

## RESEARCH LETTER

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## Key Points:

- The surface temperature response to quadrupling of CO<sub>2</sub> is largely insensitive to the stratospheric ozone feedback
- However, CO<sub>2</sub>-induced stratospheric ozone changes significantly enhance the meridional temperature gradient in the lower stratosphere
- This enhanced gradient opposes the one induced by CO<sub>2</sub> increases and thus reduces the SH midlatitude jet response

## Supporting Information:

- Figure S1

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## Reduced Southern Hemispheric circulation response to quadrupled CO<sub>2</sub> due to stratospheric ozone feedback

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**Abstract** Due to computational constraints, interactive stratospheric ozone chemistry is commonly neglected in most climate models participating in intercomparison projects. The impact of this simplification on the modeled response to external forcings remains unexplored. In this work, we examine the importance of including interactive stratospheric ozone chemistry on the Southern Hemispheric circulation response to an abrupt quadrupling of CO<sub>2</sub>. We find that including interactive ozone significantly reduces (by 20%) the response of the midlatitude jet to CO<sub>2</sub>, even though it does not alter the surface temperature response. The reduction of the tropospheric circulation response is due to CO<sub>2</sub> induced ozone changes and their effects on the meridional temperature gradient near the tropopause. Our findings suggest that neglecting this stratospheric ozone feedback results in an overestimate of the circulation response to increased CO<sub>2</sub>. This has important implications for climate projections of the Southern Hemispheric circulation response to CO<sub>2</sub>.

### 1. Introduction

An accurate assessment of the circulation response to anthropogenic greenhouse gases (GHGs) is of pivotal importance toward improved prediction of climate change. Models employed in the fifth Climate Model Intercomparison Project (CMIP5) for 21st century projections consistently predict a poleward shift of the midlatitude jet, which is more robust in the Southern Hemisphere [Collins *et al.*, 2013; Grise and Polvani, 2014a], even though the intermodel spread in the magnitude of such shift is considerable [cf. Barnes and Polvani, 2013, Figure 12]. In austral summer, the spread seems to be partly linked to intermodel differences in the equilibrium climate sensitivity (ECS) [Grise and Polvani, 2014b], while in winter, the climatological jet position may play a role [Simpson and Polvani, 2016]. Other factors, such as cloud feedbacks, have also been proposed as potential sources of these intermodel uncertainties [Ceppi *et al.*, 2014; Grise and Polvani, 2014c]. Clearly, a comprehensive understanding of the sources of intermodels spread in the circulation responses to GHGs is still lacking. In this paper, we seek to understand the role of interactive stratospheric ozone chemistry on the circulation response to increased GHGs.

Over the 21st century, stratospheric ozone recovery is projected to play a key role in canceling the poleward shift of the midlatitude jet due to GHGs [Arblaster *et al.*, 2011; Polvani *et al.*, 2011; McLandress *et al.*, 2011]. Long-term changes in stratospheric ozone, such as depletion over 1960–2000 and recovery over the 21st century, are primarily driven by ozone-depleting substances (ODSs) [WMO, 2014]. However, significant changes in stratospheric ozone can also result from an increased GHGs, via a strengthening of the Brewer-Dobson circulation (BDC) [Butchart, 2014] and a cooling of the stratosphere, as gas-phase chemistry is temperature dependent [Sander *et al.*, 2006]. Clearly, interactive ozone chemistry is a key ingredient for modeling the radiative and dynamical feedbacks of GHGs onto ozone and possibly on the evolution of the SH midlatitude jet. However, because of computational constraints, only a limited fraction of models participating in the fifth Climate Model Intercomparison Project (CMIP5) calculated ozone interactively [Eyring *et al.*, 2013]. Instead, CMIP5 models without interactive chemistry typically imposed an ozone forcing from the International Global Atmospheric Chemistry/Stratospheric Processes and their Role in Climate database, irrespective of the GHGs scenario [cf. Eyring *et al.*, 2013, Figure 6]. Thus, a possible feedback from GHGs-induced stratospheric ozone

changes was not captured by these models. By assessing the impact of interactive ozone chemistry, one can quantify the importance of ozone feedbacks on the model response to external forcings.

The impact of interactive ozone chemistry on the ECS has been recently investigated by *Dietmüller et al.* [2014], *Muthers et al.* [2014], *Nowack et al.* [2014], and *Marsh et al.* [2016]. In these studies, the stratospheric ozone response to an increase in CO<sub>2</sub> is robust. More specifically, this pattern consists of a large ozone decrease in the tropical lower stratospheric (TLS) and an increase over the SH polar cap [cf. *Nowack et al.*, 2014, Figure 3]. However, the impact of this ozone response on the ECS appears to be model dependent. A 20% reduction of the ECS was reported in *Nowack et al.* [2014], but other models showed much smaller values, ranging from 7% in *Dietmüller et al.* [2014] and *Muthers et al.* [2014] to less than 1% in *Marsh et al.* [2016]. This discrepancy could be due to intermodel differences in stratospheric water vapor response and its radiative feedbacks [*Marsh et al.*, 2016]. More work is needed to explain the spread in the magnitude of the ozone feedbacks and their contribution to the ECS.

