# Diverse policy implications for future ozone and surface UV in a changing climate

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**Abstract.** Due to the success of the Montreal Protocol in limiting emissions of ozone-depleting substances, concentrations of atmospheric carbon dioxide, nitrous oxide, and methane will control the evolution of total column and stratospheric ozone by the latter half of the 21st century. As the world proceeds down the path of reducing climate forcing set forth by the 2015 Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21), a broad range of ozone changes are possible depending on future policies enacted. While decreases in tropical stratospheric ozone will likely persist regardless of the future emissions scenario, extratropical ozone could either remain weakly depleted or even increase well above historical levels, with diverse implication for ultraviolet (UV) radiation. The ozone layer's dependence on future emissions of these gases creates a complex policy decision space for protecting humans and ecosystems, which includes unexpected options such as accepting nitrous oxide emissions in order to maintain historical column ozone and surface UV levels.

## 1. Introduction

Now that the world has agreed to curtail global warming following the 2015 Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21) in Paris, implementation requires emissions reductions of various greenhouse gases, including carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). These gases not only warm the earth, but also affect ozone abundances (WMO (World Meteorological Organization) 2014). Consequently, changes in these gas emissions and their simultaneous impacts on climate and the ozone layer become important considerations for future policy decisions.

The stratospheric ozone layer protects Earth's surface from the most damaging ultraviolet (UV) radiation. It has been substantially depleted over the last 35 years due to halocarbon emissions, which are both potent greenhouse gases and ozone-depleting substances (ODSs). An undisputed environmental policy-making success story, the Montreal Protocol and its amendments will return ODSs to near historical levels (1955-1975, prior to significant depletion) by the latter half of this century and prevent significant health consequences of excessive UV exposure (Newman & McKenzie 2011; Chipperfield et al. 2015). However, the evolution of stratospheric ozone beyond the middle of the 21$^{st}$ century, when ODS emissions are minimal and their atmospheric concentrations continue to decrease, will largely be determined by $CO_2$, $N_2O$, and methane (Eyring et al. 2013; Fleming et al. 2011; Stolarksi et al. 2015; Portmann et al. 2012; Revell et al. 2012; Oman et al. 2010; Iglesias-Suarez et al. 2016). Under some future emission scenarios, extratropical ozone far exceeds historical levels, reducing surface UV below their historical levels (Hegglin & Shepherd 2009; Watanabe et al. 2011; Bais et al. 2015).

$N_2O$ destroys stratospheric ozone by increasing reactive odd-nitrogen species. $N_2O$ is currently the largest ozone-depletion-potential (ODP)-weighted emission (Ravishankara et al. 2009) and a potent greenhouse gas; its potential mitigation via the Montreal Protocol has been examined (Kanter et al. 2013). The ODP of $N_2O$ changes with $CO_2$ and methane abundances (Ravishankara et al. 2009; Wang et al. 2014; Revell et al. 2015). The dominant effect of increased methane is increased ozone production in the lower stratosphere and troposphere down to the surface (Fleming et al. 2011; Eyring et al. 2013).

Increased $CO_2$ cools the stratosphere and consequently increases ozone particularly in the upper stratosphere (Fleming et al. 2011). Increased $CO_2$ is expected to accelerate the Brewer-Dobson Circulation (BDC), leading to stratospheric ozone decreases in the tropics and increases in the extratropics (Butchart 2014). While methane and $N_2O$ affect ozone predominantly via chemical reactions, $CO_2$ affects ozone indirectly via temperature and dynamical changes. Although $N_2O$, methane, and $CO_2$ all exacerbate climate change, they have different, and possibly non-linear (Meul et al. 2015), influences on both total column and stratospheric column ozone.

The Montreal Protocol's regulations to mitigate ODSs are expected to reduce their radiative forcing while increasing global stratospheric ozone back towards historical levels. Conversely, protecting the future ozone layer under evolving $CO_2$, $N_2O$, and methane emissions may involve the conundrum of weighing benefits for climate change against maintaining the ozone layer and surface UV radiation near historical levels.

