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Intra-annual relationships between polar ozone and the SAM

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[1] Observed co-variations between polar total column ozone and the Southern Hemisphere Annular Mode (SAM) during 1962–2004 are presented and evaluated in a chemistry-climate model (CCM). Results show that austral spring total column ozone variability at South Pole is significantly related to the SAM, perhaps up to four months later; this relationship is only seen in simulations that include ozone depletion. The austral spring SAM also is linked to following late spring – early summer total column ozone over the polar cap, since both respond to the wave-driving of the stratosphere. Overall, the CCM captures many of the observed ozone-SAM links, but over-predicts the relationship between spring ozone and austral summer SAM, as a consequence of the delayed breakdown of the polar vortex in the CCM. **Citation:** Fogt, R. L., J. Perlwitz, S. Pawson, and M. A. Olsen (2009), Intra-annual relationships between polar ozone and the SAM, *Geophys. Res. Lett.*, *36*, L04707, doi:10.1029/2008GL036627.

1. Introduction

[2] The dominant mode of climate variability across the Southern Hemisphere is the Southern Hemisphere Annular Mode (SAM), which describes the strength of the meridional pressure gradient and circumpolar zonal winds. Since the late 1960s, the SAM has displayed statistically significant positive trends in the austral summer and autumn seasons [*Marshall*, 2007]. The austral summer trends have been linked primarily to stratospheric polar ozone depletion in both observational [*Thompson and Solomon*, 2002] and modeling studies [e.g., *Perlwitz et al.*, 2008].

[3] Of interest is the fact that the climate models used in the Intergovernmental Panel on Climate Change (IPCC) assessment use prescribed ozone changes to investigate the impact of stratospheric ozone depletion on the SAM, thereby missing important temporal ozone-dynamical feedbacks [*Eyring et al.*, 2006]. Recently, *Perlwitz et al.* [2008] and *Son et al.* [2008] demonstrated the advantage of using coupled chemistry climate models (CCMs) to simulate the impacts of stratospheric ozone changes on the circulation of the Southern Hemisphere. CCMs are relatively new tools that include global dynamics and radiation as well as fully interactive stratospheric ozone chemistry, thereby simulating both ozone's influence on the atmospheric circulation and the circulation's (including transport of ozone from midlatitudes) influence on ozone concentrations. The latter is obviously not represented in IPCC models and others with prescribed ozone variations. The goal of this paper is to investigate the link between stratospheric ozone and the SAM throughout the course of the year in the longest available observation records, and to evaluate this link in a CCM. The results will improve the understanding of the nature of this link and will assess the ability to simulate it in CCMs.

2. Data and Methods

[4] The intra-annual ozone-SAM link is first investigated using lag correlations on detrended data during 1962–2004 at ±6 months lag for each 3-month overlapping period (smoothed with a 1-2-1 filter) throughout the year. Positive lags indicate that total column ozone, which is dominated by ozone concentrations in the stratosphere, leads the tropospheric SAM; negative lags indicate that total ozone lags the SAM. The slight non-linear nature of the ozone trends does not impact the detrended data as similar results are obtained during 1979–2004 when the trends are more linear. We investigate this link in observations using monthly mean total column ozone values comprised of both ozonesonde and Dobson spectrophotometer data at Amundsen-Scott (South Pole) and Syowa stations, along with the *Marshall* [2003] SAM index. These ozone observations depict ozone variability within and at the edges of the polar vortex, respectively; dependence of the results due to the completeness of the ozone observations is discussed when applicable.