While the effects of interactive ozone chemistry on ECS have been studied, its role in determining the SH circulation response to GHGs remains largely unexplored. In the context of historical CMIP5 simulations, stratospheric ozone depletion and recovery are the primary drivers of large-scale circulation changes in the midlatitude jet [*Eyring et al.*, 2013; *Previdi and Polvani*, 2014]. However, in abrupt 4xCO<sub>2</sub> experiments, where ODSs are constant, stratospheric ozone responds to GHGs-induced changes in the BDC and temperature and thus acts as a feedback. The central question of this study, therefore, is whether this feedback is important for the SH circulation response to GHGs. Here we examine this issue by carrying out model simulations from the Community Earth System Model (CESM) using the stratosphere resolving Whole Atmosphere Community Climate Model (WACCM) and different configurations for the stratospheric chemistry.

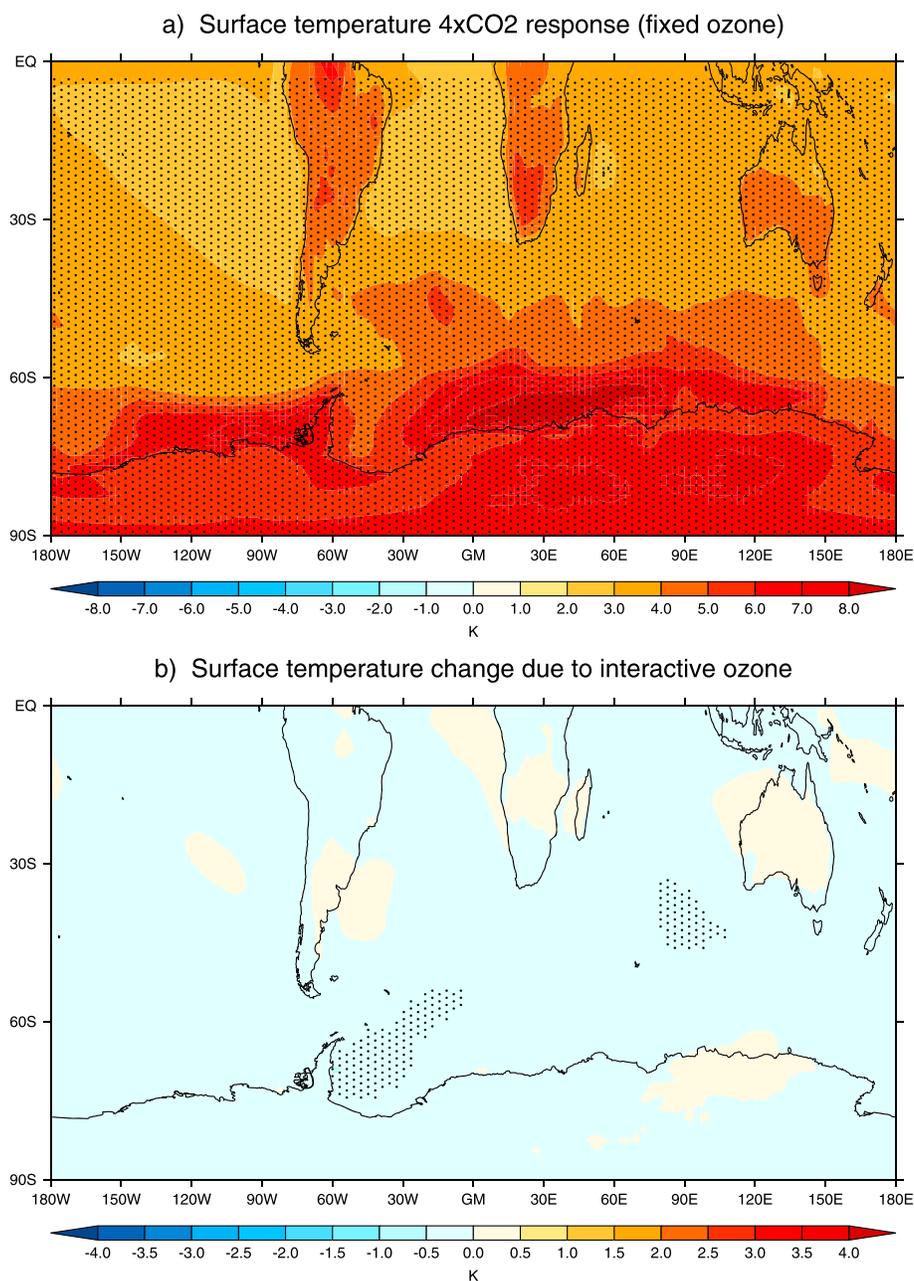
Since ozone chemistry has been shown to have no effect on surface temperature (as ECS) in our model [*Marsh et al.*, 2016], one might naively expect that the response of the atmospheric circulation will also be insensitive to interactive ozone chemistry. However, as recently shown by *Grise and Polvani* [2014b], the response of the atmospheric circulation (especially in midlatitudes) is largely independent of ECS: hence, the role of stratospheric ozone on the circulation response to increased CO<sub>2</sub> is not known a priori. In this paper, we focus exclusively on the SH, where the atmospheric circulation is approximately zonally symmetric, and a robust poleward shift of the midlatitude jet in response to CO<sub>2</sub> can be detected, as in the majority of CMIP5 models [*Barnes and Polvani*, 2013; *Grise and Polvani*, 2014b].