**2. Methods**

To demonstrate the complexities in future ozone changes when $N_2O$ or methane concentrations are increased or reduced in climates with varying $CO_2$, we ran simulations using the National Center for Atmospheric Research (NCAR) Whole Atmosphere Community Climate Model (WACCM) for the Representative Concentration Pathways (RCPs), RCP 2.6, 4.5, and 8.5. WACCM version 4 (Marsh et al. 2013) is an atmospheric extension to NCAR's Community Earth System Model (CESM) with a high model top (~140 km) and fully interactive chemistry in the middle atmosphere, though tropospheric chemistry has a limited representation (methane and carbon monoxide oxidation). The horizontal resolution is 1.9 degrees latitude by 2.5 degrees longitude with 66 vertical levels. The Quasi-Biennial Oscillation (QBO) is represented by nudging the tropical winds to match observed interannual variability.

A historical transient simulation from 1955-2005 was performed using time-evolving observed forcings (surface concentrations of radiatively active species, daily solar spectral irradiance, and volcanic sulfates). The ocean was initialized from a reference case and allowed to freely evolve. Future RCP

transient simulations were run from 2006-2095 using projected concentrations of radiatively active species (Meinshausen et al. 2011). From these transient simulations, we used the sea surface temperature (SST) and sea ice climatologies for both the historical (1955-1975) and the future (2075-2095) climates to force 20-year "time-slice" experiments (following 10 years of spin-up) with varying concentrations of $N_2O$, $CH_4$, and $CO_2$ (**Table 1**) based on the RCP scenarios. Time-slice runs simulate "slices" of time rather than the full transient response; the atmosphere responds to fixed climatological SSTs and forcings held at a constant value for a particular year. In runs where we modulate $N_2O$ or methane concentrations, we assume that the associated changes in SSTs/sea ice are not large (i.e., they are dominated by the changes in $CO_2$).

**Table 1.** Concentrations of $CO_2$, $N_2O$, $CH_4$, and $Cl_y$ used in each time-slice simulation, and the climatology period for sea surface temperatures (SSTs)/sea ice. Concentrations are from either the year 1957 (historical) or 2095 (future runs) RCPs.

| Experiment | $CO_2$ (ppm) | $N_2O$ (ppb) | $CH_4$ (ppb) | $Cl_y$ (ppb) | SSTs/Ice climatology |
|---|---|---|---|---|---|
| 1957 historical | 314 | 291 | 1211 | 0.73 | 1955-1975 |
| RCP 2.6 | 423 | 344 | 1259 | 1.19 | RCP 2.6 2075-2095 |
| RCP26_N2O_85 | | **428** | 1259 | | |
| RCP26_CH4_85 | | 344 | **3698** | | |
| RCP 4.5 | 535 | 371 | 1591 | 1.16 | RCP 4.5 2075-2095 |
| RCP 8.5 | 889 | 428 | 3698 | 1.11 | RCP 8.5 2075-2095 |
| RCP85_N2O_26 | | **344** | 3698 | | |
| RCP85_CH4_26 | | 428 | **1259** | | |

For comparison with values in **Table 1**, 2016 global concentrations of $CO_2$, $N_2O$, and $CH_4$ are ~402 ppm, ~328 ppb, and ~1840 ppb, respectively. Note that in the end-of-the-century RCP 8.5 climate, $CO_2$ and methane have increased substantially (roughly a factor of three), while $N_2O$ has increased only by ~50%, compared to the historical climate. Total chlorine ($Cl_y$) is higher for all future climates compared to $Cl_y$ in the historical run because the long-lived chlorofluorocarbons (CFCs) persist. Chlorine concentrations, aerosols, and tropospheric emission precursor concentrations in the time-slice experiments are based on corresponding historical or RCP scenario values, but we performed an additional sensitivity

run to test the role of chlorine in the RCP 8.5 scenario (not shown). Solar spectral irradiances (SSI), specified from the Lean et al. (2005) model and used for solar heating and photolysis reactions, vary on daily timescales in the transient runs, but are set constant in the historical time-slice run to 1960 values and in the future time-slice runs to 2095 values. The SSI integrated over all wavelengths is the total spectral irradiance (TSI); for comparison, the TSI is ~1362 W $m^{-2}$ in 1960 and ~1361 W $m^{-2}$ in 2095. For solar and geomagnetic parameters (e.g., the F10.7 cm flux, $K_p$, $A_p$), a constant value (the solar cycle average) was used in all time-slice runs.

We also consider changes in stratospheric ozone in coupled climate models with interactive chemistry from the Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012). Stratospheric column ozone is determined by summing ozone above 200 hPa (more complex methods using a latitudinally-varying tropopause yielded similar results).

