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2013 CRITICAL REVIEW DISCUSSION

Stratospheric ozone, global warming, and the principle of unintended consequences—An ongoing science and policy story

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Introduction

The following discussion responds to, and amplifies on, the 2013 Critical Review (Andersen et al., 2013). Complementary reviews on the topic and relevant data resources are identified. Reactions from the critical review co-authors are presented at the end.

The Andersen et al. critical review (2013) explains the history, technology, and policy status of manufactured halocarbons (including chlorofluorocarbons [CFCs], hydrofluorocarbons [HFCs], hydrochlorfluorocarbons, [HCFCs], carbon tetrachloride [CTC], methyl chloroform, methyl bromide, and other substances) that destroy stratospheric O_3. Fluorinated greenhouse gases (GHGs) are often termed F-gases. From an insider's perspective, the critical review documents the motivations behind, and the successes of, the Montreal Protocol (MP) (UNEP, 2007) in addressing ozone-depleting substances (ODSs) and climate change. HFCs are the substitutes for some ODSs and were commercialized to protect the statospheric O_3 that shields humans and natural ecosystems from excessive ultraviolet (UV) radiation exposure (Slaper et al., 1998). The crtical review documents the realization that the HFCs used to replace ODSs had "unintended consequences" as climate forcing agents (CFAs). Policy evolution was supported by the merger of science, regulatory action, and industrial cooperation to resolve stratospheric O_3 loss. Climate forcing, now being addressed as an extension of regulatory policy (Chow et al., 2010; Chow and Watson, 2011; Hidy et al., 2011; Hidy and Pennell, 2010; Unger, 2012), was an unanticipated addition to the statospheric O_3 issue. Emerging opportunities for more benign refrigerants are identified in the critical review, along with some of the drawbacks of these new substances.

Stratospheric Chemistry and the Importance of Nitrous Oxide (N_2O)

The stratospheric chemistry of ODSs requires elaboration (Dessler, 2000; Solomon, 1999) beyond that presented in critical review, especially for the role of nitrous oxide (N_2O) in O_3 depletion (Fleming et al., 2011; Ravishankara et al., 2009; Rosenfield and Douglass, 1998). Rosenfield and Douglass (1998) and Fleming et al. (2011) have examined the role of N_2O in a climate future that is projected to have higher stratospheric O_3 levels than during pre-CFC conditions, and where the N_2O–NO_y–O_3 connection is damped because of CO_2 cooling of the stratosphere. Fleming et al. (2011, p. 8515) point out that CO_2 affects stratospheric O_3 by: "1) cooling the stratosphere which increases O_3 via reduction in the O_3 chemical loss rates, and 2) accelerating the Brewer–Dobson circulation (BDC) (Brewer, 1949; Dobson, 1956) which redistributes O_3 in the lower stratosphere. The net result of CO_2 loading is an increase

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in global O_3 in the total column and upper stratosphere." Methane (CH_4) also affects O_3 by increasing water (H_2O) and odd hydrogen species. Increasing H_2O cools the middle atmosphere, influences the chlorine cycle, and increases O_3 production in the troposphere. Model projections (Fleming et al., 2011) indicate that CO_2 will have the larger effect.

Limited references (Kanter et al., 2013; Ravishankara et al., 2009) were cited in the critical review concerning whether and how the MP could manage N_2O and reduce O_3 depletion. To identify the importance of N_2O, and the links to stratospheric NO and O_3, the original references could have been evaluated (e.g., Bates and Hays, 1967; Cicerone et al., 1978; Crutzen, 1970; Hampson, 1964; Johnston, 1971; Logan et al., 1978; McElroy et al., 1977).

The justification for both N_2O and *n*-propyl bromide regulation in the critical review needs additional scientific support. Controlling short-lived ODSs depends on how much O_3 depletion they might cause and the health and environmental benefits achieved from eliminating that depletion, and this was not evaluated. The MP has experience with synthetic halocarbons, but none with N_2O. Atmospheric N_2O is emitted naturally and derives from anthropogenic activities in agriculture, forestry, and other land-use (AFOLU) sectors (Olivier et al., 1998; U.S. Environmental Protection Agency [EPA], 2013b; van Aardenne et al., 2001; Werner et al., 2007; Zhuang et al., 2012). The uncertainty in estimating AFOLU emissions is large, even for the developed countries (Prather et al., 2009). Based on Fleming et al. (2011), it is not clear that reducing future N_2O would result in an O_3 benefit. In this respect, the critical review is more judgmental of scientific information in contrast to Andersen and Sarma (2002), which brought together all the political and scientific events of the time.

