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Key Points:

- We show that stratospheric ozone depletion causes a significant deepening of the Amundsen Sea Low in austral summer
- The signal is small compared to the large natural variability in the region, so an ensemble of members is needed to detect the ozone effect
- In both models, the ozone response emerges only when the full ozone depletion period is used, starting around 1960, before the satellite era

Supporting Information:

- Supporting Information S1

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Robust response of the Amundsen Sea Low to stratospheric ozone depletion

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Abstract The effect of stratospheric ozone depletion on the Amundsen Sea Low (ASL), a climatological low-pressure center important for the climate of West Antarctica, remains uncertain. Using state-of-the-art climate models, we here show that stratospheric ozone depletion can cause a statistically significant deepening of the ASL in summer with an amplitude of approximately 1 hPa per decade. We are able to attribute the modeled changes in the ASL to stratospheric ozone depletion by contrasting ensembles of historical integrations with and without a realistic ozone hole. In the presence of very large natural variability, the robustness of the ozone impact on the ASL is established by (1) examining ensembles of model runs to isolate the forced response, (2) repeating the analysis with two different climate models, and (3) considering the entire period of stratospheric ozone depletion, the beginning of which predates the satellite era by a couple of decades.

1. Introduction

Stratospheric ozone depletion, and the occurrence of the ozone hole during spring, has been the dominant forcing of Southern Hemisphere climate change in recent decades [*Polvani et al.*, 2011], and its effects on large-scale features of the atmospheric circulation have been well documented [*Marshall*, 2003; *Son et al.*, 2010; *Thompson et al.*, 2011; *Previdi and Polvani*, 2014]. Recent research has attempted to document how ozone depletion has driven changes in the Amundsen Sea Low (ASL), one of the most important regional features in the southern high latitudes [*Turner et al.*, 2013]. The ASL is a low-pressure center located in the region 60–75°S 170–290°E. The depth and location of the ASL have been shown to have a significant impact on the surface air temperature, precipitation, and the distribution of sea ice around West Antarctica [*Turner et al.*, 1997; *Massom et al.*, 2008; *Holland and Kwok*, 2012; *Hosking et al.*, 2013], the region with the largest trends in sea ice extent [*Parkinson and Cavalieri*, 2012]. Due to the ASL's influence over the climate of West Antartica, it is important to understand how it has been affected by the forcing of stratospheric ozone depletion in the twentieth century.

Turner et al. [2013] examine the monthly trends in central pressure and location of the ASL in the years 1979–2008 using European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data and find that they are highly variable, with no robust trend in any season. Nonetheless, *Turner et al.* [2009] have proposed that a slight deepening of the autumn ASL in models might be linked to stratospheric ozone depletion. Furthermore, *Fogt and Zbacnik* [2014] offered modeling evidence for the importance of ozone depletion in deepening the summertime ASL, although were not able to demonstrate this at the 95% significance level.

The difficulty in establishing ozone-forced trends in the ASL arises from the very large natural variability in that region [*Lachlan-Cope et al.*, 2001; *Turner et al.*, 2015]. Interannual variations of the ASL have been linked to several drivers of climate variability: the phase of El Nino-Southern Oscillation is important for the ASL central pressure [*Fogt et al.*, 2011; *Pezza et al.*, 2012; *Turner et al.*, 2013], and the phase of the Southern Annular Mode influences the ASL central pressure and longitudinal location [*Lefebvre et al.*, 2004; *Fogt et al.*, 2012a; *Turner et al.*, 2013]. Furthermore, recent model studies [*Ding et al.*, 2011; *Ding and Steig*, 2013; *Fogt and Wovrosh*, 2015; *Li et al.*, 2015; *Raphael et al.*, 2015] have highlighted the importance of tropical sea surface temperatures on the ASL and West Antarctic temperatures [*Comiso*, 2000; *Marshall et al.*, 2002; *Schneider et al.*, 2012]. Finally, a stratospheric influence has been shown to be important for the location of the ASL [*England et al.*, 2016]. The goal of this paper is to bring out the ozone-forced response of the ASL and distinguish it from this large and complex natural variability.

We here isolate the effect of ozone forcing by comparing an ensemble of climate model runs with a realistic ozone hole evolution to an ensemble with stratospheric ozone concentrations fixed at 1955 levels. This comparison allows a direct attribution of the differences to stratospheric ozone depletion, and the use of ensembles allows us to extract the forced response from the large natural variability. To establish a robust result, we repeat this analysis with two different, fully coupled general circulation models: although both of these models are from the Community Earth System Model (CESM1) family, they have very different physical processes and configurations. Both models show a robust deepening of the summertime ASL forced by stratospheric ozone depletion over the second half of the twentieth century.