**3. Results**

In agreement with previous studies (Eyring et al. 2013; Stolarksi et al. 2015; Fleming et al. 2011; Portmann et al. 2012; Revell et al. 2012; Oman et al. 2010; Iglesias-Suarez et al. 2016), there is a broad range of possible changes to the stratospheric ozone layer by the end of the century (2075-2095) compared to the historical period (1955-1975) (shown in **Figure 1** for CMIP5 models with interactive chemistry). In an aggressive greenhouse gas mitigation scenario (RCP 2.6; blue shading), stratospheric ozone at most latitudes remains slightly below historical levels by the end of the 21$^{st}$ century. The ~5-10 Dobson Unit (DU) ozone depletion is due to slightly elevated $N_2O$ and anthropogenic halocarbons remaining in the atmosphere.

However, under continued greenhouse gas emissions (RCP 8.5; red shading), stratospheric ozone remains depleted in the tropics but substantially exceeds historical levels in the extratropics. Lower tropical stratospheric ozone relative to the historical period is mostly due to the accelerated BDC and partly due to $N_2O$-related loss processes (Fleming et al. 2011; Eyring et al. 2013). The extratropical ozone increases are primarily associated with the cooling effects of $CO_2$ in the mid- to upper stratosphere,

the increased advection of ozone-rich air via the strengthened BDC, and enhanced production due to increased methane (Fleming et al. 2011). In a moderate emission scenario (RCP 4.5; green shading), stratospheric ozone remains depleted in the tropics, but extratropical ozone returns to near historical levels, due to a balance between increases caused by $CO_2$ and methane, and depletion caused by ODSs and $N_2O$. The changes in stratospheric ozone from the historical period (1955-1975) to the end of the century (2075-2095) in our WACCM RCP 2.6, 4.5, and 8.5 transient runs (dashed lines) are largely consistent with the CMIP5 simulations, with the exception of weaker ozone recovery in the Southern Hemisphere extratropics and greater ozone recovery in the Northern Hemisphere extratropics (**Figure 1;** dashed lines).

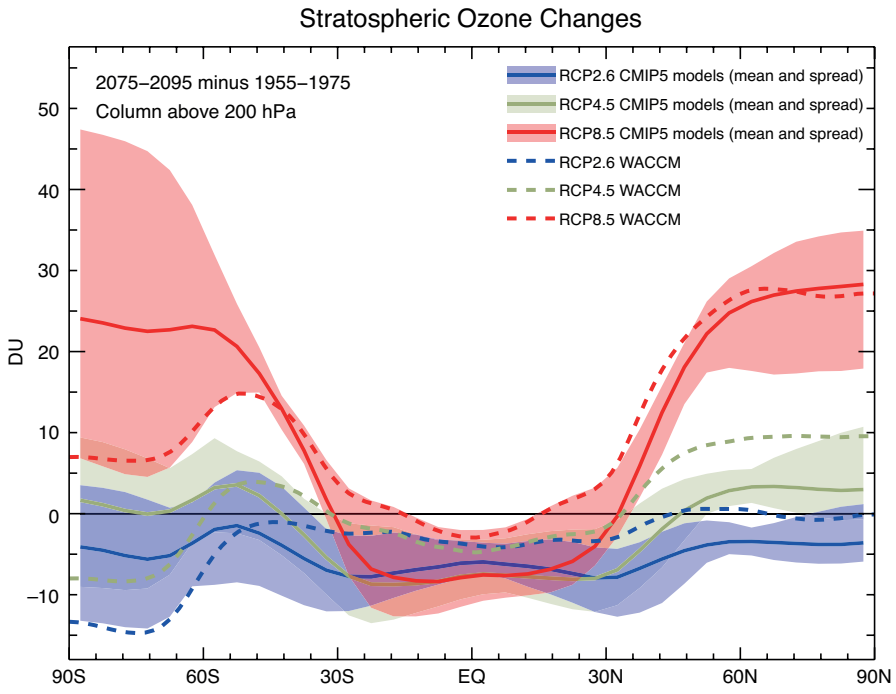


**Figure 1**. Comparison of CMIP5 model changes in stratospheric ozone [DU] between the mean 2075-2095 period and the mean 1955-1975 period as a function of latitude, for RCP 2.6 (blue), RCP 4.5 (green), and RCP 8.5 (red). The multi-model mean is shown with the solid line. The change in stratospheric ozone in the WACCM transient runs is shown in dashed lines. The CMIP5 models with interactive chemistry included here are: CESM1-WACCM, GFDL-CM3, GISS-E2-H-p2, GISS-E2-H-p2, and MIROC-ESM-CHEM.

