The Impact of Ozone-Depleting Substances on Tropical Upwelling, as Revealed by the Absence of Lower-Stratospheric Cooling since the Late 1990s

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ABSTRACT

The impact of ozone-depleting substances on global lower-stratospheric temperature trends is widely recognized. In the tropics, however, understanding lower-stratospheric temperature trends has proven more challenging. While the tropical lower-stratospheric cooling observed from 1979 to 1997 has been linked to tropical ozone decreases, those ozone trends cannot be of chemical origin, as active chlorine is not abundant in the tropical lower stratosphere. The 1979–97 tropical ozone trends are believed to originate from enhanced upwelling, which, it is often stated, would be driven by increasing concentrations of well-mixed greenhouse gases. This study, using simple arguments based on observational evidence after 1997, combined with model integrations with incrementally added single forcings, argues that trends in ozone-depleting substances, not well-mixed greenhouse gases, have been the primary driver of temperature and ozone trends in the tropical lower stratosphere until 1997, and this has occurred because ozone-depleting substances are key drivers of tropical upwelling and, more generally, of the entire Brewer–Dobson circulation.

1. Introduction

Since the inception of satellite observations, temperatures in the lower stratosphere T_{LS} have exhibited nonmonotonic and nonlinear trends; such complexity offers a challenge to our understanding of the underlying causes, be they natural or anthropogenic. Consider first the global T_{LS} time series, over the period 1979–2014, shown by the blue curve in Fig. 1a. Leaving aside the brief warming spikes after 1982 and 1991 (caused by the El Chichón and Mount Pinatubo eruptions), one notes a robust cooling trend from 1979 to 1997 and, more interestingly, the disappearance of that trend after 1997. Such a clear discontinuity is unlikely to be of natural origin and begs for a careful explanation.

The global T_{LS} cooling from 1979 to 1997 is well known to have been caused by ozone-depleting substances (ODS), as ozone losses imply a reduction in absorbed solar radiation. A vast literature has documented the dominant role of ODS on the global T_{LS} [see Pawson et al. (2014), for a recent review]. Here we simply highlight the detection and attribution study of Gillett et al. (2011), who, for the period 1979–2005, found that the response of ozone and T_{LS} to ODS is detectable in the observations, whereas the response to well-mixed greenhouse gases (GHG) is not.

The disappearance of global T_{LS} cooling after 1997 can also be understood on the basis of recent ODS trends. The abundance of stratospheric chlorine peaked in 1997 (Mäder et al. 2010), so one might expect ozone losses to cease and global cooling trends to consequently disappear. Recall that direct radiative cooling by well-mixed GHG is very small in the lower stratosphere [it peaks at much higher levels; see, e.g., Fig. 5 of Shine et al. (2003)].

The puzzling fact is that the tropical T_{LS} time series, shown by the red curve in Fig. 1a, is nearly identical to the global one. Although a little more noisy, tropical T_{LS} also shows significant cooling into the late 1990s and basically no trends thereafter (for the present discussion, the volcano spikes are just a distraction). Why is the tropical T_{LS} evolution puzzling?

Consider first the 1979–97 cooling period. On the one hand, we know that the abundance of active chlorine is

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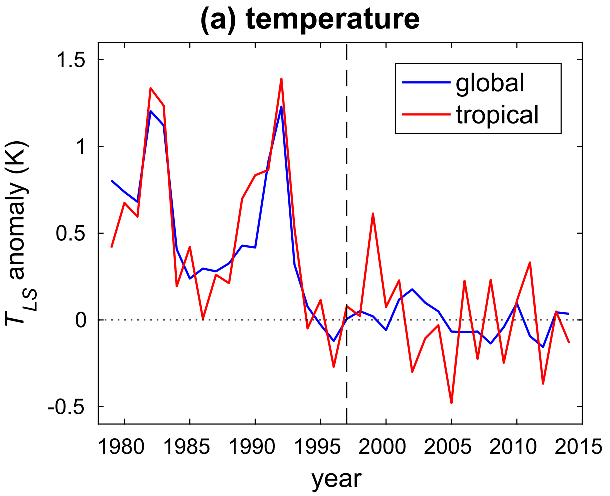

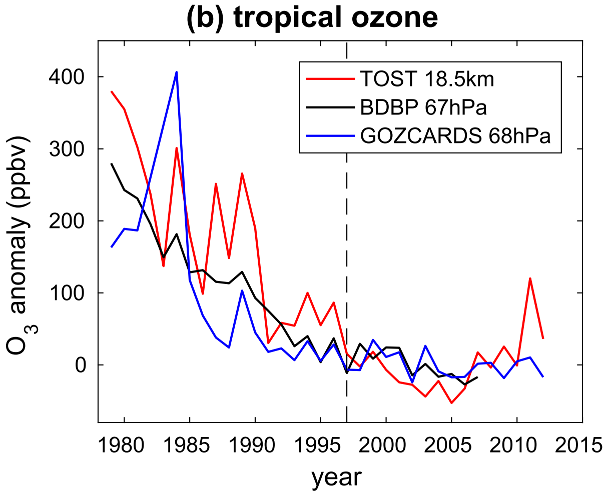

FIG. 1. (a) Observed T_{LS}, from 1979 to 2014, from the MSU (Mears and Wentz 2009). Blue: global time series (82°S–82°N). Red: tropical time series (30°S–30°N). Anomalies are computed from the 1998–2014 mean. The dashed vertical line marks the year 1997, which we use to define the first and second halves of the record. (b) Tropical (30°S–30°N) ozone in the lower stratosphere, from three gridded datasets: the trajectory-mapped ozonesonde dataset for the stratosphere and troposphere (TOST; Liu et al. 2013; for the period 1979–2013), the binary database of ozone profiles (BDBP; Hassler et al. 2009; for the period 1979–2007), and the global ozone chemistry and related trace gas data records for the stratosphere (GOZCARDS; Wang et al. 2013; for the period 1979–2012), with all anomalies computed from the post-1998 mean.

minuscule in the tropical lower stratosphere (Solomon 1999), so ODS cannot be the cause of any cooling via local chemical ozone destruction in the tropical lower stratosphere. On the other hand, there is clear evidence that cooling trends in that region have been driven by ozone losses (Forster et al. 2007; Polvani and Solomon 2012), which were indeed significant from 1979 to 1997, as illustrated in Fig. 1b. The question then becomes, what has been causing those ozone losses? It is often argued that increasing GHG are the cause, but most of the evidence for that argument comes from model integrations forced by more than a doubling in GHG concentrations (e.g., Butchart et al. 2010), not the relatively small 20% increase from 1979 to present.

