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Modulation of Antarctic vortex composition by the quasi-biennial oscillation

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Abstract Using a decade of Aura Microwave Limb Sounder observations, we show distinctly different N_2O distributions in Southern Hemisphere winter that depend on the phase of the quasi-biennial oscillation (QBO). Composites of the nitrous oxide (N_2O) anomalies calculated for westerly and easterly phases show that QBO-generated variability originating in the subtropical middle stratosphere fills the midlatitude surf zone by late winter. After the spring vortex breakup, the anomaly is transported to the Antarctic where it remains until the next vortex forms in fall. Trapped in the newly formed vortex, the anomaly descends in isolation through fall and winter, arriving in the Antarctic lower stratosphere in September—about 1 year after it formed. This transport pathway explains previously reported variability of N_2O and inorganic chlorine (Cl_y) inside the Antarctic vortex and demonstrates that the middle stratosphere QBO affects ozone depletion by modulating Antarctic Cl_y.

Key Points:
- The QBO creates N_2O anomalies in the winter southern middle stratosphere
- The N_2O anomalies reach the Antarctic lower stratosphere 1 year later
- The QBO causes chlorine variability that impacts Antarctic ozone depletion

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1. Introduction

The quasi-biennial oscillation (QBO) is a pattern of alternating easterly and westerly zonal wind regimes in the tropical lower and middle stratosphere with a variable period averaging 28 months. It is driven by a broad spectrum of vertically propagating Kelvin and Rossby gravity waves [*Lindzen and Holton*, 1968; *Holton and Lindzen*, 1972; *Dunkerton*, 1997] that cause the downward propagation of alternating wind regimes, i.e., the westerly and easterly phases. Because of geostrophic adjustment, the wave-induced QBO vertical wind shear drives an associated meridional circulation such that, on the equator, a downward, adiabatically warmed perturbation corresponds to westerlies aloft and easterlies below (i.e., westerly shear) and an upward, adiabatically cooled perturbation corresponds to easterlies aloft and westerlies below (i.e., easterly shear). This QBO-generated perturbation in the equatorial vertical motion affects trace gas distributions, making it the primary source of variability in the tropical stratosphere [*Baldwin et al.*, 2001].

A meridional circulation develops between the tropics and subtropics to maintain the thermal wind balance between the descending QBO wind shear and its temperature anomaly [*Plumb and Bell*, 1982; *Baldwin et al.*, 2001]. It is referred to in the literature as the QBO direct, meridional, or secondary circulation. The descending easterly shear (cold anomaly) causes increased tropical upwelling balanced by subtropical descent. Tropical outflow at the levels of maximum easterly winds and equatorward convergence at levels with tropical westerlies complete the circulation [*Kinnersley*, 1999; *Choi et al.*, 2002]. The opposite meridional circulation develops during descending westerly shears. While the meridional circulation was originally described as a two-celled structure [e.g., *Plumb and Bell*, 1982], horizontal momentum advection from the summer to winter hemisphere requires a larger winter temperature anomaly to maintain thermal wind balance, resulting in a much stronger meridional circulation in the winter hemisphere [*Jones et al.*, 1998; *Kinnersley*, 1999].

In the low latitudes, the meridional circulation acts on local trace gas gradients to modify constituent distributions [*Gray and Chipperfield*, 1990]. Analyses of column ozone [e.g., *Randel and Wu*, 1996; *Kinnersley and Tung*, 1998], of H_2O and CH_4 [e.g., *Randel et al.*, 1998; *O'Sullivan and Dunkerton*, 1997; *Gray and Russell*, 1999], and of aerosols [e.g., *Trepte and Hitchman*, 1992; *Hitchman et al.*, 1994] have revealed patterns associated with the QBO phases that are explained by differences in tropical and subtropical vertical advection and by strong cross-equatorial circulation into the winter hemisphere during easterlies [*Jones et al.*, 1998; *Kinnersley*, 1999].