Magnitude of HFC Reduction Estimates on Global Warming

The second example of the strong professional views of the authors regards HFC mitigation, which is based primarily on future HFC emissions as presented in Velders et al. (2007) and Andersen et al. (2010). These references correctly note that the climate threat posed by CFCs in the 1980s (Hansen et al., 1989) may be replaced by the long-lived HFCs (i.e., HFC-134a with a 100-year global warming potential [GWP] of 1430; IPCC, 2007b), but not HFC-1234yf with GWP of 4. The critical review advocates that HFCs will become a large part of anthropogenic GHG forcing and that HFC phase-down (presumably excluding HFC-1234yf) under the MP would minimize climate change. This issue has been taken up by others (Xu et al., 2013), but with no new scientific information being added to the debate.

A recent publication (Lu, 2013a) touted cosmic ray interactions with CFCs as explaining most of the surface temperature increases from the effects of other GHG emissions. This hypothesis was previously considered (Grooss and Mueller, 2011) and found inconclusive, based on the correlational rather than cause-and-effect analysis of Lu (2013a). Online critiques of this publication elaborate on its limitations (ClimateNexus, 2013; Lu, 2013b).

Today, all HFCs are responsible for about 0.6% of the total radiative forcing from GHGs, which is increasing at >1%/year (primarily due to CO_2). Current global emissions of HFCs are a greater fraction of total GWP-weighted GHG emissions, but still account for only 1%. For highly technological nations like the United States the fraction is ~2%. If HFCs were the only GHGs, there would be neither a climate treaty nor the Intergovernmental Panel on Climate Change (IPCC, 2007). Velders et al. (2007) and Andersen et al. (2010) project a fairly large growth of HFCs and make comparisons with the growth in CO_2 and other GHGs. Xu et al. (2013) hypothesized that mitigating HFC emissions could play an important role in limiting warming to less than 2°C and could help reduce it by [projected] 0.25 to 0.35°C by 2100. Bianco et al. (2013) concluded that eliminating HFC (emissions) "represents the biggest opportunity for GHG emission reductions behind [fossil fueled] power plants [emissions]."

IPCC (2007a) projections have considered options for no emissions mitigation along with and cases for large GHG reductions, including removal of atmospheric CO_2. For all of these scenarios, the relative role of HFCs in global warming by 2100 is projected to increase from <1% to values from 3% to 6%. These numbers are much lower than the 2050 numbers (e.g., 9–19% by emission) used by Velders et al. (2009). A larger effect of HFC reductions (28–45%) is often reported; however, this fraction assumes large CO_2 reductions without HFC emission decreases. Given that both are listed in the Kyoto Protocol, and given the pain and cost of CO_2 mitigation, this scenario seems unlikely. HFC emission reductions need to be part of any climate package, but HFC reductions independent of what happens to CO_2 emissions will be insufficient to address global warming.

Brominated compounds are unlikely to be as important as stated in the critical review. The critical review overgeneralizes the impact of climate change, including widespread intensification of storms, and simplifies the phase-out of HCFCs as "protecting the climate." Velders et al. (2007) calculated ODSs based on a selection of cases that exaggerate the influence of ODSs. These scenarios are highly uncertain, requiring a caveat about the significance of the ODSs as CFAs. The statement by Velders et al. (2007) that the MP impact of CFC emission growth would have dominated CO_2 climate forcing was first proposed by Hansen et al. (1989).

The Future of Mobile Air Conditioner (MAC) Refrigerants

The critical review raises the issue of unintended consequences of various cooling methods and refrigerants. Use of ice from contaminated waterways led to the development of manufactured ice using toxic refrigerants. Toxic refrigerants were then replaced by nontoxic CFC compounds. CFCs, specifically CFC-12, used in mobile air conditioners (MACs) became identified with O_3 destruction and were replaced by HFCs, particularly HFC-134a. HFC-152a was considered as a replacement when HFC-134a was deemed a contributor to global warming. HFC-1234yf is now being considered as a replacement because of its greater efficiency and lower GWP.

