Reduction in surface climate change achieved by the 1987 Montreal Protocol

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Abstract

The benefits of the 1987 Montreal Protocol in reducing chlorofluorocarbon emissions, repairing the stratospheric ozone hole, shielding incoming UV radiation, reducing the incidence of skin cancer and mitigating negative ecosystem effects are all well documented. Projected future climate impacts have also been described, mainly focused on a reduced impact of the mid-latitude jet as the ozone hole gradually repairs. However, there is little appreciation of the surface warming that has been avoided as a result of the Montreal Protocol, despite CFCs being potent greenhouse gases. Instead, the issue of ozone depletion and climate change are often thought of as two distinct problems, even though both ozone and CFCs impact Earth’s radiation budget. Here we show that a substantial amount of warming has been avoided because of the Montreal Protocol, even after factoring in the surface cooling associated with stratospheric ozone depletion. As of today, as much as 1.1 °C warming has been avoided over parts of the Arctic. Future climate benefits are even stronger, with 3 °C–4 °C Arctic warming and ~1 °C global average warming avoided by 2050; corresponding to a ~25% mitigation of global warming. The Montreal Protocol has thus not only been a major success in repairing the stratospheric ozone hole, it has also achieved substantial mitigation of anthropogenic climate change both today and into the future.

1. Introduction

Chlorofluorocarbons (CFCs) are major ozone-depleting substances (ODS) known to be the primary cause of the unprecedented stratospheric ozone depletion observed during the late 20th Century (Anderson \textit{et al} 1991). The seminal work of Molina and Rowland (Molina and Rowland 1974) in the mid 1970s provided an early warning of what was to come, proposing that increases in CFCs could be a potential threat to stratospheric ozone. Shortly after, new observations confirmed their hypothesis with the discovery of the ‘ozone hole’ in the mid 1980s (Farman \textit{et al} 1985). Following this unprecedented change to atmospheric chemistry, a new global treaty, \textit{The Montreal Protocol on Substances that Deplete the Ozone Layer}, was signed in 1987 to reduce and eventually phase out the substances that deplete ozone in the stratosphere.

Industrial use of CFCs began in the early 1930s, with production surging in the 1950s and 1960s (England 1995). Being non-toxic, inert, and inexpensive synthetic chemical compounds, they were commonly used as aerosol propellants, in refrigeration and air-conditioning, in plastic foams as insolation and packaging, and as solvents for cleaning electrical appliances. After implementation of the Montreal Protocol and its amendments in the following years, the use of ODS was reduced with the aim of eventually phasing out all major ODS by introducing non-ozone-depleting substitutes. The success of this protocol is already evident with a reduction in observed atmospheric CFC concentrations and the first signs of ozone hole recovery appearing in the early 21st Century (Newchurch 2003). Ozone is expected to recover to early 1970 levels somewhere between 2040 and 2070 (Newman \textit{et al} 2006, Eyring \textit{et al} 2010).
In addition to their effect on stratospheric ozone, CFCs are potent greenhouse gases (Montzka et al 2011), being thousands of times more efficient at trapping heat than an equivalent mass of CO$_2$ (Lashof and Ahuja 1990). As such, the Montreal Protocol has resulted in two major changes to global atmospheric composition that have relevance to Earth’s climate: (1) ozone depletion has reversed and a recovery in the ozone hole is now underway, and (2) several potent varieties of greenhouse gases, most notably CFC-11 and CFC-12, have been stabilized and are now reducing in concentration in the atmosphere (refer to solid red and orange lines in figure 1(a)).