## 2. Methods

We perform numerical integrations from the Community Earth System Model (CESM), using the stratosphere resolving Whole Atmosphere Community Climate Model [*Marsh et al.*, 2013], coupled to the Parallel Ocean Program (POP) ocean [*Gent et al.*, 2011]. The standard configuration of WACCM includes a fully interactive stratospheric chemistry module, based on the version 3 of MOZART, which calculates chemical reactions for 217 gas-phase chemical reaction and advects a total of 59 species, including ozone [*Kinnison et al.*, 2007]. In addition, we also take advantage of an alternative configuration of the CESM model which uses, as atmospheric component, the Specified Chemistry Whole Atmosphere Community Climate Model (SC-WACCM) [*Smith et al.*, 2014]. In this model, the concentrations of radiatively active gases such as ozone, NO, O, O<sub>2</sub>, and CO<sub>2</sub> are simply prescribed throughout the atmospheric domain, using zonal mean values obtained from a 200 year long WACCM preindustrial control simulation. The other active components, such as land, ocean, and sea ice are identical between WACCM and SC-WACCM.

To quantify the role of interactive ozone chemistry, we have performed two pairs of 200 year long integrations. First, one preindustrial control integration was carried out (denoted **ctrl\_intO3**) with interactive stratospheric ozone chemistry. This was compared to another integration (denoted **4xCO2\_intO3**), forced with an instantaneous quadrupling of CO<sub>2</sub> [*Gregory et al.*, 2004; *Andrews et al.*, 2012]. The difference between these integrations allows us to establish a response to CO<sub>2</sub> forcing with stratospheric ozone feedbacks. Note that concentrations of ODS in these simulations are identical: any ozone changes are CO<sub>2</sub> induced and hence are a feedback.

Second, a similar pair of integrations was then performed but without interactive stratospheric ozone chemistry, i.e., in which an identical zonal mean, monthly mean climatological ozone was prescribed from the 200 year mean climatology from the WACCM preindustrial control run. The runs in this pair are denoted as **ctrl\_fixO3** and **4xCO2\_fixO3**, respectively, and their difference allows us to establish the response to CO<sub>2</sub>



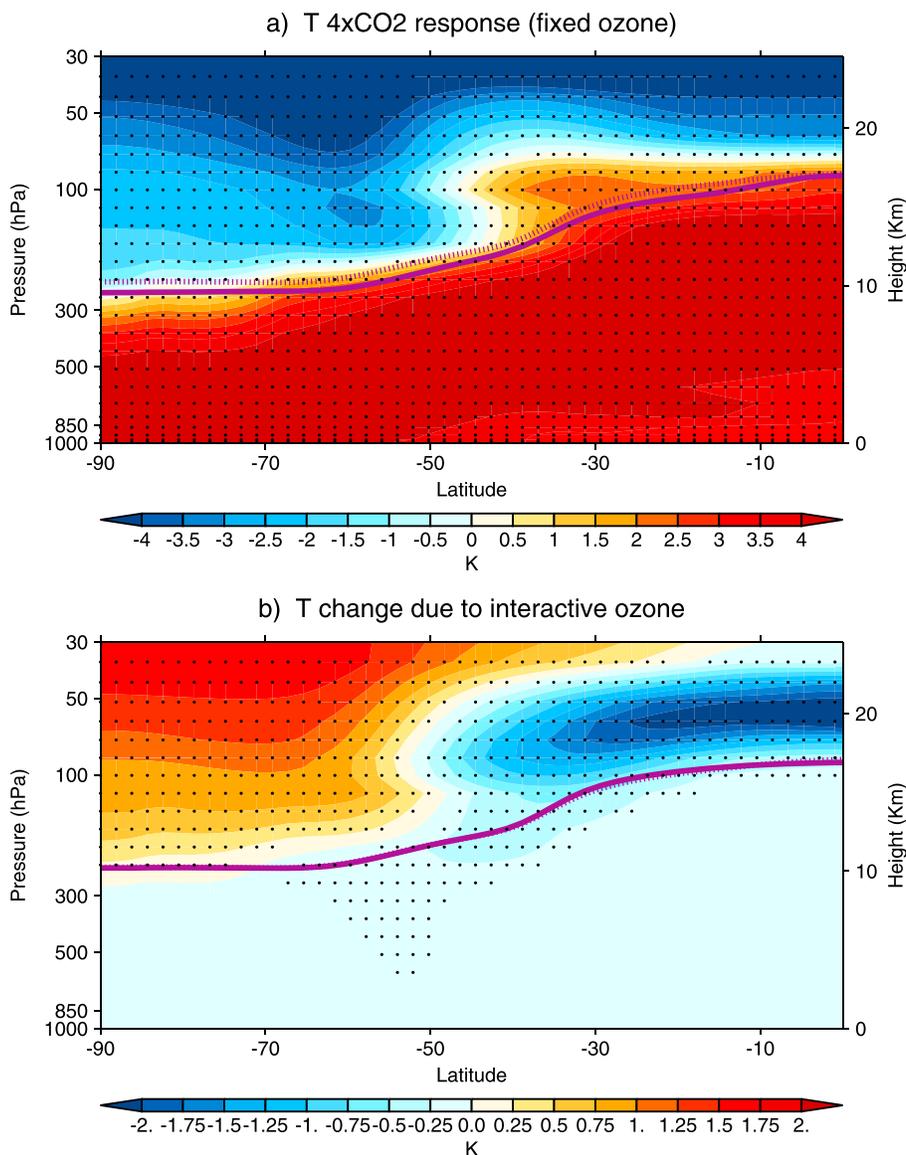
**Figure 1.** (a) Annual mean surface temperature response to 4xCO<sub>2</sub> in integrations with fixed (climatological) ozone ( $4xCO_2\_fixO3 - ctrl\_fixO3$ ). (b) change due to interactive ozone chemistry ( $4xCO_2\_intO3 - 4xCO_2\_fixO3$ ). Dotted areas identify statistically significant differences (at the 99% confidence level). Units in kelvin.