[5] This link is then evaluated in the Goddard Earth Observing System Chemistry- Climate model (GEOS CCM) Version 1. Details of the model configuration and biases are given by *Pawson et al.* [2008]. Four simulations with well-mixed observed greenhouse gas changes were investigated: two ensemble runs (P1 and P2) which start from different initial conditions but are forced with observed sea surface temperatures (SSTs), sea ice, and halogen changes; and two sensitivity runs, one (Cl1960) with chlorine fixed at 1960 values, and the other (P-SSTclim) with SSTs fixed at an annually repeating monthly climatology. The sensitivity runs isolate the impacts of ozone depletion and temporal SST variability. For each simulation, a SAM index was constructed from the difference of standardized zonal mean sea level pressure at 40° and 65°S [*Gong and Wang*, 1999]; the standardization is based on data from the European Centre for Medium Range Weather Forecasts 40-year reanalysis (ERA-40) during 1979–2001 to retain any model differences in mean or variance compared to ERA-40. The total column ozone

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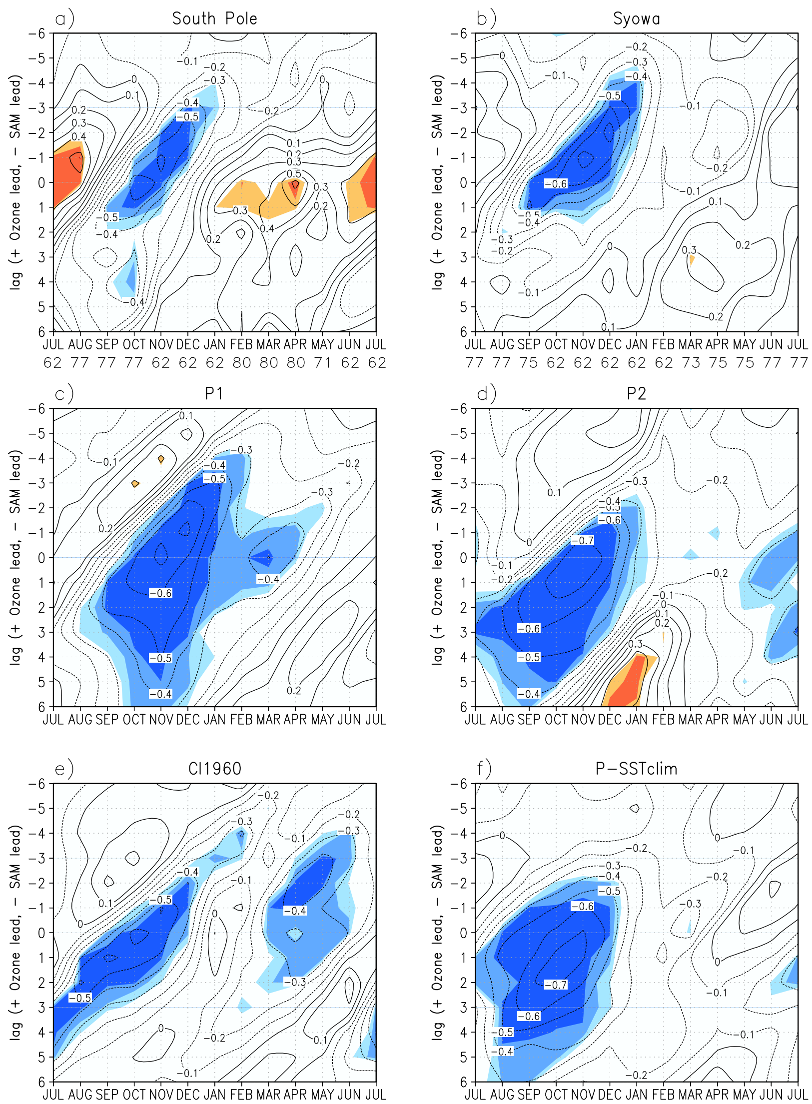

Figure 1. Correlation (1962–2004) of detrended total column ozone and SAM index at ±6 months lag for each 3-month overlapping period (smoothed with a 1-2-1 filter, defined on middle month of the 3-month period for total column ozone). (a)–(b) Ozone measurements from South Pole and Syowa stations, respectively, along with the *Marshall* [2003] SAM index. On the horizontal axis is also the year after which the observations are 75% complete. (c)–(f) Four runs of the GEOS CCM. The shading denotes the $p < 0.10$, $p < 0.05$, and $p < 0.01$ significance levels, with the degrees of freedom reduced by the lag-1 autocorrelation.

value at the South Pole is used to define ozone variability in the simulations.