Previous studies have focused on the importance of this protocol in relation to ozone, both in terms of the amount of UV radiation reaching Earth’s surface (Chipperfield et al 2015), and in terms of ozone’s role in climate (Purich and Son 2012, Bandoro et al 2014), both today (Thompson et al 2011) and into the future (Son et al 2008). The importance of this protocol in reducing the net anthropogenic imbalance in the top of atmosphere radiation budget (Velders et al 2007, Estrada et al 2013), reducing cooling of the lower stratosphere (Morgenstern et al 2008, Garcia et al 2012) and reducing warming over the surface (Hansen et al 1989, Morgenstern et al 2008, Garcia et al 2012, Egorova et al 2013) has also been examined. Despite the findings of these seminal papers, overall awareness of the global warming mitigation achieved by the Montreal Protocol remains rather limited, with most people, even many climate scientists, exclusively associating the protocol with success at halting and reversing stratospheric ozone depletion. Awareness of the protocol’s success at warming mitigation is largely limited to the very small community of modellers who have studied the problem directly. Here, we extend on past studies by investigating the global and regional effects that CFC avoidance has had on surface temperature, sea ice, precipitation and the Atlantic meridional overturning circulation (AMOC). In addition, we also separate out the competing radiative effects of reduced CFCs and reduced stratospheric ozone depletion on surface climate. We will show that even though the Protocol’s main aim was to tackle the problem of ozone depletion, this international agreement also turned out to be one of the earliest and most
important steps towards global warming mitigation undertaken to date.

2. Methods

2.1. Coupled climate model

We evaluate a suite of ensemble experiments using the Australian Community Climate and Earth-System Simulator v1.0 (ACCESS1.0) coupled atmosphere-ocean-land-sea-ice model to estimate the surface warming mitigation achieved by the Montreal Protocol. The transient climate sensitivity of ACCESS1.0 to greenhouse gas forcing appears to be close to the multi-model mean of CMIP5 models (figure S1 is available online at stacks.iop.org/ERL/14/124041/mmedia). The ACCESS1.0 model (Bi et al 2013, Dix et al 2013) is a fully coupled global model, similar in configuration to other models that took part in the Coupled Model Intercomparison Project phase 5 (CMIP5), with three-dimensional coupled sub-models of the atmosphere, ocean, land-surface and sea-ice, but with prescribed atmospheric chemistry effects. The atmospheric component of the model used here is the United Kingdom Met Office atmospheric Unified Model (UM, Davies et al 2005, Martin et al 2011) which has a Gaussian N96 horizontal resolution of approximately 1.25° latitude × 1.875° longitude and 38 vertical levels. The UM is coupled to the Geophysical Fluid Dynamics Laboratory Modular Modular Ocean Model, Version 4.1 (MOM4.1, Griffies et al 2010) and the Los Alamos National Laboratory sea ice model, version 4.1 (CICE4.1, Hunke et al 2008). The ACCESS1.0 configuration of MOM4.1 and CICE4.1 employs 360 longitude × 300 latitude grid points on a rectangular grid with enhanced resolution at the Equator, and 50 vertical levels with 10 m resolution in the upper 200 m (Bi et al 2013).

When forced by suitable historical variations in greenhouse gases and other atmospheric constituents like aerosols and ozone, the ACCESS1.0 model is able to capture the broad scale features of the recent observed warming over the past half century (figures 2(a), (b)). This is the case for both the pattern and magnitude of global warming, with the classical fingerprint of amplified warming over land and polar regions, especially over the Arctic, apparent in historical simulations (figures 2(a), (b)). The model also largely captures the recent observed delayed warming over the North Atlantic and Southern Oceans. Going forward in time, the transient climate sensitivity of the ACCESS1.0 model appears to be mid-range across the spread of CMIP5 models, with the projected end of 21st Century warming close to the CMIP5 multi-model mean (figure S1).