Time-slice experiments were forced using sea surface temperature (SST) and sea ice climatologies from the transient simulations and the concentrations of $CO_2$, $N_2O$, methane, and total chlorine shown in **Table 1**. Here we focus on the RCP 2.6 and 8.5 scenarios, since the stratospheric ozone response to RCP 4.5 falls in between these extreme scenarios (**Figure 1**). For the RCP 2.6 future time-slice run (**Figure 2A, 2C**; bold black line), ozone is slightly below historical levels at most latitudes by the end of the 21$^{st}$ century in agreement with the transient simulation (**Figure 1**). We can then examine what would happen if either methane or $N_2O$ were not aggressively mitigated. If methane were increased to RCP 8.5 concentrations for 2095, column ozone increases at all latitudes due to large tropospheric ozone increases (**Figure 2A, 2C**; green shading). If $N_2O$ were increased to RCP 8.5 concentrations for 2095, ozone decreases at all latitudes due to stratospheric ozone depletion (**Figure 2A, 2C**; purple shading). Note that the tropical ozone depletion in this scenario would potentially be larger than during the period of maximum historic ozone layer depletion (1985-2005, dotted line). A key point is that if the world were to achieve reductions of $CO_2$ and methane concentrations to RCP 2.6 levels, $N_2O$ mitigation would become important to avoid exacerbation of both climate change and ozone layer depletion. On the other hand, if $CO_2$ and $N_2O$ were reduced to RCP 2.6 levels but methane concentrations increased, we expect stratospheric ozone increases towards historical levels and large increases in global tropospheric ozone.

In contrast, modulating $N_2O$ or methane in a climate with high greenhouse gas concentrations has different consequences for the total and stratospheric column ozone. In the RCP 8.5 future time-slice run, stratospheric ozone remains depleted in the tropics but substantially exceeds historical levels in the extratropics (**Figure 2B**; bold black line). Large methane increases in the RCP 8.5 scenario (and thus large increases in tropospheric ozone) leads to increases in the total column ozone above historical levels at all latitudes (**Figure 2D**; bold black line). Note that increases in column ozone due to enhanced methane occurs more in the troposphere than in the stratosphere, as to be expected. In this climate, a reduction in $N_2O$ concentrations would reduce anthropogenic climate forcing and slightly reduce stratospheric ozone depletion at low latitudes, but would increase column ozone beyond historical levels

in the extratropical stratosphere and at all latitudes (**Figure 2B, 2D**; purple shading). A reduction in methane concentrations would also reduce anthropogenic climate forcing and tropospheric ozone, and thus decrease extratropical ozone levels towards historical levels, but could exacerbate tropical stratospheric ozone decreases (**Figure 2B, 2D**; green shading).