3. Results

[6] The observations indicate several interesting and significant relationships between ozone and the SAM. Readily apparent in both the South Pole (Figure 1a) and Syowa (Figure 1b) record is the band of significant negative correlations extending from August at positive lags to December at negative lags (the time reference is based on the total column ozone series, also given is the year after which the observations are more than 75% complete). The significant negative correlations at positive lags imply that spring decreases (increases) in total ozone are associated with SAM increases (decreases) anywhere from one to four months later, supporting and extending the ozone- geopotential height correlations presented by *Thompson and Solomon* [2002]. These significant correlations are not a direct link, but result from stratospheric warming/cooling and the subsequent dynamic responses associated with ozone changes [e.g., *Perlwitz et al.*, 2008]. Since Syowa lies at the fringe of the polar vortex and is not always beneath the ozone minimum, the link between ozone and the SAM is weaker, with significant correlations only extending to one month positive lag. In comparison, in the polar vortex interior at South Pole (Figure 1a), spring ozone is significantly ($p < 0.05$) correlated with the SAM up to four months later. However, the fact that the South Pole spring ozone observations are only 75% complete after 1977 prevents us from determining whether this link exists

over the full 43 years or is prominent only during the last three decades. Further caution should be exercised regarding the significant correlations at four months lag, since these may be a result of data smoothing. However, unsmoothed time series of the SAM and ozone display a similar (although insignificant) maximum at 4 months, suggesting that this may be a unique feature of total column ozone within the vortex not previously presented.

[7] Observed ozone at both South Pole and Syowa also displays significant negative correlations with the SAM at negative time lags, which represent the relationship between October SAM and the following late spring - early summer (Oct–Dec) total ozone concentration. These results, based on nearly complete data in both records, suggest when the tropospheric SAM is weak, more ozone is transported from midlatitudes to the polar vortex. Meanwhile, an important feature seen only in the South Pole ozone observations is the band of significant positive correlations that occur during the polar night at zero lag (Figure 1a), meaning that lower surface pressures over Antarctica are associated with increased total column ozone in winter. This positive relationship is due to the expanding/shrinking of the stratospheric column in regions of surface low/high pressure inside the isolated winter vortex [*Appenzeller et al.*, 2000]. It does not extend to the vortex fringes, evident by insignificant correlations at Syowa (Figure 1b), and occurs throughout the full 43 years as winter data at South Pole (predominantly based on integrated ozonesonde measurements) are more than 75% complete back until 1962.

[8] Next, we investigate the ozone-SAM relationship in the GEOS-CCM simulations (Figures 1c–1e). Notably, the simulations capture the majority of the observed ozone-SAM links discussed previously, including the significant negative correlations between ozone and the SAM at negative time lags. Model simulations (auxiliary Figure S1) indicate this relationship exists as both the SAM and ozone over the polar cap strongly respond to the wave driving of the stratosphere [*Polvani and Waugh*, 2004].[1] In Figure S1, the vertical component of the Eliassen-Palm flux at 100 hPa from 44°–76°S, a measure of the wave driving of the stratosphere, shows significant similar relationships with both the SAM and polar ozone. In spring, anomalously strong upward flux of wave activity into the stratosphere is associated with a weaker stratospheric vortex and subsequent tropospheric SAM state by downward influence [e.g., *Thompson et al.*, 2006; *Chen and Held*, 2007] from one to three months later, as well as increased transport of ozone into the vortex. Opposite conditions are found during periods of anomalously weak upward flux of wave activity in spring. The timing of this underlying relationship is consistent with and fully explains the significant correlations at negative lags in Figure 1. Notably, the link ends when the polar stratospheric winds become easterly (Dec–Jan), thus isolating it from tropospheric wave activity.

