converse is not true: those investigating the global picture *should* give attention to residential fuels, which produce impacts of the type and magnitude caused by greenhouse gases.

4.2. A full comparison of technology choice

Using the combined global warming potential (GWP), Figure 6 shows a comparison of global change impacts for different residential cooking technologies. The figure compares total emissions from processes that deliver 1 GJ of energy to a cooking pot. This analysis combines the concepts introduced by Smith et al. [2000] and Jacobson [2002], combining the effects of greenhouse gases, ozone-forming gases, and particles on Earth's radiative balance. The GWPs listed in Table 1, for 20-year and 100-year time-scales, are applied to the total emissions. For this analysis, we have used emission factors and efficiencies tabulated by Bhattacharya et al. [2000], Andreae and Merlet [2001], and Bond et al. [2004], supplementing them with more recent measurements by Smith et al. [2000], Zhang et al. [2000], Venkataraman and Rao [2001], Pennise et al. [2001], and Bhattacharya et al. [2002].

In Figure 6, the total without dotted bars represents the contribution of renewably harvested biomass; total with dotted bars represents the GWP that would occur if wood came from deforestation. For aerosol bars, the additive bars beneath show the warming by BC, while the bars above show the offsetting cooling by co-emitted OC. The net warming is given by the difference between the two bars, and is often far smaller than the warming by BC, but the presence of large amounts of aerosol results in climatic effects other than warming that cannot be represented in the graph. Because of large uncertainties, this figure should be taken to represent only a qualitative comparison. The values underlying the figure come from a limited number of measurements of biofuel-burning, and more studies are needed to reduce these uncertainties. More detailed analyses of all fuels, including full fuel-cycle

calculations, are also needed to refine the comparison. Emissions from other parts of the fuel cycle, including extraction, processing or harvesting and transportation, may alter the comparisons shown in the figure.

It should be emphasized that Figure 6 compares only technologies for which emission factors of all climate-active gases and particles (not just CO₂) have been measured. These measurements are not available for many cleaner technologies, including gasification, densification, or other transformations of biomass fuels. Thus, the figure represents only the most prevalent practices and does not reflect the promise of technologies that may spread in the future, including "modern" biomass.

The discussion here will compare the general technology classes for which measurements are available: traditional and improved biomass stoves, charcoal, and clean (distilled) fossil fuels. Figure 6 also shows high emissions of both greenhouse gases and other species from raw coal, while briquetted coal has high CO₂ emissions but low emissions of other material. For charcoal, emissions from production and consumption were added to determine the atmospheric impacts of that fuel. No emissions from other parts of the fuel cycle were included, such as emissions during transport or extraction. The combination of greenhouse gas emissions and ozone-forming gases repeats the analysis presented by Smith et al. [2000] with emission factors updated from the other studies, but no previous analysis has combined the effects of greenhouse gases and aerosols from residential fuels, nor has a comparison using the 100-year GWP appeared previously.

Averaging the data in Figure 6, Table 2 shows the approximate change in the impact by switching from traditional stoves when considering only traditional greenhouse-gas emissions, all gases, and gases plus black carbon. Previously, we discussed how aerosols other than black carbon reduce energy getting to the Earth system, causing cooling instead of warming. The last column in

Table 2, and the offset bars in Figure 6, show the effects of these cooling particles. Considering non-absorbing aerosols alters the magnitude of impacts of each technology, but it does not change the sign of the comparison in this analysis. However, the uncertainties in emission rates and aerosol GWP might very well lead to a change in sign. Given the uncertainties in the underlying calculations, Table 2 should not suggest that we can calculate exact impacts of technology change on climate. Instead, the main message is that consideration of non-greenhouse gas species can lead to vastly different conclusions about technology choice.

Use of the 20-year GWP emphasizes short-lived species relative to CO₂ and follows the analysis of Smith et al. [2000]. The effect of switching to improved stoves is the same no matter what species are considered. For traditional greenhouse-gas emissions only, fossil fuels appear to have the largest impact, but that conclusion changes when the other species are considered. Clean fossil fuels and improved stoves provide similar improvements when all gases are considered, and those fuels appear far better when considering particles as well. The high impact of charcoal is a result of the production process, which involves oxygen-starved heating of wood and releases both organic gases and particles.

Using the 100-year GWP increases the emphasis on long-lived greenhouse gases. Under this framework, fossil fuels show a much greater impact when traditional greenhouse gases are compared, but again fossil fuels and improved stoves look favorable when other species are included. By reducing emissions from residential solid fuels, it is possible to decrease human effects on large-scale atmospheric chemistry in addition to achieving local and household benefits. Two general classes of improvements are possible: cleaning up existing combustion, or changing to different energy sources.

