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Review

Climate Change and Air Pollution: Exploring the Synergies and Potential for Mitigation in Industrializing Countries

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Abstract: Air pollutants such as tropospheric ozone and black carbon (soot) also contribute to the greenhouse effect. Black carbon is thought to be the second or third most important anthropogenic contributor to global warming, while troposheric ozone is the fourth most important. Both are also major components of indoor and outdoor air pollution. This paper reviews the existing literature of the health, economic, and climatic impacts of tropospheric ozone and black carbon emissions, together with mitigation options. The local nature of many of the impacts, combined with their short atmospheric lifetime and the existence of cost-effective abatement technologies that are already widely deployed in developed countries means reducing these emissions provides a highly climatically-effective mitigation option that is also appropriate to the development strategy of industrializing countries.

Keywords: Climate change; black carbon; post-Kyoto; mitigation; ozone.

1. Introduction

Climate change is likely to be the defining environmental problem of the twenty first century. Increasing scientific evidence suggests that the impacts of warming will be more serious and will occur sooner than had previously been believed and several studies have suggested that temperature stabilization at or below 2°C above pre-industrial temperatures should be the goal of climate change policy. Warming above this level would likely cause large areas of the Greenland Ice Sheet to melt, would put the West Antarctic Ice Sheet at substantial risk, and would cause widespread disruption to global ecosystems and the hydrologic cycle [1-3]. The atmosphere already contains enough long-lived greenhouse gases to raise global temperature by over 2 ℃ (assuming a climate sensitivity of approximately 3 °C). Of that, 0.8 °C of warming has already been realized, 0.6 °C will be realized as the climate system comes to equilibrium, and the remainder is being offset by the cooling effect of (relatively short-lived) sulfate aerosols [4]. Clearly the world is already close a threshold level of climate change that could be considered dangerous. This implies that we should consider all warming agents as possible avenues for climate change mitigation, but the current Kyoto Protocol regulates only six gases: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. These gases are all relatively long-lived and so can be compared (and so exchanged) relatively easily with carbon dioxide.

Additional warming comes from short-lived warming agents such as black carbon (a component of soot) and tropospheric ozone. Black carbon is a particulate emitted from incomplete fuel burning and principle sources are wood burning stoves, diesel engines and biomass burning. Increasing observational evidence suggests that it is playing an important role in the earth’s radiative budget [5]. Tropospheric ozone is not emitted directly but is formed from the reaction of nitrous oxides (NO_x), released from fossil fuel burning, and volatile organic compounds (VOCs) released from certain organic chemical products [6]. Both tropospheric ozone and black carbon are air pollutants and also greenhouse gases, so mitigating global warming by reducing concentrations of these pollutants promises substantial co-benefits in terms of improved human health. Moreover, urban air pollution is a substantial problem in most industrializing countries and many are actively seeking to improve air quality. Explicitly integrating climate change considerations into air quality regulations can maximize the global, as well as the local, environmental benefit.

This paper will review the role played by black carbon and tropospheric ozone in global radiative forcing and the potential for fast-track, inexpensive mitigation of global warming by targeting these emissions in industrializing countries. It will then look at co-benefits that such a strategy might have on human health, agriculture and regional climate. The final section will examine what role short-lived greenhouse gas / air pollutants might play in a post-Kyoto international climate agreement.

2. Radiative Forcing

Table 1 shows the changes in radiative forcing between the pre-industrial era and 2005 that can be attributed to emission of various warming agents. The Intergovernmental Panel on Climate Change (IPCC) estimates forcing from black carbon at 0.44 Wm^{-2}, making it the third most important anthropogenic warming agent after carbon dioxide and methane [4]. New results from Ramanathan and Carmichael [5] that include observational evidence suggest that warming from black carbon may be as high as 0.9 Wm^{-2}, making it the second most significant warming agent. Tropospheric ozone is not included in table 1 because it is not emitted directly, but half of the forcing attributed to CO/VOC emissions and a quarter of the forcing from methane emissions results from the effect these gases have of increasing ozone concentrations. The IPCC estimates tropospheric ozone forcing at 0.39 Wm^{-2} [4].