More importantly, that argument simply cannot be reconciled with current observations; GHG have not stopped increasing after 1997, and yet both T_{LS} and ozone trends in the tropics have basically disappeared after that year (Fig. 1). This raises a major issue: How can we explain the disappearance of trends in the second half of the record if GHG were indeed forcing those trends in the first half? The purpose of this paper is to resolve this conundrum.

We accomplish this by analyzing a sequence of runs from a chemistry–climate model with incrementally added single forcings. The same runs were recently analyzed by Aquila et al. (2016) to detail the contribution of each forcing to global stratospheric temperatures. Here, instead, we focus specifically on the tropical lower stratosphere and show that ODS (and not GHG, as widely believed) have been the dominant forcing of the strong tropical upwelling—and the resulting ozone loss and cooling trends—from 1979 to the late 1990s. In addition, the ODS reduction in the last couple of decades, as a consequence of the Montreal Protocol, is able to explain the disappearance of T_{LS} and ozone trends from the late 1990s to the present, in the model and in the observations.

2. Methods

To elucidate the forcings causing the recent tropical T_{LS} trends, we exploit a set of model integrations, covering the period from 1960 to 2014, recently performed with the NASA Goddard Earth Observing System Chemistry–Climate Model (GEOS CCM), an atmospheric general circulation model with radiatively and chemically coupled aerosols and ozone (Aquila et al. 2016). We analyze five small ensembles, each comprising three members, with incrementally added single forcings. Only one forcing is added from one ensemble to the next, so that attribution of changes at each step is immediate and unambiguous. In brief, the five ensembles are labeled, and forced, as follows:

1) SST: only sea surface temperatures (SSTs) and sea ice concentrations vary in time and are taken from reanalyses, with all natural and anthropogenic forcings held constant at 1960 values.
2) +GHG: in addition to varying SSTs, the concentrations of greenhouse gases are increased, using observations up to 2005 and RCP4.5 afterward (Meinshausen et al. 2011).

3) +ODS: in addition to SSTs and GHG, the surface values of ozone-depleting substances are varied following the Montzka et al. (2010) specifications.
4) +Volc: SO_2 from volcanic eruptions are also injected, following Diehl et al. (2012) until December 2010 and Carn et al. (2015) from January 2011 to December 2014.
5) +Sun: finally, the solar constant is varied in time, following Lean (2000) with later updates from Coddington et al. (2016).

For the reader who may not immediately appreciate why the forcings were added in the above order we offer a brief clarification. Obviously the volcanic and solar forcings are just a distraction to the question at hand (the relative importance of ODS and GHG), so those are added last. Since the main effect of GHG on the climate system is to warm Earth's surface, it makes sense to add GHG to SST first (so as to group together what one could call the "climate change" forcings, as many papers do) and then add ODS. It is conceivable that some nonlinearity might exist (e.g., if we had added the ODS last), but they are likely to be small [as noted in Aquila et al. (2016)].

The precise model configuration and the forcings used in these runs are fully documented in Aquila et al. (2016), to which the reader is referred for details. For comparison with observations, we here focus on the period 1979–2014, and, following the latest WMO assessment report (Pawson et al. 2014), we simply divide this period in two halves, with a break point at 1997.

Finally, to contrast our model results with observations, we use the Microwave Sounding Unit channel 4 (MSU) combined with the Advanced Microwave Sounding Unit (AMSU), which were merged into the Remote Sensing Systems/Temperature Lower Stratosphere (RSS/TLS) channel as detailed in Mears and Wentz (2009). For simplicity, following Seidel et al. (2016), we just refer to this as the MSU data throughout the paper.

3. Results

The 1979–2014 time series of tropical T_{LS} for the five GEOS CCM ensembles with incrementally added single forcings—from top to bottom—are shown in Fig. 2 (left). The thin curves show the individual members, the straight lines show linear fits for the first (1979–97) and second (1998–2014) halves of the integrations separately (solid lines indicate statistical significance and dashed lines if not), and the black curves show T_{LS} from the MSU (Mears and Wentz 2009). For each ensemble, the corresponding forcing is shown in Fig. 2 (right).

When the model is forced uniquely with a lower boundary condition consisting of warming SSTs (Fig. 2), a slight tropical T_{LS} warming is seen; note, however, that these apparent warming trends are not statistically significant, owing to the large internal variability. Similarly, the addition of increasing GHG does not yield any statistically significant trends, although a weak T_{LS} cooling now appears in this ensemble. Notice, also, that both SSTs and GHG produce nearly linear T_{LS} trends in the tropics across the entire 1979–2014 period, with no apparent kink in 1997.

It is only when ODS are added to the model forcing, as one can see in the middle row of Fig. 2, that a statistically significant T_{LS} cooling appears from 1979 to 1997. Furthermore, this cooling trend disappears (i.e., ceases to be significant) after 1997, as one would expect from the nonmonotonic shape of the forcing function (Fig. 2, right). This makes it very clear that the basic shape of the observed tropical T_{LS} time series, cooling followed by flattening, is due to ODS, and not GHG, as has been often suggested.