2. Data and Methods

In this study we employ two configurations of a state of the art model, the CESM1, to investigate the effect of stratospheric ozone depletion on the ASL. The Whole Atmosphere Community Climate Model (WACCM4), documented by *Marsh et al.* [2013], is the high-top atmosphere model configuration included in CESM1. It has a horizontal resolution of 1.9° latitude by 2.5° longitude, with 66 vertical levels and a model lid height extending up to the lower thermosphere, 140 km. WACCM4 has fully interactive middle atmosphere chemistry, so is able to realistically capture the development of the Antarctic ozone hole in austral spring. The Community Atmosphere Model (CAM5) is the low-top atmosphere model configuration of CESM1 [*Kay et al.*, 2015]. It has a higher horizontal resolution of 0.9° latitude by 1.25° longitude. There are 30 levels in the vertical direction, with a rigid lid at 50 km above the surface. Both models are coupled to fully prognostic ocean, sea ice, and land components [*Gent et al.*, 2011].

For each model configuration, we analyze two ensembles of 51 year runs 1955–2005, differing only in the levels of stratospheric ozone depletion. The first ensemble comprises standard "historical" Coupled Model Intercomparison Project Phase 5 (CMIP5) integrations [*Taylor et al.*, 2012], including all known natural and anthropogenic forcings. These runs will be referred to as "ozone hole" runs. The second ensemble is identical in every respect, except that ozone depleting substances (ODSs) and, for CAM5, the levels of stratospheric ozone, are held fixed at 1955 levels (preozone hole). These runs will be referred to as "fixed ozone" runs because no ozone hole develops in the springtime. Since the ozone concentrations in CAM5 are specified from the mean of the WACCM4 historical runs, the amplitude and evolution of stratospheric ozone depletion is practically identical between the WACCM4 and CAM5 runs. Spring polar cap ozone levels for the individual WACCM4 members are shown in Figure S1 in the supporting information, and these were found by *Marsh et al.* [2013] to compare very well with observations. There are six members contained in both WACCM4 ensembles, previously analyzed by *Solomon et al.* [2015] in the context of the Southern Ocean response to changing ODSs, and eight members contained in both CAM5 ensembles.

To put the model results in the context of observations, monthly mean sea level pressure is analyzed from two reanalysis data sets, the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) [*Dee et al.*, 2011] and the National Centre for Environmental Prediction: U.S. Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project-II reanalysis [*Kanamitsu et al.*, 2002] over the period 1979–2005. As in other investigations of the ASL [eg. *Fogt et al.*, 2012b], the usage of reanalyis products is limited to the years following 1979, after the assimilation of satellite data.

Finally, we introduce the three metrics used to define the ASL: the absolute central pressure, and its position in longitude and latitude. The location is determined from monthly sea level pressure data using the same method as *Turner et al.* [2013]: it is the location with the lowest mean sea level pressure in the region 50–180°W, 60–75°S. Figure 1 shows the climatalogical seasonal cycle of the three ASL metrics for the historical runs of CAM5 and WACCM4. The seasonal cycle of the ASL for the ensemble average WACCM4 (green) and CAM5 (red) ozone hole runs are compared to reanalysis (black) as well as a range of 26 CMIP5 models (shaded envelope). Both WACCM4 and CAM5 display better skill in simulating the seasonal cycle of these three ASL properties compared to the majority of the models [*Hosking et al.*, 2013], especially the location.

Building upon previous work by *Fogt and Zbacnik* [2014] and *Fogt and Wovrosh* [2015], we are able to detect a robust signal of ozone depletion on the ASL. By employing large ensembles of runs from two state of the art climate models, which are able to well represent the ASL climatology (Figure 1), we are able to isolate the forced signal from the large natural variability [*Lachlan-Cope et al.*, 2001]. Moreover, comparing fixed ozone and ozone hole ensembles allows us to directly attribute any differences in the ASL to stratospheric ozone depletion because all other factors are held fixed.