A portion of the significant effect that black carbon has on radiative forcing results from that fact that it not only absorbs radiation to warm the atmosphere but also changes the albedo of snow and ice to cause further warming. Falling snowflakes are effective at scavenging black carbon particles out of the atmosphere, and concentrations have been found to vary from 10 – 50 parts per billion by weight (ppbw) in the Arctic to 100 – 300 ppbw in the French Alps [7]. Even snow in relatively pristine

Antarctica far from black carbon emission sources has measurable concentrations of 0.1 – 0.3 ppbw [7]. Jacobsen [8] estimates that black carbon in snow and ice has lowered global albedo by 0.4% and Northern Hemisphere albedo by 1%. Including this effect in climate models, Hansen and Nazarenko [7] estimate the radiative forcing effect at 0.3 Wm^{-2} in the Northern Hemisphere (0.15 Wm^{-2} globally averaged) but in further work [9] suggest that the 'efficacy' of this forcing (the climate response given an increase in radiative forcing, relative to the same increase from CO_2) is as much as 1.7, meaning black carbon deposition on snow and ice may have a disproportionately large effect on regional and global climate.

Table 1. Change in radiative forcing from 1750 to 2005 due to emission of various agents. Note for comparison that total radiative forcing due to anthropogenic emission of O_3 precursors (VOCs, CO, NO_x and CH_4) is 0.39 Wm^{-2} [4].

Agent Emitted	**Net Change in Radiative Forcing in 2005 due to Emissions 1750 – 2005 (Wm^{-2})**	**Atmospheric Lifetime**	**Primary Sources**
CO_2	1.56	Centuries-Millennia	Fossil fuel burning, deforestation and land use change, cement production.
CH_4	0.86	12 years	Landfills, natural gas leakage, agriculture.
N_2O	0.14	114 years	Fertilizer use, livestock sector, fossil fuel combustion.
CFC / HCFC	0.28	100 – 1000 years	Aerosols, cleaning products and refrigerants.
CO / VOC (O_3 precursor)	0.27	CO – months VOC – hours (O_3 – days)	CO – incomplete fossil fuel combustion; VOCs – petroleum production and consumption, solvents.
Black Carbon	0.44 – 0.9	1 week	Fossil fuel combustion, biomass burning.

Source: [4,5]

Even though tropospheric ozone and black carbon are relatively short-lived pollutants that tend to form local 'hotspots' of high concentration, the radiative effects of these warming agents are global. The U.S. Climate Change Science Program reports that the spatial distribution of forcing is less important in determining impacts that the spatial distribution of climate response, meaning that both short- and long-lived gases produce a climate response in the same regions [10]. Similarly, modeling studies by Menon *et al.* [11] indicate that black carbon emissions in India and China produce warming around the world, with particular climatic effects in the Sahara and west and central Canada. Although often considered a local air pollutant, increasing studies are showing significant ozone transport across continents. For example, O_3 pollution from east Asia can be detected in western North America within

6 days and is thought to account for, on average, 10% of the O_3 concentration in California national parks [12,13]. Models also suggest that O_3 emissions from Asia and North America contribute substantially to O_3 concentrations in Europe [14]. Therefore, although the human health benefits of reduced black carbon and tropospheric ozone concentrations will be mainly local, the climate benefits of reduced global warming will be felt globally.

A final important point on the radiative forcing of black carbon and tropospheric ozone relates to the short atmospheric lifetime of these pollutants. Unlike carbon dioxide and nitrous oxide which have atmospheric lifetimes of a century or longer (and, to a lesser extent, methane, which has a twelve year lifetime) black carbon and tropospheric ozone remain in the atmosphere for only weeks or days respectively (see Table 1). The long-lived greenhouse gases regulated by the Kyoto Protocol are best considered ‘stock’ pollutants, in that constant emissions will increase the concentration , or stock, of the gas (above the level at which annual emissions are equal to annual removal by sinks, which for long-lived gases is very low). In contrast, black carbon and tropospheric ozone are ‘flow’ pollutants, meaning that constant emissions maintain a constant atmospheric concentration and that decreasing emissions causes concentration to decrease. The consequences of this distinction for climate policy are that while reducing emissions of the ‘traditional’ long-lived greenhouse gases only slows or halts the rate of radiative forcing increase, lowered emissions of black carbon or tropospheric ozone actually reduce atmospheric concentrations and decrease radiative forcing.