The two bottom rows of Fig. 2 complete the picture. The volcanic aerosol forcing produces the well-known spikes in 1982 and 1991, and the solar forcing allows the modeled tropical T_{LS} to more closely match the observed ones. Contrast the blue and black lines in the bottom-left panel of Fig. 2; clearly the GEOS CCM, when driven by all known natural and anthropogenic forcing, captures the observations very well. This is important, as it gives us confidence that the conclusions drawn from this model are likely to be meaningful.

To summarize these results and, more importantly, to bring out the importance of internal (i.e., unforced) variability, we plot the tropical T_{LS} trends for each model integration in Fig. 3 (colored bars) together with the MSU observations (black bar). For the earlier period (Fig. 3, left), when forced with only SST (pink) or SST and GHG (yellow), individual integrations with identical forcings can show both cooling or warming trends; this clearly illustrates that those forcings are unable to produce statistically significant trends. Only when ODS are added to the forcings (red bars) do the observations fall within the range[1] of modeled trends across the three ensemble members. Volcanoes and solar forcing do not affect this key result. Finally, note that all modeled trends are insignificant for the period 1998–2014 (Fig. 3, right).

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[1] Recall that observations ought not be directly compared to the ensemble mean itself since they are a single realization of a noisy system with potentially large internal variability. Only the forced response is retained in the ensemble mean, from which internal variability is expunged by the averaging.

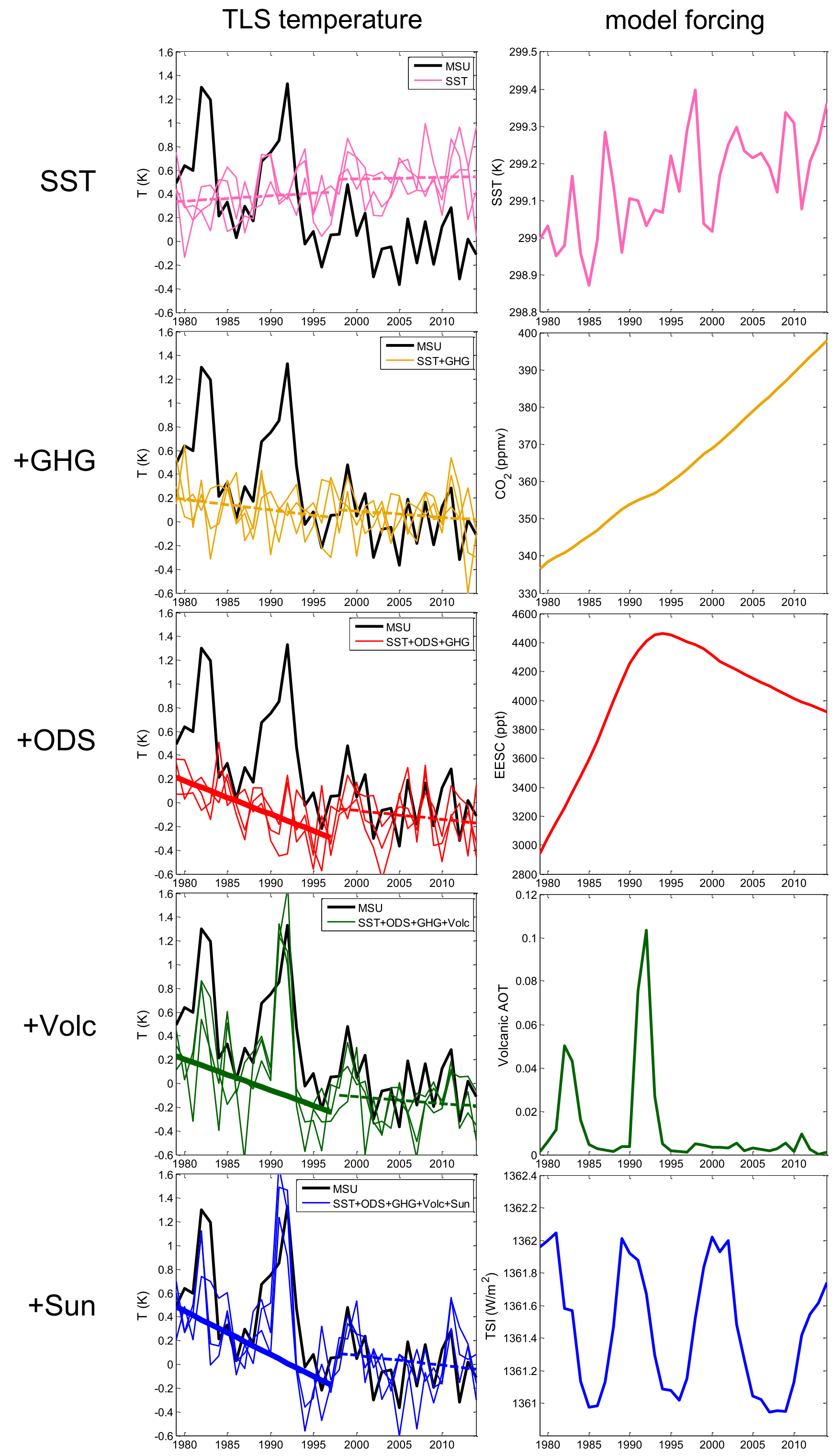

FIG. 2. (left) Tropical T_{LS}, averaged from 30°S to 30°N, and (right) the corresponding forcing for the five ensembles of GEOS CCM integrations with incrementally added single forcings, from top to bottom, as described in the text. At (left), the black curve shows T_{LS} from MSU (Mears and Wentz 2009), the thin colored curves show the three individual GEOS CCM members, and the straight lines show linear fits for the two halves of the integrations separately (i.e., 1979–97 and 1998–2014; solid if the linear trend is statistically significant at the 95% interval and dashed if not). The T_{LS} are shown as anomalies from the 1998–2014 mean; for the model time series, this mean is computed only for the +Sun integrations and then applied in all panels.