Although the QBO meridional circulation spans the equator to ~30°, its effect on composition can be found at higher latitudes. Several studies have shown that QBO-driven column O_3 anomalies originating in the southern subtropics in early winter reach 60°S by the early spring [*Gray and Ruth*, 1993; *Randel and Wu*, 1996; *Kinnersley and Tung*, 1998]. Some 2-D model studies, e.g., *Gray and Pyle* [1989] and *Gray and Dunkerton* [1990], argued that planetary wave-driven mixing transported the subtropical anomalies poleward, and *Kinnersley* [1999] showed that by adding planetary wave drag to a simple 2-D model, they could extend the meridional circulation cell to midlatitudes. In a comprehensive study investigating the mechanism for middle- and high-latitude ozone anomalies, *Kinnersley and Tung* [1999] concluded that the direct QBO circulation was responsible for O_3 anomalies to 50°S, but beyond that, the cause was ascribed to changes in the mean meridional circulation from the modulation of planetary wave (PW) fluxes by the latitude of the critical line (i.e., the Holton-Tan effect). *Holton and Tan* [1980] proposed that the presence of a zonal wind critical line in the winter hemisphere during the easterly phase (QBO-E) focused PW activity toward low latitudes, increasing poleward momentum fluxes. Studies of Antarctic ozone loss rates during the 1980s found biennial variability that appeared attributable to the QBO via a Holton-Tan effect on polar temperature [*Poole et al.*, 1989; *Lait et al.*, 1989], with greater springtime losses occurring during (colder) westerly (QBO-W) years. *Hofmann et al.* [1997], however, found no QBO signature in the Antarctic column ozone minima or in South Pole lower stratospheric temperatures after 1989.

In this study, we use Aura Microwave Limb Sounder (MLS) N_2O observations from 2004 to 2014 to show that the QBO modulates Southern Hemisphere (SH) composition, causing subtropical anomalies which are then transported by the Brewer Dobson circulation to the polar lower stratosphere. By tracking the N_2O middle stratosphere anomalies, i.e., those above ~30 hPa (~22 km or ~600 K), we identify a previously unrecognized transport pathway for QBO-generated trace gas variability to reach the Antarctic lower stratosphere over the course of 1 year. This transport pathway explains the composition variability in the lower stratospheric vortex reported by *Strahan et al.* [2014]. Building on our recent results, we establish how the QBO in the middle stratosphere directly affects Cl_y variability in the Antarctic lower stratosphere, impacting Antarctic ozone depletion and the detection of ozone recovery. This newly identified transport pathway illuminates the far-reaching role played by the QBO in the SH.

2. Methods and Data Sets

Aura MLS version 3.3 level 2 measurements of N_2O and temperature from 3 to 100 hPa are used in this analysis. The accuracies of version 3.3 N_2O and temperature are unchanged from version 2.2 [*Livesey et al.*, 2011; *Lambert et al.*, 2007]. Both have vertical resolution of ~4 km. MLS temperatures have a -1 K bias in the stratosphere with respect to correlative measurements. MLS temperatures are used to calculate N_2O zonal monthly means on potential temperature (isentropic) surfaces. The estimated 2σ accuracy of N_2O data is 9–13% for levels 2.15–68 hPa and 25% for 100 hPa. The primary band for MLS N_2O retrievals failed on 6 June 2013, and subsequent profiles retrieved using a different band are noisier and ~30% high biased at 100 hPa compared to measurements using the primary band. Much smaller biases are found at 68 hPa (5–10%) and above ($<5\%$) [*Livesey et al.*, 2015]. No 100 hPa data are used in the analysis after May 2013. MLS samples a latitude range of 82°S–82°N. Spearman's rank is used for reported correlations and their confidence levels.

The QBO phase on isentropic surfaces was calculated with temperature and zonal mean zonal winds from the Modern Era Retrospective Analysis for Research and Applications (MERRA) [*Rienecker et al.*, 2011]. QBO phase-dependent composites of N_2O distributions are determined by the direction of the tropical winds near winter solstice (June/July average, 10°S–10°N at 650 K (~20 hPa)). The years with a QBO westerly phase at these levels at winter solstice are 2004, 2006, 2008, and 2013; all others in the 2004–2014 period are easterly.