Figure 1. Radiative forcing from CO_2 from fossil fuels, CO_2 from land use change, methane, nitrous oxide, soot (black carbon) and tropospheric ozone in 2000 and 2050. Yellow represents warming from emissions that have already occurred. Green represents warming from emissions taking place between 2000 – 2050. Adapted from [15] with black carbon emissions from [16].

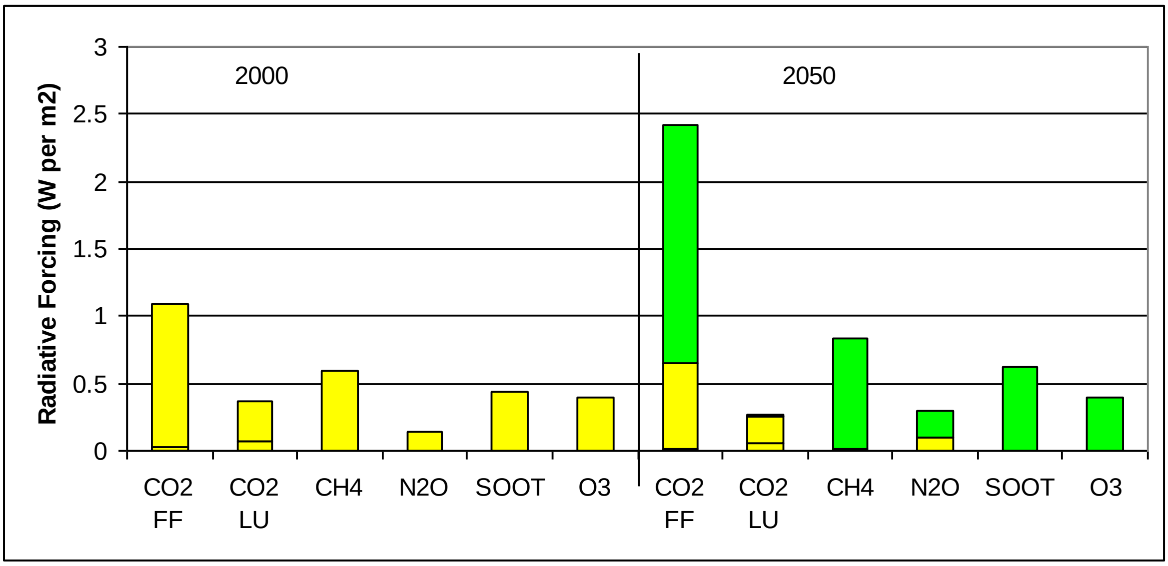

Figure 1 summarizes this effect by showing radiative forcing in 2000 and 2050 by warming agent. The yellow bars show forcing from emissions that have already taken place, which is therefore ‘locked into the system’ and can not be affected by climate policy. The green bars show forcing from emissions that will likely take place between 2000 and 2050, which can therefore be avoided by action taken today. Even in the unlikely event that carbon dioxide emissions went to zero immediately, radiative forcing from CO_2 would only decrease by 38 percent. In contrast, a similar degree of control on black carbon and ozone-precursor emissions would eliminate forcing from these pollutants. Ramanthan [17] estimates that reducing global black carbon emissions by a factor of five would offset the business-as-usual increase in carbon dioxide for between ten and twenty years. Since the world is currently struggling to get a handle on carbon dioxide emissions, with several Annex 1 countries likely to fail to reach their emission-reduction targets under the Kyoto Protocol, abating black carbon and tropospheric ozone using existing technologies to reduce radiative forcing could provide a climate 'breathing space' in which to get a better handle on carbon dioxide emissions.

3. Co-Benefits of Black Carbon and Tropospheric Ozone Mitigation

The World Health Organization estimates that 1.6 million people die each year from indoor air pollution, making it the 8th most important health risk factor, responsible for 2.7 percent of the global burden of disease [18]. This burden is higher in developing countries, reaching 3.5 percent in India and more than 5 percent in poorer African countries such as Mali, Malawi and Rwanda [19]. Indoor air pollution results principally from soot (black carbon) and dust particles released during the burning of traditional biomass fuels such as wood or dung. An additional 800,000 premature deaths are caused each year by urban air pollution, a principle component of which is particulate matter (including black carbon) and tropospheric ozone [20].