Other MAC refrigerants such as compressed CO_2 and various hydrocarbon blends (e.g., propane) have also been considered and dismissed because of low efficiency or potential flammability. It seems plausible that new vehicles (e.g., electric, hybrid, and plug-in hybrid) could be designed with an environmentally safe refrigerant, such as propane. Tables 3 and 5 of the critical review show the feasibility of CO_2 as a refrigerant without specifying its merits relative to HFC-1234yf. There are challenges for CO_2, such as energy efficiency, safety, and reliability, but the advantages of using a readily available compound, which is abundant in the atmosphere, should not be underestimated.

Compliance and enforcement of the MP need attention because of the growing global deployment of refrigeration, especially MACs. There is a need to define the best practices to be deployed in the developing world. The key question is how this should be designed for the maximum global effectiveness in monitoring and controlling emissions of refrigerants (Molina et al., 2009). The recent China–United States statement on F-gases (U.S. White House, 2013) is important. Hille (2013) identifies the critical role of HFC-23 releases (an unwanted by-product of HCFC-22 production) by developing countries, noting that a ban on climate credits means that there are no incentives to destroy the gas by incineration.

The critical review points to the leakage of MAC refrigerants and their impact on O_3 depletion and global warming. Other issues, such as methyl-*tert*-butyl ether (MTBE), lubricating oil and its zinc-based additive (zinc dialkyldithiophosphate [ZDDP]), and asbestos and copper from brake linings, also have the potential to adversely affect public health and the environment. Use of the MTBE additive in gasoline was mandated to reduce air emissions. However, leakage of gasoline laced with MTBE into groundwater resulted in contamination costing billions of dollars to remediate. Before the introduction of MTBE, it was known that oxygenates and alcohol-based fuels or additives could leak into waterways and underground aquifers (Owen et al., 1995). The unintended consequences could have been avoided if available scientific knowledge had been taken into consideration.

Based on a review of material safety data sheets (MSDS) for various refrigerants (e.g., CFCs, HFCs, HCs, and CO_2), it appears that compressed CO_2 has the best health characteristics, while the fluorinated HFCs and CFCs pose potential long-term chronic health effects from hydrofluoric acid (a combustion product when fluoridated compounds are exposed to extreme heat). The critical review only touched on the uncertainties of long-term fluorine emissions and their decay products. Toohey (2010) states that “for thorough understanding of the environmental impacts of replacements for CFCs, HCFCs, and long-lived HFCs, an evaluation of the ozone depleting potential (ODP), global warming potential (GWP), atmospheric fate, safety, and toxicity is required for each replacement.”

Hodnebrog et al. (2013) have updated GWPs and radiative efficiencies (REs) for more than 100 halocarbons by reinterpreting their infrared spectra, showing a bias of more than 5% in previous estimates. HFC-1234yf has a short lifetime (11 days) in the atmosphere with trifluoroacetic acid (TFA) as a decay product (Henne et al., 2012). TFA is water-soluble and can remain in surface waters and the ocean for 40,000 years (Spatz and Minor, 2008). The rapid breakdown of HFC-1234yf in the atmosphere suggests higher ambient TFA (and decay products) concentrations than those of slower decaying HFCs and CFCs.

The critical review acknowledges the hazards of flammability of different MAC refrigerants within vehicle cabs. Spatz and Minor (2008) report that the flammability risk of injury or fatality by HFC-1234yf is less than 1×10^{-11} to 2×10^{-12}. Based on data presented in the critical review, Figures S1–S5 in the supplemental material assess the potential impacts of ODP, GWP, flammability, toxicity, and health impacts due to leaks or emissions of MAC refrigerants.