in the absence of ozone changes. Finally, contrasting the two pairs allows us to quantify the importance of stratospheric ozone chemistry (and thus of the ozone feedback), which is the key purpose of the present study.

Throughout this paper, differences are considered significant when they exceed the 0.01 (99%) confidence level from a statistical *t* test. To calculate the latitude of the midlatitude SH jet, we employ the same method used in Barnes and Polvani [2013] and Grise and Polvani [2014b], which identifies the jet latitude by using a polynomial fit to the model data at a resolution of 0.01°.

### 3. Results

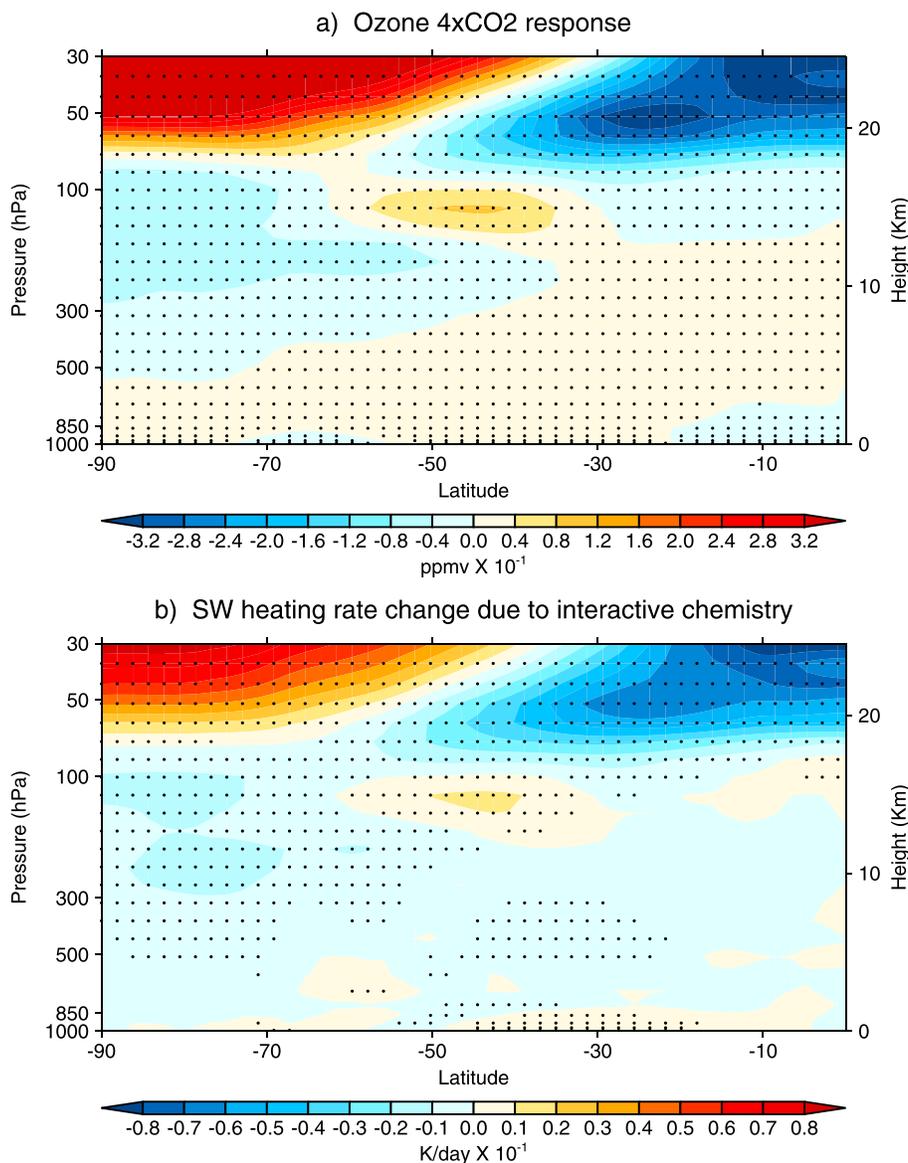
Consider first the surface temperature response to 4xCO<sub>2</sub> in the integrations of our model with fixed (i.e., climatological) ozone, shown in Figure 1a. The spatial pattern of the response to CO<sub>2</sub> consists of stronger