This disease burden caused by air pollution has a quantifiable economic impact. Early estimates indicate that the health effects of small particulate matter ($PM_{2.5}$) in India and China could be as high as 3.6 and 2.2 percent of GDP, respectively [21]. Moreover, Sapadaro and Rabl [22] have compared the economic costs of different air pollutants and found that particulate matter was the most damaging at between €160,000 and €2.2 million per ton ($215,000 to $2.9 million). Although previously the link between tropospheric ozone and mortality risk was unclear, recent studies have indicated that high ozone concentrations are linked with mortality, and that even very low levels of ozone can cause an increase in mortality risk [23].

Ozone also causes economic losses by damaging crops and lowering agricultural yields [24]. Currently mean ozone levels in Asia reach 50 ppb during the spring and experimental studies suggest that mean ozone concentrations between 30 – 45 ppb can cause losses of 10 – 40 percent in sensitive wheat, rice and legumes cultivars [21]. This compares to IPCC-projected yield declines due to global warming of 2.5 – 10 percent by 2020 for parts of Asia [1]. Economic estimates of agricultural losses attributed to ozone are $5 billion for wheat, rice, corn and soybeans in Japan, South Korea and China [25]. Under business-as-usual ozone emissions, these losses will increase to over $8 billion by 2020 [25].

Additional climate effects of black carbon stem from its role in contributing to regional clouds of haze known as Atmospheric Brown Clouds (ABCs). These are clouds of particulate aerosols and pollutant gases that result from the burning of fossil fuels, biofuels or biomass in densely inhabited regions [21]. They extend several kilometers into the troposphere and form regional hotspots over polluted regions. ABC hotspots identified to date include East Asia, South Asia, Southeast Asia, Southern Africa, and the Amazon Basin [21]. Because they are made up of many substances, ABCs have a complex effect on climate. For global average climate, top-of-atmosphere (TOA) forcing is critical, and this is negative for ABCs. Regionally, however, surface forcing and atmospheric heating are more important because they are factors of 3 – 10 times larger than the TOA forcing. Aerosols in the clouds scatter and reflect incoming solar radiation, causing a reduction in solar irradiance (dimming) at the surface, while black carbon particles in the clouds absorb radiation and heat the lower atmosphere [21]. These two effects cancel somewhat to give a smaller, negative TOA forcing.

Observational evidence of ABCs suggests black carbon heating is contributing as much as greenhouse gases to regional warming over Asia [26], while dimming has decreased solar radiation at the surface in India and China by 6 percent since pre-industrial times [21]. These large climatic effects have perturbed the regional climate, most notably through a southward shift in the East Asian monsoon and a weakening of the South Asian monsoon that has decreased by 5 – 7 percent between 1950 and 2000 [21]. Modeling studies indicate that these changes cannot be explained by greenhouse warming alone, but require the surface dimming effect of ABCs. The black carbon component of ABCs may play a dominant role in driving monsoonal shifts because black carbon both dims the surface and warms the lower atmosphere, producing strong effects on the vertical atmospheric temperature profile, evaporation, atmospheric stability and the strength of convection [11]. Surface dimming also affects agricultural yields with one study estimating that this 'haze effect' is depressing the optimal yield of 70 percent of the crops grown in China by 5 – 30 percent [27].

Black carbon in ABCs also appears to be contributing substantially to the retreat of glaciers in the Himalayas, Hindu Kush and Tibetan Plateau. Ninety percent of glaciers on the Tibetan Plateau are currently in retreat and many will disappear by 2060 [28]. Similarly, the IPCC estimates that many Himalayan glaciers will melt by 2035 [1]. These glaciers feed rivers that affect 40 percent of the world's population [29]. River systems particularly at risk because of their high dependence on glacial meltwater include the Indus, the Ganges, the Brahmaputra and the Yangtzee. Although increased temperatures in the Himalayan region due to global warming are a factor in the glacial retreat, recent evidence indicates that black carbon is also important. In addition to the surface albedo effect (described in the previous section), black carbon in ABCs warms the atmosphere at the elevated-levels where mountain glaciers are present [26]. Satellite data shows the Tibetan Plateau surrounded by a blanket of ABC-haze suggesting the black carbon black carbon portion of these clouds may be having a substantial warming effect on the region, probably equal in magnitude to the warming effect of greenhouse gases [5].

