



RESEARCH ARTICLE

Non-additive response of the high-latitude Southern Hemisphere climate to aerosol forcing in a climate model with interactive chemistry

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Abstract

A suite of chemistry-climate model simulations, forced by pairs of anthropogenic forcings [comprising greenhouse gases (GHGs), ozone depleting substances (ODSs), or aerosols], were employed to investigate whether the high-latitude Southern Hemisphere (SH) circulation response to these forcings is linearly additive, a common assumption in attribution studies. We find that the geographical pattern of sea-level pressure (SLP) response to a combination of GHGs and ODSs is linearly additive. However, we find significant differences in the SLP response when combining GHGs and aerosols compared to the sum of the individual forcings, a non-additivity that is currently masked by the dominance of the ODSs forcing. This non-linearity also results in changes to the SH split jet. These results were obtained using a coupled chemistry-climate model, indicating that the non-linear response is due to chemical interactions between the forcing agents. As such, future simulations investigating a post-ozone hole Southern Hemisphere climate should consider this chemical interaction.

KEYWORDS

Antarctica, anthropogenic aerosols, chemistry-climate models, greenhouse gases, ozone depletion, sea-level pressure

1 | INTRODUCTION

Over the past few decades, the surface climate of the high-latitude Southern Hemisphere has demonstrated robust changes in response to both increasing greenhouse gases (GHGs; e.g. Fyfe *et al.*, 1999; Kushner *et al.*, 2001) and the formation of the Antarctic ozone hole (e.g. Thompson and Solomon, 2002; Polvani *et al.*, 2011; Orr *et al.*, 2012), which occurred because of the release of

ozone-depleting substances (ODSs) such as chlorofluorocarbons. These changes include a strengthening and poleward shift of surface westerlies, particularly during austral summer and autumn, which is associated with a shift towards the positive polarity of the Southern Annular Mode (SAM; e.g. Thompson and Solomon, 2002; Marshall, 2003; Arblaster and Meehl, 2006; Thompson *et al.*, 2011). Another influence on the high-latitude Southern Hemisphere, albeit weaker and less-frequently

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studied, is the increased emission of anthropogenic aerosol particles, which opposes the influence of increased GHGs and the ozone hole by causing a shift towards the negative polarity of the SAM (e.g. Fyfe *et al.*, 2012, 2013; Gillett *et al.*, 2013). The subsequent effect on the regional circulation has had important impacts on surface temperature, precipitation, ice shelf melt, ocean carbon uptake, and sea ice advection (Thompson and Solomon, 2002; Le Quéré *et al.*, 2007; Marshall *et al.*, 2006; Orr *et al.*, 2008; Bromwich and Nicholas, 2011; Holland and Kwok, 2012; Nicolas and Bromwich, 2014; Turner *et al.*, 2015; Pope *et al.*, 2017; Clem *et al.*, 2018; Deb *et al.*, 2018).

Investigation into possible changes in high-latitude Southern Hemisphere climate throughout the remainder of the 21st century have also largely focused on the combination of GHGs and ozone forcing, particularly how the expected recovery of stratospheric ozone levels by approximately mid-century (resulting in a shift towards a higher frequency of negative SAM polarity in austral summer) will offset the effects of ever increasing GHGs (e.g. Barnes *et al.*, 2014; Previdi and Polvani, 2014; Iglesias-Suarez *et al.*, 2016; Chiodo and Polvani, 2017). However, the possible impact of anthropogenic aerosols, which are expected to remain elevated relative to their pre-industrial levels (Westervelt *et al.*, 2015), together with increasing GHGs and Antarctic ozone hole recovery, on the high-latitude Southern Hemisphere climate have not been considered. In addition, the separate effects of anthropogenic aerosols are not typically estimated by running a climate model experiment forced with aerosols alone, but rather by examining the differences between a simulation with combined GHGs and aerosol forcing, and a simulation with GHGs alone. This strategy typically assumes that the climate response to a combination of anthropogenic forcings is equal to the additive (i.e. linear) responses to all the individual forcings. This assumption of additivity has also formed the basis of many detection and attribution studies that perform sensitivity tests by running single-forcing climate model simulations in an attempt to identify the response and mechanisms to different forcings (e.g. Tett *et al.*, 1999; McLandress *et al.*, 2010, 2011; Stott *et al.*, 2001, 2010).