[9] Although the model simulations capture this feature, they do not display the positive correlations during late autumn - winter at South Pole. It is also clear that the model over-predicts the link at positive lags (ozone leading SAM), with significant negative correlations during more months of the year and for longer lags than observed. Although the model over-predicts the persistence of this relationship, the unit change of the SAM to changes in ozone (i.e., the regression coefficient) is consistent among all the runs including temporal ozone depletion and observations (not shown). This implies the quantitative ozone-SAM relationship is well simulated in the model, despite the stronger correlations seen in Figure 1 at positive lags.

[10] Importantly, there are a few key differences between the ensemble and sensitivity simulations that are suggestive of relevant mechanisms. Notably, the large difference between the Cl1960 run and the other simulations at positive lags during spring-summer (Figure 1e, > +3 months) strongly indicates that ozone depletion over the recent decades increases the persistence and strength of the ozone-SAM relationships seen in the South Pole ozone observations (Figure 1a). A more subtle difference occurs in the P-SSTclim run (Figure 1f), where the strongest correlations are shifted towards positive lags, compared to zero or negative lags in the other simulations and observations. This suggests that SST variability has slightly weakened the ozone-SAM relationship when SAM leads and/or strengthened the relationship when ozone leads, although additional ensemble simulations with fixed SSTs are needed to affirm this hypothesis since the differences are small and hard to separate from climate noise.

[11] A possible explanation why the positive correlations during polar night are missing in the GEOS CCM is because the modeled polar vortex in winter is too variable, and therefore not isolated enough to establish the link between the depth of the stratospheric column and total column ozone [*Pawson et al.*, 2008; *Braesicke et al.*, 2008]. However, we expect the absence of significant positive winter correlations to have little implication on the chemistry-climate link, predominantly because the observed interannual ozone variability during winter is less than half the variability in spring. Furthermore, the observed significant correlations during polar night occur only near zero lag, indicating a simultaneous relationship with very little persistence. Nonetheless, other CCMs need to be studied to both understand why the positive winter correlations are absent and what impacts this may have on the chemistry-climate link.

[12] In contrast, the over-prediction of the negative correlation by the GEOS CCM has stronger implications for the chemistry-climate link as the correlations at positive lags extend several months too long and occur during the period of maximum ozone variability. The over-persistence of these correlations in the model can be due to differences in the simulated ozone and/or SAM variability. To examine this, we compare the simulated and observed autocorrelation functions for each variable. Here, we correlate each of the interannual ozone and SAM time series with itself for up to six months positive lag; however, since the ozone and SAM time series are smoothed with a 1-2-1 filter, only autocorrelations beyond two lags are meaningful. The total column ozone autocorrelation (auxiliary Figure S2) displays two distinct peaks near August–September and February–March. These peaks are related to inflection points in the seasonal ozone cycle: after a decrease in ozone concentrations over the South Pole in September–October, ozone begins a steady increase until December–January, after

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036627.