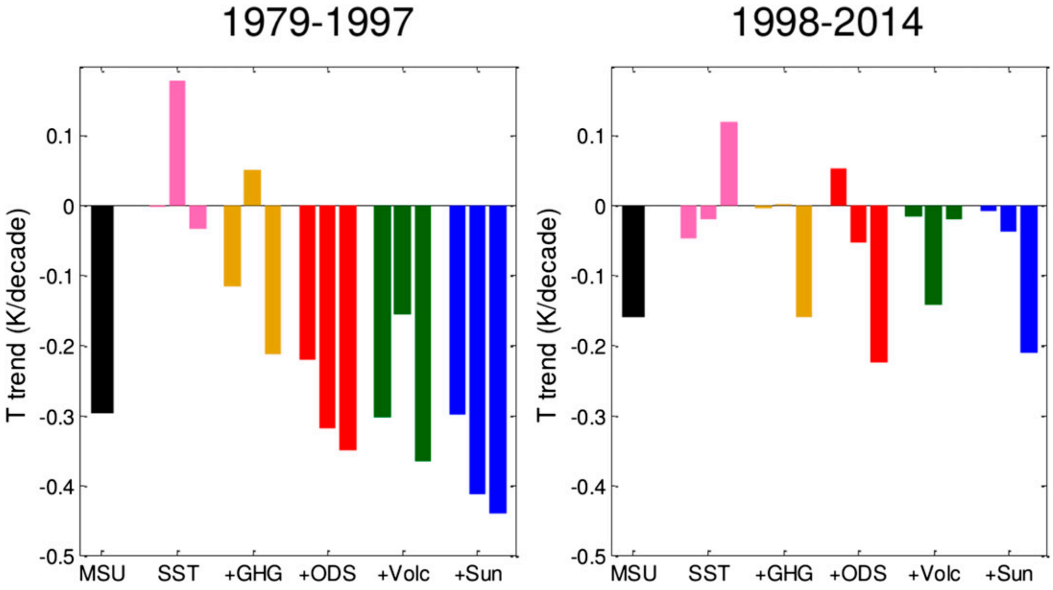

FIG. 3. Tropical T_{LS} trends for each model integration (K decade^{-1}), computed over the period (left) 1979–97 and (right) 1998–2014. Black bars: MSU observations; colored bars: the GEOS CCM integrations, forced as per the labels on the abscissa.

For the period 1979–97, the modeled tropical T_{LS} trends are given in Tables 1 and 2 for the ensemble mean and for the individual members, respectively (statistically significant trends are shown in boldface). Note how T_{LS} trends are not significant without ODS forcing, not only in the ensemble mean but for each individual model integration of our small three-member ensembles, although the two large volcanic eruptions, which both fall in the first half of the record, produce a large amount of noise. For the period 1998–2014, no T_{LS} trends are significant.

Going beyond piecewise linear trends, the dominant role of ODS becomes compellingly clear upon examination of the latitude–longitude maps of tropical T_{LS} trends. These are shown in Fig. 4 for the period 1979–97, over which they are statistically significant. In the top row of Fig. 4, the MSU data show a strong cooling in the tropics; however, when only SST and GHG are used to force the model (second and third rows in Fig. 4) the variability is large enough that identically forced integrations can show both warming or cooling in the tropics. In contrast, once ODS are added, all model integrations show a strong cooling trend. From this we deduce that the observed 1979–97 cooling is very likely a forced response to increasing ODS and not a mere accident due to internal climate variability. For the sake of completeness, the statistically insignificant trends for the 1998–2014 period are shown in Fig. 5; contrasting it with Fig. 4, one immediately sees how the ODS reversal following the Montreal Protocol has resulted in the disappearance of cooling trends since the late 1990s.

Since we have progressively added one model forcing at a time, the attribution of the statistically significant 1979–97 tropical T_{LS} trends to ODS is crystal clear. However, we now wish to clarify the chain of causality and link these modeled temperature trends to ozone trends, as the observations suggest (Fig. 1). Tropical ozone at 70 hPa is shown in Fig. 6 (left); note how the 1979–97 ozone trends become much larger once ODS

TABLE 1. Ensemble mean trends, over the period 1979–97, in T_{LS}, O_3 (at 70 hPa), and w^* (at 85 hPa) from our model integrations with incrementally added single forcings. The number following the plus/minus symbol indicates the trend uncertainty at the 95% confidence interval, computed with a simple Student's t test. Statistically significant trends are in boldface. The years 1982–83 and 1991–92 are excluded in the trend calculation for +Volc and +Sun integrations, to remove the impact from volcanic eruptions. All trends for the period 1998–2014 are statistically insignificant, and are therefore not shown.

	SST	+GHG	+ODS	+Volc	+Sun
T_{LS} (K decade^{-1})	0.05 ± 0.16	−0.09 ± 0.13	**−0.30 ± 0.12**	**−0.27 ± 0.19**	**−0.38 ± 0.19**
O_3 at 70 hPa (ppbv decade^{-1})	−7.2 ± 11	−4.3 ± 9.7	**−22 ± 8.8**	**−22 ± 12**	**−28 ± 13**
w^* at 85 hPa (km yr^{-1} decade^{-1})	0.04 ± 0.09	0.10 ± 0.11	**0.21 ± 0.11**	**0.21 ± 0.12**	**0.20 ± 0.13**

TABLE 2. As in Table 1, but for the individual ensemble members.