Translating Experience from Halocarbon Control to Action on Climate Change

The critical review does not address lessons learned from the development of the MP process for halocarbon management or the process of seeking reduction in CFAs. Considering the MP as a successful arrangement to curtail (stratospheric) O_3 change with CFC/HCFC reductions or substitutions, why hasn’t the long series of negotiations to reduce CFAs been more successful? Both processes have involved the following key areas: (1) complex and credible atmospheric and impact science; (2) potentially viable technology alternatives; (3) geopolitical considerations relating to conflicting economic versus environmental goals; (4) stakeholder support or lack thereof; and (5) perceived timing for aggressive action versus increasing risk. Similarities and differences between stratospheric O_3 and climate forcing issues are summarized in Table 1.

First, the science of CFCs/HCFCs is relatively straightforward and compelling through observations. In contrast, the science of climate change and its environmental impact involves worldwide CFA emissions, as well as long-term changes in the atmosphere and the “earth system,” including major intercontinental or global environmental impacts. Climate science continues to be endorsed by “consensus” with expanding quantities of literature—but consensus does not imply the resolution of uncertainties.

Second, regulated halocarbons other than methyl bromide are manufactured without natural sources, and an evolution of technological solutions has emerged with expanding complexity, as pointed out by the critical review. Technological fixes for reduction in carbon-based CFA emissions exist in principle, but these are resource-intensive and expensive with debatable reliability (Edgerton et al., 2008; Hidy et al., 2012; MacCracken, 2008; Wilson, 2012). The drivers for energy production and use continue to be accessibility, low cost, and reliability. These requirements are difficult to fulfill without a major carbon-fueled component.

Third, the approach varies by geopolitical environment. For halocarbons, mediation and reduction took place rapidly following the MP agreement, resulting in measureable improvements to the stratospheric O_3 layer (Yang et al., 2006). The MP signatories continue to meet with an expanded agenda considering CFAs. Despite a series of conferences from 1992 (Rio de Janeiro) to 2010 (Copenhagen) to reduce CFA emissions, significant reductions (mainly CO_2) have yet to be achieved. Barriers for decarbonization are tangential to the science, and involve negotiations for major changes in energy production and

Table 1. Comparison of policy drivers[a] for CFC emission reductions to protect stratospheric O_3 and CFA emission changes to reduce global warming

Issue	Science	Technology	Geopolitical	Stakeholder support	Time scale and timing	Response
Chlorofluorocarbons (CFCs)	Atmospheric science was complex, but it was supported by observations. Effects were straightforward and proven: excessive UV exposure to humans and ecosystems.	Chemical substitutes were available and technologies could be adapted at reasonable cost. Lack of technology was not an impediment.	Resistance to science was overcome early (post 1974) and stakeholders were engaged from the start. International consensus was achieved.	Initial resistance to change, but stakeholder decisions were supported by rapid technological advances. Change was possible without loss of benefits.	Science imposed early urgency to address O_3 depletion, with a time scale of decades. Measurements catalyzed aggressive action to change, and results were detectable within a decade after implementation.	MP consensus set in motion with major emission reductions over a decade with industry concurrence; Evolution of CFC control continues in response to O_3 chemistry and to climate forcing.
Climate forcing agents (CFAs)	Atmospheric science is more complex with earth system effects and interactions. New knowledge is still emerging on carbon cycles and GHG properties. Projections were made from imperfect models but observations beginning to confirm modeled forecasts.	Large CFA emissions of a larger set of GHGs. Noncarbon energy-production solutions are available, but they are limited in quantity, expensive, and have slow market penetration. There are many stranded costs in existing fossil-fuel uses.	Contentious debate on climate science. Lack of agreement on costs and benefits of decreasing GHG emissions. Large disparity in approaches from developed and developing nations.	Many more stakeholders than for O_3 layer protection with competing economic interests. Many see scientific uncertainty as a reason to delay action. Others feel investments in adaptation are more cost-effective than GHG emission reductions.	50 to 100 years before adverse effects become important. Environmental variability of measurements obscures definitive relationships to manmade emissions. Changing energy infrastructure requires a 50- to 100-year time horizon.	Research continues on GHG alternatives and climate science, but minimal GHG reductions or commitments to raise costs of carbon-emitting fuels have not been globally implemented. Efforts to curtail CFA emissions are still at the margin.

Notes: [a]See Sunstein (2007) for a legal examination of policy drivers within the contexts of the Montreal and Kyoto protocols.

use in all countries. This is seen in the 2009 estimates of per-capita CO_2 emissions (e.g., United States: 17.3 tonnes/person; China: 5.8 tonnes/person; and India: 1.7 tonnes/person) (The World Bank, 2013).

