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LETTER

Early action on HFCs mitigates future atmospheric change

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Abstract

As countries take action to mitigate global warming, both by ratifying the UNFCCC Paris Agreement and enacting the Kigali Amendment to the Montreal Protocol to manage hydrofluorocarbons (HFCs), it is important to consider the relative importance of the pertinent greenhouse gases and the distinct structure of their atmospheric impacts, and how the timing of potential greenhouse gas regulations would affect future changes in atmospheric temperature and ozone. HFCs should be explicitly considered in upcoming climate and ozone assessments, since chemistry-climate model simulations demonstrate that HFCs could contribute substantially to anthropogenic climate change by the mid-21st century, particularly in the upper troposphere and lower stratosphere i.e., global average warming up to 0.19 K at 80 hPa. The HFC mitigation scenarios described in this study demonstrate the benefits of taking early action in avoiding future atmospheric change: more than 90% of the climate change impacts of HFCs can be avoided if emissions stop by 2030.

1. Introduction

This year, as countries take action to mitigate global warming, both by ratifying the UN Framework Conventional on Climate Change (UNFCCC) Paris Agreement (http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf) and enacting the Kigali Amendment to the Montreal Protocol to manage hydrofluorocarbons (HFCs) (www.unep.org/newscentre/Default.aspx?DocumentID=27086&ArticleID=36283&l=en), it is important to consider the relative importance of the pertinent greenhouse gases (GHGs) and the distinct structure of their atmospheric impacts, and how the timing of potential GHG regulations would affect future changes in atmospheric temperature and ozone.

Atmospheric concentrations of HFCs are increasing rapidly, as HFCs replace the ozone-depleting substances (ODSs, e.g., the chlorofluorocarbons (CFCs)) (United Nations Environment Programme (UNEP) 2012; see figure 1(a)). This growth is a response to increasing global demand for HFC applications such as air conditioning and refrigeration. While HFCs are projected to make only a minor contribution to future ozone depletion (Hurwitz *et al* 2015), many HFCs (like the CFCs and hydrofluorocarbons (HCFCs) they replace) are strong radiative forcers (figure 1(b)). The five HFC species expected to make the largest contributions to surface radiative forcing by the mid-21st century, and in turn cause the largest atmospheric impacts, are HFC-23, HFC-32, HFC-125, HFC-134a and HFC-143a (Velders *et al* 2015). These HFC species have 100-year global warming potentials in the range of 700–14 000 (WMO 2014) (i.e., 1 kg of HFC emissions on average causes thousands of times more surface warming than does 1 kg of CO_2) and have relatively long atmospheric lifetimes of 14 to 228 years (SPARC 2013).

HFCs are expected to make increasing contributions to global climate change in the coming decades, as atmospheric concentrations of HFCs rise (Forster and Joshi 2005, United Nations Environment Programme (UNEP) 2012). However, HFC emissions scenarios, and thus their resulting climate impacts, have largely been based on statistical and socio-economic projections of HFC emissions inventories (e.g., Velders *et al* 2015). Hurwitz *et al* (2015) demonstrated the potential atmospheric temperature impacts of HFCs in 2050 in a coupled chemistry-climate model, which incorporates the interactions between atmospheric chemistry, radiation and dynamics. The present study extends that of Hurwitz *et al* (2015) by quantifying