Finally, ozone abatement policies will help to weaken the positive-feedback effect in which higher temperatures due to global warming increase the rate of ozone production, which in turn damages forest ecosystems so reducing the land carbon sink and resulting in accelerated CO_2 build up in the atmosphere [30]. Ozone damages forest ecosystems by causing cellular damage within leaves resulting in reduced net primary productivity and decreased carbon storage [31]. Modeling studies indicate that the indirect radiative forcing from this feedback effect in 2100 will be comparable to the direct forcing from elevated O_3 concentrations [30]. Ozone abatement will therefore improve the health of forest ecosystems while protecting the land carbon sink.

This section has highlighted damages resulting from black carbon and tropospheric ozone independent of their effect on global radiative forcing. Perhaps the most important of these is their adverse impacts on human health, particularly the disproportionate impact of black carbon on the health of women and children through its contribution to indoor air pollution. Other impacts include damage to agricultural crops and forest ecosystems, heating of Himalayan glaciers causing declines in Asian water supply, and disruption of regional climate by incorporation into Atmospheric Brown Clouds. These problems could all be reduced through an integrated climate/air pollution policy strategy that focused on mitigating black carbon and tropospheric ozone.

4. Abatement Technologies

Concentrating air pollution control on black carbon and tropospheric ozone is likely to yield significant cross-cutting benefits in terms of climate, health, and agriculture and is also likely to be highly cost-effective because much of the technology to control emissions already exists and has been deployed with effect in developed countries. This stands in contrast to technology to mitigate carbon dioxide emissions which, while technically feasible, has yet to be deployed on a large scale in developed countries.

Developed countries have reduced their emissions of black carbon by a factor of five since the 1950s, so abatement technologies already exist and have been implemented [17]. Twenty percent of black carbon emissions come from household biofuel burning in cookstoves and options to abate this include promoting the use of improved stoves or encouraging fuel switching to cleaner-burning kerosene or liquefied petroleum gas [32]. A successful model of such a program is the Chinese National Improved Stove Program that introduced 129 million improved stoves into rural areas between 1982 and 1992 [33]. Even considering only climate benefits, and ignoring the substantial improvements in health, such a program is likely to be highly cost-effective [32].

A second major source of black carbon is diesel engines, which account for approximately 25 percent of global emissions [32]. These can be addressed by regulations requiring diesel oxidation catalysts that can be fitted to almost any vehicle and reduce total particulate emissions 20 – 50 percent, or with diesel particulate filters which eliminate 90 percent of black carbon emissions [34]. Recent EPA regulations for diesel vehicles mean that U.S. black carbon emissions are projected to decline by 42 percent between 2001 and 2020 [35]. Another possible approach is fuel switching, as was recently done in the New Delhi public transport system after the court ordered a switch to compressed natural gas that produces much fewer particulate emissions [35]. Additional gains can be made in industrial coal boilers through the shift to pulverized coal use [32].

At 40 percent of the global total, biomass burning is the final major source of black carbon emissions (as well as a significant source of ozone precursor emissions, particularly in the southern hemisphere [36]). However, it is unlikely to provide many opportunities for emissions reduction. Deforestation provides no technological options for control and emission reductions would have to come from decreasing the amount of forest burnt every year. To date, governments have appeared unable or unwilling to slow the rate of deforestation, although these efforts may be scaled up if avoided deforestation is incorporated into the carbon market under a new climate treaty. Black carbon emissions from biomass burning are co-released with substantial amounts of organic carbon aerosols that scatter rather than absorb radiation and so have a net cooling effect. Thus, even though biomass burning is a substantial sources of black carbon, it is not a substantial source of black carbon heating and so is not necessarily a promising target for mitigation efforts [32].

Mitigating tropospheric ozone means reducing emissions of precursor chemicals, particularly NO_x and VOCs. In the U.S., NO_x (as well as ozone itself) is currently regulated as a criteria pollutant under the Clean Air Act. Control options for ozone include tailpipe NO_x filters in vehicles and regulation of oil tankers and gasoline stations to reduce leakage into the environment [37]. Because the chemical reactions that produce ozone run faster at higher temperature, simple measures that reduce the urban heat-island effect (such as white roofs or shade trees) can also lower ozone concentrations [37]. These strategies also have the co-benefits of mitigating the temperature increase associated with global warming and so reducing heat-related impacts.

