Early action on HFCs mitigates future atmospheric change

Margaret M Hurwitz1,2, Eric L Fleming1,2, Paul A Newman1, Feng Li1,3 and Qing Liang1,3

1 NASA Goddard Space Flight Center, Greenbelt, MD, USA
2 Science Systems and Applications, Inc., Lanham, MD, USA
3 GESTAR, Universities Space Research Association, Columbia, MD, USA
E-mail: margaret.m.hurwitz@nasa.gov

Keywords: climate change, HFC, chemistry-climate model, mitigation scenario, stratosphere

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 Convention 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&d=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 CO2) 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
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 (CO₂), methane (CH₄), nitrous oxide (N₂O) 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 CO₂, CH₄ and N₂O 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 CO₂ (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
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$_2$O 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$_2$O 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).

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.

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.

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...
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&fl=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

The authors acknowledge funding from the NASA ACMAP program. NASA GSFC 2D model output will be made available upon request.

### References

Butchart N 2014 The brewer-dobson circulation Rev. Geophys. 52 157–84

Fahey D W, Newman P A, Pyle J A and Safari B 2016 Scientific assessment of ozone depletion 2018: meeting the needs of the parties to the montreal protocol SPARC Newsletter 46

Flato G et al 2013 Evaluation of climate models Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed TF Stocker et al (Cambridge: Cambridge University Press Cambridge) pp 741–866

Fleming E L, Jackman C H, Stolarski R S and Douglass A R 2011 A model study of the impact of source gas changes on the stratosphere for 1850–2100 Atmos. Chem. Phys. 11 8515–41

Forster P M D and Joshi M 2005 The role of halocarbons in the climate change of the troposphere and stratosphere Clim. Change 71 249–66

Fujino J, Nair R, Kainuma M, Masui T and Matsuoka Y 2006 Multigas mitigation analysis on stabilization scenarios using
AIM global model, multigas mitigation and climate policy

Hurwitz M M, Fleming E L, Newman P A, Li F, Mlawer E, Cady-Pereira K and Bailey R 2015 Ozone depletion by hydrofluorocarbons Geophys. Res. Lett. 42 8686–92

Kratz D P, Chou M-D and Yan M M-H 1993 Infrared radiation parameterizations for the minor CO₂ bands and for several CFC bands in the window region J. Clim. 6 1269–81

Li F, Stolarski R S and Newman P A 2009 Stratospheric ozone in the post-CFC era Atmos. Chem. Phys. 9 2207–13

Miller B R and Kuijpers L J M 2011 Projecting future HFC-23 emissions Atmos. Chem. Phys. 11 13259–13267

Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N and Rafaj P 2011 RCP 8.5—a scenario of comparatively high greenhouse gas emissions Clim. Change 109 33

Rienecker M M et al 2011 MERRA: NASA’s modern-era retrospective analysis for research and applications J. Clim. 24 3624–48

Shepherd T G and Jonsson A I 2008 On the attribution of stratospheric ozone and temperature changes to changes in ozone-depleting substances and well-mixed greenhouse gases Atmos. Chem. Phys. 8 1435–44

Stratosphere-Troposphere Processes and their Role in Climate (SPARC) 2013 Lifetimes of stratospheric ozone-depleting substances, their replacements, and related species SPARC Rep. no. 6 ed M K W Ko et al

United Nations Environment Programme 2012 HFCs: a critical link in protecting climate and the ozone layer, UNEP 36 p (http://unep.org/dewa/Portals/67/pdf/HFC_report.pdf)

Velders G J M, Fahey D W, Daniel J S, Andersen S O and McFarland M 2015 Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFCs) emissions Atmos. Environ. 123A 200–9

World Meteorological Organization (WMO) 2014 Scientific assessment of ozone depletion: 2014 Global Ozone Research and Monitoring Project Rep. no. 55 Geneva, Switzerland