**Figure 2.** (a) Annual mean zonal mean temperature response to 4xCO<sub>2</sub>. The thick violet solid (stippled) line in Figure 2a identifies the tropopause in the **ctrl\_fixO3 (4xCO<sub>2</sub>\_fixO3)** integration. (b) Zonal mean temperature change due to interactive ozone (**4xCO<sub>2</sub>\_intO3 – 4xCO<sub>2</sub>\_fixO3**). The thick violet solid (stippled) line in Figure 2b identifies the tropopause in the **4xCO<sub>2</sub>\_fixO3 (4xCO<sub>2</sub>\_intO3)** experiments. Dotted areas identify statistically significant differences at the 99% confidence level.

warming over the continents than over the ocean and a polar amplification effect near the Antarctic continent. This pattern is in good agreement with the multimodel mean response for the Representative Concentration Pathway 8.5 (RCP8.5) scenario [cf. Collins *et al.*, 2013, Figure 12.11]. Including interactive ozone chemistry only very slightly reduces the warming response (Figure 1b), but the magnitude of this effect is within a few tenths of degrees kelvin and therefore not statistically significant in most regions. This result clearly indicates that in our model, an interactive ozone chemistry does not affect the surface temperature response in the SH, which confirms previous findings [Marsh *et al.*, 2016].

While interactive ozone chemistry has virtually no impact on surface temperature, it has a sizable effect on the stratospheric temperature. This can be seen by comparing the zonal mean temperature response to 4xCO<sub>2</sub> in the integrations with fixed ozone (Figure 2a) to the difference between interactive and fixed ozone configurations (Figure 2b). The temperature response to 4xCO<sub>2</sub> consists of a well-known pattern: warming of the troposphere, cooling of the stratosphere, and increased tropopause height. This pattern is consistent with