3. The Impact of the QBO on N_2O in the Southern Stratosphere

3.1. The QBO Meridional Circulation and Midlatitude Anomalies

N_2O is a long-lived trace gas with surface sources and middle and upper stratospheric losses. Figures 1a and 1b show QBO-W and QBO-E composites of the N_2O zonal monthly mean latitude-height structure in Southern Hemisphere winter. The zero wind line (solid) and easterly zonal wind contours (dashed) near

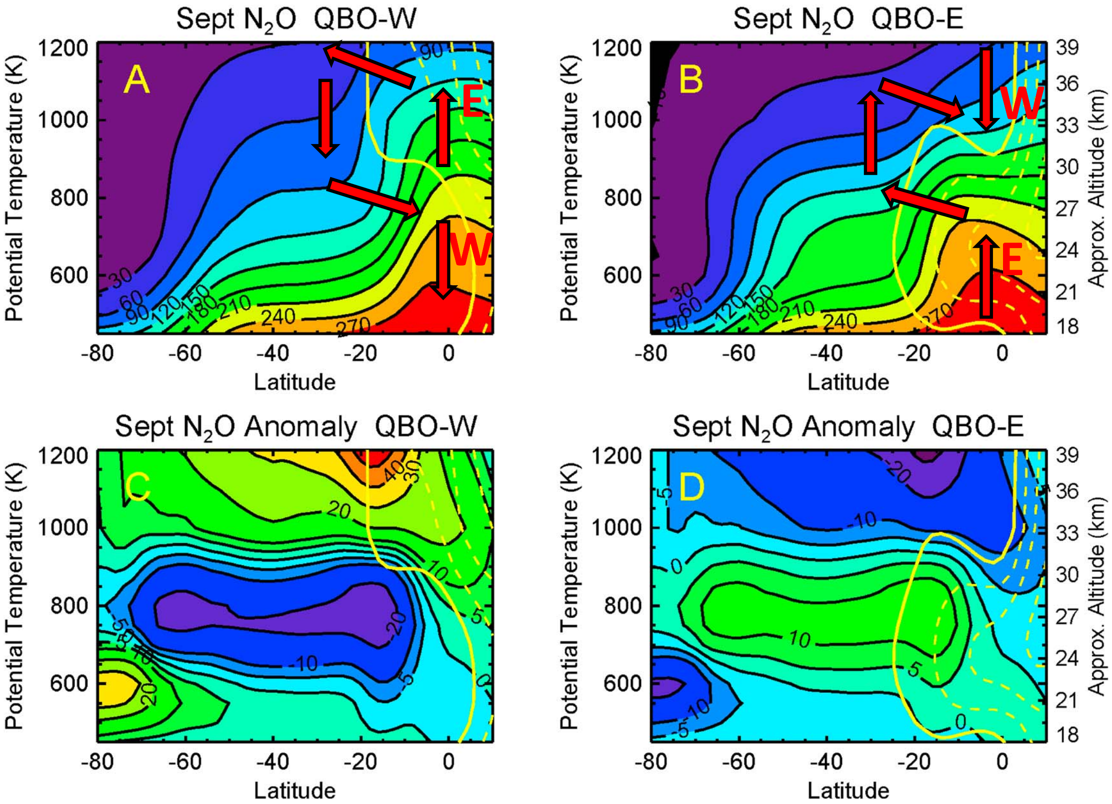

Figure 1. Composites of MLS September zonal mean N$_2$O in ppbv for (a) QBO-W years and (b) QBO-E years. The QBO phase is identified by the direction of the zonal mean wind 10°S–10°N at 650 K near solstice (June–July). Westerly years are 2004, 2006, 2008, and 2013; easterly years are 2005, 2007, 2009–2012, and 2014. Composites of the anomalies calculated as a percentage difference from the 10 year mean MLS N$_2$O September mixing ratios are shown for (c) QBO-W years and (d) QBO-E years. The zero wind line is shown in solid yellow, and easterly zonal winds are shown as yellow dashed lines. The red arrows in Figures 1a and 1b indicate the direction of the QBO meridional circulation in the middle stratosphere during each phase.

solstice when the meridional circulation is strongest are shown in yellow. The steepest subtropical slopes of N$_2$O isopleths are found from 600 to 800 K in the QBO-E composite and from 800 to 1000 K in the QBO-W composite where tropical winds are becoming easterly. This is consistent with the relationship between tropical winds and the observed subtropical CH$_4$ gradient reported by *Gray and Russell* [1999].