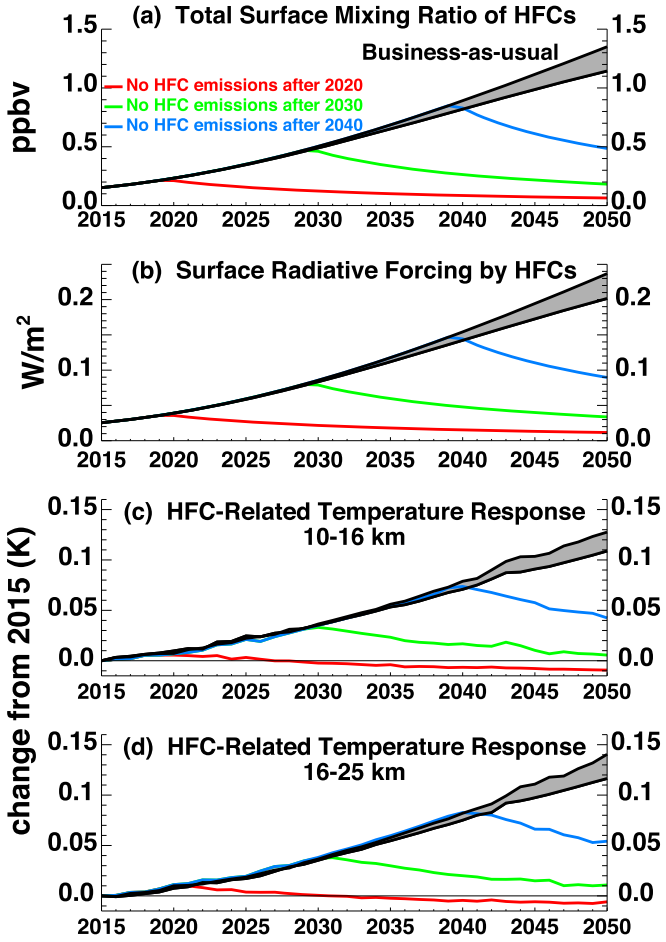

Figure 1. Timeseries of (a) surface mixing ratio for the sum of all five HFC species (ppbv); (b) the surface radiative forcing by HFCs (W m^{-2}); (c) the temperature response to HFCs in the 10–16 km layer (K), as compared with 2015 conditions; (d) the temperature response to HFCs in the 16–25 km layer (K), as compared to 2015 conditions. The gray shading shows the projected contributions due to increasing HFCs under business-as-usual scenarios (Miller and Kuijpers 2011, Velders *et al* 2015). The red, green and blue lines, respectively, show the total surface mixing ratio, surface radiative forcing and temperature responses for the three mitigation scenarios in which HFC emissions initially follow the Velders *et al* (2015) SSP5 scenario, then are eliminated beginning in 2020, 2030 or 2040. Note that the slight negative values for the 2020 mitigation scenario (red lines) indicate recovery to pre-2015 conditions.

both the relative contribution of HFCs to future atmospheric change, and the effects of several HFC mitigation scenarios.

2. Results

2.1. Relative impact of the HFCs in 2050

The atmospheric impacts of increasing carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and HFCs, and decreasing ODSs, can be distinguished by comparing NASA GSFC atmospheric 2D model sensitivity simulations (Fleming *et al* 2011, Hurwitz *et al* 2015) in which one of these five sets of trace species evolves according to business-as-usual scenarios while the other species are held fixed at 2015 values. In this study, HFC-32, HFC-125, HFC-134a and HFC-143a evolve according to the Velders *et al* (2015) flux-based boundary conditions, based on either the Shared Socioeconomic Pathway 3 (SSP3) or the SSP5 scenarios, while HFC-23 emissions follow the Miller and Kuijpers (2011) business-as-usual scenario (figure 1(a)) through 2035 and are held fixed at 2035 levels thereafter. The mixing ratios for the ozone-depleting substances follow the WMO A1 scenario (WMO 2014). Mixing ratios of CO_2, CH_4 and N_2O evolve according to either the Representative Concentration Pathways 6.0 (RCP6.0) (Fujino *et al* 2006) scenario or the RCP8.5 (Riahi *et al* 2011) scenario; these scenarios have been used recently in global climate model projections (i.e., Flato *et al* 2013). Between 2015 and 2050, HFCs add ~0.2 W m^{-2} to surface radiative forcing (figure 1(b)), as compared with ~1.1 W m^{-2} by CO_2 (following the RCP6.0 scenario).

This study examines the temperature response to HFCs in the upper troposphere and stratosphere. As the GSFC 2D model is an atmosphere-only model, boundary conditions must be specified at the surface. These surface boundary conditions are based on NASA's Modern-Era Retrospective Analysis for Research and Applications (Rienecker *et al* 2011). Since explicit ocean-atmosphere model calculations of the surface temperature response to HFCs have yet to