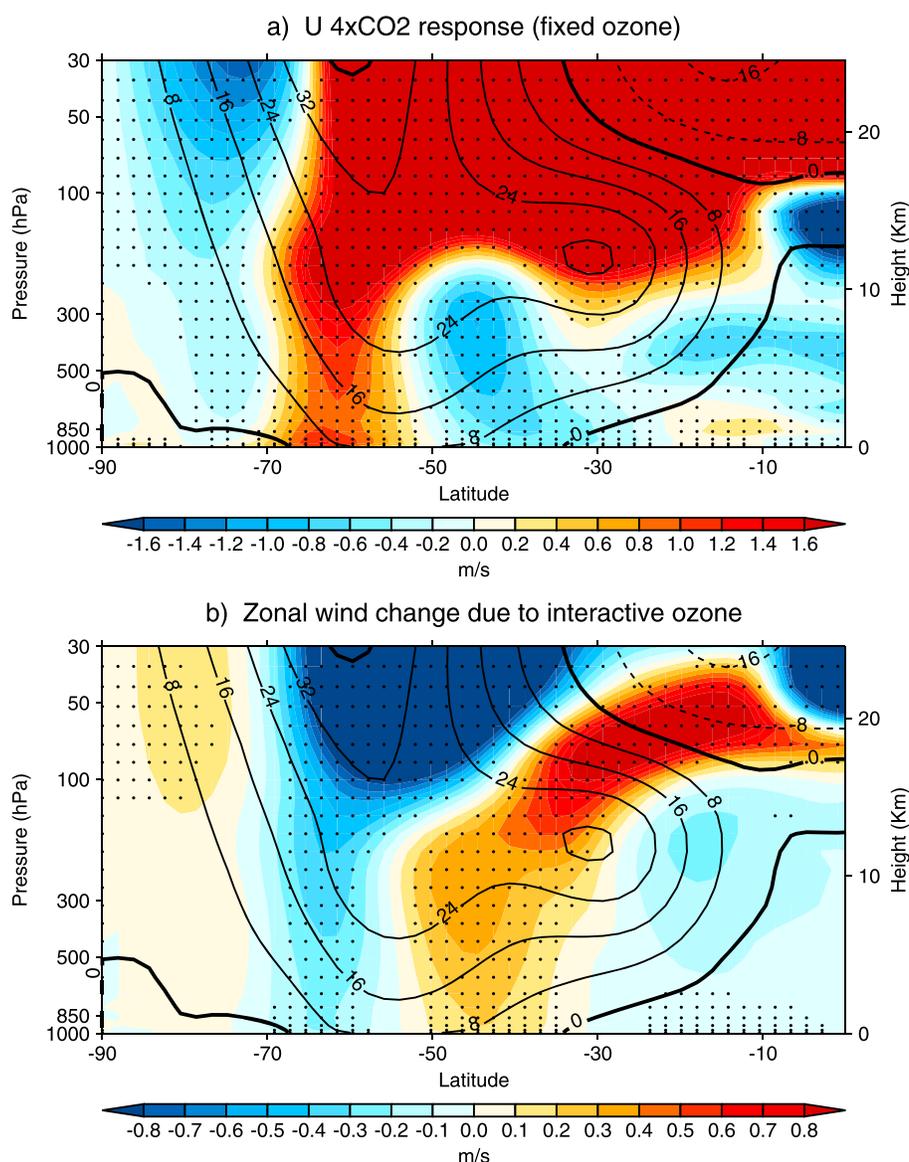


**Figure 3.** (a) Annual mean zonal mean ozone response to 4xCO<sub>2</sub> in integrations with interactive ozone chemistry (**4xCO<sub>2</sub>\_intO3** – **ctrl\_intO3**). Units in ppmv × 10<sup>-1</sup>. (b) Zonal mean shortwave heating rate change due to interactive ozone (**4xCO<sub>2</sub>\_intO3** – **4xCO<sub>2</sub>\_fixO3**). Dotted areas identify statistically significant differences (at the 99% confidence level). Units K/d × 10<sup>-1</sup>.

the near totality of CMIP3 [Meehl et al., 2007] and CMIP5 models [cf. Collins et al., 2013, Figure 12.12] and is physically well understood [Vallis et al., 2015].

The interesting point here is that interactive ozone chemistry induces a significant 1.5 K warming at the pole and cooling of similar magnitude in the tropical lower stratosphere (TLS) (Figure 2b). These temperature changes consist a large fraction (40–50%) of the response to CO<sub>2</sub> in the stratosphere (Figure 2a). Thus, interactive ozone chemistry significantly alters the stratospheric temperature response to CO<sub>2</sub>, reducing the cooling at high latitudes and enhancing it near the tropical tropopause layer. It is important to appreciate that this pattern is remarkably similar the one obtained in previous studies [Dietmüller et al., 2014; Nowack et al., 2014; Marsh et al., 2016], indicating robustness in the impact of interactive ozone chemistry on the thermal structure of the lower stratosphere.

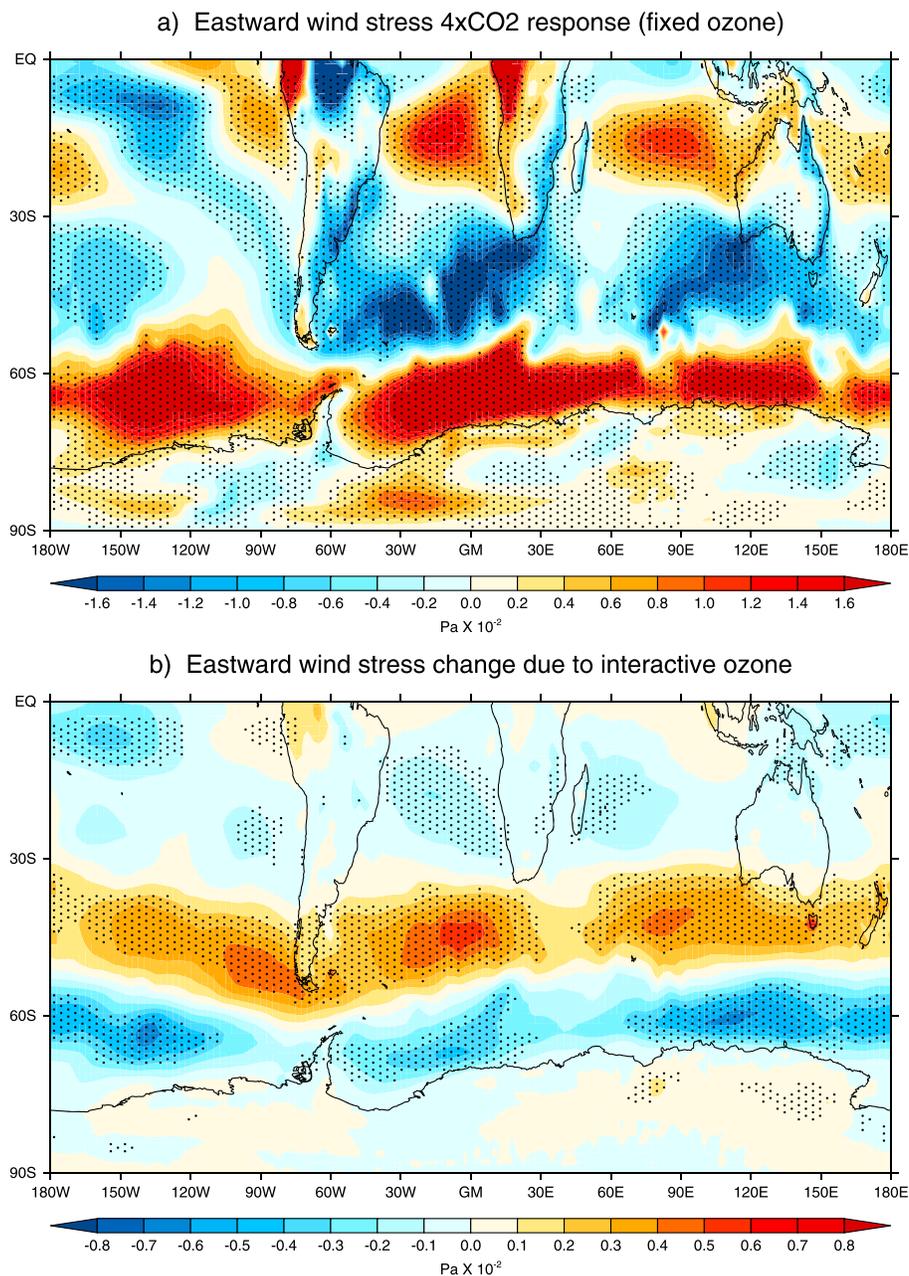
The impact of interactive ozone chemistry on stratospheric temperature is a simple consequence of the ozone changes induced by CO<sub>2</sub>, which are shown in Figure 3a. The largest ozone changes (0.3 ppmv) are found in the