Figure 2. Observed and simulated temperature change. Change in surface air temperature averaged between 1951–1980 and 1998–2017; (a) observations (GISTEMP Team 2019, Hansen et al 2010) and (b) the coupled climate model (RCP8.5 scenario). Model results are based on the mean of 5 ensemble members. Average estimated amount by which Earth’s surface would have warmed by year 2019 (c) without the Montreal Protocol and (d) without the Montreal Protocol (CFC effect only). 2019 values are taken as the 2015–2024 average across 5 ensemble members.
2.2. Forcing

The impact of the Montreal Protocol on Earth’s climate is estimated by simulating a climate from 1974 onwards in which no ozone/CFC policy was implemented (referred to as the No Protocol scenario), i.e. both CFC increases and the associated stratospheric ozone depletion are assumed to continue unmitigated by the Montreal Protocol (figure 1). For a no ozone/CFC policy framework, an annual growth rate of between 3% (Hammitt et al 1987) and 7% (Prather et al 1996) for both CFC-11 and CFC-12 has been used in previous studies (Velders et al 2007, Newman et al 2009, Wu et al 2013), representing the projected growth rates under mature (Hammitt et al 1987) and free (Prather et al 1996) markets, respectively. Here we adopt an annual growth rate at the low end of this range; taken to be 3% from 1974 to 2065 for both CFC-11 and CFC-12 (refer to the dashed red and orange lines respectively in figure 1(a)). Because the Montreal Protocol is never implemented in the No Protocol simulation without ozone/CFC policy, the non-ODS substitutes (i.e. hydrofluorocarbons (HFC)-125 and HFC-134a) are never introduced and thus their concentrations are set to zero throughout the simulation. For non-ODS that were already present before 1974, such as hydrochlorofluorocarbons (HCFC)-22, their concentrations remain at 1974 levels for the purposes of the No Protocol simulation. Zonally averaged ozone profiles from a previous No Protocol experiment (described below) with a 3% per annum CFC growth rate and coupled chemistry (Newman et al 2009), in which the global ozone depletes further into the future (shown as the maroon curve in figure 1(b)), are used to prescribe ozone concentrations in our No Protocol simulations.

All simulations otherwise employed observed historical anthropogenic and natural forcings up until 2005, followed by the standard business-as-usual RCP8.5 forcing thereafter, as implemented in CMIP5. The various experiments we examine differ only in their radiative forcing due to both ozone and ozone depleting substances (ODS), reaching values of less than 10 DU by 2065 (maroon curve in figure 1(b)), with ODS increasing at 3% per annum from 1974 on (dashed lines in figure 1(a)). Ozone forcing for the standard RCP8.5 simulations is taken from the Stratrophic-tropospheric Processes and their Role in Climate (SPARC, Gionni et al 2011) program (green curve in figure 1(b)) and ODS forcing (i.e. CFCs) follows the RCP8.5 scenario of CMIP5 (solid lines in figure 1(a)).

The prescribed concentrations of ozone in our No Protocol experiment are obtained from a simulation of the Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM, Pawson et al 2008), which is a fully-coupled radiation-chemical-dynamical chemistry climate model, run with a 3% per annum increase in ODS concentrations from 1974 on (figure S2). The low-pass filtered evolution of ozone from the No Protocol coupled chemistry model is added to the variability in the SPARC ozone dataset to maintain consistency between the No Protocol and RCP8.5 simulations. Imposed ozone changes are only significant in the stratosphere (above ~200 hPa), as ozone depletion due to CFCs is largely limited to these altitudes (Rowland 2006). Tropospheric ozone changes are also not radiatively important here and are mainly associated with air pollution (Lelieveld and Dentener 2000). Concentrations of tropospheric ozone are thus kept the same between the No Protocol and RCP8.5 scenarios.

2.3. Model simulations

Four sets of simulations are performed using the ACCESS1.0 coupled climate model, differing only in the prescribed ozone and ODS forcing. In the standard RCP8.5 scenario (which includes concatenated historical and standard RCP8.5 forcing), ozone recovers in the future (green curve in figure 1(b)), while ODS (CFC-11 and CFC-12) decrease and their substitutes (HCFC-22, HFC-125 and HFC-134a) increase (solid lines in figure 1(a)). For the No Protocol scenario, in which CFCs, HCFCs and ozone all progress as though no mitigation of ODS was ever undertaken, ozone (maroon curve in figure 1(b)) depletes further into the future in association with the assumed 3% per annum increase in ODS (Newman et al 2009). Substitutes are either set to zero or are fixed at 1974 levels (dashed lines in figure 1(a)).