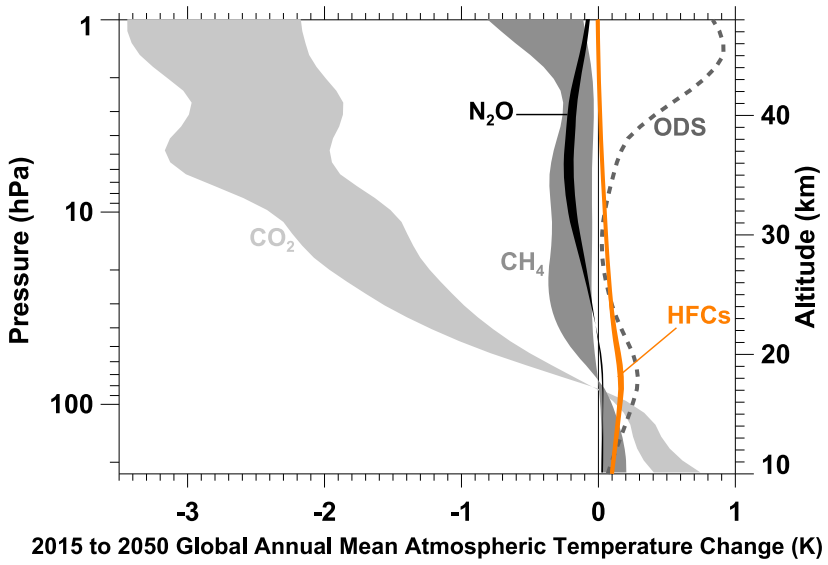

Figure 2. Projected global and annual mean temperature change (K) in the upper troposphere and stratosphere between 2015 and 2050, for five HFCs, the major ozone-depleting substances, CO_2, methane and N_2O. The emissions scenarios used to make these projections are described in section 2.1.

be performed, the HFC responses are estimated by scaling to those of HCFC-22 (Kratz *et al* 1993). The GSFC 2D model is relatively insensitive to the imposed surface temperature boundary conditions above 10 km (as discussed by Hurwitz *et al* 2015).

The modeled temperature responses to increased atmospheric concentrations of these GHGs are the result of full coupling between the model's radiation, transport and stratospheric chemistry components. Figure 2 (orange shading) shows that HFCs augment the projected upper tropospheric warming due to CO_2, and somewhat reduce stratospheric cooling. The magnitude of the atmospheric warming response to HFCs depends on the scenario for future emissions; a peak global mean warming of 0.19 K at 80 hPa is simulated when HFCs increase according to the Velders *et al* (2015) SSP5 scenario. In the upper troposphere, at 250 hPa, HFCs warm 10%–20% as much as CO_2. Total column ozone decreases by 0.1 DU due to projected increases in HFCs (not shown), as compared with the 2.5–4.0DU increase due to increasing CO_2 (e.g., Li *et al* 2009).

Like the impact of increasing HFCs, future decreases in ODSs (because of the Montreal Protocol) will lead to warming of the upper troposphere and stratosphere. As ODSs decline, so does stratospheric ozone depletion and therefore solar (UV) heating is increased. In contrast, the contributions of CH_4 and N_2O have the same pattern as CO_2 (i.e., upper tropospheric warming and stratospheric cooling), but their smaller contributions to radiative forcing correspond with their relatively smaller atmospheric temperature impacts. The IR absorption by CO_2, CH_4 and N_2O directly impacts atmospheric temperatures (i.e., enhancing tropospheric warming and stratospheric cooling) and modifies the stratospheric Brewer–Dobson circulation. This global mass circulation is important in determining the thermodynamic balance of the stratosphere, as well as the distribution and atmospheric lifetime of trace species. The GHG-induced acceleration of the Brewer-Dobson circulation is a robust result among chemistry-climate models, including the GSFC 2D model, with a projected range of ~2%–3.2% per decade, depending on the GHG scenario (Fleming *et al* 2011, Butchart 2014). CH_4 and N_2O have additional and important indirect effects on the atmospheric temperature structure due to their chemical reactivity (i.e., in changing the concentrations of radiatively active species such as ozone and water vapor).

The structure of the multi-decadal atmospheric temperature responses to CO_2 and the ODSs, shown in figure 2, are consistent with previous model studies. Separating the stratospheric effects of CO_2 and the ODSs, Shepherd and Jonsson (2008) found that, for the 2010–2040 period, the response is dominated by cooling by CO_2, which increases with height, while declining ODSs lead to warming of the upper stratosphere. However, Shepherd and Jonsson (2008) did not consider the effects of heterogeneous ozone loss due to ODSs in the lower stratosphere, nor the effects of the other major GHGs.