Many studies have examined whether the climate response to multiple forcings is linearly additive on both global and regional scales (e.g. Meehl *et al.*, 2004; Gillett *et al.*, 2004; Ming and Ramaswamy, 2009; McLandress *et al.*, 2010, 2011; Shiogama *et al.*, 2013; Marvel *et al.*, 2015). Evidence of the linearity of the zonal wind and temperature response on global scales to GHGs and ODS was provided by McLandress *et al.* (2010, 2011). Meehl *et al.* (2004) and Shiogama *et al.* (2013) showed for a range of forcings (including GHGs, ozone, and both the direct and indirect effects of anthropogenic aerosols) that

the response of temperature was generally additive on both global and regional scales. Gillett *et al.* (2004) also concluded that linear additivity on both global and regional scales holds for the temperature response to GHGs and the direct effect of anthropogenic aerosols. By contrast, studies such as Ming and Ramaswamy (2009) showed that linear additivity did not hold for the temperature response to GHGs and the indirect effect of anthropogenic aerosols. Moreover, Marvel *et al.* (2015) found that temperature on global scales was additive in climate models in which aerosol and ozone concentrations were prescribed (and the aerosol indirect effects parameterized), but not in a model with interactive atmospheric chemistry to compute aerosol and ozone composition.

In this study, we use results from a suite of atmosphere-only climate model simulations with interactive chemistry forced by pairs of anthropogenic forcings (comprising either GHGs, ODSs, or aerosols) to investigate the effect of (non-additive) interactions on the Southern Hemisphere high-latitude atmospheric circulation. We focus on two cases, comprising the combination of GHGs and ODS, and GHGs and aerosols, with all forcings representative of present-day for simplicity and practical reasons. The previously reported dominance of the ozone hole could be hiding non-additive anthropogenic forcings which could influence future Antarctic climate. Therefore, we chose to investigate the additivity of GHG and aerosol forcings without the dominating ODS component.

2 | MATERIALS AND METHODS

We use the Unified Model – United Kingdom Chemistry and Aerosol (UM-UKCA) chemistry-climate global model, based on the atmosphere-only third-generation Hadley Centre Global Environment Model configuration of the Met Office UM (Hewitt *et al.*, 2011; Walters *et al.*, 2014) and the UKCA chemistry-aerosol module. This module combines well-established tropospheric (O'Connor *et al.*, 2014) and stratospheric (Morgenstern *et al.*, 2009) chemistries in a whole atmosphere configuration (e.g. as used in Banerjee *et al.*, 2014) with the comprehensive Global Model of Aerosol Processes (GLOMAP) aerosol scheme (Mann *et al.*, 2010), and includes both direct and indirect aerosol effects. Hindcast simulations of the past few decades using UM-UKCA represented accurately the observed response of the high-latitude Southern Hemisphere climate system to ODSs (Keeble *et al.*, 2014; Hardiman *et al.*, 2017) and the aerosol optical depth (Bellouin *et al.*, 2013). The model was run at N96 resolution (equivalent to 1.875° latitude \times 1.25° longitude), with 85 vertical levels up to a height of 85 km (Walters *et al.*, 2014).

The model setup was used to run a pre-industrial control simulation (labelled CTRL) and an additional five sensitivity runs (starting from CTRL):

CTRL: Forced by fixed GHG concentrations (including CO₂, CH₄, and N₂O) and aerosols (including sulphate, organic carbon, sea salt and mineral dust) representative of the 1860's, that is, a pre-industrial control simulation. Note that pre-industrial ODS concentrations are taken as zero in this experiment.