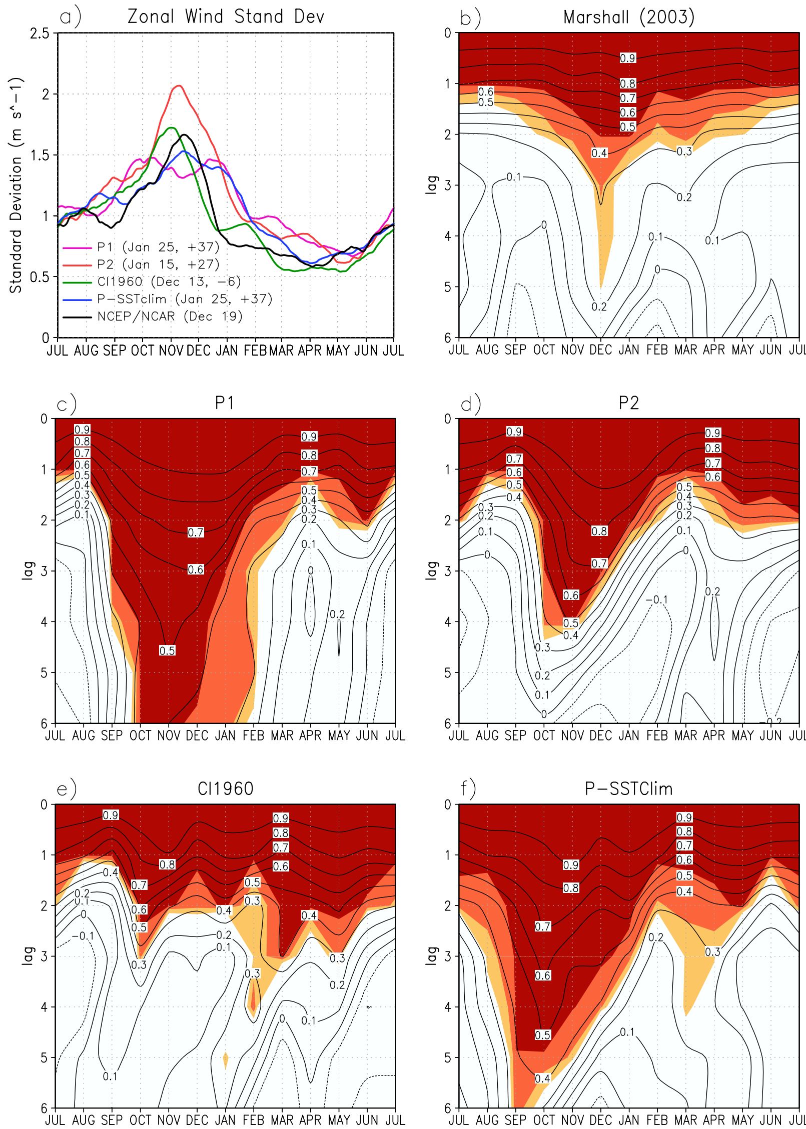

Figure 2. (a) Time series of daily variance of 50 hPa zonal mean zonal wind averaged from 50° to 70°S from the NCEP/NCAR reanalysis and the four runs from the GEOS CCM, 1979–2004. The daily values were first band-pass filtered to retain variability less than 365 days. Autocorrelation (1962–2004) of detrended SAM index up to 6 months positive lag for each 3-month overlapping period (smoothed with a 1-2-1 filter, defined on middle month of the 3-month period). (b) *Marshall* [2003] SAM index and (c)–(f) four runs of the GEOS CCM. The shading denotes the $p < 0.10$, $p < 0.05$, and $p < 0.01$ significance levels, with the degrees of freedom reduced by the lag-1 autocorrelation.

which it is relatively stable through winter. Since the model captures the main features of the observed total column ozone autocorrelations with only small differences, the simulated ozone variability is likely not contributing to the increased persistence of the modeled ozone-SAM relationships in Figure 1. However, there are notable differences in the observed and simulated SAM autocorrelations. For the Marshall SAM index (Figure 2b), significant autocorrelations extend beyond two months during December, consistent with previous studies using daily data [*Baldwin et al.*, 2003; *Gerber et al.*, 2008]. Meanwhile, the SAM autocorrelations in simulations that include chlorine changes strongly over-predict SAM persistence during October–December. Notably, the SAM persistence is much smaller in the Cl1960 run, indicating that simulated chemistry-climate interactions increase SAM persistence. This mechanism cannot explain the result of *Gerber et al.* [2008], who found that in the IPCC climate models the SAM is similarly more persistent than observed.

