Improved seasonal forecast using ozone hole variability?

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[1] Southern Hemisphere (SH) climate change has been partly attributed to Antarctic ozone depletion in the literatures. Here we show that the ozone hole has affected not only the long-term climate change but also the interannual variability of SH surface climate. A significant negative correlation is observed between September ozone concentration and the October southern annular mode index, resulting in systematic variations in precipitation and surface air temperature throughout the SH. This time-lagged relationship is comparable to and independent of that associated with El Niño-Southern Oscillation and the Indian Ocean Dipole Mode, suggesting that SH seasonal forecasts could be improved by considering Antarctic stratospheric variability. **Citation:** Son, S.-W., A. Purich, H. H. Hendon, B.-M. Kim, and L. M. Polvani (2013), Improved seasonal forecast using ozone hole variability?, *Geophys. Res. Lett.*, *40*, 6231–6235, doi:10.1002/2013GL057731.

1. Introduction

[2] The Antarctic ozone hole has been identified as one of the most important driving forces of Southern Hemisphere (SH)-summer climate change in the late twentieth century [e.g., *Thompson et al.*, 2011, and references therein]. The dramatic loss of ozone in the Antarctic stratosphere in spring has caused, for instance, summertime sea level pressure to decrease in high latitudes and to increase in midlatitudes over the decades [*Perlwitz et al.*, 2008; *McLandress et al.*, 2010; *Polvani et al.*, 2011; *Thompson et al.*, 2011]. Although the mechanism is not well understood, this seasonally delayed sea level pressure change highly resembles the positive phase of the southern annular mode (SAM), indicating that ozone hole-induced climate change has strongly projected onto the internal variability of the SH extratropics.

[3] While the Antarctic ozone hole has been widely examined in the context of climate change, its surface impact on intraseasonal to interannual timescales has received little attention. On intraseasonal timescales, it is known that the sudden breakdown of the stratospheric polar vortex (and consequently the ozone hole), so-called stratospheric sudden warming (SSW) events, can influence the wintertime surface climate for up to 3 months [*Baldwin and Dunkerton*, 2001]. Although such events are common in the Northern Hemisphere, they are very rare in the SH, as the polar vortex is too strong and tropospheric wave driving too weak. As such, only a weak hint of a tropospheric response to stratospheric disturbances has been observed in the SH, with the exception of the 2002 SSW event [e.g., *Thompson et al.*, 2005].

[4] In contrast to rather weak intraseasonal variability, interannual variability of the springtime ozone hole is significantly large [*Salby et al.*, 2011]. However, their impact on surface climate has not been examined in detail. In this study we show that the early-spring polar stratospheric disturbances modulate the SH surface climate in a major way with an associated time lag. This differs from previous studies that have related interannual variability of the timing of stratospheric final warming with tropospheric circulation anomalies [*Black and McDaniel*, 2007]. It also differs from intraseasonal downward coupling associated with extreme stratospheric events that occur sporadically from August to November [*Thompson et al.*, 2005].

2. Data and Method

[5] The temporal variability of the ozone hole, hereafter referred to as the O_3 index, is quantified by integrating National Institute of Water and Atmospheric Research ozone data (version 2.8 patched data) [*Bodeker et al.*, 2005] over 63°S to the South Pole with an area weight. The O_3 index is computed for all months except May–August when satellite observations are lacking because of polar night. Even in September, polar cap ozone is integrated only from 63°S to 77°S because of polar darkness over higher latitudes. The interannual variability of the ozone hole, the O_3-dt index, is then defined by removing the slowly varying component or nonlinear trend from the O_3 index. Following *Salby et al.* [2011], the slowly varying component is derived by second-order polynomial fitting. Although not shown, overall results are insensitive to the choice of fitting function.

[6] The O_3 and O_3-dt indices are correlated with meteorological fields in the free atmosphere and surface. Meteorological variables examined in this study include the station-based SAM index [*Marshall*, 2003], polar cap geopotential height anomalies derived from European Centre for Medium Range Weather Forecasts Re-Analysis (ERA)-Interim data [*Dee et al.*, 2011], station-based precipitation and temperature data throughout the SH archived at the Climate Research Unit (CRU) of University of East Anglia [*Jones et al.*, 2012], and high-resolution Australian