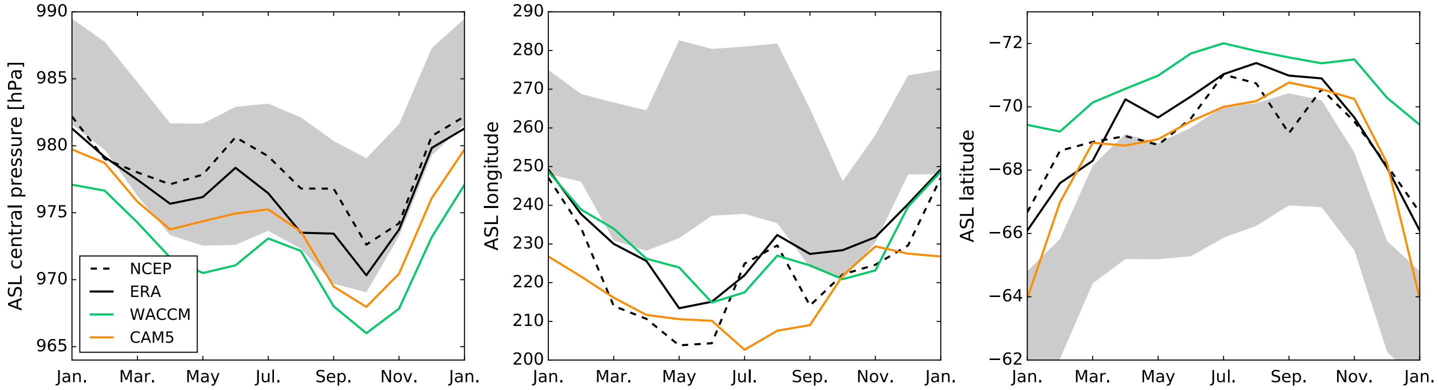

Figure 1. Seasonal cycle (average over 1979–2005) of three key metrics that define the Amundsen Sea Low: (left) central pressure, (center) longitude, and (right) latitude. An ensemble average of six WACCM4 (green) and eight CAM5 (orange) historical integrations are compared with NCEP-DOE II (dashed black) and ERA-Interim (solid black). The grey shading indicates the $\pm 1\sigma$ envelope for 26 CMIP5 models.

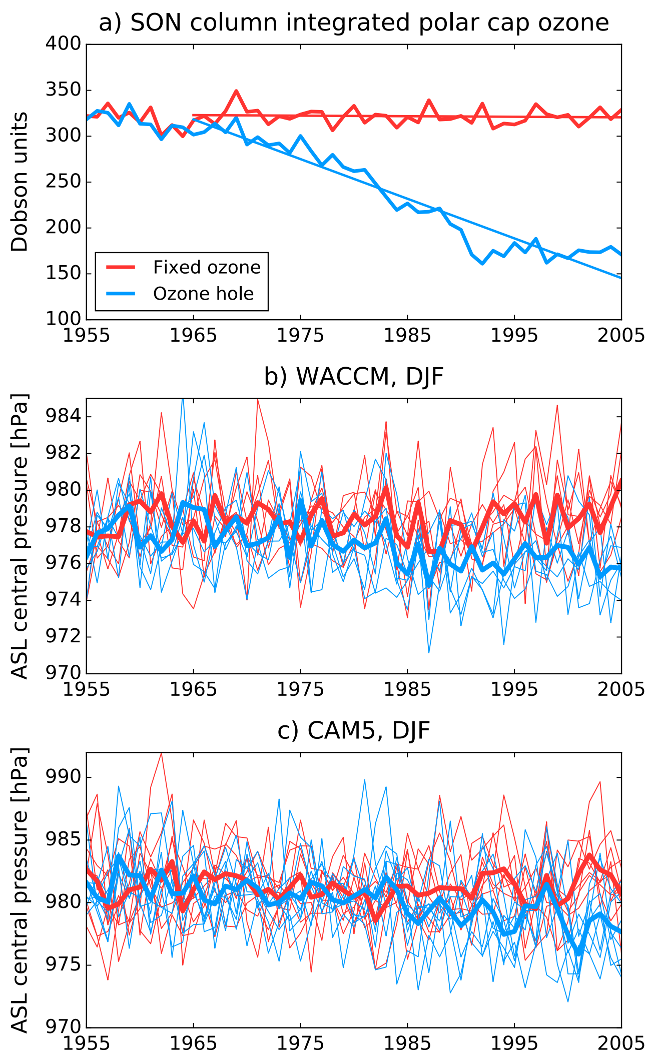

Figure 2. (a) Column-integrated polar (60–90°S) ozone in the Southern Hemisphere, averaged over September–November, used for the CAM5 runs with fixed ozone (red) and historic ozone levels (blue). The trendlines show trends over the period 1965–2005. Ozone levels for the individual WACCM members are shown in the supporting information Figure S1. (b) The ASL central pressure during DJF for six fixed ozone runs and six ozone hole runs in WACCM4 with the bold lines indicating the ensemble averages. (c) The ASL central pressure during DJF for eight fixed ozone runs and eight ozone hole runs in CAM5 with the bold lines indicating the ensemble averages.

