Large cancellation, due to ozone recovery, of future Southern Hemisphere atmospheric circulation trends

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[1] The role of stratospheric ozone recovery in the Southern Hemisphere climate system, in the coming decades, is examined by contrasting two 10-member ensembles of Community Atmospheric Model (CAM3) integrations, over the period 2000–2060. Model integrations in the first ensemble are conducted with a complete set of forcings: greenhouse gas concentrations from the A1B scenario, SSTs from corresponding ocean-atmosphere coupled model integrations, and ozone starting with severe depletion over the South Pole and recovering by mid-century. The integrations in the second ensemble are very similar to the first, except that only the transient ozone forcing is specified, and all other forcings are kept at year 2000 levels. Specifying ozone recovery in isolation allows us to determine unambiguously how it impacts the atmospheric circulation. We find that, in DJF, most key indices of atmospheric circulation show significant trends in the second ensemble, due to the closing of the ozone hole. In the first ensemble, however, trends are found to be statistically insignificant for nearly all key circulation indices. This suggests that ozone recovery will result in a nearly complete cancellation (and possible reversal) of the atmospheric circulation effects associated with increasing greenhouse gases, in Southern Hemisphere summer, over the coming half century. **Citation:** Polvani, L. M., M. Previdi, and C. Deser (2011), Large cancellation, due to ozone recovery, of future Southern Hemisphere atmospheric circulation trends, *Geophys. Res. Lett.*, *38*, L04707, doi:10.1029/2011GL046712.

1. Introduction

[2] It is now widely documented that stratospheric ozone depletion has played a major role in causing the atmospheric circulation changes that have been observed in the Southern Hemisphere (SH) during the second half of the 20th century [see, e.g., *Polvani et al.*, 2011, and references therein]. It is thus likely that the projected ozone recovery will have a considerable impact in the coming decades: understanding that impact is the goal of this paper. It may be worth recalling, as originally pointed out by *Shindell and Schmidt* [2004], that in the late 20th century the depletion of stratospheric ozone has *added* to the circulation changes associated with increasing greenhouse gases (GHGs), whereas in the 21st century ozone recovery will *subtract* from them. The opposite effects of ozone recovery and increasing GHGs have been highlighted in a recent study of *Arblaster et al.* [2011], who have suggested that climate sensitivity may play an important role in the future cancellation.

[3] In fact, this cancellation is well documented in the model integrations performed for the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) used for Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, as reported by *Son et al.* [2009], and also in those performed for the Stratospheric Processes and their Role in Climate (SPARC)/Chemistry-Climate Model Validation project phase 2 (CCMVal-2), as reported by *Son et al.* [2010]. Neither of these intercomparison projects, however, yields a clean picture of the effect of ozone recovery on the climate system in the next half century, since the ozone fields were not varied independently of the other forcings.

[4] The goal of this paper, therefore, is to perform a clean sensitivity study on the role of ozone recovery on the atmospheric circulation of the SH over the period 2000–2060. We use an IPCC-class atmospheric model and compare two ensembles of integrations, one with all forcings specified and one with ozone forcing alone: using a relatively large number of ensemble members (10) we show that, in the coming half century, stratospheric ozone recovery will cause a nearly complete cancellation of all GHG-induced summer circulation trends in the SH.

2. Methods

[5] The numerical model used in this study is the Community Atmospheric Model, version 3 (CAM3). It is integrated at T42 horizontal resolution (approximately a 2.8° × 2.8° grid in latitude and longitude) and with 26 hybrid vertical levels, 8 of which are located above 100 hPa. All integrations are carried out over the period 2000–2060, and an ensemble of 10 distinct integrations is constructed by initializing the model with different days, between December 1999 and January 2000, of a 20th century integration of the Community Climate System Model Version 3 (CCSM3); the latter is based on CAM3, but also includes an ocean and a cryosphere model (see, for all details, *Deser et al.* [2010, hereafter DEA10]).