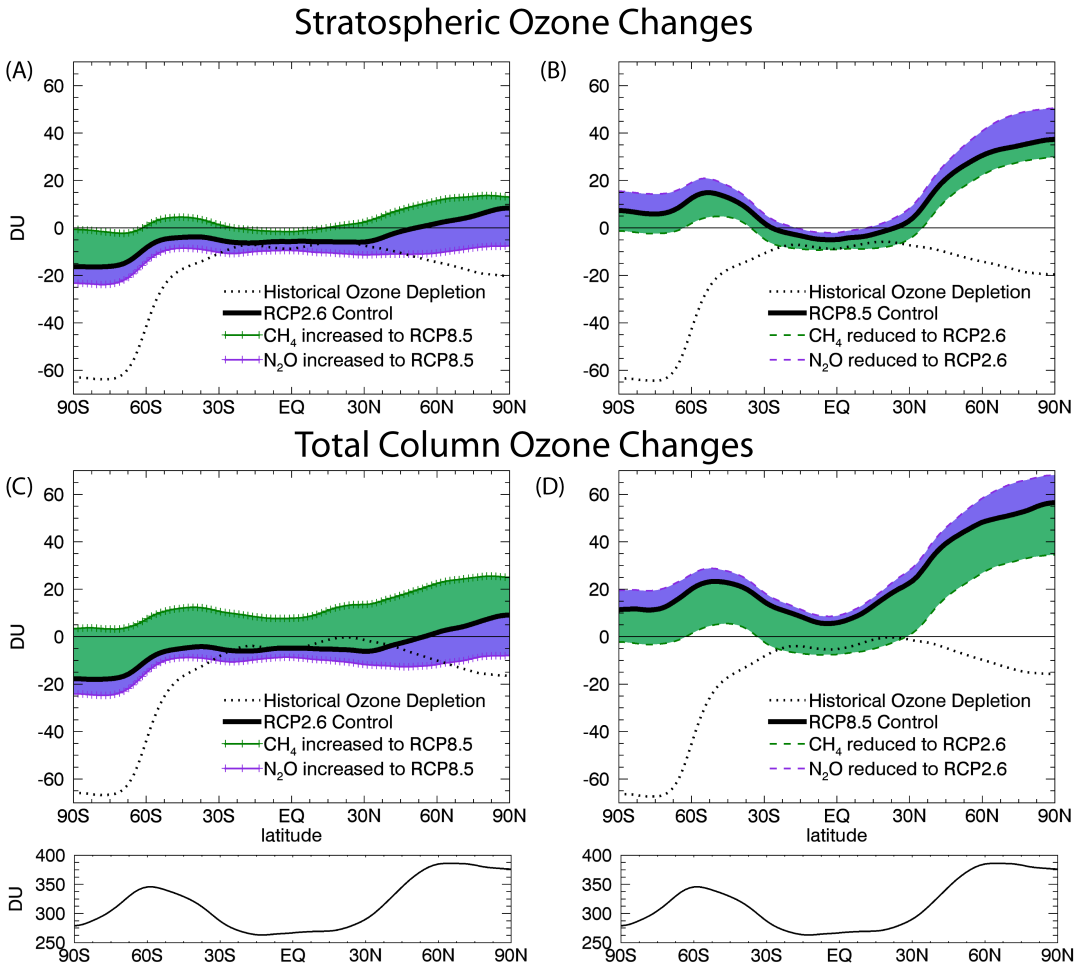


**Figure 2**. Stratospheric and total column ozone changes [Dobson Units] for the future time-slice runs (2075-2095) relative to the historical time-slice run (1955-1975) for (**A, C**) the RCP 2.6 climate and (**B, D**) the RCP 8.5 climate. The black dotted line shows the historical ozone depletion from 1985-2005 relative to the period 1955-1975 in a transient historical climate simulation. The green (purple) line shows the changes in ozone when only methane ($N_2O$) is increased (**A,C**) or reduced (**B,D**). The bottom panels show, for context, the total column ozone as a function of latitude for the historical run in WACCM. Stratospheric ozone is calculated as the ozone column above 200 hPa at all latitudes.

There are many potential impacts of changes in tropospheric and stratospheric ozone on human health and the ecosystem. There are large uncertainties in tropospheric ozone due to uncertainties in

tropospheric precursor emissions, but the changes simulated in WACCM fall within the CMIP5 multi-model spread (Eyring et al. 2013; Young et al. 2013). We assess the latitudinal changes in the UV index (UVI) at local noon using an approximation based on calculated total column ozone for cloud-free, aerosol-free, low-surface albedo conditions (Madronich 2007):

$$UVI \sim 12.5\mu_o^{2.42}\left(\frac{\Omega}{300}\right)^{-1.23} \quad (1)$$

where $\mu_o$ is the cosine of the solar zenith angle at solar noon on the 15$^{th}$ of each month, and $\Omega$ is the total column ozone. Note that the noon UVI ranges from zero at the poles to ~12 at the equator, and varies substantially with latitude and season, with the highest values in the extratropical summer hemisphere. Thus a 20% change in UVI at 45° latitude represents absolute increases in the UVI of ~ 2 in the summer but only ~0.5 in the winter.