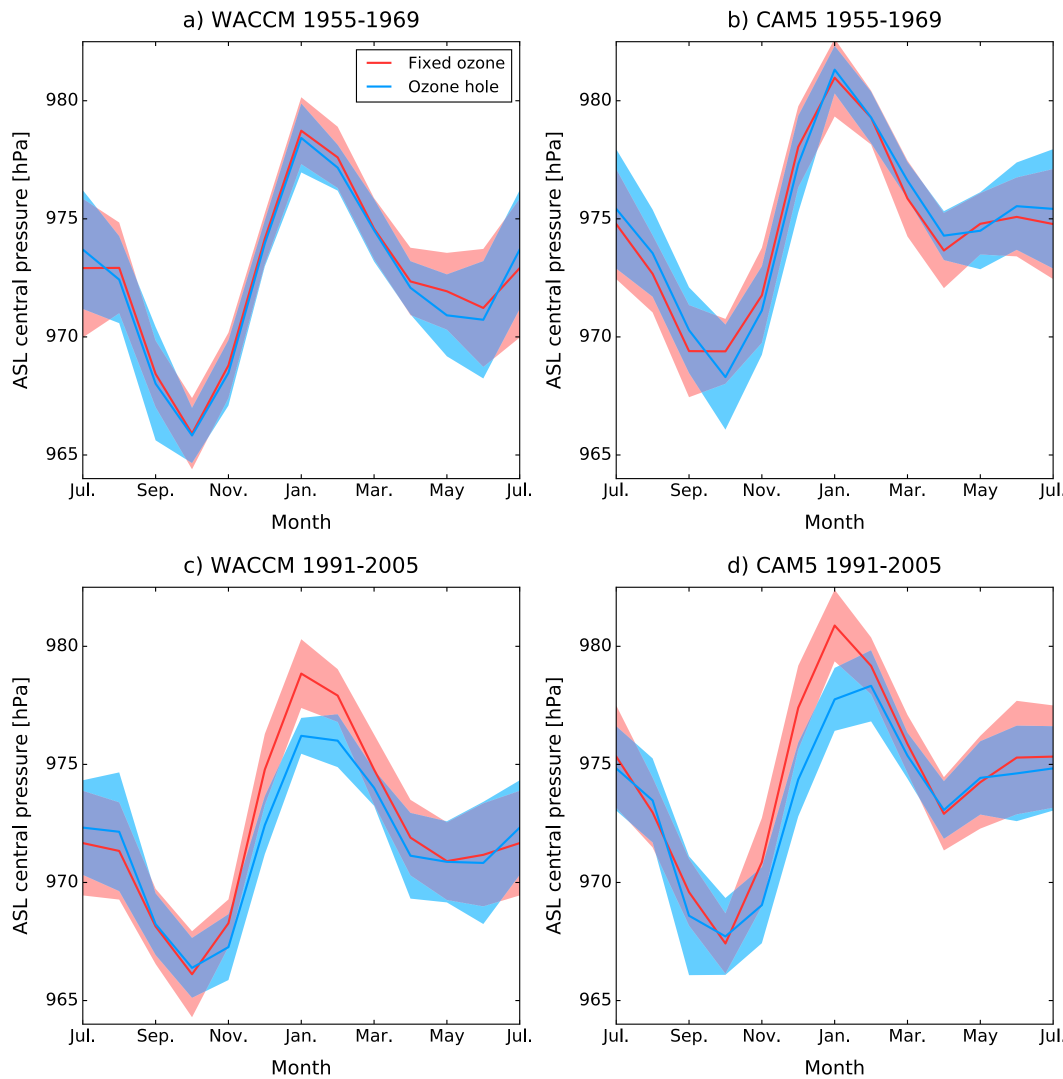

Figure 3. Seasonal cycle of ASL central pressure taken over 15 year periods: (a and b) the early period (1955–1969) before the effects of ozone depletion and (c and d) the late period (1991–2005) with the effects of ozone. Fixed ozone (red) and realistic ozone (blue) runs from WACCM4 (Figures 3a and 3c and CAM5 (Figures 3b and 3d) are compared. The lines indicate the ensemble average and the shading represents the $\pm 1\sigma$ of the yearly variability across the ensemble over the 15 year period.