[6] All 10 integrations in the first ensemble are forced with GHGs following the A1B scenario, stratospheric ozone fields starting with a severe depletion in 2000 and recovering by 2060, and smaller forcings (in the SH) related to sulfate aerosols and black carbon: these forcings are identical to the ones used for the A1B integration contributed by CCSM3 to the CMIP3 project, and all details are given by *Meehl et al.* [2006]. (The ozone field used in our study is

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documented on page 2599 of *Meehl et al.* [2006], and its SH polar cap trend, over the period 2000–2060, is nearly identical to the one in the AC&C/SPARC Ozone Dataset (I. Cionni et al., Multi-model mean ozone time series in support of CMIP5 simulations, manuscript in preparation, 2010).) In addition to these radiative forcings, the sea surface temperature and sea ice concentrations (SSTs for short) are specified, for all 10 integrations, using the mean of a large ensemble (30 members) of CCSM3 integrations, over the same period, and with identical forcings, as described by DEA10. This first ensemble of 10 integrations is labeled "ALL", to make it clear that all forcings are operative.

[7] To clearly bring out the impact of stratospheric ozone recovery on the atmospheric circulation, a second ensemble of 10 integrations is performed with the same model (CAM3). In this second ensemble, labeled "OZONE", the integrations are identical in most respects to the ones of the ALL ensemble, except that *only the ozone* field is changed over the period 2000–2060: all other forcings have no time dependence other than a seasonal cycle. The SSTs are held fixed at the 2000–2009 mean, and the values of GHG concentrations and all other forcings taken from the year 2000.

[8] Owing to limited computational resources, we have not performed the complementary ensemble of integrations, i.e., with all forcings changing in time except for ozone recovery. Nonetheless, assuming additivity, the difference between the means of the ALL and OZONE ensembles is shown in all plots below: this difference is labeled "GHG/SST", as it gives an indication of the effects associated with increasing GHGs and the accompanying warming of the SSTs. As a note of reassurance, we note that *Deser and Phillips* [2009], in a very similar exercise to the one presented in this paper, found close additivity for the SAM trends in DJF during 1950–2000 [see *Deser and Phillips*, 2009, Figure 6].

3. Results

[9] The DJF ensemble mean SH climate responses associated with the ALL and OZONE ensembles are shown in Figure 1 (left and middle, respectively); also in Figure 1 (right), we show their difference (GHG/SST). In all panels, we present the response in terms of trends, computed using linear, least-square fits, over the period 2001–2060.

[10] Consider first the temperature response. In Figure 1c, one can see the familiar patterns associated with GHG induced climate change: an overall warming of the troposphere, with maximum warming in the tropical upper troposphere, together with a cooling of the stratosphere. This, however, differs greatly from the result when all forcings are included (Figure 1a): most of the differences are in the lower stratosphere, which warms by more than 8° K near the pole, as a direct radiative consequence of ozone recovery in the polar lower stratosphere. Note that, in the absence of GHG increases the warming would be even larger, as can be seen in Figure 1b, where ozone recovery alone produces a warming of 10–12° K in the polar lower stratosphere.

[11] It is perhaps not widely appreciated that the direct radiative effect of ozone recovery, while confined to the polar lower stratosphere, is able to influence the atmospheric circulation over the entire SH. Consider the response of the zonal mean zonal wind, shown in Figure 1 (middle). The effect of ozone recovery (Figure 1e) is to produce a strong *equatorward* shift of the midlatitude jet, which is *opposite in sign* to the response associated with increasing GHG (Figure 1f): this results in a near cancellation of the trends, so that the combined response (Figure 1d) basically vanishes below 500 hPa.

[12] Another way to visualize the surprisingly large surface signature associated with stratospheric ozone recovery is to take a look at the sea-level pressure (SLP), which is closely related to the Southern Annular Mode (SAM), a widely used metric of the extratropical atmospheric circulation. The SLP response for the ALL and OZONE integration ensembles, and their difference, in DJF, is shown in the Figure 2 (left). The negative SAM response accompanying ozone recovery (Figure 2b) overwhelms the positive one associated with GHG increases (Figure 2c), and results in a weak, negative, and not statistically significant (see below) response for the ALL integrations (Figure 2a).

[13] Next, recall that the position of the midlatitude jet is highly correlated with the edge of the Hadley circulation in SH summer, both in terms of the internal climate variability on interannual time scales [*Polvani et al.*, 2011; *Kang and Polvani*, 2011], and in terms of the climate response to external forcings on centennial timescales [*Lu et al.*, 2008]. Hence it is not surprising that, together with an equatorward shift of the midlatitude jet, ozone recovery will induce a considerable contraction of the tropical circulation, as can be seen in Figure 1h, where the response of the mean-meridional streamfunction ψ is shown. Again, this effect is opposite to the one induced by GHGs (Figure 1i), and the combined response again yields extremely weak, overall Hadley cell expansion (Figure 1g) which is not, in fact, statistically significant (see below).