**Figure 3** shows the percent change in the UVI (based on total, not stratospheric, column ozone) compared to the historical period as a function of month for (**A, C**) the RCP 2.6 future climate and (**B, D**) the RCP 8.5 future climate for $N_2O$ concentrations fixed at 344 ppbv (the 2095 RCP 2.6 value) or 428 ppbv (the 2095 RCP 8.5 value). **Figures 3A** and **3D** represent the "control" RCP 2.6 and 8.5 climates, respectively, while **Figures 3B** and **3C** correspond to the lower and upper boundary for potential future changes in ozone in **Figure 2**. Clearly, changes in UVI by the latter half of the century depend more on future $CO_2$ concentrations than on $N_2O$ concentrations. In the RCP 2.6 future climate, UVI remains only slightly larger than historical levels, except in the Southern Hemisphere (SH) spring where remaining halocarbons preferentially deplete polar ozone and increase surface UV exposure (highlighting the need to phase out these compounds). Conversely, in the RCP 8.5 future climate, UVI decreases everywhere relative to historical levels, and especially in the extratropics. These results are in general agreement with previous studies, though some studies find weak increases in UV exposure in the tropics (Bais et al. 2011; Watanabe et al. 2011). It is clear that lower concentrations of $N_2O$ would reduce UVI towards historical levels (i.e., zero percent change) in the RCP 2.6 climate (**Figure 3A versus Figure 3C**) but further away from historical levels in the RCP 8.5 climate (**Figure 3B versus Figure 3D**). In the RCP 8.5 future

climate with $N_2O$ mitigated to RCP 2.6 levels (**Figure 3B**), the UVI is reduced up to ~20% in the Northern Hemisphere (NH) extratropics. The UVI is actually closer to historical levels when $N_2O$ is increased (**Figure 3D**).

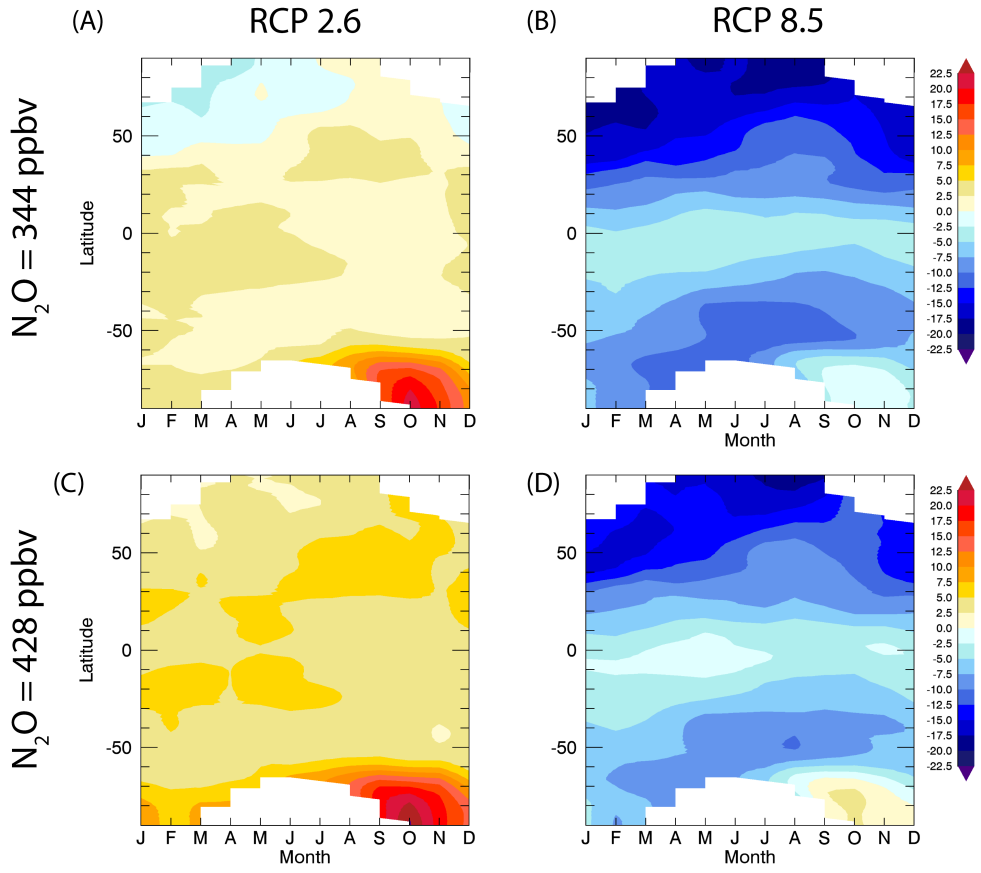


**Figure 3.** Percent change in the UV index (UVI) as a function of month and latitude for the future time-slice runs (2075-2095) relative to the historical time-slice run (1955-1975) for (**A, C**) the RCP 2.6 scenario and (**B, D**) the RCP 8.5 scenario, and for (**top**) RCP 2.6 levels of $N_2O$ (344 ppbv) in 2095 and (**bottom**) RCP 8.5 levels of $N_2O$ (428 ppbv) in 2095.