The descending wind shears drive a meridional circulation between the tropics and 20°–30° [*Plumb and Bell*, 1982; *Baldwin et al.*, 2001; *Choi et al.*, 2002]. The red arrows in Figure 1 illustrate the sense of this circulation for descending easterly and descending westerly winds, which modify the N$_2$O distribution by acting on the N$_2$O vertical and horizontal gradients [*O'Sullivan and Dunkerton*, 1997]. The circulation's impact is shown by the N$_2$O anomalies with respect to the 10 year MLS mean (expressed as percentage difference), shown as QBO-W and QBO-E composites in Figures 1c and 1d. These spatial patterns are not present in fall before the meridional circulation cell shifts to the SH. In the subtropics, descent and convergence at the level of the tropical westerlies creates a negative anomaly (Figure 1c). In the tropics, the enhanced upwelling of the QBO-E shear acting on the N$_2$O vertical gradient creates a positive anomaly, while enhanced downwelling in the QBO-W shear creates a negative anomaly. A positive subtropical anomaly in the QBO-E is created by enhanced tropical upwelling plus poleward advection out of the tropics. These composites are consistent with the QBO-dependent H$_2$O and CH$_4$ subtropical distribution differences reported by *Gray and Russell* [1999]. Their analysis showed that advection by the QBO meridional circulation was the primary mechanism for the effects on subtropical trace gas distributions from 500 to 750 K. Cross-equatorial flow toward the winter hemisphere during the QBO-E contributes to the positive subtropical anomaly [*Jones et al.*, 1998] and explains the flat isopleths in the middle stratosphere between 10°N and 15°S in Figure 1b.