[13] *Baldwin et al.* [2003] suggested that the increased persistence of tropospheric SAM is due to the stratospheric variability, since the peak of SAM persistence is aligned with the peak of lower stratospheric vortex variability. The stratospheric polar vortex breaks down too late in many CCMs, including the GEOS CCM [*Eyring et al.*, 2006]. As a consequence, the polar vortex is dynamically coupled to the troposphere during its prolonged weak westerly state with potential downward impact on the SAM behavior. To

examine this, we compare the daily standard deviation of the 50-hPa zonal mean zonal winds averaged over 50°–70°S between the GEOS CCM simulations and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, and link the results to the SAM autocorrelations. The period from 1979 to 2004 was analyzed, with the annual cycle removed and the anomalies band-pass filtered to retain variability less than 365 days. The seasonal cycle of the daily standard deviation is shown smoothed with a 31-day running mean in Figure 2a. The legend provides the date when the smoothed standard deviation first crosses and remains below 1 m s^{-1} for one month and the difference (in days) between the model runs and the NCEP/NCAR reanalysis.

[14] Immediately apparent from Figure 2a is the fact that the peak in the 50 hPa zonal wind standard deviation during spring/early summer is much broader in the simulations than in the reanalysis. In the simulations that include ozone depletion, the maximum stratospheric variability extends approximately one month later than the reanalysis. This increase results from the delayed westerly stratospheric basic state that allows the propagation of tropospheric wave activity into the stratosphere. Thus, the delayed polar vortex breakdown increases the period when the stratosphere is dynamically coupled to the troposphere, thereby increasing the length that stratospheric circulation changes resulting from ozone variations impact the troposphere. As a result, the negative correlations seen in Figure 1 at positive lags in simulations that include ozone depletion are much larger than observed. Additionally, the lengthened period with stratospheric variability may also increase the SAM persistence; see *Baldwin et al.* [2003]. This is clear in observations, where the maximum stratospheric variance in the reanalysis occurs from October to January, with the peak just before December, consistent with the maximum in the Marshall autocorrelation (Figure 2b). Although the individual peaks in stratospheric vortex variability do not precisely align with the maximum SAM persistence in the model as shown by *Baldwin et al.* [2003], the SAM persistence is still strongly related to the stratospheric variability in these simulations. Here, the strength of the SAM persistence depends on the length of maximum stratospheric variability, with significant autocorrelations at longer lags in the simulations with prolonged stratospheric variability. Thus, prolonged stratospheric vortex variability in the GEOS CCM leads to the increased persistence of the ozone-SAM correlations in Figure 1 by increasing both the dynamic stratosphere-troposphere coupling and the SAM persistence.

4. Discussion

[15] The paper has examined the intra-annual link between total column ozone and the SAM throughout the year using the longest reliable observations available, and then evaluated the simulation of these links in the GEOS CCM. The analysis presented here can be further developed to aid evaluation of CCMs, where these important chemistry-climate interactions are simulated. Lag correlations (as in Figure 1) between ozone and SAM provide a process-oriented diagnostic that can identify model biases and their impacts on the tropospheric circulation; understanding these biases is important to assess the reliability of future climate projections made by the CCMs. From the current evaluation, the GEOS CCM captures many of the features of the observed ozone-SAM links, but it does over-predict the link between spring ozone and the summer SAM. This deficiency is related to the prolonged variability of the polar stratospheric vortex, which results from a combination of too much dynamical variability in late winter and a delayed vortex breakdown during spring, biases common among CCMs. The simulated impact of a delayed vortex breakdown on the SAM persistence is an example of the dependence of tropospheric variability on the stratospheric basic state and illustrates the importance of a correct simulation of the stratospheric basic state and its change.

[16] The results also increase the understanding of ozone-SAM links, as they represent potential climate feedbacks not previously considered. Although it is well documented that ozone variability is associated with tropospheric SAM variability a few months later, it is also apparent from these results that austral spring stratospheric wave driving impacts the SAM and polar ozone variability several months later. This suggests that reliable simulations of the stratospheric wave driving are required in order to correctly simulate not only the rate of ozone recovery (and depletion), but also to simulate the resulting tropospheric SAM variations. As CCMs fully account for these dynamics better than models with prescribed ozone variability, CCMs will serve as a valuable tool for predicting future circulation changes across the Southern Hemisphere [*Perlwitz et al.*, 2008; *Son et al.*, 2008].

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