GHG: CTRL plus fixed GHGs concentrations representative of 2013 (including CO₂, CH₄, N₂O, CFC-11, CFC-12, CFC-13, and HCFC). Note the model set up was designed to ensure that the ODS included in this run (e.g. CFC-11, CFC-12, and CFC-13) did not deplete stratospheric ozone but did exert direct radiative forcing.

ODS: CTRL plus fixed ODS concentrations representative of 1999 (including CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, MCF, HCFC-141b, and HCFC-142b). Note the model set up was designed to ensure that this simulation did not include the direct radiative forcing due to ODS.

AA: CTRL plus fixed anthropogenic (and natural) sources of aerosol particles representative of 2006 (including black carbon, sulphate, organic carbon, sea salt and mineral dust). Note that the direct effect of anthropogenic sulphate aerosols resulting from fossil fuel burning is known to have a large impact on the climate (e.g. Meehl *et al.* 2004; Arblaster and Meehl, 2006).

(GHG & ODS): CTRL plus fixed GHGs and ODS representative of the years 2013 and 1999. Performed to test whether linear additivity holds for the high-latitude Southern Hemisphere climate response to the two dominant present-day forcings.

(GHG & AA): CTRL plus fixed GHGs and AA representative of the years 2013 and 2006 (as described above). Performed to test the sensitivity of the high-latitude Southern Hemisphere climate response, without the dominance of ODS forcing and whether linear additivity holds.

The pre-industrial and present-day GHGs and present-day ODS concentrations were taken from the Chemistry-Climate Modelling Initiative (Eyring *et al.*, 2013). The pre-industrial and present-day aerosol emissions were taken from the Aerosol Comparisons between Observations and Models project (Dentener *et al.*, 2006). These data sets are the most recently available to this study, as well as our current best estimates of present-day forcings.

In order to reduce the influence of natural variability, the simulations were forced by prescribed repeating annual cycles of sea surface temperature (SST) and sea ice concentration climatologies, generated from output from a historical simulation using the HadGEM2-CC

coupled atmosphere–ocean climate model (Martin *et al.*, 2011) for the period 1861 to 1900, that is, broadly representative of pre-industrial conditions. We note that this methodology is also used for some of the AerChemMIP experiments, detailed in table 6 of Collins *et al.* (2017). A limitation of this choice is that our model simulations will be missing the impact of oceanic feedbacks in response to the forcings (e.g. Grise and Polvani, 2014; Ferreira *et al.*, 2015; Seviour *et al.* 2019). However, the CMIP5 generation of coupled atmosphere–ocean climate models (including the Met Office UM) have an established weakness in their dynamic simulation of Antarctic sea ice (i.e. Turner *et al.*, 2013; Holmes *et al.*, 2019). With a focus on Antarctic climate and surface circulation, our a priori expectation was that controlling the sea ice extent was more important for our results than the response of SSTs to GHG forcing. Each of the simulations ran for 56 years, with climatological averages produced from the final 30 years of each simulation. The results are presented as differences relative to the CTRL simulation, hereafter denoted by the symbol Δ , for example, Δ GHG refers to differences between GHG and CTRL. The statistical significance of the model anomalies was assessed using the Mann–Whitney–Wilcox test (Pettitt, 2006), statistical significance was calculated based on monthly model output.

3 | RESULTS

3.1 | Additivity

For the individual forcings, both Δ ODS (Figure 1(a)) and Δ GHG (Figure 1b) show decreases in zonally averaged geopotential heights over high southern latitudes, with particularly marked decreases in the lower stratosphere from ozone depletion, while Δ GHG also shows increases over mid-latitudes. By comparison, Δ AA (Figure 1c) shows weaker and opposing changes. These differences are also readily apparent in the spatial distribution of SLP (Figure 2a–c), and are consistent with ODS and GHG forcing (AA forcing) resulting in a shift towards the positive (negative) polarity of the SAM. Note that the seasonal response is strongest in the austral summer for both Δ ODS and Δ AA, while the response to Δ GHG displays relatively little seasonal variability (not shown). Moreover, these results are similar in both amplitude and pattern to analogous results based on runs using a global coupled atmosphere–ocean model (Arblaster and Meehl, 2006).