**Figure 4.** As in Figure 2 for zonal mean zonal wind. Solid lines show the climatological values in the control integration (*ctrl\_fixO3*). Units in m/s.

lower stratosphere, with an increase in the polar cap and a decrease in the TLS. Again, this pattern of ozone changes is remarkably robust across different models [Dietmüller et al., 2014; Nowack et al., 2014; Marsh et al., 2016] and has been attributed to changes in both ozone chemistry and transport induced by CO<sub>2</sub> increases [Marsh et al., 2016]. This stratospheric ozone change due to CO<sub>2</sub> forcing is also in agreement with earlier results based on CMIP5 models, suggesting that more extreme RCP emission scenarios (e.g., RCP8.5) lead to larger (smaller) ozone concentrations at high (low) latitudes than low emission scenarios (e.g., RCP2.6) [cf. Eyring et al., 2013, Figure 6]. Note, however, that the comparison of different RCP scenarios does not cleanly isolate the impact of CO<sub>2</sub> on ozone, as methane and nitrous oxide (CH<sub>4</sub> and N<sub>2</sub>O) vary among these scenarios [Myhre et al., 2013]. These chemicals have important effects on stratospheric ozone [Revell et al., 2012], potentially offsetting the effects of CO<sub>2</sub> alone.

By altering the UV absorption, the CO<sub>2</sub> induced stratospheric ozone changes cause temperature changes of the same sign: the difference in SW heating rates induced by interactive ozone clearly reflects this (Figure 3b). Thus, the effects of interactive ozone chemistry on lower stratospheric temperature displayed in Figure 2b simply result from increased (reduced) SW absorption in the polar (tropical) stratosphere.



**Figure 5.** As in Figure 2 for eastward wind stress at the model's surface. Units in Pa ( $\times 10^{-2}$ ).

We now come to the central question of this study: What is the impact of interactive ozone chemistry on the tropospheric circulation response to a quadrupling of CO<sub>2</sub>? In the integrations with fixed ozone, the CO<sub>2</sub> forcing leads to a poleward migration of the midlatitude jet, as indicated by the dipole of positive (negative) anomalies of 0.5–1 m/s near 60°S (40°S) (Figure 4a), which is in good agreement with the vast majority of CMIP5 models [cf. *Grise and Polvani, 2014a, Figure 1*]. Most importantly, interactive ozone chemistry leads to wind anomalies of opposite sign (Figure 4b), suggesting a reduction of the tropospheric zonal wind response to CO<sub>2</sub>. Interactive ozone chemistry leads to a weakening of the poleward flank of the stratospheric polar vortex near 50 hPa and a strengthening of the westerlies equatorward of 60°S. This pattern extends throughout the depth of the troposphere near 50°S. The amplitude of the zonal wind perturbations induced by the interactive ozone chemistry (0.2–0.3 m/s) constitutes a considerable fraction of the CO<sub>2</sub> response (20%). Moreover, it is consistent with the ozone-induced temperature perturbation near the tropopause and the resulting change in the meridional temperature gradient at these levels (Figure 2b). This is the key result of

this study: while inducing no surface temperature changes (Figure 1b), interactive ozone chemistry reduces the tropospheric circulation response to a quadrupling of CO<sub>2</sub>.

To more carefully quantify the near-surface (850 hPa) circulation response to 4xCO<sub>2</sub> forcing and the effects of interactive ozone chemistry, we contrast the position of the SH midlatitude jet in the different model experiments. In integrations with fixed ozone, the 4xCO<sub>2</sub> forcing leads to a poleward shift of 0.8° (i.e., the difference between the climatological positions in **4xCO2\_fixO3** and **ctrl\_fixO3**). Most importantly, the poleward shift in the integrations with interactive ozone is significantly reduced from 0.8° to 0.65°; i.e., 20% reduction. The effect of interactive ozone chemistry is mostly significant in austral summer (December to February) and fall (March to May) (see Figure S1 in the supporting information), the seasons showing the largest poleward shift in response to CO<sub>2</sub> (1.52° and 1.35°, respectively), in agreement with the majority of CMIP5 models [cf. *Barnes and Polvani*, 2013, Figure 12].