Member	SST	+GHG	+ODS	+Volc	+Sun
T_{LS} (K decade^{-1})					
1	0.00 ± 0.24	−0.12 ± 0.20	**−0.22 ± 0.21**	−0.30 ± 0.31	**−0.30 ± 0.30**
2	0.18 ± 0.22	0.05 ± 0.18	**−0.32 ± 0.18**	−0.16 ± 0.27	**−0.41 ± 0.19**
3	−0.03 ± 0.17	−0.21 ± 0.23	**−0.35 ± 0.23**	**−0.36 ± 0.25**	**−0.44 ± 0.28**
O_3 at 70 hPa (ppbv decade^{-1})					
1	−8.9 ± 14	−4.1 ± 12	**−20 ± 14**	**−24 ± 18**	**−25 ± 19**
2	−4.9 ± 16	−2.9 ± 9.5	**−22 ± 11**	−15 ± 17	**−32 ± 14**
3	−7.7 ± 10	−12 ± 15	**−22 ± 14**	**−26 ± 16**	**−26 ± 17**
w^* at 85 hPa (km yr^{-1} decade^{-1})					
1	0.11 ± 0.17	0.08 ± 0.16	**0.18 ± 0.14**	**0.23 ± 0.22**	0.15 ± 0.20
2	−0.05 ± 0.13	0.02 ± 0.13	**0.23 ± 0.11**	0.11 ± 0.16	**0.24 ± 0.15**
3	0.06 ± 0.11	**0.18 ± 0.15**	**0.23 ± 0.17**	**0.29 ± 0.12**	**0.20 ± 0.18**

are added to the model forcings (contrast Figs. 6b,c). The key role of ODS on tropical lower-stratospheric ozone is also seen in Tables 1 and 2; ozone trends for 1979–97 become significant only with ODS forcing, in the ensemble mean and for each ensemble member separately.

As a final step, we now link ozone trends to upwelling trends. It is well established that tropical lower-stratospheric ozone is closely tied to tropical upwelling w^*—so much so that it can serve as an excellent proxy for upwelling, as noted by Randel and Thompson (2011). Hence, it is not surprising to find that the time series of w^* in our integrations mirror the ozone ones very closely, as seen in Fig. 6 (right). Again, only when ODS forcing is present does w^* increase significantly from 1979 to 1997, as seen in Table 1. Note, however, that since w^* is a relatively noisy field, not all individual members show statistically significant trends[2] when volcanic or solar forcings are added (see Table 2). Be that as it may, the key result stands: in our model integrations, over the 1979–97 period, increasing ODS are the key forcing that causes a statistically significant tropical upwelling, and thus ozone reduction, and thus tropical lower-stratospheric cooling. Moreover, and crucially, this chain of causality helps resolve the conundrum presented in the introduction, as it also explains why tropical T_{LS} trends should have largely disappeared over the period 1998–2014.

We conclude by broadening the discussion beyond the tropical lower stratosphere and demonstrating that increasing ODS have likely affected the entire stratospheric circulation during the last two decades of the twentieth century. In Fig. 7 we show the pole-to-pole cross section of w^* trends for the period 1979–97, averaged over the three integrations (i.e., the response to each forcing). It is readily apparent that ODS forcing causes a major strengthening of tropical upwelling (red contours between 30°S and 30°N). In addition, however, one can see that high-latitude downwelling is also considerably strengthened by ODS forcing (blue contours over the polar regions). This clearly demonstrates that, in our model, ODS affect not only tropical upwelling but the entire Brewer–Dobson circulation (BDC).

4. Summary and discussion

Analyzing integrations with a stratosphere-resolving chemistry-coupled model, in which forcings were incrementally added, we have clarified which anthropogenic emissions are able to explain the kinked shape of tropical lower-stratospheric temperatures over the period 1979–2014. In a nutshell, our modeling evidence clearly points to ODS, and not GHG, as the key players, since ODS have reversed sign since the late 1990s as a consequence of the Montreal Protocol, whereas GHG have been growing steadily.

We have also shown that ODS act on tropical T_{LS} via ozone anomalies produced by changes in tropical upwelling. Notably, for the period 1979–97, only when ODS are added to the forcings do w^* trends become statistically significant in our model. This suggests that ODS may be able to affect the BDC. For this, the reader is referred to Garfinkel et al. (2017), where the effects of various forcings on the structure of BDC are contrasted, in the same model runs analyzed here.

Beyond our own GEOS CCM results, many other modeling studies have presented evidence showing how ODS can affect tropical T_{LS} and w^*, although the

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[2] This illustrates why it is difficult to determine, in the observations, if tropical upwelling has been increasing; recall that observations represent a single realization of a system with large internal variability. The difficulty is further aggravated, in many recent studies, by the failure to separate the time series into two periods before and after 1997; computing a single linear trend across the entire period considerably reduces the signal-to-noise ratio since all time series flatten after 1997 with the waning of ODS forcing.