Because ozone is also a greenhouse gas, its depletion under a No Protocol scenario offsets some of the warming caused by increases in the ODS greenhouse gases such as CFC-11 and CFC-12 (Yang et al 2015). In the No Protocol (ozone only) experiments, ozone follows the same evolution as in the standard No Protocol experiment, however CFC concentrations are prescribed as per the RCP8.5 scenario (solid lines in figure 1(a)). While this is unrealistic (i.e. ozone should deplete as CFCs increase), this experiment allows us to estimate the effect of ozone depletion in isolation of CFC changes, as the difference between the No Protocol (ozone only) and RCP8.5 scenarios provides an estimate of the cooling due to ozone depletion. Another simulation (No Protocol (with substitutes)) is also carried out, similar to the No Protocol simulation; only here the CFC substitutes are also introduced following the RCP8.5 scenario. As such, the difference between the No Protocol and No Protocol (with substitutes) ensemble means provides an estimate of the warming effect due to the CFC substitutes alone.

All other greenhouse gas and aerosol concentrations are prescribed based on the historical scenario to 2005 followed by the high emission Representative Concentration Pathway (RCP) 8.5 scenario, as implemented in CMIP5. The main comparison evaluated in our study is between the No Protocol and RCP8.5 simulations, to give an estimate of the overall surface warming mitigation achieved by the Montreal
Protocol. These two main simulations differ only in their historical and future projected concentrations of CFCs and ODS substitutes (figure 1(a)), and in the way ozone either depletes or recovers into the future (figure 1(b)). Any climatic differences between these two experiments are due to a combination of the net warming resulting from increases in ODS (i.e. CFCs), less the cooling due to stratospheric ozone depletion and any additional warming due to the CFC substitutes. For all experiments considered, we run a total of five ensemble members; all results presented in this study are derived from the ensemble mean of this set to reduce the effect of internal variability on our results.

3. Results

The climate model simulations under the RCP8.5 scenario capture the broad-scale observed climate change patterns over the past half-century, including increased warming over land compared to the oceans, polar amplification over the Arctic, and reduced warming over the Southern Hemisphere mid-latitudes and North Atlantic Ocean (figures 2(a), (b)). There are some minor differences that are typical of CMIP5 models; for example, regions of cooling around the Antarctic margin in the observations, which are not captured by the model (Purich et al. 2016a). These differences have been attributed to both known biases in CMIP5 models over the Southern Ocean (Purich et al. 2016a) and to internal variability present in the observations (Purich et al. 2016b). However, based on a first order comparison, the model captures both the pattern and magnitude of observed surface warming seen over the past half century with a good level of accuracy.

The effects of the Montreal Protocol can be estimated by examining the difference between the standard No Protocol experiment and the RCP8.5 experiment. This analysis reveals that significant warming has already been avoided as a result of the Montreal Protocol (figure 2(c)); primarily over the Arctic where regional warming of ~1 °C relative to RCP8.5 has been avoided. This is associated with a reduction in the rate of Arctic sea-ice retreat (figure 3), which, via ice-albedo feedbacks, would likely imply reduced melting of the Greenland Ice Sheet, although land-ice is not explicitly simulated in the model. Other climatic benefits from the Montreal Protocol can be seen, with substantial warming (0.5 °C–1.0 °C) avoided over large regions of land, particularly over parts of Africa, North America and Eurasia. The warming avoided due to CFCs alone is even higher (figure 2(d)), with ~20% more avoided warming on the global average compared to the standard No Protocol experiment, offset by cooling due to stratospheric ozone depletion in the No Protocol climate. Overall, the pattern of avoided warming under the protocol (figure 2(c)) mirrors the classical global warming pattern, with the most warming avoided over land areas and over the Arctic. Cooling effects can be seen over parts of the Southern Ocean and North Atlantic; the latter caused by a relative slowdown of the AMOC (figure 4).