Despite a history of regulation in the U.S., substantial areas of ozone non-attainment still exist [38], suggesting that effective ozone control technologies may be difficult to implement or are more expensive than black carbon technologies. In addition, the complex relationship between precursor emissions and O_3 concentration, combined with contributions from long-range, transcontinental transport, means that policies to reduce emissions can have mixed results on concentration: For example, although Europe reduced O_3 precursor emissions 36% between 1990 and 2004, ozone exposure has not decreased [39]. This has implications for transfer to developing countries and suggests that black carbon control technologies that have a long history of development and deployment in industrialized countries may be more easily transferred.

Working Group 3 of the IPCC Fourth Assessment Report discusses several climate change mitigation policies that also have air pollution co-benefits. Most decarbonization strategies in the electricity and transport sector, either increasing energy efficiency or switching to renewable technologies, will reduce emissions of air pollutants, including ozone precursors and black carbon. Depending on the valuation of these health benefits, they could amount to as much as three to four times the cost of mitigation [24]. Nevertheless, from the perspective of the implementing country, there is substantial difference (in terms of the size of the benefits and who those benefits accrue to) between undertaking measures to improve local air quality that have global co-benefits (as principally discussed in this paper) and undertaking measures to mitigate global climate change that have local co-benefits. The final section will examine how measures to reduce black carbon and tropospheric ozone concentrations might fit into a larger climate agreement and will suggest that the former of these policy options may be a particularly effective way of engaging key industrializing countries in climate change mitigation efforts.

5. Conclusion: Short-Lived Greenhouse Gases as Part of a Holistic Climate Agreement

In the Byrd-Hagel resolution passed by the Senate prior to the signing of the Kyoto Protocol in 1997, the Senate expresses the view that:

> “the United States should not be a signatory to any protocol ….which would mandate new commitments to limit or reduce greenhouse gas emissions for the Annex 1 Parties, unless the protocol or other agreement also mandates new specific scheduled commitments to limit or reduce greenhouse gas emissions from Developing Country Parties within the same compliance period…”

However, it also seems unlikely that developing countries will agree to take on emissions limits before developed countries that are responsible for a significant majority of the current warming problem [40] demonstrate that economic growth and a low-carbon society can co-exist. For example, the Indian Prime Minister Manmohan Singh has stated that Indian per-capita emissions will never exceed those of developed countries, a stance that, while equitable, is unlikely to result in an effective climate agreement that keeps warming below 2^{o}C. The qualities of black carbon and tropospheric ozone as short-lived greenhouse gases that are also air pollutants suggest they may offer a way out of this current stand-off between developed and developing countries.

Tropospheric ozone and, in particular, black carbon offer the opportunity to substantially mitigate climate change but with local co-benefits that more than justify their implementation. Local and regional benefits that will accrue to the implementing country include improved health and increased agricultural yields. In India and China, reduced ABC pollution should also reduce warming on the Tibetan Plateau, helping to stabilize glaciers and improve the security of regional water supplies [21]. Because the proportion of benefits that accrue locally are larger than in policies undertaken primarily to mitigate climate change, the barriers to implementation are lower. This is apparent in the fact that both China and India are implementing programs that start to improve urban air quality, indicating that demand for these controls already exists to some degree [41]. Moreover, because black carbon and, to a lesser extent, ozone controls are already in place in industrialized countries, developing countries can undertake commitments to reduce these pollutants confident that cost-effective implementation mechanisms exist.

Air pollution control measures undertaken by industrializing countries, especially if they focus explicitly on black carbon and ozone, will likely be at least as effective at slowing global warming in the short- to medium-term as efforts to control carbon dioxide emissions in developed countries. While control of short-lived pollutants is no substitute for the control of long-lived greenhouse gases that will ultimately be needed to stabilize temperatures, only short-lived black carbon and ozone offer the opportunity to actually *reduce* radiative forcing in the next decades. In this respect, integrated climate / air pollution policies in industrializing countries are both appropriate to their state of development and comparable to carbon dioxide abatement in industrialized countries. They can thus be a way of leveraging constructive agreement in the international climate negotiations: if industrializing countries were to continue unrestricted carbon dioxide emissions but accept emission reduction caps on short-lived greenhouse gases / air pollutants, it may be enough to overcome the reluctance of some developed nations (particularly the United States) to accept carbon dioxide emission reduction requirements and join an international treaty. Recognizing the important role of certain air pollutants in global warming and incorporating these explicitly into the climate negotiations may thus be an effective way of both protecting the climate and generating international agreement on a post-Kyoto treaty.

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