Figures 1d and 2d confirm a shift towards the positive polarity of the SAM for present-day forcing, with Δ (ODS & GHG) showing marked decreases (increases) in

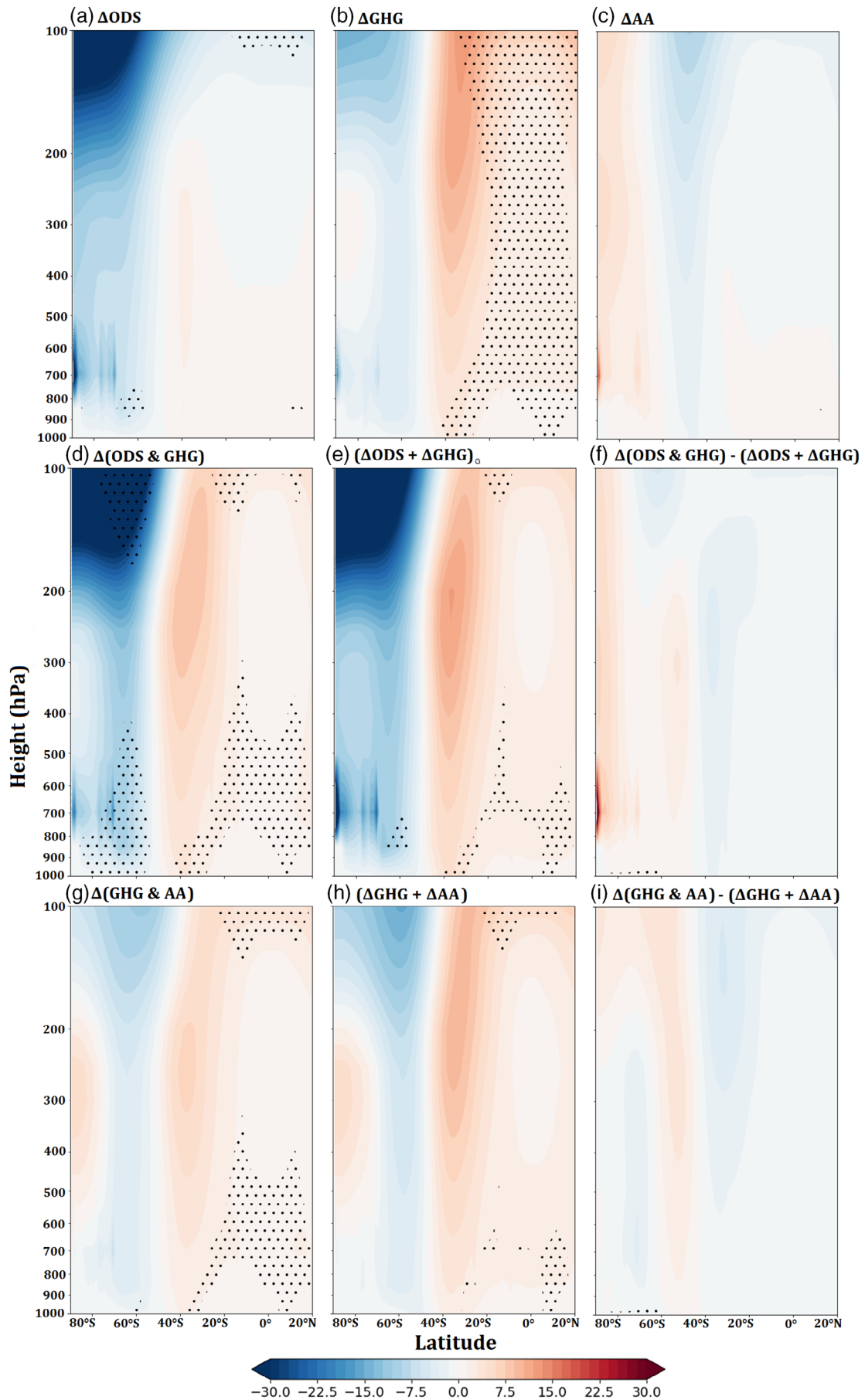


FIGURE 1 Legend on next page.