2.2. HFC mitigation scenarios

GSFC 2D model simulations testing HFC mitigation scenarios show that earlier restrictions on HFC emissions considerably reduce the HFC-related impacts on the upper troposphere and stratosphere. In the business-as-usual cases (black lines, figure 1), HFC-32, HFC-125, HFC-134a and HFC-143a emissions follow either the SSP3 or SSP5 scenario (Velders *et al* 2015), while HFC-23 emissions follow Miller and Kuijpers (2011). In three additional simulations, HFC emissions initially follow the Velders *et al* (2015) SSP5 and

Table 1. Upper row: 2015–2050 changes in temperature (K) and layer column ozone (DU) in the upper troposphere (10–16 km), lower stratosphere (16–25 km), and upper stratosphere (25–50 km), due to increasing HFCs (following the SSP5 scenario for HFC-32, HFC-125, HFC-134a and HFC-143a (Velders *et al* 2015), and a business-as-usual scenario for HFC-23 (Miller and Kuijpers 2011)). Lower rows: HFC-related temperature change, ozone change and emissions avoided by 2050, in three HFC mitigation scenarios in which HFC emissions are eliminated beginning in 2020, 2030 or 2040. The % of 2050 impacts avoided is listed in parentheses. Note that the slight, negative temperature values for the 2020 mitigation scenario indicate recovery to pre-2015 conditions.

	HFC-Related Temperature Response (K)			HFC-Related Column Ozone Response (DU)		% HFC Emissions Avoided
	10–16 km	16–25 km	25–50 km	16–25 km	25–50 km	
Business-as-usual 2050	0.13	0.14	0.03	−0.080	−0.12	N/A
No HFC emissions after 2020	−0.009 (>99%)	−0.006 (>99%)	−0.005 (>99%)	0.003 (>99%)	−0.006 (95%)	95%
No HFC emissions after 2030	0.006 (96%)	0.010 (93%)	0.002 (94%)	−0.008 (90%)	−0.022 (82%)	77%
No HFC emissions after 2040	0.042 (67%)	0.054 (62%)	0.014 (56%)	−0.038 (52%)	−0.058 (52%)	47%

Miller and Kuijpers (2011) scenarios, then are eliminated as of 2020, 2030 and 2040, respectively (red, green and blue lines, figure 1). Projected emissions for the other GHGs (e.g., CO_2) are used in all four simulations (as in section 2.1). As compared with business-as-usual projections, these HFC mitigation scenarios represent 95%, 77% and 47% reductions in cumulative HFC emissions between 2015 and 2050 (table 1; figure 1(a)). Likewise, much of the projected surface radiative forcing is avoided (figure 1(b)).

Eliminating HFC emissions as of 2020 essentially avoids the HFC-related upper tropospheric and stratospheric warming that would have occurred by 2050 (table 1; red line, figures 1(c) and (d). The lower stratospheric ozone loss, resulting from the combination of changes in the atmospheric temperature structure and a strengthened Brewer-Dobson circulation (Hurwitz *et al* 2015), is avoided. More than 90% of the HFC-related upper tropospheric and stratospheric warming, as well as 90% of the ozone loss, that would have otherwise occurred by 2050 can be avoided by eliminating HFC emissions by 2030 (green line, figures 1(c) and (d). Likewise, 67% of the upper tropospheric warming, approximately 60% of the stratospheric warming and 52% of the ozone loss that would have occurred by 2050 can be avoided by eliminating HFC emissions by 2040 (blue line, figures 1(c) and (d)).

3. Conclusions

Separating the relative impacts of climate gases on the future stratosphere was recently recognized as a priority for the 2018 World Meteorological Organisation (WMO) Scientific Assessment of Ozone Depletion (Fahey *et al* 2016). HFCs should be explicitly considered in this and other upcoming climate and ozone assessments. While smaller than the impacts of increasing CO_2, the chemistry-climate model simulations presented above demonstrate that HFCs could contribute substantially to anthropogenic climate change by the mid-21st century, particularly in the upper troposphere and lower stratosphere.

On 15 October 2016, the parties to the Montreal Protocol agreed to a gradual phase down of HFC production and use (www.unep.org/newscentre/Default.aspx?DocumentID=27086&ArticleID=36283&l=en). While this Kigali Amendment to the Montreal Protocol includes a larger number of HFC species, and considers more subtleties of the transition to climate-friendlier alternatives, the simple HFC mitigation scenarios described in this study demonstrate the benefits of taking early action in preventing future atmospheric change.

Acknowledgments

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