Fourth, public and private stakeholders supported CFC/HCFC reduction policies, while no such global consensus has been reached for other CFA emissions; trade-offs between the potential for disruption of national economies and reducing earth system and environmental risks reveal the short-term economic argument as the clear winner. Fear of risk from a slowly creeping, induced change in climate has not motivated the public for regulatory action (Sunstein, 2013; Sunstein and Zeckhauser, 2011).

Lastly, the timing of the issues differs—CFC/HCFC effects on O_3 could be demonstrated by reducing lower stratosphere O_3 concentrations. In contrast, climate warming by CFAs was based largely on models of unknown reliability in the 1980s. This was followed by long-term climate-scale observations that have provided temperature records along with sea-level and cryospheric changes. This is contradicted by the fact that the global temperature of surface air has remained essentially the same since 2001 (NASA, 2013).

Steinhaeuser and Tsonis (2013) have compared the reliability of model projections. Atmospheric climate models have ranged from simple one-dimensional representations to three-dimensional (3D), spatially and temporally resolved calculations of the atmosphere's general circulation. The 3D model now includes detailed earth system components (e.g., the oceans and the pedosphere). The calculations involve 10^5 or more projections per single 100-year run with spatial resolution >100 km^2, using ~10 atmospheric layers and 2 oceanic layers. Detailed evaluation of such a data collection with observations is beyond human assimilative capability. Interpretation of model projections for policy development has been a challenge to both scientists and policymakers, as discussed by Crutzen and Oppenheimer (2008).

Assessment of the risk from climate warming was rudimentary in the 1980s (Hidy and Peck, 1991). Subsequent science investment has developed and advanced risk assessment and atmospheric models. However, these models have not been comprehensively tested for their reliability and comparability with long-term observations. Table 1 also addresses the geopolitical response time for substantive action between stratospheric O_3 and climate. As the CFC/HCFC choices have changed and the issue has expanded to add the CFAs, response time can be constrained by ~20 years for CFC/HFC, but exceeds 30–40 years for major CFA actions. Despite the stated progress in United States CFA reductions, the 3-year averages (1990–1992) and (2009–2011) for $TgCO_2$ equivalents ($TgCO_{2\ \mathrm{equivalent}\ [e]}$ [1 teragram (Tg) = 1×10^6 tonnes]) are 6191 and 6700, respectively. Unlike the MP, the United States has yet to commit to a major treaty for CFA reductions.

The critical review could have expanded the discussion of short-lived climate forcers (SLCFs) (U.S.EPA, 2012d) and the CH_4 emission increases due to growing development of natural gas from fracking (Burnham et al., 2012). The success of controlling black carbon (BC) emissions from transportation sources depends on the ability to make ultra-low-sulfur fuels (ULSF) available (Pawelec et al., 2011). ULSFs are necessary so that diesel particulate filters (DPFs) can be applied to after-engine exhaust to effectively eliminate BC emissions. Ideally, the fuel content should be no more than 10 ppmw sulfur. Without ULSF, the catalyst in the DPF will be poisoned by the sulfur in the fuel (Hesterberg et al., 2011).

Figure 1 shows the effect of controlling BC emissions from on-road vehicles by attaining Euro 6/VI emission limits, which require the use of DPFs and NO_x controls (Weiss et al., 2012). The Euro6/VI modeling scenarios in Figure 1 show a baseline that reflects current regulations and what can be done if state-of-the-art technologies are applied. Fuel use in the developing countries of China and India will have important effects on global non-CO_2 GHG emissions. The dramatic growth in the baseline can be reduced as shown in a hypothetical accelerated CFA reduction policy. Worldwide adoption of Euro 6/VI for on-road vehicles could avoid the near-term climate impacts of 800 million tonnes of CO_2 equivalent ($MtCO_2e$) by 2030. The long-term impacts avoided would be equivalent to the damage done by 220 $MtCO_2e$. Facanha et al. (2012) estimate that, by 2030, the tank-to-wheels (TTW) emission reductions from pipeline policies would produce benefits equivalent to the removal of 1,100 $MtCO_2e$. Worldwide adoption of Euro 6/VI, therefore, would be expected to produce near-term benefits equivalent to 72% of energy and climate policies to be adopted in the transportation sector. In contrast, the climate benefits over the long term are 20%, since the pollutants reduced have short lifetimes.