3. Results

Figure 2a shows the column-integrated polar cap ozone levels during spring; levels of stratospheric ozone are seen to start depleting after 1965, reaching a minimum value by 2005. While the Antarctic ozone hole forms in spring, it takes time for the signature to migrate down to the surface resulting in the largest effects of ozone depletion in the troposphere occurring in summer [*Thompson et al.*, 2011]. Consistent with this, we find that stratospheric ozone depletion only has an impact on the ASL in DJF (December, January, and February).

When forced with a realistic ozone hole the ASL is seen to deepen by 1 hPa per decade in DJF over a 41 year period of stratospheric ozone depletion in both WACCM4 and CAM5 (Figures 2b and 2c, blue curves). In contrast, the fixed ozone ensembles (red curves) display no trends in the central pressure of the ASL over the same time period (Figures 2b and 2c, red curves). The difference between the two ensembles becomes statistically significant at 95% levels by 1993 in WACCM4 and 1999 in CAM5. It must be noted that the magnitude of the change is smaller than the natural variability of the ASL as depicted by the large spread across the individual ensemble members (thin blue and red curves). The presence of the ozone effect in two very different models provides confidence in the result. Of the three ASL metrics, stratospheric ozone depletion

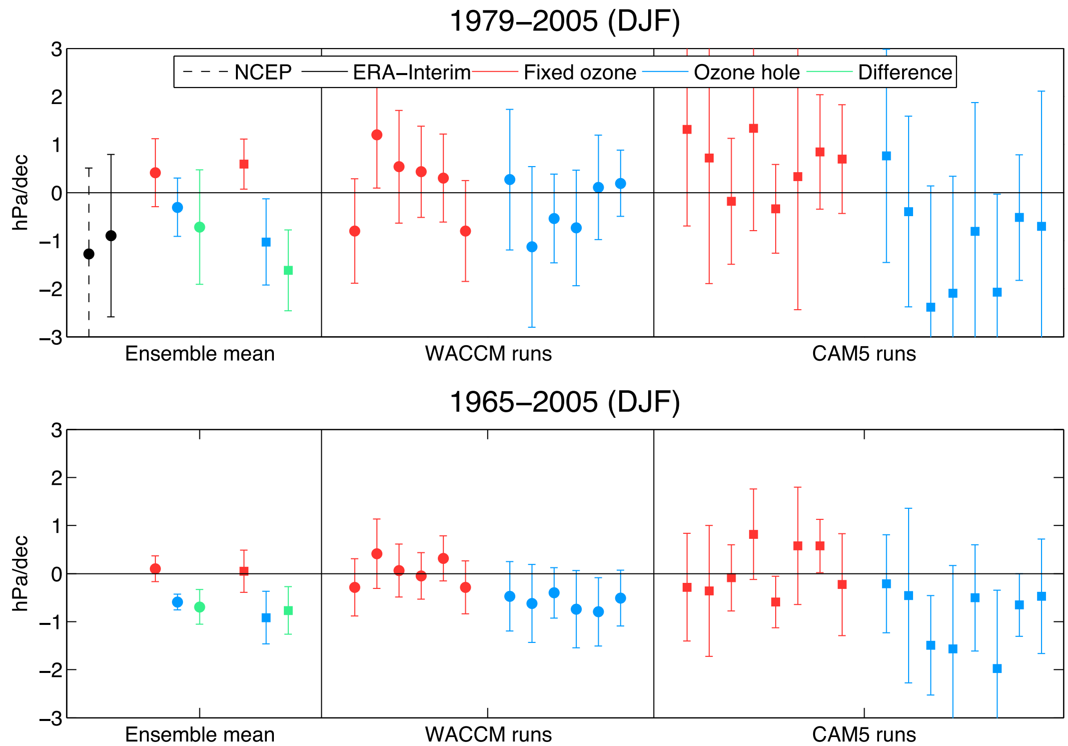

Figure 4. Trends in ASL central pressure in DJF during years (top) 1979–2005 and (bottom) 1965–2005. The ensemble average for both WACCM4 (circles) and CAM5 (squares) runs, as well as the individual members, are displayed with error bars indicating 95% significance. NCEP-DOE II and ERA-Interim are plotted for the shorter time period. Red indicates runs with fixed ozone levels, blue indicates runs with realistic ozone, and green shows the difference between them.

only has an effect on the ASL central pressure; in agreement with *Fogt and Wovrosh* [2015], we find no statistical difference between the fixed ozone and ozone hole ensembles when examining the latitudinal or longitudinal position of the ASL over the same time period (not shown).