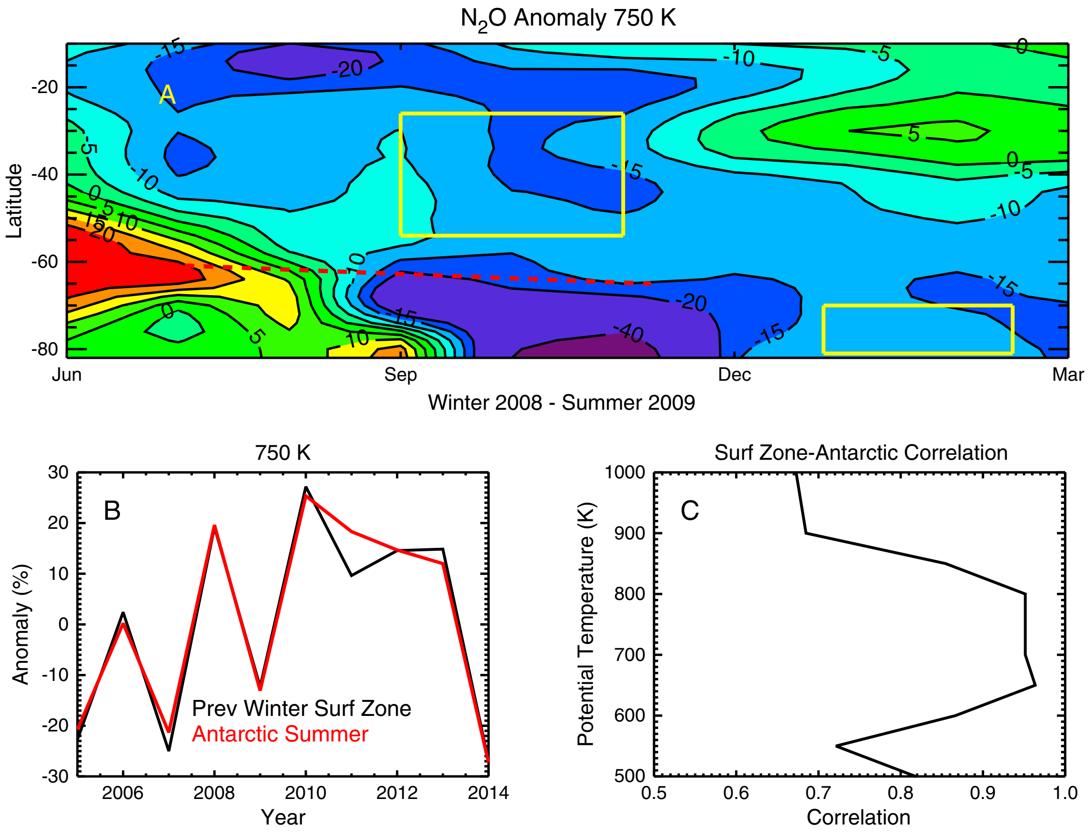

Figure 2. (a) Latitude-time contour of the monthly mean MLS N_2O anomaly on the 750 K isentropic surface from southern winter (June 2008) through summer (March 2009). The dashed red line indicates the approximate edge of the polar vortex. (b) Time series of late winter surf zone N_2O anomalies (26–54°S), 2004–2013, and Antarctic (70–82°S) summer anomalies, 2005–2014, on the 750 K potential temperature surface. The locations of these regions are identified by the yellow boxes in Figure 2a. (c) Correlations between the surf zone and Antarctic anomaly time series as a function of potential temperature.

The QBO meridional circulation operating between ~0° and 30°S begins to form low-latitude N_2O anomalies in June. By September they are fully developed and appear well mixed from 15°S to 70°S. This region, known as the "surf zone" [*McIntyre and Palmer*, 1983, 1984], develops in winter when planetary wave breaking around the polar vortex causes irreversible quasi-isentropic mixing between the low latitudes and the vortex (~70°S), flattening trace gas isopleths. The lack of horizontal gradients in the anomalies suggests that surf zone mixing plays an important role in transporting subtropical anomalies to higher latitudes in both phases. In addition, the latitudes of constant anomalies span the same range in both composites. This indicates that in spite of planetary wave modulation by the QBO (i.e., the Holton-Tan effect), there is sufficient wave-driven mixing to homogenize the surf zone in both phases of the QBO. These results support the argument of *Gray and Russell* [1999] that QBO phase-dependent differences in isentropic mixing, arising through the Holton-Tan effect, are not the primary mechanism for the QBO influence on the subtropical middle stratosphere.

3.2. Transport of Anomalies to the Antarctic Middle and Lower Stratosphere

Before the Antarctic vortex breaks down, N_2O anomalies are confined to the midlatitude surf zone by steep potential vorticity gradients at the edge of the polar vortex [*McIntyre and Palmer*, 1983]. This is shown in Figure 2a with an example of the negative N_2O anomaly in 2008 on the 750 K surface, a level near the maximum anomaly. The anomaly (blue) is fairly well mixed in September and October between the subtropics and the polar vortex; the approximate location of the steepest potential vorticity gradients is shown in red. Planetary wave activity reaches a maximum in early southern spring [*Randel and Newman*, 1998], leading to the vortex breakup in early December followed by mixing between the surf zone and polar air masses [*Waugh*, 1996]. The anomaly is largely unchanged by mixing with polar air because the area of the surf zone anomaly, ~10–70°S, is more than 10 times the area of 70–90°. Similar transport of

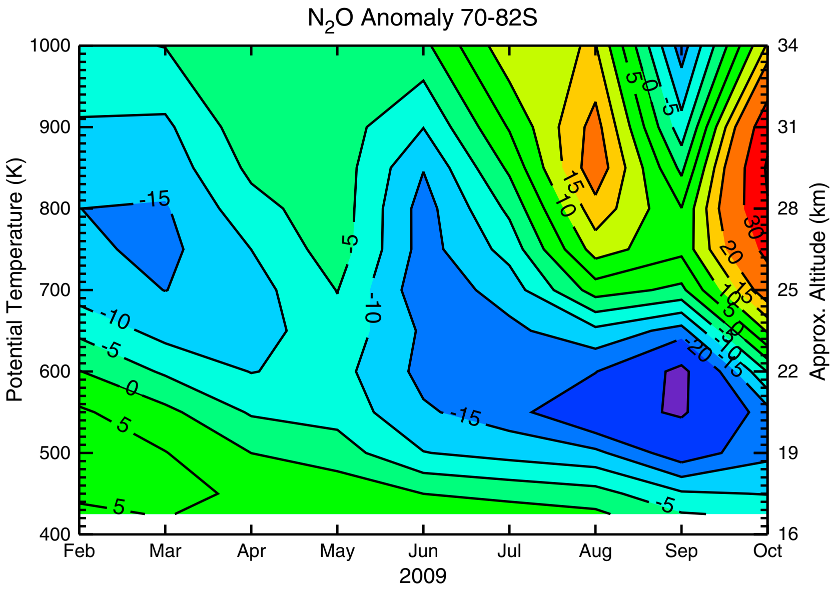

Figure 3. Height-time contours showing the descent of the N_2O Antarctic anomaly (70–82°S) from late summer to the end of winter 2009.