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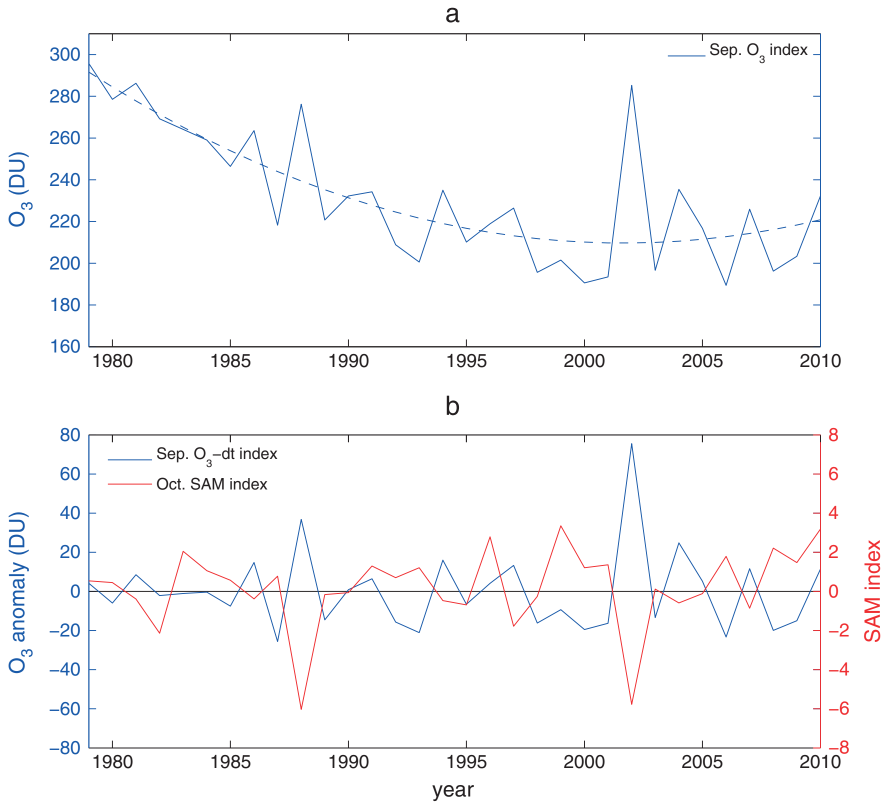

Figure 1. Time series of (a) September O_3 and (b) September O_3-dt and October SAM indices. In Figure 1a, the slowly varying component (dashed line) is defined by second-order polynomial fitting of the O_3 index.

regional analyses [*Hendon et al.*, 2007]. For CRU data, only stations with data availability of at least 75% of the analysis period are used [*Gillett et al.*, 2006]. In all analyses, monthly mean data are used for the time period of 1979–2010, unless specified otherwise.

3. Results

[7] The time series of the September O_3 index and its slowly varying component are presented in Figure 1a (see Figure S1 in the supporting information for other months). A strong interannual variability, on top of a distinct declining trend, is evident. The detrended time series, O_3-dt index, in fact shows that year-to-year variability, ranging from ± 20 DU, is comparable in magnitude to the long-term trend (Figure 1b). In 2002, the O_3 index exhibits an extremely high value, almost equivalent to the preozone hole era. This resulted from a SSW event; the only one to have occurred in the SH since the 1960s [*Roscoe et al.*, 2005]. In the course of this event, cold and ozone-deficient polar air, which was trapped within the polar vortex, was rapidly split into two parts as the vortex broke down and was replaced by warm and ozone-rich air from the midlatitudes.

[8] The interannual variability of ozone hole is known to be largely driven by extratropical wave forcing in the upper troposphere and lower stratosphere [*Salby et al.*, 2011]. More specifically, years of higher ozone concentration in spring are typically associated with stronger wave forcing in winter: Stronger wave forcing tends to cause warmer temperatures in the Antarctic stratosphere (and colder temperatures in the tropical stratosphere) by enhancing stratospheric mean meridional circulation (see dipolar pattern in Figure S2). The warmer polar temperatures then reduce the formation of polar stratospheric clouds in winter that are crucial for springtime ozone depletion as discussed by *Salby et al.* [2011]. Enhanced mean meridional circulation also likely transports more ozone from the tropics to the pole, resulting in a higher ozone concentration in spring.