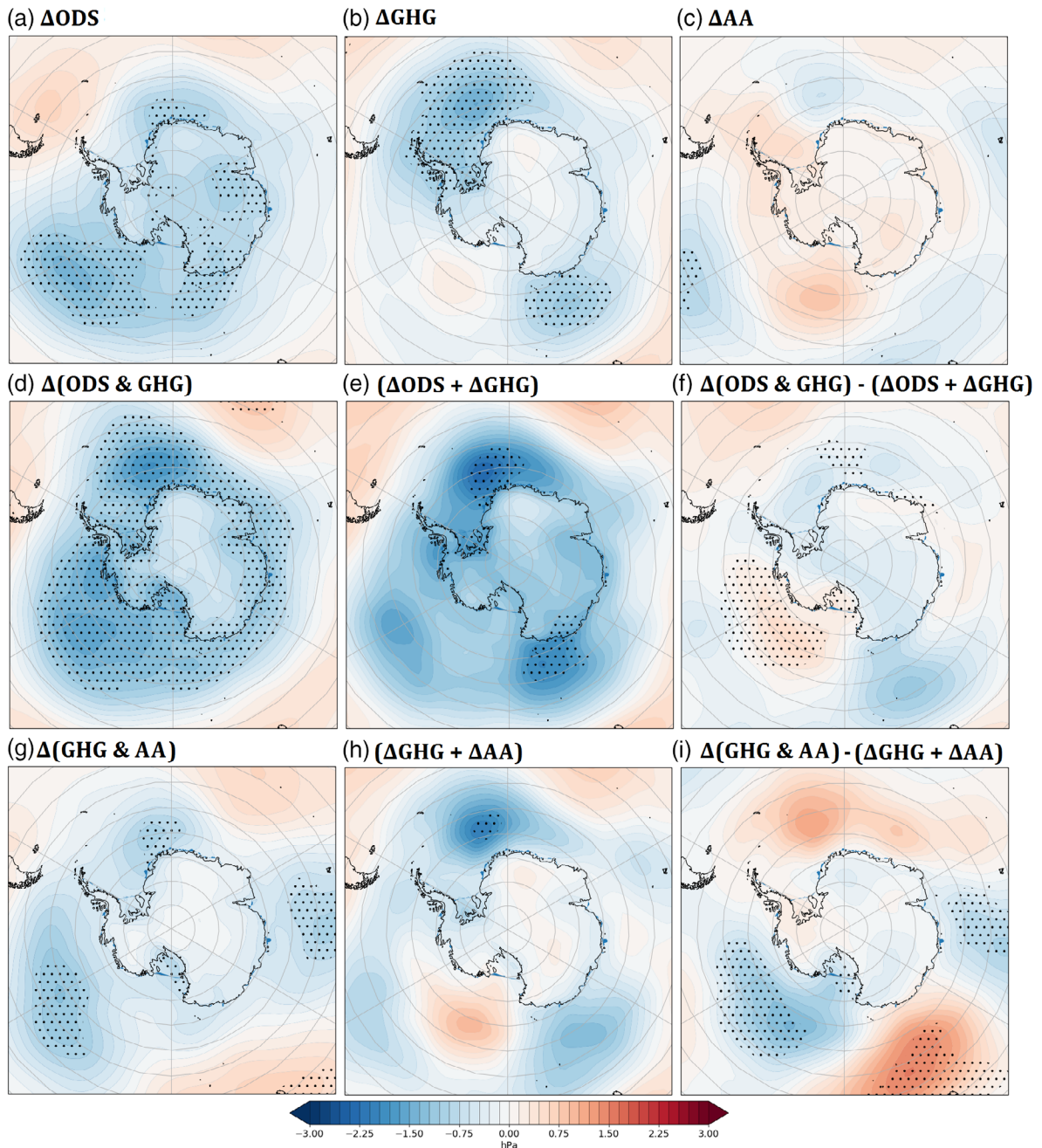


FIGURE 2 As Figure 1, but for annual mean sea-level pressure (hPa)