southern subtropical column ozone anomalies to polar latitudes between spring and summer was reported by *Kinnersley and Tung* [1998].

The transport of the winter surf zone N_2O anomaly to the summer polar stratosphere shown here for 2008 is typical. Figure 2b shows the nearly 1:1 relationship between the late winter surf zone anomaly (averaged 26°–54°S, in black) and the Antarctic summer anomaly (averaged 70°–82°S, in red) on the 750 K surface for 2004–2014; these regions are identified by the yellow boxes in Figure 2a. Isentropic transport of the QBO-driven anomalies to the Antarctic occurs over a thick layer in the middle stratosphere. Figure 2c shows that the correlation between the winter surf zone and Antarctic summer time series is greater than 0.8 from 600 to 850 K; all correlations from 500 to 1000 K are significant above the 95% confidence level. The correlations are insensitive to ±5° variations in the surf zone latitudes chosen. The high correlations over a deep layer of the middle stratosphere are consistent with the well-known role of springtime planetary wave-driven quasi-isentropic transport [e.g., *Plumb*, 2002].

The N_2O anomalies that reach polar latitudes in December persist through the summer. Easterly winds in the summer extratropical stratosphere block the upward propagation of planetary waves, resulting in weak circulation and mixing. In the Antarctic summer middle stratosphere, photochemical losses of N_2O are small, less than 10%, and do not affect the anomaly (a percentage deviation from the mean). In fall the air cools as the Sun leaves the Antarctic, the winds become westerly, and the polar vortex forms. Steep potential vorticity gradients develop at the edge of the nascent vortex, creating a strong barrier to mixing with the midlatitudes. The anomaly that originated half a year earlier in the midlatitudes becomes trapped inside the vortex.

Isolated inside the vortex, polar air experiences strong diabatic cooling and descent in fall and early winter [*Fisher and O'Neill*, 1993; *Plumb*, 2002]. Figure 3 shows descent of a negative Antarctic N_2O anomaly from 700–900 K in February to 450–600 K by September 2009. The Antarctic anomalies are calculated from zonal monthly means at latitudes generally inside the vortex (70–82°S); MLS does not sample poleward of 82°. Similar descent rates are observed for each year of MLS observations for both positive and negative anomalies. The descent rate of the anomaly shown here is in excellent agreement with the descent of isentropic surfaces inside the Antarctic vortex calculated by *Rosenfield et al.* [1994]. We choose September for the correlation calculation because winter descent is essentially complete but the vortex is not yet weakened by spring wave activity.

The N_2O anomalies reveal a path whereby low-latitude variability generated by the middle stratospheric QBO travels nearly undiminished to the Antarctic lower stratosphere. The strongest link between these regions connects the 650 K surface in the midlatitude southern winter and the 450 K surface in the Antarctic about