[9] The statistical relationship between the O_3 and SAM indices are summarized in Table 1 in terms of correlation coefficients (see Table S1 for an extended table). Two distinct maxima emerge: an almost instantaneous correlation in October and a seasonally delayed correlation in January. No significant correlations, however, are observed between spring time O_3 and the November–December SAM indices. By removing the slowly varying component from the O_3 index, correlation coefficients are substantially increased in October (Table 1 (bottom)). In sharp contrast, the January SAM index shows essentially no correlation with the springtime O_3-dt index. This suggests that the October correlation is largely due to the interannual variability of the ozone hole, especially that over eastern Antarctica (Figure S3), whereas the January correlation is primarily due to the long-term trend. The latter is in good agreement with previous studies: that is, tropospheric response to the Antarctic ozone depletion is delayed for one season. Note that in Table 1, the SAM index is not detrended as its trend is quite weak and detrending does not impact the strength of correlations (Table S1).

[10] Table 1 also reveals the presence of a time-lagged correlation between the stratosphere and troposphere in spring, i.e., the maximum anticorrelation of –0.70 occurs

Table 1. Cross Correlation of (top) O_3 and (bottom) O_3-dt Indices Against the SAM Index, for the Period 1979–2010 (1980–2011 for the SAM Index in January–March)[a]

O_3 \ SAM	Sep	Oct	Nov	Dec	Jan	Feb
Sep	–0.17	–0.48[c]	–0.09	–0.13	–0.50[c]	–0.15
Oct	–0.27	–0.46[c]	–0.18	–0.29	–0.50[c]	–0.21
Nov	–0.33	–0.51[c]	–0.20	–0.31	–0.49[c]	–0.33
O_3-dt \ SAM						
Sep	–0.23	**–0.69**[c]	–0.16	0.03	–0.10	–0.08
Oct	–0.32	**–0.66**[c]	–0.29	–0.21	–0.17	–0.18
Nov	–0.40[b]	**–0.58**[c]	–0.26	–0.25	–0.19	–0.32

[a]Here the O_3 index is defined as the monthly mean total column ozone concentration integrated poleward of 63°S. Its detrended component, O_3-dt, is obtained by removing the slowly varying component from the raw data (see Figure 1a). Only September to November are considered as O_3 and O_3-dt indices show maximum year-to-year variability in these months.

[b]Correlation statistically significant at the 95% confidence level.

[c]Correlations statistically significant at the 99% confidence level. The values which are significant at the 99.9% confidence level are further denoted in bold. A two-tailed t test is used to test significance.

between the September O_3-dt index and the October SAM index. This time-lagged coupling is not simply dictated by stratospheric extreme events. Even without the 2002 SSW event, the correlation coefficient is –0.54, which is statistically significant at the 99% confidence level. By analyzing station data at the South Pole, *Fogt et al.* [2009] also found a similar result, namely, that September–October ozone variability leads SAM-index variability on interannual timescales (see their Figure 1a). However, in their study, November–December ozone variability further lags behind the SAM-index variability for up to 4 months. This subtle difference is likely caused by different definition and smoothing: *Fogt et al.* [2009] defined interannual variability of the South Pole ozone concentration by removing a linear trend and smoothed the resulting time series with 1-2-1 filter. Local observations versus satellite observations