[14] Finally, closely related with the mean meridional circulation, we illustrate how the hydrological cycle will be directly affected by stratospheric ozone recovery. In Figure 2 (right), the $P - E$ (precipitation minus evaporation) fields are shown; the black contour indicates the latitudes where $P - E = 0$ during 2001–2010. Note how the large poleward expansion of the subtropical dry zones (i.e., the brown regions where $P - E < 0$) associated with increasing GHGs (Figure 2f) is largely canceled by the dry zone contraction due to ozone recovery (Figure 2e), so that the overall response consists of a relatively weak poleward expansion.

[15] In order to quantify the statistical significance of our results, we report in Table 1, the ensemble mean and the associated 95% confidence interval for several key metrics of the atmospheric circulation, for the ALL and OZONE ensembles (the rows labeled GHG/SST simply show the difference between these two ensemble means). Statistically significant responses are those in which the 95% confidence interval does not bracket zero (the null hypothesis being that the response is zero).

[16] Consider the DJF rows first. Note that for the OZONE ensemble, the response in nearly all metrics is statistically significant, whereas for the ALL ensemble only the polar cap temperature and the $P - E$ responses are. The lack of statistical significance in most atmospheric circulation trends in the ALL ensemble is directly attributable to ozone recovery, which severely reduces the amplitude of the response. As shown by DEA10 with the coupled version of the same model, over the same period, with the same forcings as the ALL ensemble, detection of statistically significant SLP trends in DJF requires approximately 15–20 ensemble members. This may appear surprising, but simply