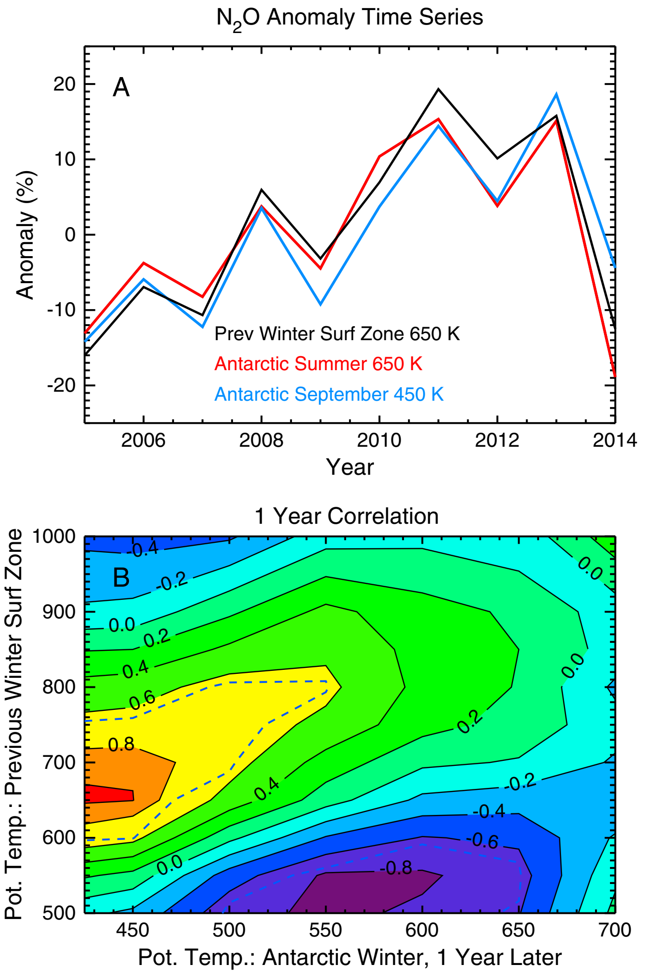

Figure 4. (a) N_2O anomaly time series from three locations: the Antarctic vortex at 450 K in September (blue), the Antarctic 650 K surface 7 months earlier (70–82°S summer, red), and the September surf zone 650 K surface 1 year earlier (black). (b) Contours of the anomaly time series correlations between isentropic surfaces in the Antarctic winter (*x* axis) and isentropic surfaces in the previous winter surf zone (*y* axis). All correlations inside the dashed blue contour are significant at greater than 95% confidence. Correlations inside the highest contour (red) are ≥0.9.

1 year later: their time series correlation is 0.9. The anomaly time series for these two regions are shown in Figure 4a along with the time series of the Antarctic summer stratosphere. The anomalies in the Antarctic lower stratosphere are opposite in sign to the surf zone anomalies (Figures 1c and 1d) because the timescale for anomaly transport to the lower stratosphere is about 1 year and because the QBO phase usually changes each year.

Transport pathways to the Antarctic vortex connect a range of isentropic surfaces. Figure 4b maps the correlations between initial isentropic surfaces in the winter midlatitude middle stratosphere and final surfaces in the Antarctic lower stratosphere 1 year later. Correlations significant with 95% or greater confidence (dashed line) are roughly coincident with the 0.6 contour. Surf zone starting levels of 600–800 K are significantly correlated with final levels of 425–550 K. The transport pathway is expected from the extratropical Brewer-Dobson circulation [e.g., *Plumb*, 2002]: (1) in spring, strong wave activity leads to the vortex breakup and isentropic mixing of midlatitude and polar air masses, and (2) high-latitude cooling in fall leads to formation of the polar vortex, where polar air descends in isolation through winter. What is unexpected is that the anomalies persist so coherently over such large spatial and temporal scales.

The Brewer-Dobson circulation drives the same seasonal transport in both hemispheres, but the Northern Hemisphere (NH) has stronger planetary wave activity and greater interannual variability unrelated to the QBO. *Kinnersley and Tung* [1998] found that high-latitude NH ozone anomalies were strongly influenced by interannual variability in PW forcing and uncorrelated with the QBO. We find correlations of up to 0.8 between the anomaly time series in the NH late winter surf zone and the Arctic in summer from 550 to 1200 K, similar to the Antarctic. However, the Arctic summer anomalies that become trapped in the winter vortex are modified by dynamical disturbances such as sudden warmings as they descend and do not survive intact to the lower stratosphere. As a result, the correlation is weak between anomalies in the northern middle stratospheric surf zone and the Arctic lower stratosphere 1 year later.