geopotential heights over high southern latitudes (mid-latitudes), and a zonally symmetric pattern of decreased (increased) SLP of 1–2 hPa magnitude that is consistent with observed trends (e.g. Thompson and Solomon, 2002). Moreover, $\Delta(\text{ODS \& GHG})$ shows a strong

resemblance to the additive sum of the individual forcings $\Delta\text{ODS} + \Delta\text{GHG}$ for both zonally averaged geopotential heights (Figure 1d,e) and SLP (Figure 2d,e), which is evident by the small differences between the responses (Figure 1f and 2f). These results are in

FIGURE 1 Annual zonal-mean geopotential height (m) for (a) ΔODS , (b) ΔGHG , (c) ΔAA , (d) $\Delta(\text{ODS \& GHG})$, (e) the difference between the additive sum of the response from the separate ODS and GHG simulations and the CTRL simulation ($\Delta\text{ODS} + \Delta\text{GHG}$), (f) the difference between (d) and (e), (g) $\Delta(\text{GHG \& AA})$, (h) $\Delta(\Delta\text{GHG} + \Delta\text{AA})$, and (i) the difference between (g) and (h). Stippling indicates significance at 95% confidence

agreement with the aforementioned studies, and confirm that present-day changes in the circulation are dominated by ODS and GHG forcing, that the response to these is additive, and that inclusion of anthropogenic aerosols is largely inconsequential.

By contrast, $\Delta(\text{GHG} \& \text{AA})$ shows much weaker changes in terms of both zonally averaged geopotential heights (Figure 1g) and SLP (Figure 2g) compared to $\Delta(\text{ODS} \& \text{GHG})$, but still consistent with a shift towards the positive polarity of the SAM. Furthermore, comparison of $\Delta(\text{GHG} \& \text{AA})$ and the additive sum of the individual forcings shows that although the zonally averaged geopotential height differences are broadly similar (cf. Figure 1g,h), the spatial patterns of the SLP responses are markedly different despite both showing a shift towards the positive polarity of the SAM (cf. Figure 2g,h). Consequently, the differences between the responses (Figure 2i) highlight three regions of the Southern Ocean where the SLP difference is statistically significant (at the 95% confidence level): the Ross Sea ($\sim 130^\circ\text{W}$), the region of the climatological Amundsen Sea Low (Raphael *et al.*, 2016), West Pacific sector ($\sim 160^\circ\text{E}$) and Indian Ocean sector ($\sim 90^\circ\text{E}$) (Figure 2i).

3.2 | Role of forcings

To help understand the cause of these differences, Figure 3 examines the corresponding changes in the strength of the jet structure of the Southern Hemisphere high latitudes, as represented by the zonal wind component at 300 hPa. Figure 3a shows the mean climatological structure from CTRL, which has a distinct split jet from $\sim 70^\circ$ to 240°E . The equatorward branch at $\sim 25^\circ\text{S}$ is termed the subtropical jet (STJ) while the poleward branch at $\sim 50^\circ\text{S}$ is often referred to as the polar front jet (PFJ) (e.g. BalsElsholz *et al.* 2001). The split jet is evident in all seasons other than summer. The ΔGHG response (Figure 3b) shows a marked dipole between 120° and 180°E corresponding to a weakening of the STJ and a strengthening of the zonal wind of $\sim 1 \text{ m}\cdot\text{s}^{-1}$ on the northern side of the climatological PFJ. The change in maximum PFJ velocity is much more muted in the ΔAA response (Figure 3c). Thus, a broadly similar response in the split jet to ΔGHG is also apparent in the linear sum of these two forcings ($\Delta\text{GHG} + \Delta\text{AA}$) (Figure 3e), while $\Delta(\text{GHG} \& \text{AA})$ actually demonstrates a lesser strengthening ($\sim 0.5 \text{ m}\cdot\text{s}^{-1}$) and a smaller northward shift of the PFJ in the vicinity of New Zealand (Figure 3d). Therefore, as the change in the meridional jet structure in ($\Delta\text{GHG} + \Delta\text{AA}$) (Figure 3e) is broadly similar to that for ΔGHG (Figure 3b), we postulate that the difference between $\Delta(\text{GHG} \& \text{AA})$ and ($\Delta\text{GHG} + \Delta\text{AA}$) (cf. Figure 3f) is primarily due