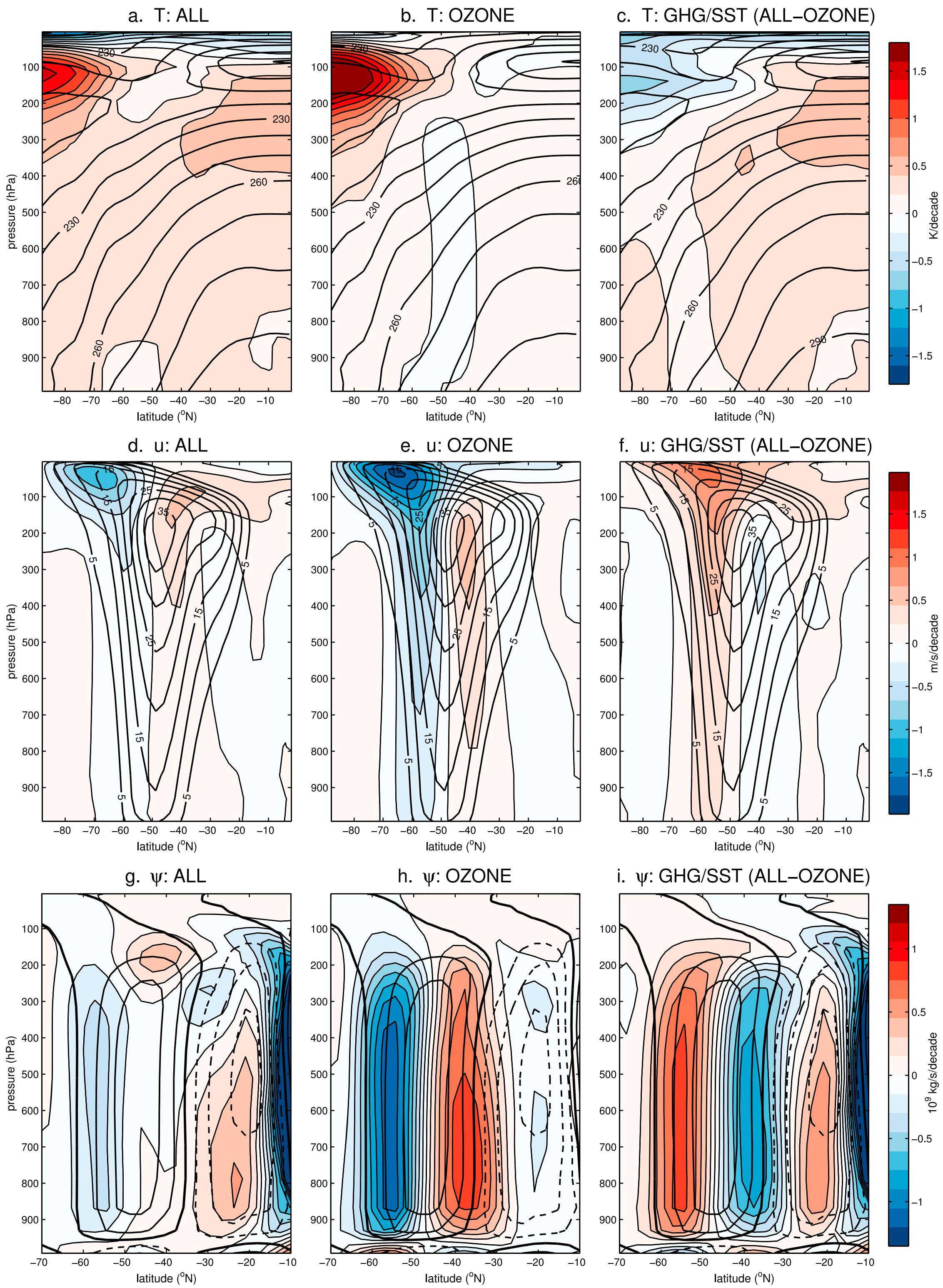

Figure 1. Ensemble mean DJF (top) zonal mean temperature, (middle) zonal wind and (bottom) mass streamfunction responses, during 2001–2060, for the integrations in (left) the ALL ensemble, (middle) the OZONE ensemble and (right) their difference. Contour intervals are, top to bottom: 0.2° K/decade, 0.22 m/s/decade, and 0.15 × 10^9 kg/s/decade. Black contours: the climatological mean (2001–2010), with contour intervals of 10° K, 5 m s^{-1} and 1.5 × 10^{10} kg s^{-1}, respectively, and negative contours dashed (and thicker zero contour).