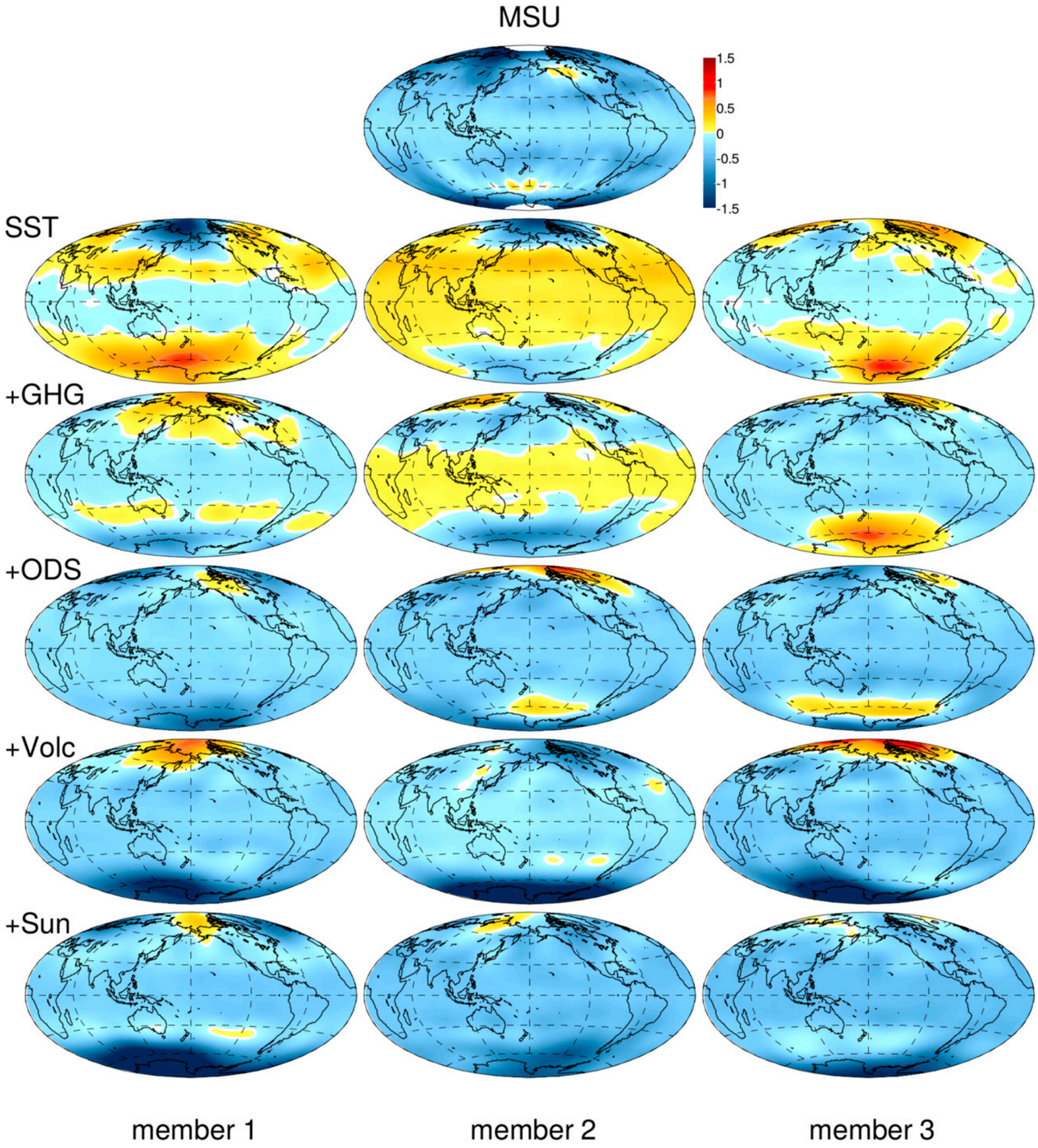

FIG. 4. Hammer projection with T_{LS} trends over the period 1979–97 (K decade^{-1}) for (top row) MSU and (other rows) GEOS CCM, forced as indicated. Each column shows a different ensemble member.

authors have not always emphasized such evidence. For instance, Waugh et al. (2009, see their Fig. 2b) find that, when ODS are held fixed at 1960 values, ozone trends in the tropical lower stratosphere are considerably reduced in the late twentieth century. And, for the same period, Oman et al. (2009, see their Fig. 8) report that polar ozone depletion—which is ultimately driven by ODS—has been a major factor in increasing tropical upwelling. Stolarski et al. (2010, see their Fig. 5), averaging a number of model runs over the period 1979–98, clearly show that ODS produce a cooling in the tropical lower stratosphere, whereas GHG do not. Plummer et al. (2010,