The benefits of the Montreal Protocol are set to become even greater over future decades, with substantial warming avoided by the middle of this century despite the cooling effects of ozone depletion (figure 5 top panels). Warming of 3 °C–4 °C is set to be avoided over most regions of the Arctic by mid-century. This represents more than a 30% reduction in the warming that would otherwise have occurred at this time under a business as usual scenario. The warming avoided due to CFC reduction alone is much higher, exceeding 4 °C–5 °C over parts of the Arctic (figure 5(c)); some fraction of this warming is offset by cooling due to ozone depletion (figure 5(d)). Globally averaged, by the middle of this century, we estimate that approximately 1 °C warming will be avoided due to the Montreal Protocol (from ~4 °C warming in the No Protocol climate state to ~3 °C in RCP8.5, figure 6). This represents a significant mitigation of global warming. The reduction in CFCs contributes to ~1.4 °C of this avoided warming, with ozone depletion offsetting the warming by ~0.3 °C and CFC substitutes contributing to ~0.1 °C warming by 2050 (figure 6).

The avoided surface warming over the Arctic region also translates to avoided sea-ice melt, with the simulations suggesting that by mid-century, around 26% more sea-ice (by area) will remain in summer, and ~13% more will remain in winter (figure 3) thanks to the Montreal Protocol. This equates to 0.9 × 106 km2 and 1.6 × 106 km2 less Arctic sea-ice loss in summer and winter, respectively. There are also avoided changes in the hydrological cycle due to the Montreal Protocol, with a significant reduction in the magnitude of projected wetting and drying across much of the globe by mid-century (compare the RCP8.5 and No Protocol scenarios in figure 7). The largest proportional effect is found in polar regions, with the Arctic and Antarctic-wide precipitation increases reduced from 46% to 28% over the Arctic and from 27% to 16% over the Antarctic, in the No Protocol experiment compared to the RCP8.5 scenario. The projected increase in precipitation over high latitudes in a warming world is primarily related to thermodynamic increases in water content explained by the Clausius-Clapeyron relationship, and, to a lesser extent, dynamic changes in moisture transport associated with the poleward shift in the midlatitude winds (Emori and Brown 2005, Sen Gupta and England 2006). In the No Protocol scenario, both these effects are strongly enhanced due to polar amplification and due to a larger wind shift tied to the compounding influence of greenhouse warming and ozone depletion.
4. Summary and discussion

Using ensembles of coupled climate model simulations combined with suitable anthropogenic forcing, we have shown that a substantial amount of warming has been avoided by virtue of the Montreal Protocol of 1987. As of 2019, the protocol has likely already avoided regional warming of the order 0.5°C–1.0°C over some land areas, and of the Arctic. Greater climate change mitigation is projected by mid-century, with regional warming of the order of 1.5°C–2°C avoided over some land areas, and 3°C–4°C warming avoided over parts of the Arctic. We estimate that global mean warming of at least 1.0°C will be avoided by 2050 due to the implementation of the Montreal Protocol. This equates to a ~25% reduction in global warming, a remarkable success in climate change mitigation. Furthermore, these estimates are likely to be conservative, given that historical CFC growth rates (12%–17% between 1960 and 1974 (Velders et al 2007)) were far higher than the 3% value we use in our simulations. As such, the Montreal