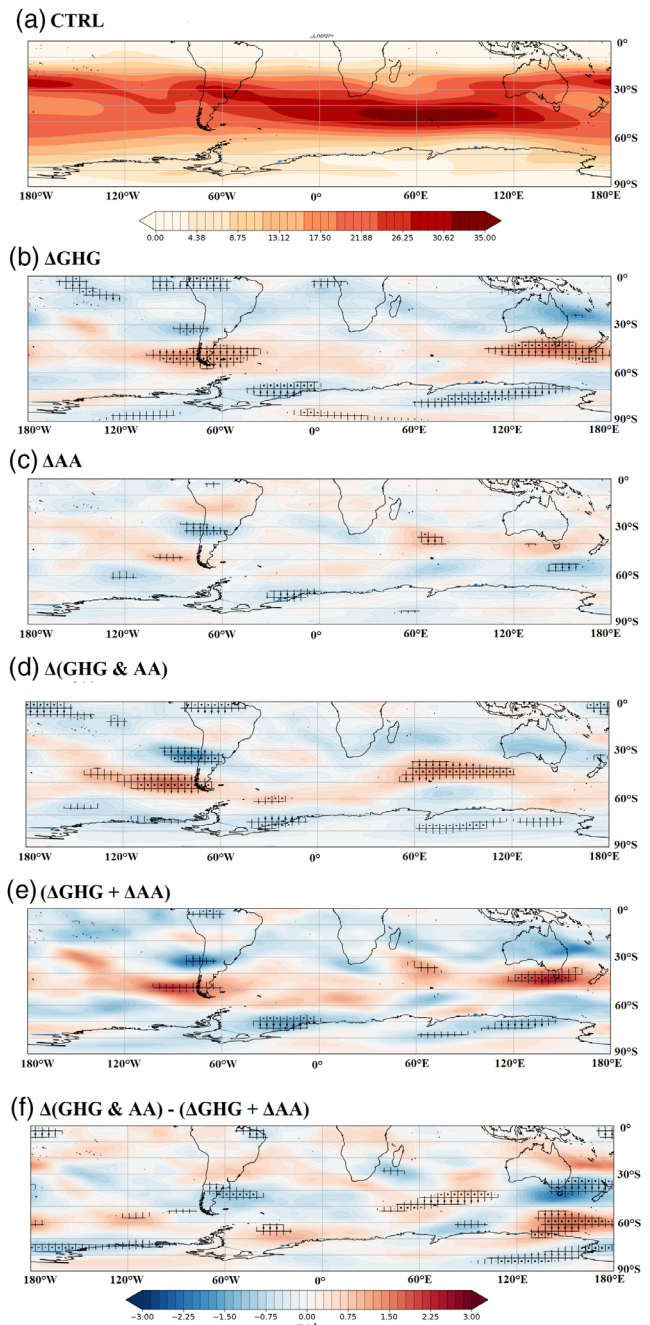


FIGURE 3 (a) Annual zonal wind at 300 hPa for the CTRL simulation ($\text{m}\cdot\text{s}^{-1}$), (b) ΔGHG , (c) ΔAA , and (d) $\Delta(\text{GHG} \& \text{AA})$, (e) $\Delta(\text{GHG} + \Delta\text{AA})$, and (f) the difference between (d) and (e). Stippling indicates significance at 95% confidence, boxes indicate significance at 90% confidence

to the interaction between GHGs and aerosols. In our model experiments these interactions act to reduce the northward shift in the PFJ that occurs in the model as a response to GHG increases alone.