Progress Toward Emission Reductions

Just as policymakers took action in phasing out ODS, there has been increasing recognition of the need to phase-down HFC emissions. President Barack Obama indicated that curbing HFC emissions was an important domestic and international priority as part of the Climate Action Plan (Executive Office of the President, 2013), and the United States and China have likewise agreed to work together to phase-down the consumption and production of HFCs.

The critical review sets forth the power of business innovation in overcoming health and environmental challenges. It questions whether this pace of innovation will continue and will help produce alternatives to high-GWP HFCs. Businesses have been at the cutting edge of developing low-GWP substitutes like HFC-1234yf, which is replacing HFCs in some MAC systems. Similarly, hydrocarbon refrigeration systems and innovations in cryogenic refrigerated transport techniques are helping reduce climate pollution from these sources. Some notable examples of business initiatives are:

- In 2012, Unilever (2013) deployed 900,000 hydrocarbon ice-cream freezers around the world (South Africa, China, Europe, Brazil, United States trial) and indicated that by 2015 all new ice cream freezers would be HFC free.
- In 2009, Coca-Cola announced that 100% of its new vending machines and coolers globally will be HFC free by 2015 (Refrigerants, 2013).
- The Consumer Goods Forum is comprised of over 400 companies around the world, including supermarkets, retailers, and food and beverage companies. This group has pledged to begin phasing out HFCs in 2015 (Green, 2013).