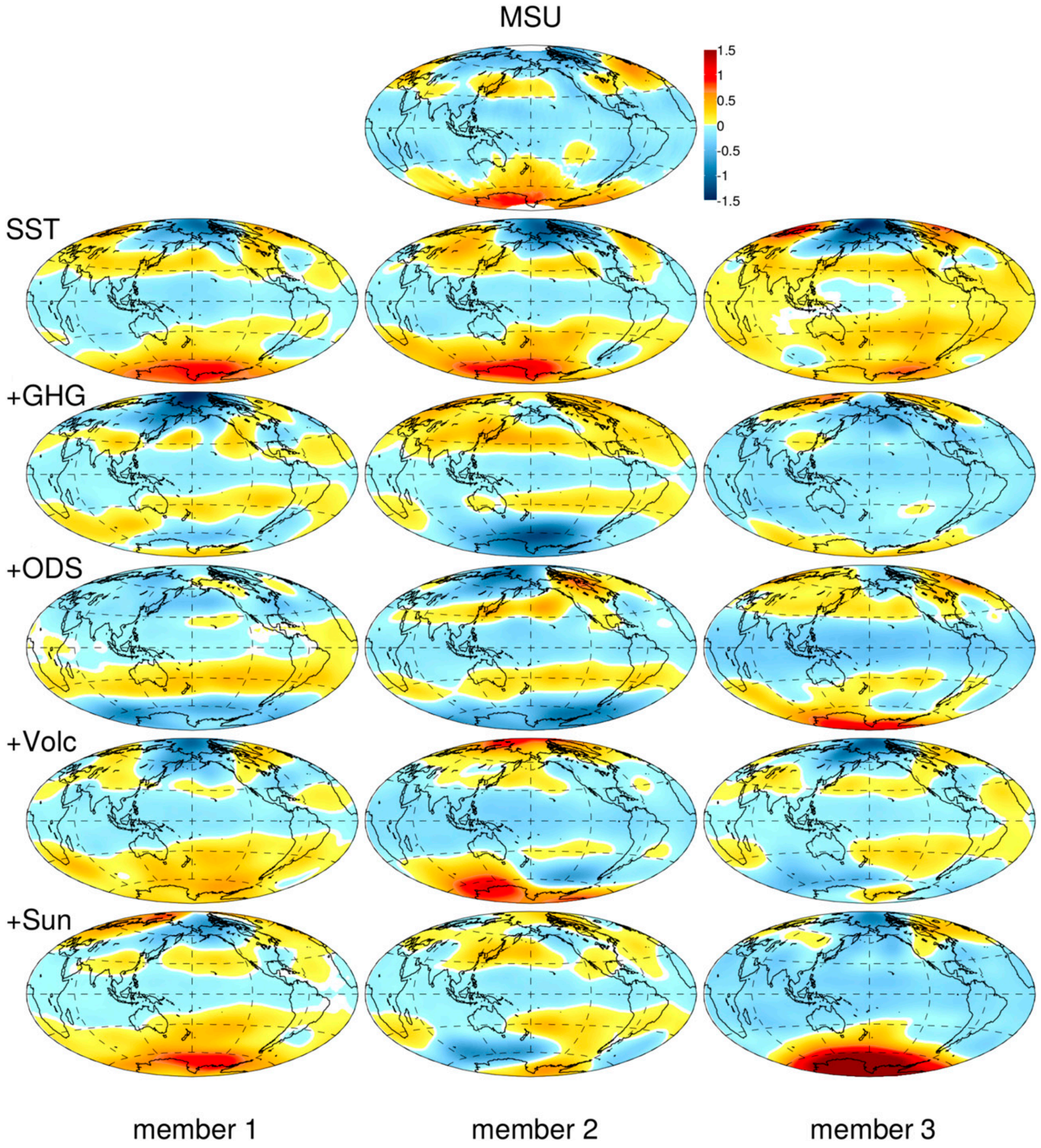

FIG. 5. As in Fig. 4, but for the period 1998–2014.

see their Fig. 9b) find that 1960–2000 trends in the tropical ozone column above 100 hPa are very weak when forced with GHG alone, as ODS are the largest contributor to those trends. The impact of ODS on BDC trends was also earlier reported by Li et al. (2008), who found that ozone depletion was responsible for 60% of the BDC increase in their model over the period 1960–2004 (although they noted, unfortunately, that their model exhibited a serious bias in the ozone trends). And, more recently, Oberländer-Hayn et al. (2015), contrasting time-slice integrations at 1960 and 2000 (which cannot be directly compared to observations), conclude that ODS and GHG equally contribute to tropical upwelling trends.

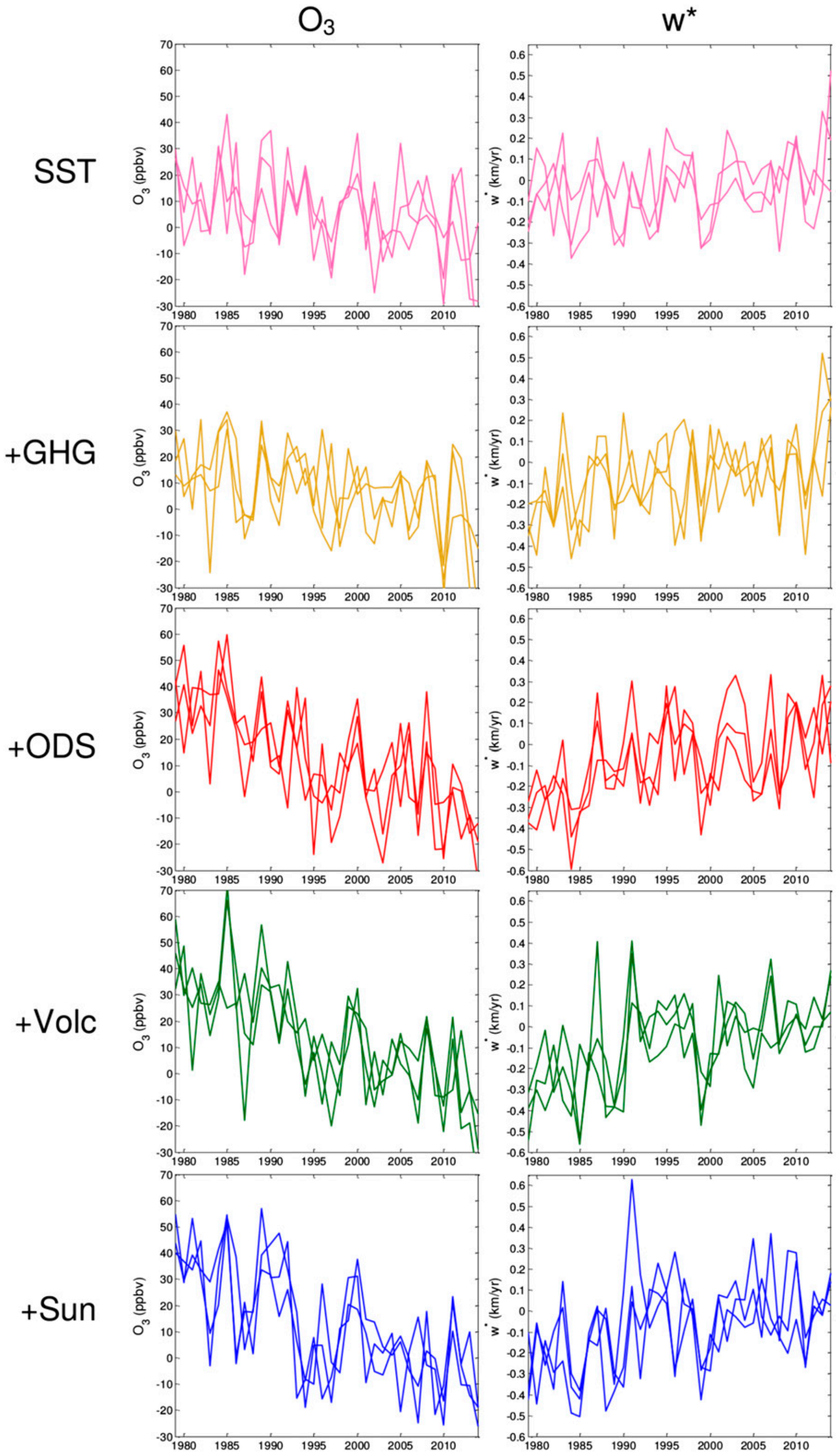

FIG. 6. As in Fig. 2, but for (left) ozone at 70 hPa and (right) w^* at 85 hPa.