## 4. Discussion and Conclusions

The negative health effects of enhanced UV exposure, namely increased incidence of skin cancers and cataracts (Lucas et al. 2015; Williamson et al. 2014), could continue to impact the Southern Hemisphere as well as much of the globe in an RCP 2.6 future climate, particularly if $N_2O$ concentrations increase. This enhanced UV exposure could be especially detrimental in the tropics, where UV exposure is already high. In contrast, consequences of reduced UV exposure are not as clear and need to be better

understood, particularly if greenhouse gas emissions continue to increase (Hegglin & Shepherd 2009; Bais et al. 2015). For humans, one primary concern of lower UV is a reduction in vitamin D synthesis, which is associated with increased risks of osteoporosis, rickets, certain types of cancer, cardiovascular disease, multiple sclerosis, and rheumatoid arthritis (Autier et al. 2014). Some recent studies are unable to find evidence of vitamin D supplementation reducing risk of these diseases (Lucas et al. 2015). Extratropical UV reduction may be particularly important because it occurs in regions where vitamin D deficiencies are already prevalent (Lucas et al. 2015; Correa et al. 2013). Reductions in UV could also affect terrestrial and aquatic ecosystems, as well as biogeochemical and carbon cycles (Williamson et al. 2014; Erickson III et al. 2015; Ballare et al. 2011; Bornman et al. 2015; Hader et al. 2015).

The UV changes presented here are based on a number of assumptions, such as cloud-free and unpolluted conditions. Potential future increases in cloud cover and reductions in surface reflectivity over the Arctic would cause additional decreases in UV at northern high-latitudes, while projected decreases in aerosols may counter these surface UV reductions; however, these effects are uncertain (Watanabe et al. 2011; Correa et al. 2013; Bais et al. 2015). In addition, there are uncertainties in the tropospheric emission scenarios, and limitations of the model simulations themselves (such as limited tropospheric chemistry). Volcanic eruptions are not considered in our future simulations but can have substantial transient effects on stratospheric ozone and associated UV. Warmer temperatures and changing precipitation patterns may also cause behavioral changes, such as altering the time people spend outdoors and thus, possibly, their overall UV exposure (Lucas et al. 2015).

Uncertainties aside, it is reasonable to assert that a comprehensive scientific foundation for future policy decisions to protect the ozone layer will include (a) the collective impacts of expected $CO_2$, methane, and $N_2O$ emissions on ozone, (b) the intricacies of balancing continued tropical stratospheric ozone decreases with potential extratropical ozone increases, and (c) the amount of total ozone increases or decreases that are deemed a concern for human and ecosystem health. Because of the large global warming influence of $CO_2$ and its enhancing effects on ozone, reducing $CO_2$ emissions may be the ideal policy for both reducing climate change and returning ozone to near historical levels at all latitudes by the

latter half of the century. Reducing methane emissions would have similar co-benefits. In contrast, reducing $N_2O$ emissions increases stratospheric ozone, which is beneficial in the present-day climate and for certain future scenarios where ozone depletion persists; but decreasing $N_2O$ may actually raise ozone above historical levels in the latter half of the century if $CO_2$ and methane emissions continue unabated as in the RCP 8.5 scenario.

Reducing greenhouse gas emissions to at least the RCP 4.5 trajectory is required to obtain the goals set forth by COP 21, which aim to limit global temperature changes to less than 2 degrees Celsius above pre-industrial levels (Collins et al. 2013). If achieved, this would also return stratospheric ozone and UV to near historical levels globally by 2100. If we aim to limit global temperature changes to less than 1.5 degrees Celsius, $CO_2$, methane, and $N_2O$ all need to be reduced to near RCP 2.6 levels, which would also benefit the ozone layer. If the world cannot achieve a reduction in $CO_2$ emissions to at least RCP 4.5 levels, the range of policy options to protect the ozone layer would necessarily broaden. One possibility includes allowing increased $N_2O$ emissions in order to maintain historical ozone and UV levels in the extratropics. For this option, the benefits of reducing ozone levels in the extratropics would need to be carefully weighed against slightly larger depletion in the tropics and the greenhouse gas effects of $N_2O$. This again highlights the importance of meeting COP21 goals to minimize future climate change and maintain surface UV at historical levels for human health and ecosystems.

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