The first option includes improved cookstoves, which are shown in Figure 6, as well as some cleaner options such as biogas from anaerobic digesters or thermal gasification that are not shown. The figure shows that improved cookstoves are better than traditional cookstoves, but still have substantial emissions. However, previous stove improvements have often focused on efficiency for deforestation considerations, not emission reductions. The "improved" stoves shown in the figure do not represent the maximum reduction that could be achieved if both efficiency and emissions were addressed. Biogas technologies would nearly eliminate the impact from both short-lived and long-lived species. Capturing and utilizing the off-gas from charcoal production would greatly reduce the atmospheric impacts of that fuel. These latter two options are not represented in Figure 6 simply because there is no emission data on these improved technologies.

The second option includes clean fossil fuels and renewable energy sources such as solar electricity. Figure 6 shows that clean fossil fuels can also lead to major improvements in the global impacts associated with non-CO₂ species, even if they add CO₂ to the atmosphere. Similar to biogas, renewable energy sources would eliminate the

impact from both short-lived and long-lived species.

For each of these options, affordability, availability, distribution, and maintenance play a role in acceptance, and are particularly important when identifying viable options for the poor. Because of the diversity of situations and needs, multiple-fuel strategies [Masera et al., 2000] that include a range of solutions, including clean fossil fuels, improved biofuel technologies, and renewables, should be considered.

4.3. Final note: sustainability as a balance

The discussion here, as well as that in previous work [Smith et al., 2000; Hansen et al., 2000; Jacobson, 2002], suggests an urgent need to develop a holistic understanding of the impacts of technology choice, including residential fuels. Both long-lived and short-lived species play important roles in the global energy balance. Consideration of short-lived species has highlighted new scientific areas for investigation, and including these species in comparisons of global change might affect how society views specific technologies. Discussions on sustainability typically require balancing long-term and short-term considerations. We are learning that the challenging task of addressing atmospheric chemistry and the Earth's radiative balance is no exception. ■

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Appendix A. GWP of carbon aerosols

As mentioned in the text, the use of global warming potential (GWP) for aerosols is not established in the scientific community. Our purpose in using it in this paper is to examine which species and which technologies have the greatest impacts on direct radiative forcing, a comparison that requires some measure that incorporates radiative forcing and lifetime. The full derivation of the current understanding of GWP for black carbon (BC) will appear elsewhere [Bond and Sun, 2004]. Here we provide a general discussion of how the values used in this paper were derived.

The GWP of BC is calculated as described in [IPCC, 2001, Sec. 6.12], by integrating the forcing of BC over its lifetime, and dividing that integral by the integrated

forcing of the same mass of CO₂, which has a lifetime of several decades, over the period of interest (in this case, 20 or 100 years). The atmospheric lifetimes of aerosols, and the forcing by aerosol mass in the atmosphere, are estimated by synthesizing the results of seven different modeling groups, including all those tabulated by IPCC [2001, Ch. 6] and work since that assessment.

There is a common perception that model complexities are the cause of the varying radiative forcing reported by different groups and tabulated by Chung and Seinfeld [2002]. On the contrary, it can be shown that differences in basic assumptions (particle size, morphology, water uptake, and composition) are responsible for most of the major discrepancies. Our best estimates of forcing by BC

and OC are based on combining the information from these studies in the light of current knowledge. The simulation results shown in Figure 5 of this paper are not used to estimate GWP, although the aerosol lifetimes do compare well with those of the other modeling groups.

The large GWP of aerosols, particularly BC, may come as a surprise. However, a simple thought experiment based on the information published by IPCC [2001] can confirm the order of magnitude. Forcing by fossil-fuel BC is estimated at +0.2 W/m² based on emissions of about 7 × 10¹² g/year. The lifetime of aerosols is about one week, so the atmospheric burden is about 1.3 × 10¹¹ g. Forcing by CO₂ is estimated as about +1.5 W/m² based on an anthropogenic concentration of 87 ppm, or 5.6 × 10¹⁷ g of atmospheric concentration. So forcing by the same mass of BC and CO₂ differs by a factor of about 6 × 10⁵, an estimate that concurs with the comparison made by Jacobson [2002]. However, the lifetime of BC is much shorter than that of CO₂ – about 5,000 times shorter if

one week is compared to 100 years – leading to the preliminary result that the warming of BC integrated over 100 years is about 100 times that of CO₂. The GWP used in this paper is somewhat larger because we account for the initial rapid decay of CO₂ as represented in the Bern carbon-cycle model, and because we account for some new considerations raised since the IPCC summary was published in 2001.

Values of GWP for OC and SO₂ were derived for this paper in a manner similar to that described by Bond and Sun [2004] – that is, by combining normalized direct radiative forcing (NDRF) with atmospheric lifetime. For OC, we estimated a value of -150 W/g for NDRF by comparing the modeling studies summarized by IPCC [2001, Table 6.5]. This value was intermediate between forcing values for “dry” OC (no water uptake) and “wet” OC (assuming water uptake). The lifetime of OC was the same as assumed by Bond and Sun [2004] for BC, 6.4 days.

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