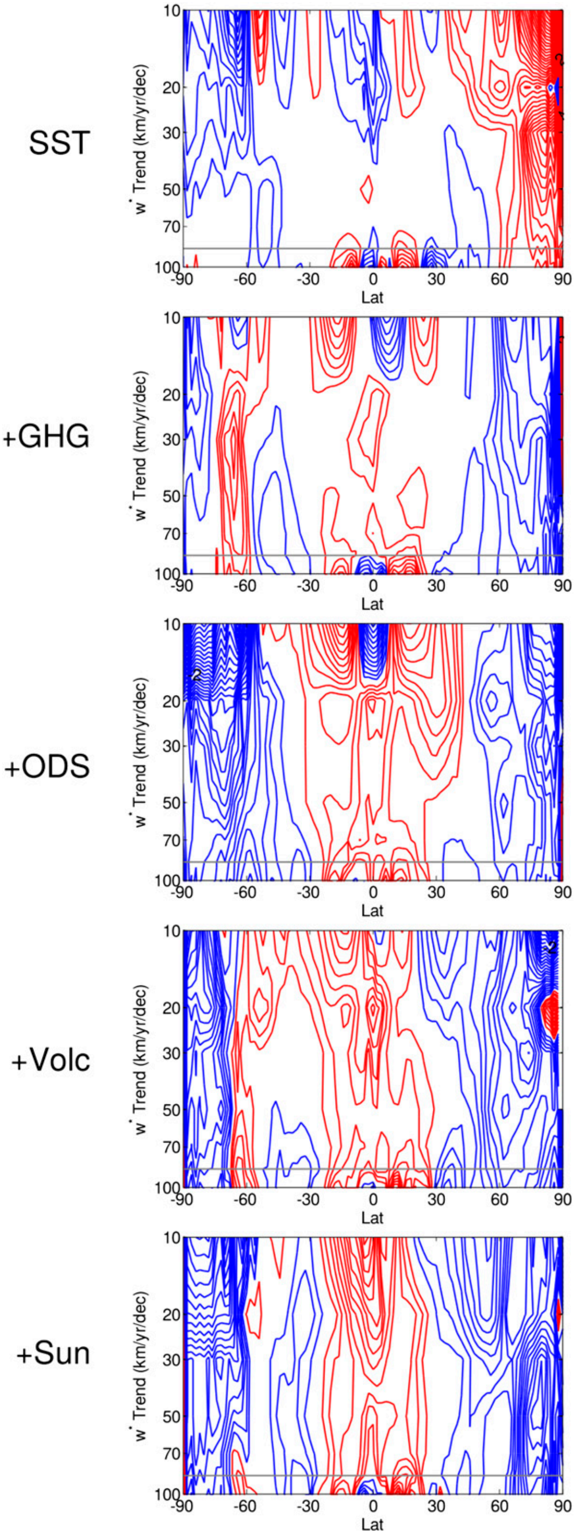

FIG. 7. Annual mean w^* trends over the period 1979–97, averaged for the three model integrations with forcings as indicated. Positive trends are in red, and negative trends are in blue, with a contour interval of 0.1 km yr^{-1} decade^{-1}. The thin gray lines mark the 85-hPa level.

In addition to these modeling papers, the observational studies of Fu et al. (2010, 2015) strongly support our conclusions. In particular, Fu et al. (2015) demonstrate that recent tropical T_{LS} trends are in large part driven by a high-latitude "dynamical" component (i.e., by BDC trends) and that those BDC trends are primarily found in the Southern Hemisphere. This clearly points to the ozone hole, and thus ultimately to ODS, as the ultimate cause, corroborating our findings.

While there is abundant observational and modeling evidence for the key role of ODS on tropical upwelling in recent decades, we also note a couple of modeling studies that appear at odds with that conclusion. McLandress et al. (2010) do not find a statistically significant impact of ODS on tropical upwelling in their model, over the period 1960–99, in the annual mean (as a consequence of large cancellations between different seasons). We are not sure how to interpret that result; we simply note that, unlike the studies mentioned above, they used a coupled atmosphere–ocean model, and thus their SST trends may be quite different from the observed ones.

More importantly, we need to reconcile our findings with those of Lamarque and Solomon (2010). Using observed SSTs and single-forcing simulations similar to ours, they concluded that GHG—not ODS—were the key drivers of tropical upwelling, ozone, and thus T_{LS} trends in the last few decades of the twentieth century. To explain their findings, we offer the following considerations. First, that study explored only the period 1960–2005, before the flattening of the tropical temperature and ozone curves became clear; hence, we have benefited from an additional decade of observations (which show no T_{LS} trends past 2005) to reach our conclusions. Second, we note that Lamarque and Solomon (2010) employed a so-called low-top model, with only 26 vertical levels, of which a mere 8 were located above the 100 hPa, and a model top at 40 km. It is not unreasonable to believe that this could result in a somewhat poor representation of the stratospheric circulation. Third, and most crucially, we note the conclusions of that study were drawn from *a single pair* of single-forcing model integrations, one with GHG and the other with ODS. As we have shown above, the internal variability is large, and a single model integration can be quite misleading.

Finally, we concede that while the evidence for ODS being a key forcing for temperature, ozone, and upwelling in the tropical lower stratosphere appears very convincing, the underlying mechanism remains largely unexplored. The open question is this: How are ODS able to affect the stratospheric circulation? To first order, ODS cause polar ozone depletion and thus cause large temperature gradients in the lower stratosphere. Since the stratospheric circulation is essentially wave driven, these large temperature gradients must be able to affect planetary wave propagation. Tantalizing evidence for this has recently been presented by Abalos et al. (2015); using a number of reanalyses, they have shown the existence of statistically significant trends in Eliassen–Palm fluxes since 1979 and, more crucially, that the largest signal is found in the Southern Hemisphere in the months December–February (see their Fig. 15b). Needless to say, a detailed analysis is beyond the scope of this brief study. We hope to report on this in a future paper.

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