Although not as marked as the split jet region (160°E), other latitudinal dipoles in 300 hPa zonal wind difference occur in Figure 3f, centred at 90°E and 120°W .

Together these three longitudes correspond closely to the areas of significant difference in SLP, highlighted in Figure 2i. Given the widespread similarities between Figure 3b (ΔGHG) and Figure 3(e) ($\Delta\text{GHG} + \Delta\text{AA}$) across SH high latitudes, we suggest that that GHG–aerosol interactions are likely responsible for the pattern of the three significant SLP differences in Figure 2i. They will thus impact Antarctic climate by changing the longitudinal distribution of the meridional advection of heat and moisture into and out of the continent.

We note that there is comparatively little difference between the change in 300 hPa zonal wind in the $\Delta(\text{GHG} \& \text{AA})$ and $(\Delta\text{GHG} + \Delta\text{AA})$ model data (Figure 3f) in the vicinity of the southern tip of South America, another region where increasing GHGs have a major impact on the zonal wind component (cf. Figure 3b). However, although such non-linear interactions are far less evident in the annual data, the equivalent seasonal data (not shown) do reveal significant differences here: in contrast to the region of the split jet, these differences tend to cancel out across the seasons. Note also that analysis of differences in outgoing shortwave at the top-of-atmosphere radiation (i.e. a proxy for cloud reflection) suggested some small and highly localized regions (typically statistically insignificant) of increased cloud for ΔAA , which were absent for ΔGHG .

4 | DISCUSSION AND CONCLUSIONS

Despite being principally a feature of the austral spring and summer, the depletion of stratospheric ozone (in conjunction with greenhouse gas emissions) dominates our simulated mean annual Southern Hemisphere circulation response. This result, which is in agreement with previous analyses (i.e. Thompson *et al.*, 2011), indicates that any climate model simulations including these two forcings will likely simulate a realistic representation of anthropogenic high latitude Southern Hemisphere climate.

In contrast, our results indicate that in a simulation without the influence of ozone depletion, the linear relationships may cease. A marked non-linearity between the forcing effects of GHGs and aerosols manifests itself in the Southern Hemisphere high latitude atmospheric circulation, principally in the region of the climatological split jet at the longitudes of Australia and New Zealand (120° – 180°E). By comparing model experiments forced by increased GHGs with and without aerosols, we propose that interactions between GHGs and aerosols are responsible for changes in the SH split jet. Moreover, they also drive marked changes in the longitudinal pattern of

meridional flow of heat and moisture into and out of the Antarctic continent, particularly in West Antarctica via changes to the Amundsen Sea Low. Therefore, such GHG–aerosol interactions may play an important role in governing regional climate variability.

Given both computational limitations and our focus on high-latitude Southern Hemisphere circulation, it was a logical choice within our experimental design to use prescribed SSTs and sea ice. This choice enabled us to utilize a complex chemistry model interactively with a state of the art atmospheric model with a full representation of the troposphere and stratosphere, which allowed us to focus on the role of chemical interactions between the various forcing agents and their impact on the atmospheric circulation. It also allowed us to limit the impact of uncertainties surrounding the representation of Antarctic sea ice and SSTs in the UM model. This choice also meant that we did not fully account for the interactivity between the atmosphere and the ocean, for example, the influence of changes in wind patterns on ocean mixing (Ferreira *et al.*, 2015; Seviour *et al.*, 2019). However, while our experimental design excludes these effects, it is noteworthy that the response to the individual forcings was similar to analogous results based on runs using a coupled atmosphere–ocean model (Arblaster and Meehl, 2006).

Our results suggest that the non-linear response to greenhouse gas and aerosol forcings is due to chemical interactions between the forcing agents (Marvel *et al.*, 2015). As such, it is important that future studies into Southern Hemisphere climate after the closure of the Ozone Hole consider these chemical interactions and utilize appropriate model tools.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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