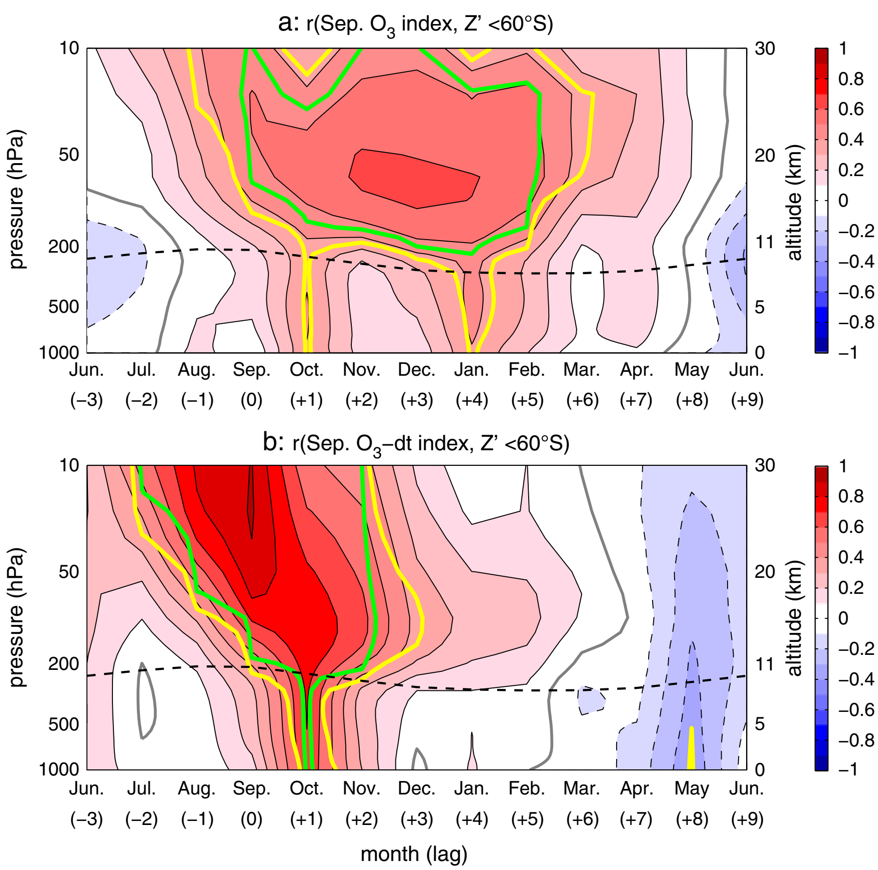

Figure 2. Lag correlation of polar cap geopotential height anomaly Z', integrated poleward of 60°S, with (a) September O_3 and (b) September O_3-dt indices. The contour interval is 0.1, and the zero line is denoted by the thick grey line. The correlation coefficients that are statistically significant at the 95% and 99% confidence levels are bound by yellow and green contour lines, respectively. A two-tailed t test is used to test significance. The approximate location of the thermal tropopause, the boundary between the stratosphere and troposphere, is denoted by the thick black dashed line.

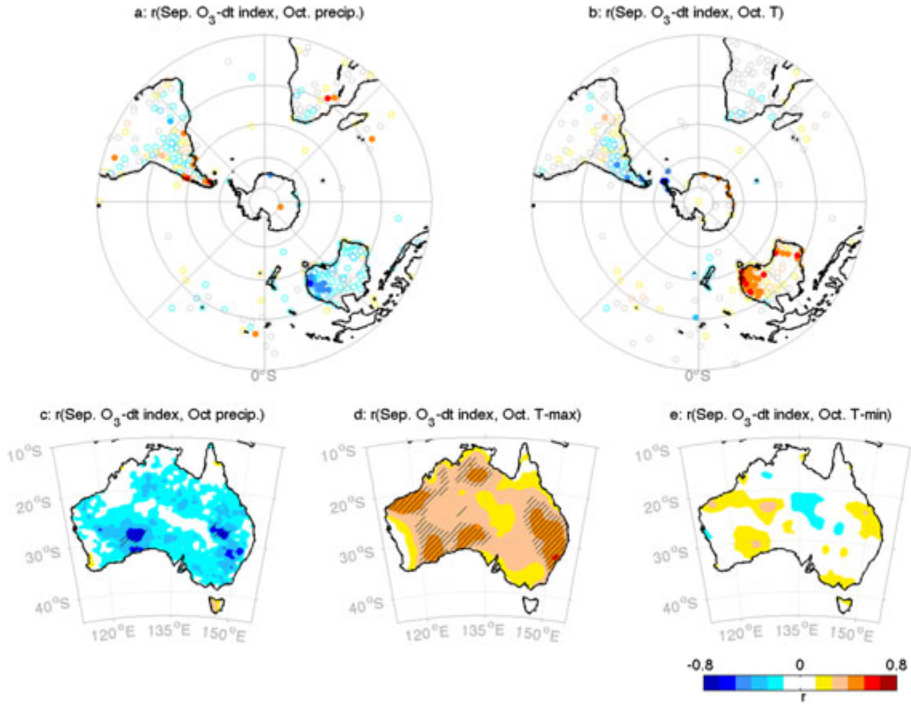

Figure 3. Lag correlation maps between the September O_3-dt index and October meteorological fields. (a) CRU precipitation; (b) CRU daily mean temperature; (c) Australian precipitation; (d) Australian daily maximum temperature; and (e) Australian daily minimum temperature. For CRU data, only stations with data availability of at least 75% of the analysis period are used. The correlation coefficients that are statistically significant at the 95% confidence level are shown by filled circles in Figures 3a and 3b and hatched in Figures 3c–3e. A two-tailed *t* test is used to test significance.

covering the whole polar vortex over differing periods may also account for the difference.