According to these results, the CO<sub>2</sub>-induced changes in ozone act to shift the midlatitude jet *equatorward* relative to the 4xCO<sub>2</sub> integration with fixed ozone. A similar effect of ozone changes on the tropospheric circulation has also been widely documented for future ozone recovery [*Son et al.*, 2008; *Polvani et al.*, 2011; *Gerber and Son*, 2014]. Although the drivers of the ozone changes are fundamentally different (ODS in the aforementioned studies and CO<sub>2</sub> in the present study), the mechanism is similar: ozone changes induce meridional temperature gradients at the tropopause, and these induce a jet shift. This is also seen in idealized model studies where in the absence of any surface temperature changes, the meridional temperature gradient at the tropopause can shift the midlatitude jet [*Polvani and Kushner*, 2002; *Kushner and Polvani*, 2004].

Finally, the annually averaged zonal (eastward) component of surface wind stress response to CO<sub>2</sub> in the integrations with fixed climatological ozone is shown on Figure 5a. This variable is of great relevance for ocean dynamics [*Swart and Fyfe*, 2012], since it captures the surface drag imparted by the near-surface westerlies. We find a dipole of positive (negative) anomalies between 60 and 70°S (30–60°S), which is zonally symmetric around 55–60°S, thus reflecting the poleward shift in the near-surface wind maximum [*Swart and Fyfe*, 2012]. The key point of this paper, however, is that the inclusion of CO<sub>2</sub> effects on stratospheric ozone induces an opposite signed wind stress signal over the Southern Ocean of 0.003–0.005 Pa (Figure 5b). The wind stress response in the integration with interactive ozone decreases from 0.018 Pa to 0.014 Pa at 60–65°S and from –0.008 Pa to –0.005 Pa at 45°S: a 20–25% reduction in the circulation response due to the interactive ozone chemistry, which could also impact carbon uptake over the Southern Ocean [*Marshall and Speer*, 2012]. These results suggest that interactive stratospheric ozone provides an important negative feedback on the circulation response to increased CO<sub>2</sub>.

#### 4. Conclusions

The main finding of this paper is that the ozone response to CO<sub>2</sub> in the coupled chemistry configuration significantly reduces the SH circulation response to CO<sub>2</sub>. This result may seem surprising, since including interactive ozone chemistry does not alter the surface warming (Figure 1). In short, the CO<sub>2</sub>-induced strengthening of the BDC and changes in gas-phase chemistry act to decrease ozone concentrations in the TLS and to increase them in the SH polar cap (Figure 3). By changing the SW absorption in the lower stratosphere, ozone alters the meridional temperature gradient near the tropopause (Figure 2), shifting the midlatitude jet equatorward relative to a 4xCO<sub>2</sub> integration in which ozone is held constant (Figure 4), thereby reducing (by 20%) the poleward shift of the jet. Moreover, interactive stratospheric ozone (via its changes due to CO<sub>2</sub>) significantly influences near-surface parameters that are key to atmosphere-ocean coupling, such as surface wind stress (Figure 5): this has possible implications for the meridional circulation of the ocean [*Abernathey et al.*, 2011; *Fyfe and Saenko*, 2006] and possibly sea level [*Frankcombe et al.*, 2013].

It is important to note that the stratospheric ozone change due to CO<sub>2</sub> discussed here occurs in absence of any changes in ODSs and can be thus considered as a feedback. The dynamical effects reported in this paper are induced by stratospheric ozone changes (Figure 3) due to increased CO<sub>2</sub> alone, and these are robust across all studies that have recently appeared in the literature [*Dietmüller et al.*, 2014; *Muthers et al.*, 2014; *Nowack et al.*, 2014; *Marsh et al.*, 2016]. Thus, the conclusions presented here are likely to be robust.

Finally, we wish to emphasize that our results imply that a substantial portion of the dynamical sensitivity, quantified as the SH midlatitude jet response to a given CO<sub>2</sub> forcing, is fundamentally unrelated to the surface temperature response. These results support the finding dynamical sensitivity is being poorly correlated with

the ECS in CMIP5 models [Grise and Polvani, 2014b, 2016]. While the ozone feedbacks do not influence the ECS of our model [Marsh et al., 2016], they are critical for the determination of the circulation response to CO<sub>2</sub>.

Models that neglect stratospheric chemistry, such as most CMIP class models, often prescribe a scenario-independent ozone data set [Eyring et al., 2013]. In doing so, these models miss an important negative feedback on the tropospheric circulation, which arises from stratospheric ozone and its sensitivity to CO<sub>2</sub>. For the next phase (CMIP6), we suggest that more effort is needed in producing scenario specific ozone data sets from models with interactive ozone chemistry.

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