4. Consequences for QBO-Driven Composition Variability

For the period 2004–2014, we have shown that the QBO drives composition anomalies in the subtropical middle stratosphere that travel nearly undiluted to the Antarctic lower stratospheric vortex over the course of 1 year. Because the same transport processes affect all long-lived trace gases, the QBO will drive similar composition variability in species such as CH_4, chlorofluorocarbon (CFCs), and long-lived “families” including odd nitrogen (NO_y) and inorganic chlorine (Cl_y). The details of the variability depend on each species' spatial gradients in the middle stratosphere. The QBO is the source of the interannual variability of Antarctic lower stratospheric N_2O and Cl_y reported by *Strahan et al.* [2014]. Stratospheric Cl_y is declining at a mean rate of ~20 parts per trillion/yr due to the Montreal Protocol and its amendments, that is, due to the cessation of CFC emissions and the slow destruction of CFCs in the stratosphere [*Newman et al.*, 2007]. Temperature and Cl_y levels are the most important factors controlling the size of the ozone hole [*Newman et al.*, 2004]. Previously we reported that vortex Cl_y variability is nearly 10 times greater than its estimated mean decline rate; building on that result we find that the QBO is responsible for this chlorine variability. Could the QBO affect Antarctic ozone depletion in two separate ways: through vortex composition variability and through a dynamical effect on vortex temperature, i.e., the Holton-Tan effect?

Strahan et al. [2014] examined the relationship between Antarctic temperatures, Cl_y, and the ozone hole area during the past 30 years. They showed that while Cl_y levels matter to size of the ozone hole, temperature variability—and not Cl_y variability—is the main driver of area variations. They showed that year-to-year area variations are correlated with Cl_y variations only during very cold years. The September Antarctic lower stratospheric temperature has considerable interannual variability, but as shown in their Figure 6, it is not obviously quasi-biennial. *Strahan et al.* [2014] concluded that the year-to-year Antarctic Cl_y variations increase the time required to attribute ozone recovery to Cl_y reduction.

With less than a decade of observations, some studies proposed that variability in Antarctic ozone loss rates [*Lait et al.*, 1989] and in polar stratospheric cloud (PSC) coverage [*Poole et al.*, 1989] was due to the QBO modulation of polar temperature via the Holton-Tan effect. Analyzing longer data sets, *Hofmann et al.* [1997, 2009] found no QBO signal in September South Pole temperature data from 18 to 22 km after 1989. They saw periodic high ozone loss rates from 1986 to 2007 and speculated that the presence of a QBO-W phase in the previous summer increased the transport of halogens to the Antarctic. However, the periodicity they observed was not quasi-biennial and the high O_3 loss rates are explained by below average vortex temperatures in the lower stratosphere in each of those high loss years. Using the MERRA reanalysis, 1979–2013, we compared September Antarctic temperatures from 30 to 100 hPa for years with QBO-W at 50 hPa with years having QBO-E winds. The differences were small (<0.3 K) and not significantly different from zero. The QBO modulates midlatitude PW activity in winter, but it does not significantly modulate the strength or temperature of the Antarctic vortex until midspring (November) near the time of the final warming [*Baldwin and Dunkerton*, 1998]; thus, the Holton-Tan mechanism is unlikely to have any effect on vortex temperature or stability in late winter and early spring when ozone depletion occurs. We conclude that the QBO does impact Antarctic ozone depletion and it does so by modulating Cl_y levels inside the vortex. Only during very cold years can the effect of QBO modulation of chlorine on ozone hole area be distinguished from the much larger impact of temperature variability [*Strahan et al.*, 2014].

The QBO plays a large role in southern hemisphere composition variability. Future changes in its period or amplitude are likely to affect that variability and, consequently, the ability to detect a change in the mean Brewer-Dobson circulation. *Kawatani and Hamilton* [2013] calculated a significant negative trend in the QBO amplitude at 70 hPa and a significant positive trend of ~5%/decade at 15 hPa for the period 1953–2012. They attributed the trends to increased tropical upwelling caused by increasing greenhouse gases. The 15 hPa pressure level is equivalent to 750 K, the level where we find the largest N_2O anomalies. They reported no long-term trend in the QBO period; thus, the positive amplitude trend at 15 hPa implies a positive trend in the equatorial vertical wind shear. Should this trend continue, larger wind shears will lead to a stronger QBO meridional circulation and increased variability of long-lived and radiatively important long-lived gases such as N_2O, CH_4, H_2O, and the CFCs. Increased stratospheric composition variability will increase the difficulty of using long-lived trace gas measurements to detect a significant stratospheric circulation trend distinct from QBO-generated variability.

Acknowledgments
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