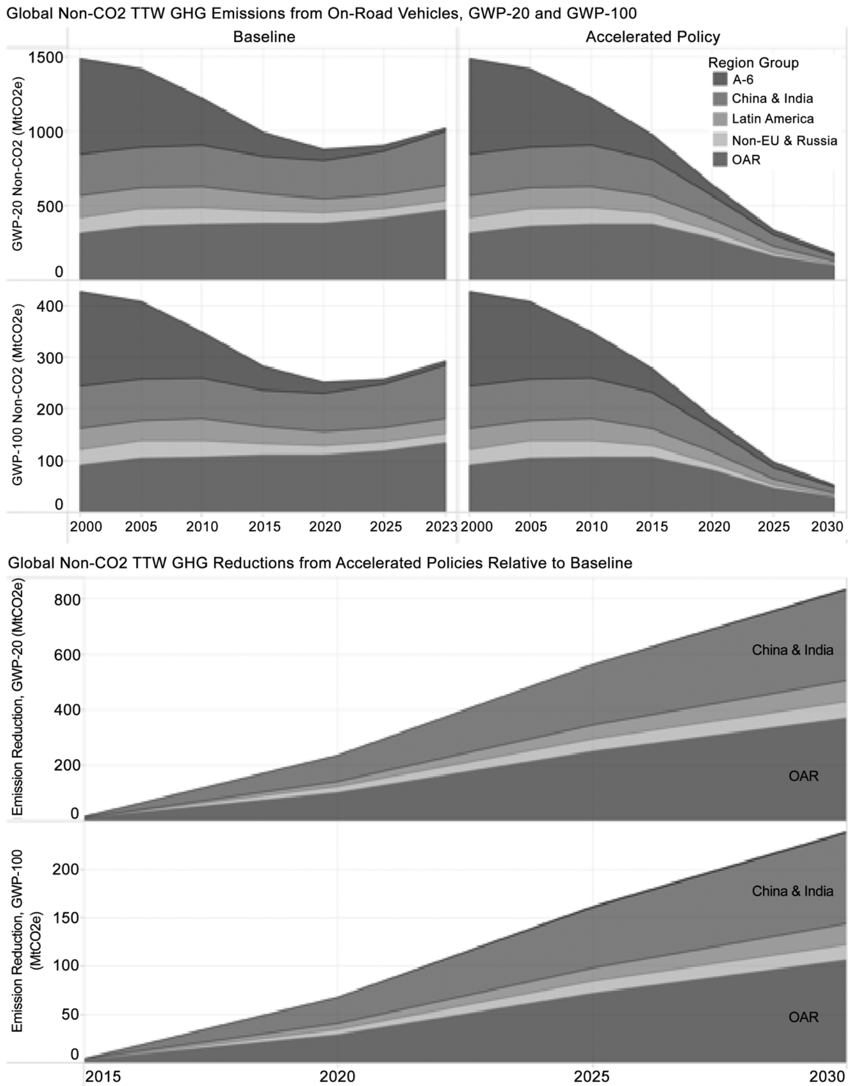

Figure 1. Climate co-benefits of Euro 6/VI with two global warming potentials (i.e., GWP-20 and GWP-100 for 20 and 100 years, respectively) for: (a) global non-CO_2 tank-to-wheels (TTW) greenhouse gas (GHG) emissions from on-road vehicles; and (b) global non-CO_2 TTW GHG reductions from accelerated policies relative to baseline. (Best practices: United States, European Union, South Korea, Japan, Australia, and Canada; OAR: Africa, Middle East, and all other Asia Pacific countries [excluding China, India, and South Korea]; MtCO2e: million tonnes of carbon dioxide equivalent.).

The critical review highlights actions (like bans on CFCs in spray cans) that helped to build momentum toward the eventual phase-out of these pollutants under the MP. Similarly, there are transformative domestic policies and partnerships aimed at phasing down HFCs that can help to catalyze global change. These common sense national policies include:

- *Title VI of the Clean Air Act (CAA).* EPA's authority to regulate ODS is set out in Title VI of the CAA. Pursuant to its Significant New Alternatives Program (SNAP), which calls for ODS replacements, Title VI provides the authority to substitute HFCs with low-GWP substances in many applications, implement new technologies that use fewer HFCs, and pursue opportunities for responsible disposal of these substances (EPA, 2012a).
- *Clean Cars and Clean Trucks Rules.* EPA (2010a, 2012a) has already made progress in reducing vehicle HFC emissions through its Clean Cars Phase I and II Rulemakings and its first-phase greenhouse gas standards for medium- and heavy-duty trucks. These rules were the product of historic cooperation among government, business, public health, and environmental interests. They powerfully incentivize deployment of low-GWP alternatives and reach the ~80% of transportation-related HFCs that come from car and truck air conditioning systems. The other ~20% of HFC emissions from the transportation sector, however, come from refrigerated transport—an additional opportunity that the EPA can address in its upcoming second-phase standards for medium- and heavy-duty trucks.
- *EPA Greenhouse Gas Reporting Program.* The EPA (2010b) requires many sources of F-gas emissions to quantify and report these emissions. The reporting program now has data for sources from 2010 and 2011 (U.S.EPA, 2013a), and

leveraging this information can provide transparency and encourage best practices for smaller sources of F-gases like the semiconductor industry.

There is momentum building for action under the MP, and pursuing common sense domestic policies can help catalyze change in the same way that domestic actions helped to build momentum for the international phase-out of ODS under the MP. While the phase-out of ODS has resulted in higher HFC emissions, the public has the tools to deal with this new problem and they are the same ones that have been successful in forging public health and environmental progress in many different areas. Science, business solutions, and common sense policies are available to help effectuate a swift transition away from HFCs, and it is critical to embrace these opportunities and ensure the narrative is one of continuous environmental progress and not unintended consequences.

Additional Reviews and Data Bases

No critical review on a complex topic is ever complete. Additional reviews have been published related to: 1) stratospheric ozone and the MP (Aucamp, 2007; Gareau, 2010; Jadin et al., 2005; Jia et al., 2006; Kaniaru, 2007; Kuijpers, 1990; McCulloch, 1999; McCulloch, 2003; Plumb, 2002; Solomon, 1999; Zerefos et al., 2009); 2) refrigerants and climate (Calm, 2008; Kim et al., 2011; McCulloch, 2003; Minjares, 2011; Powell, 2002; Sherman et al., 1998); 3) climate and health; and 4) policies for emission changes. IPCC (2013) provides the best overall introduction to science and policies. Several data bases and compilations are also web-accessible (GEIA, 2012; NASA, 2013; NOAA, 2012; U.S.EPA, 2012b; 2012c; 2013a).