To illustrate that the ozone effect on the ASL is confined to summer, we show in Figure 3 the full seasonal cycle of ASL central pressure in WACCM4 (a and c) and CAM5 (b and d) averaged over the 15 years before the dramatic depletion of stratospheric ozone (1955–1969) and the 15 years when stratospheric ozone levels reached their minimum (1991–2005). The 15 year averaging window was chosen to maximize the signal-to-noise ratio. Although *Turner et al.* [2009] and *Fogt and Zbacnik* [2014] suggested that there was a possible relationship between ozone depletion and the ASL in austral autumn, our models show no evidence for this. For the ozone hole ensemble there is a pronounced deepening in summer, most notably in January, found in the years after the ozone hole has peaked. In contrast, the seasonal cycle of ASL for the fixed ozone ensemble remains unchanged between the two periods.

Recent studies into the link between ozone depletion and changes in the ASL [*Turner et al.*, 2009; *Fogt and Zbacnik*, 2014] only looked at the years following 1979, constrained by available reanalysis and model data. However, it is well established that levels of stratospheric ozone started to significantly decrease from the mid-1960s, so these studies miss out on roughly 15 years of ozone-forced trends. Figure 4 compares DJF trends in ASL central pressure for the WACCM4 and CAM5 ensembles found over the truncated period 1979–2005 and those from the full period 1965–2005. Trends for the ensemble means (left panels) are calculated by examining the distribution of trends of the individual members (center and right panels). Trends are statistically different from zero at 95% significance if the error bars do not cross the zero line. The deepening of the ASL in DJF due to ozone depletion can be seen in Figure 4 from the trend in the difference (green) between the ozone hole (blue) and fixed ozone (red) ensembles.

For the WACCM4 runs, even with the large number of members used, this nonzero trend is only statistically significant at a 95% level using the longer time period. This would explain why previous studies found it difficult to diagnose a robust ozone effect on the ASL. Trends for individual members of each ensemble are also shown; broadly, the individual ozone hole runs have negative trends, while the individual fixed ozone runs have no trends. Averaging over all members of the ensemble, as well as the full time period 1965–2005, is required to clearly see that stratospheric ozone depletion causes a deepening of the ASL in summer.

4. Summary and Discussion

Using two CESM1 models, CAM5 and WACCM4, we have demonstrated that stratospheric ozone depletion causes a deepening of the summertime ASL of roughly 1 hPa per decade. Previous studies have struggled to isolate the impact of stratospheric ozone on the ASL, mostly due to the large natural variability of the ASL itself. This study makes it clear, however, that using ensembles of model integrations and analyzing them over the full period of ozone depletion (which started a couple of decades before the satellite era) are crucial in determining the ozone impact on the ASL.

In contrast with similar studies [*Turner et al.*, 2009; *Fogt and Wovrosh*, 2015; *Hosking et al.*, 2016] which only analyzed integrations with all known forcings present, the changes seen here can be unequivocally attributed to stratospheric ozone depletion since we have explicitly run the model with and without ozone depletion. One might question, however, whether two models are enough to draw robust conclusions. It should be emphasized that these are two very different models, with markedly different climate sensitivities [*Gettelman et al.*, 2013]. Furthermore, impacts of stratospheric ozone depletion being confined to summer is consistent with the observational study by *Thompson et al.* [2011], and we are able to build upon the modeling study by *Fogt and Zbacnik* [2014] to more cleanly isolate the signal.

Although beyond the scope of this study, the next step would be to establish the precise mechanism connecting stratospheric ozone depletion and the ASL. One reasonable hypothesis pertains to changes in synoptic-scale activity around West Antarctica. High-latitude cyclones in the Amundsen and Bellingshausen Seas have been shown to be important for the formation of the ASL [*Walsh et al.*, 2000; *Fogt et al.*, 2012b]. *Grise et al.* [2014] demonstrate that stratospheric ozone depletion has induced a significant poleward shift in cyclone frequency in summer, with a marked increase in the frequency of the strongest cyclones in the Amundsen and Bellingshausen Seas region. Therefore, an intensification of cyclonic activity around West Antarctica, as a result of stratospheric ozone depletion, is a potential mechanism which would cause the ASL to deepen in summer.

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