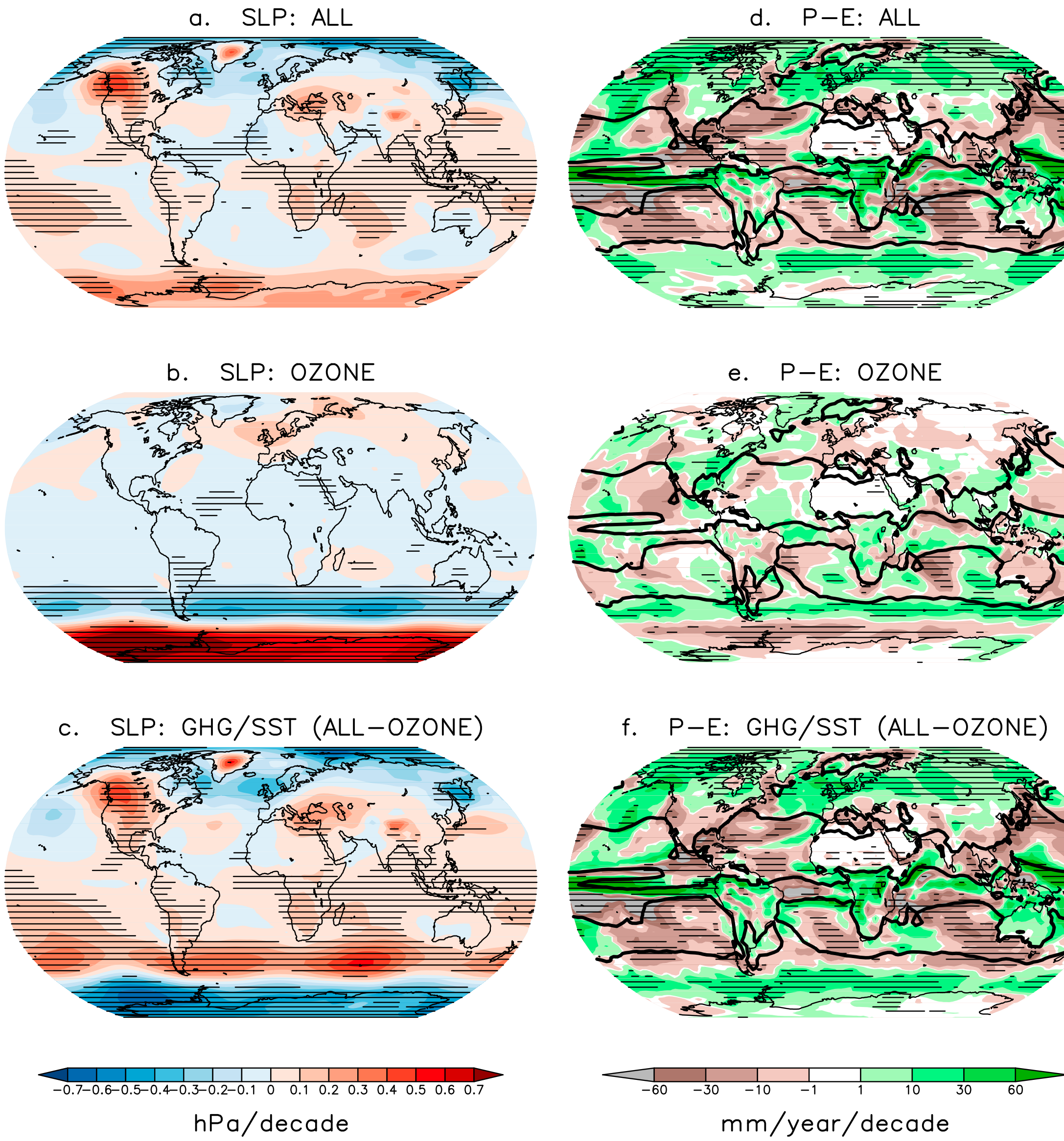

Figure 2. (left) DJF ensemble mean SLP response, 2001–2060, for (top) the ALL ensemble, (middle) the OZONE ensemble, and (bottom) their difference. (right) As in Figure 2 (left), but for $P - E$ (thick black lines: climatological mean $P - E = 0$ during 2001–2010). Statistically significant responses, at the 95% level, are hatched.

Table 1. DJF and JJA Responses During 2001–2060 of 100 hPa Polar Cap (60° S–90° S) Temperature, Latitude of 850 hPa Zonal Wind Maximum, SAM Index, Latitude of $\psi = 0$ at 500 hPa, and Latitude of $P - E = 0$[a]

Ensemble Name	Polar Cap T (° K)	Jet Maximum (° Latitude)	SAM Index (hPa)	ψ(500 hPa) = 0 (° Latitude)	$P - E = 0$ (° Latitude)
			DJF		
ALL	**5.24 ± 0.57**	0.24 ± 0.58	−1.16 ± 1.79	−0.02 ± 0.30	**−0.23 ± 0.16**
OZONE	**7.62 ± 0.70**	**1.33 ± 0.52**	**−4.93 ± 2.11**	**0.68 ± 0.31**	0.18 ± 0.19
GHG/SST	**−2.38 ± .93**	**−1.09 ± 0.49**	**3.77 ± 2.00**	**−0.70 ± 0.31**	**−0.41 ± 0.22**
			JJA		
ALL	**−1.90 ± 0.58**	**−0.73 ± 0.69**	**3.17 ± 1.52**	**−0.61 ± 0.20**	**−1.00 ± 0.25**
OZONE	**0.68 ± 0.46**	0.11 ± 1.01	−0.11 ± 1.37	0.06 ± 0.09	0.01 ± 0.13
GHG/SST	**−2.58 ± 0.75**	−0.84 ± 1.38	**3.28 ± 2.37**	**−0.67 ± 0.24**	**−1.01 ± 0.32**

[a]The ensemble mean and associated 95% confidence interval are given for the ALL and OZONE ensembles, with the rows labeled GHG/SST showing the difference between these two ensemble means. Boldface type indicates statistically significant responses.

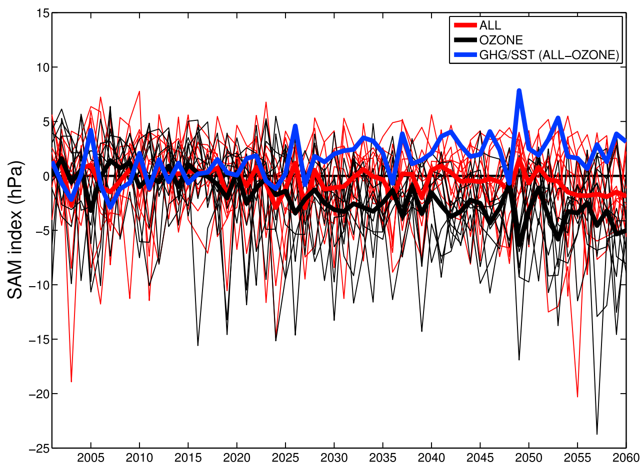

Figure 3. SAM index (anomalies from 2001–2010) in DJF for the two, 10-member ensembles. Thin red and black lines: individual members in the ALL and OZONE ensembles, respectively. Thick red and black lines: the corresponding ensemble means. Thick blue line: the difference of the thick red and black lines, i.e., the SAM response due to all forcings other than ozone recovery.

reflects the presence of very large internal variability which makes even broad, integral measures of the circulation (such as SLP) difficult to predict without large ensembles.