Figure 3. Changes in sea-ice extent avoided by mid-21st Century due to the Montreal Protocol. Analyses are derived from the ensemble mean of the No Protocol scenario compared to RCP8.5 over the same time-period. Shown are Arctic sea ice extent for summer (Jun–Jul–Aug) and winter (Dec–Jan–Feb); green and red lines show the 15% contour of sea-ice concentration for the RCP8.5 and No Protocol scenarios, respectively, averaged over 2041–2060. Underlaid is the baseline average Arctic sea ice concentration (%) simulated for 1951–1980 for summer and winter.
Protocol has not only helped us avoid the worst impacts of ozone depletion, it has also mitigated a substantial fraction of greenhouse gas warming by reducing CFC concentrations in the atmosphere. The Kyoto Protocol, widely considered to be the first international policy to curb global warming due to greenhouse gas emissions, is estimated to mitigate global warming by just $\sim 0.12 °C \pm 0.07 °C$ by the middle of the 21st Century (Wigley 1998), a small fraction of the warming we estimate that will be mitigated by the Montreal Protocol. The results of our study thus show that the Montreal Protocol should

![Figure 4](image-url) Time series of simulated Atlantic meridional overturning circulation (AMOC). Black lines represent the RCP8.5 scenario and red lines the No Protocol scenario. Thick lines indicate the ensemble mean and thin lines the individual ensemble members. AMOC transport is calculated as the maximum Meridional Overturning Circulation in the Atlantic Ocean below 500-m depth. Values are given in Sverdrup ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$).

![Figure 5](image-url) Change in surface air temperature under different forcing scenarios averaged for years 2041–2060. (a) Mid-century temperature change in the business-as-usual RCP8.5 scenario compared to a 1951–1980 baseline, (b) Difference between the No Protocol scenario and the RCP8.5 scenario, showing the estimated total mid-century warming avoided under the Montreal Protocol. (c) Estimated effects of CFCs only and (d) ozone only in the No Protocol simulations. The estimates in (c) and (d) are derived from differences between the respective No Protocol scenarios with and without commensurate ozone changes (see Methods section for further details; i.e. the sum of panels (c) and (d) equals panel (b)). All data are shown nominally for year 2050, taken as the average temperature changes across the 5 ensemble members for years 2041–2060.
instead be regarded as the first successful treaty to mitigate a substantial amount of greenhouse gas warming. The success of this protocol, negotiated internationally more than 30 years ago, should provide motivation that regulating greenhouse gas emissions is a highly effective means of minimising future global climate change.

Figure 6. Time series of simulated global-mean surface air temperature anomalies. Shown are the global-mean anomalies from 1974 to 2050 calculated with respect to the 1951–1980 average under the different forcing scenarios. Solid black and red lines represent the RCP8.5 scenario and the No Protocol scenario, respectively. The solid blue line represents the scenario in which the No Protocol ozone is prescribed (i.e. ozone depletes further into the future) while CFC concentrations reduce as per the Montreal Protocol and the RCP8.5 scenario. Thin lines represent the individual ensemble members for each experiment. Right panel shows the mean (thick line) and ±1.64 standard deviations from the mean (corresponding to a 95% confidence interval) for RCP8.5, No Protocol and No Protocol (ozone only) as light black, red and blue bars respectively. Red, pink and blue dashed lines indicate the estimated CFCs-only, substitutes-only and ozone-only warming/cooling effects in the No Protocol simulations, respectively, derived from differences between the respective No Protocol scenarios with and without commensurate ozone changes (see Methods section for further details). Red, pink and blue bars in the right-hand panel represent estimated mid-21st Century warming/cooling due to CFCs (ODS), substitutes and ozone, respectively.

Figure 7. Changes in precipitation avoided by mid-21st Century due to the Montreal Protocol. Analyses are derived from the ensemble mean of the No Protocol scenario compared to RCP8.5 over the same time-period. Shown are Mid-21st Century changes in precipitation avoided by the Montreal Protocol, averaged over 2041–2060 (i.e. the difference between the No Protocol and RCP8.5 scenarios). Right panel shows the zonal averaged percentage change in precipitation in the RCP8.5 and No Protocol scenarios with respect to 1951–1980 baseline, respectively, averaged over 2041–2060.
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