Critical Review Authors' Response to Discussion

The authors agree that the critical review could have been more complete with respect to N_2O and BC, but these topics were considered too far afield from the core topics. Unless action is taken under the Montreal, Kyoto, or other protocols, N_2O from unnatural sources will soon be the largest ODS to the atmosphere—given that other sources are phased out from production and slowly eliminated by atmospheric processes. Like methyl bromide, N_2O has natural sources that are likely uncontrollable, but a phase-out of manufactured N_2O is important.

The authors agree that scientists are in near-consensus that halons, methyl bromide, and methyl chloroform make little contribution to climate change. Nonetheless, the climate benefits of the aerosol spray-can boycott inspired by Molina and Rowland (1974) and the subsequent MP avoided a world where climate change might already have been irreversible—surely the best proof of the precautionary principle and the importance of science to early warning of potential environmental harm.

The authors strongly disagree with the view that HFCs pose little threat. It is true that HFCs are currently <1% of long-lived GHG emissions, but it is also true that they are the most rapidly growing GHG in many countries and will likely grow out of control as incomes increase in markets with billions of customers where refrigeration and air conditioning have not yet penetrated. The recent agreement between the United States and China (U.S. White House, 2013) to phase out HFCs using the institutions of the MP makes an HFC phase-out all but certain. The devil is in the diplomatic details and in the ability of businesses to commercialize replacement products with superior lifecycle climate change performance (LCCP). The authors' view is that success in phasing down HFCs under the MP will add to the evidence that sector-by-sector focus is superior to reliance on carbon trading alone.

The authors also agree that the search for environmentally sustainable technology has made great strides, but is nowhere near a "final" solution. It is daunting to imagine curtailment of CO_2 emissions caused by human activities or to identify the carbon capture and sequestration (Chow et al., 2003; White et al., 2003) required to counteract past emissions. Choices could include:

- Tracking progress in MAC and room AC where environmentally superior refrigerants are already available.
- Quantifying the claim that HFC-1234yf is too flammable to use in MAC systems. What are the implications for the use of far more flammable refrigerants in applications where larger refrigerant charges are necessary, where there is less experience with flammable chemicals, and where evacuation from fire is more difficult? The damage done by this claim will continue to unfold as the European Community grapples with how to penalize violation of the F-gas directive without either crippling German vehicle production and jobs or crippling respect for and compliance with laws necessary to protect climate.
- Look for corporate leadership to follow the pledges of the members of Refrigerants, Naturally!, the Consumer Goods Council, and the core work of nongovernmental organizations (NGOs) such as SAE international and other public and private standards and industry associations.
- Considering that HFC-152a has higher potential for energy efficiency than either HFC-1234yf or CO_2 in MACs, and that HFC-152a produces no TFA atmospheric by-products. Furthermore, recent scientific studies of atmospheric lifetime report a lower GWP for HFC-1234yf to <1, making it superior with respect to the GWP of CO_2. However, the analysis will want to stay focused on LCCP because the energy embodied in manufacture of a refrigerant easily exceeds the climate impact of the chemical refrigerant itself by more than an order of magnitude. Furthermore, the other embodied energy and indirect fuel use to power refrigeration and AC exceeds the refrigerant impact by up to many orders of magnitude, depending on the climate where the product is used and the carbon intensity of the energy source.
- Study the long-term environmental effects of atmospheric decomposition products of HFC-1234yf, presumably mainly TFA. One might also add a multiyear study of the effects on the refrigerant and refrigeration systems using HFC-1234yf. Current knowledge suggests there is no cause for alarm or even concern, but it is unwise to rule out another unanticipated consequence in the making.
- Reevaluate whether the success on ODS was because it was easier than reducing non-ODS GHGs or because the Kyoto

Protocol is the wrong mechanism and approach to global market transformation. This topic is the subject of ongoing debate. Scholars of the MP identify its strengths as Start and Strengthen, Easy First, Government/Industry Partnerships, Corporate Pledges and Consumer Boycotts, Incremental Finance, and the Confidence and Spirit of Success itself. Consider that MP meetings never attract many more than 500 participants, while climate meetings have achieved the carnival status of tens of thousands. Add “Small is Beautiful” to the MP advantage.

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