[17] To make this more immediately clear, we show in Figure 3, the yearly time series of SAM in DJF, for all 20 integrations in the two ensembles we have discussed in the paper. The SAM index is here computed as the anomalous (relative to 2001–2010) zonal mean SLP difference between 40° S and 65° S [*Marshall*, 2003]. The thin lines are the individual ensemble members, and the thick lines the ensemble mean. Note how small the trend one is trying to capture is, in comparison with the year-to-year oscillations. A discernible (and statistically significant) negative trend can be seen in the thick black line (the mean of the OZONE ensemble), but the trend in the thick red line (mean of the ALL ensemble) is very small, and not statistically significant. Figure 3 illustrates the challenge of determining trends in the atmospheric circulation, and raises issues about many earlier modeling studies that often used a very small number of ensemble members to determine trends.

[18] Finally, from Table 1, we note that nearly all JJA trends for the OZONE ensemble are not significant, as one would expect from the high seasonal nature of ozone recovery, which reaches its maximum in SON and has its largest effect in DJF. More importantly, note that all JJA metrics are statistically significant in the ALL ensemble, in agreement with DEA10. Contrasting the trends for the ALL ensemble in JJA and DJF, again highlights the key role of stratospheric ozone recovery in canceling the effects of increasing greenhouse gases during SH summer in the coming decades.

4. Discussion

[19] This paper confirms and extends an earlier study of *Shindell and Schmidt* [2004], and demonstrates that stratospheric ozone recovery will likely lead to large cancellations (and possibly reversals) in SH atmospheric circulation trends in the first half of the 21st century. Our sensitivity study corroborates the results of both the CCMVal-2 and the CMIP3 multimodel ensemble projections (provided ozone recovery is taken in to account).

[20] Our results are obtained with an IPCC-class atmospheric model, and this might suggest that interactive stratospheric chemistry and a well resolved stratospheric circulation may not be needed to capture the effect of ozone recovery on the tropospheric circulation. This, however, remains unclear. First, the amount of cancellation accompanying ozone recovery depends on the magnitude of the ozone trends, as clearly illustrated by *Karpechko et al.* [2010]. Second, the rate of recovery of ozone depends on GHG concentrations, as documented by *Waugh et al.* [2009a] and *Eyring et al.* [2010], so that stratospheric chemistry may be needed for a chemically consistent calculation. Third, unlike the ozone fields used in this study (and most IPCC class models), substantial zonal asymmetries exist in polar stratospheric ozone, and these have important effects [*Waugh et al.*, 2009b; *Gillett et al.*, 2009].

[21] Finally, a comment on the role of the ocean, which we have neglected up to this point. One might argue that the ocean temperatures would also respond to ozone recovery, and thus integrations of an atmospheric model with specified SSTs are not fully consistent. However, the radiative effects at the surface associated with ozone recovery are probably small, and unlikely to fundamentally alter the results presented here. As evidence, the 40-member ensemble of CCSM3 integrations discussed by DEA10 – which employ the same atmospheric model used in this study yet fully coupled to ocean and cryosphere models, and with radiative forcings identical to those prescribed in our ALL ensemble over the same 2000–2060 period – show nearly identical SLP trends in the SH to the ones presented here (compare our Figure 2a with Figure 1a of DEA10). Moreover, the recent study of *Sigmond et al.* [2010], has carefully addressed the issue of whether the ocean impacts the atmospheric response to stratospheric ozone depletion, and concluded that the addition of an ocean model has little effect. (After our manuscript had been completed, Dr. Ted Shepherd made us aware of the existence of a related paper [*McLandress et al.*, 2011], which will soon appear. In that paper the main conclusion of our study is confirmed, from integrations of a coupled ocean-atmosphere model with active stratospheric chemistry).

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