[11] The downward coupling is further illustrated in Figure 2 where the September O_3 and O_3-dt indices are correlated with the polar cap geopotential height anomaly, Z', integrated south of 60°S in each month. Consistent with Table 1, the September O_3 index is significantly correlated with tropospheric Z' in October and January (Figure 2a). The latter correlation, however, disappears when the slowly varying component is removed from the O_3 time series (Figure 2b). A similar downward coupling is also evident in pentad data (Figure S4), indicating that this is not an artifact of monthly mean data analysis.

[12] Figure 2b also reveals that the September O_3-dt index is highly correlated with the July–August Z' at 10 hPa. This confirms the fact that springtime ozone concentration is largely controlled by late winter wave activities in the lower stratosphere [*Salby et al.*, 2011] and indicates an extended link between stratospheric disturbances and October SAM-index variability. In fact, the October SAM index is significantly anticorrelated with August Z' at 10 hPa (Table S2), although the maximum anticorrelation is still found with the September Z'. This result suggests that stratosphere-troposphere coupling in southern high latitudes is modulated not only by the ozone hole itself but also by the related dynamic and thermodynamic processes in the lower stratosphere. The relative importance of chemistry, dynamics, and thermodynamics is, however, difficult to assess as these factors are intimately related to one another.

[13] The above result suggests that the late winter to early spring stratospheric disturbances could affect surface weather systems. This is expected as the SAM is linked to, for example, surface temperature and precipitation variations across the SH through large-scale atmospheric circulation changes [*Gillett et al.*, 2006; *Son et al.*, 2009; *Thompson et al.*, 2011]. Figures 3a and 3b present the relationship between the September O_3-dt index and October precipitation and temperature on interannual timescales (see also Figure S5). Although the limited spatial coverage of weather stations hinders recognition of this relationship over the entire SH, the detected precipitation and temperature correlations are consistent with what has been previously reported to occur during the negative phase of the SAM index [*Gillett et al.*, 2006; *Hendon et al.*, 2007].

[14] High-resolution Australian analysis further reveals that while a statistically significant relationship is observed in the precipitation and daily maximum temperature fields (Figures 3c and 3d), no correlation is found in the daily minimum temperature field (Figure 3e). This result suggests that the pronounced correlation in daily mean surface temperature (Figure 3b) is mainly due to daytime temperature change. The similarity in correlation maps between precipitation and daily maximum temperature further suggests that daytime temperature is being modulated by cloud cover change associated with precipitation. A high SAM index, resulting from low ozone concentration, is typically associated with anomalous surface easterlies in the midlatitudes that enhance moisture transport from the ocean to eastern Australia [*Hendon et al.*, 2007]. It is also linked to anomalous ascent on the poleward side of the Hadley circulation [*Kang et al.*, 2011]. These features cause more rainfall across subtropical Australia, especially in the east, and thus less

daytime insolation and colder maximum surface temperature in the years of low O_3-dt index.

[15] What causes the time-lagged downward coupling? Although the detailed mechanism(s) remains to be determined, it in part results from the long-term memory of the ozone hole. September is the onset month for the October ozone hole, whose variability is strongly coupled with tropospheric circulation. This explains why the November O_3-dt index is strongly correlated with the October SAM index (Table 1), although upward wave forcing also likely contributes to this correlation [*Salby et al.*, 2011]. It is, however, questionable why downward coupling is pronounced in October but not in November when the Antarctic ozone hole exhibits maximum year-to-year variability in association with stratospheric final warming (Figure S1, Table S3). It is also unclear whether ozone chemistry is crucial to explain downward coupling. Although such coupling has been qualitatively reproduced by a chemistry-climate model simulation [*Fogt et al.*, 2009], it is still plausible that ozone variability in the observations and models is merely a passive response to the circulation. Further studies using chemistry-climate model are needed.

[16] The findings of this study suggest that seasonal forecast of the SH extratropical climate could be improved by considering the Antarctic lower stratospheric variability in springtime. This would require a stratosphere-resolving climate model with reliable stratospheric conditions or interactive chemistry. Although such a model might be computationally expensive, its benefit on forecast improvement is likely at least as good as tropical sea surface temperature (SST) variabilities, such as El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) mode, which have traditionally been viewed as the leading drivers of predictable climate variability in the SH [*Risbey et al.*, 2009]. In terms of lag-correlation coefficients, daily maximum temperature in October shows a stronger correlation with the September O_3-dt index than with ENSO or IOD indices, whereas precipitation is comparably correlated (see Figures S6 and S7). More importantly, climate variability associated with the Antarctic ozone hole is independent from that associated with tropical SST (Table S4).

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