The signature of ozone depletion on tropical temperature trends, as revealed by their seasonal cycle in model integrations with single forcings

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[1] The effect of ozone depletion on temperature trends in the tropical lower stratosphere is explored with an atmospheric general circulation model, and directly contrasted to the effect of increased greenhouse gases and warmer sea surface temperatures. Confirming and extending earlier studies we find that, over the second half of the 20th Century, the model's lower-stratospheric cooling caused by ozone depletion is several times larger than that induced by increasing greenhouse gases. Moreover, our model suggests that the response to different forcings is highly additive. Finally we demonstrate that when ozone depletion alone is prescribed in the model, the seasonal cycle of the resultant cooling trends in the lower stratosphere is quite similar to that recently reported in satellite and radiosonde observations: this constitutes strong, new evidence for the key role of ozone depletion on tropical lower-stratospheric temperature trends.

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1. Introduction

[2] The goal of this paper is to shed light on the effect of ozone depletion on tropical lower-stratospheric temperature trends in the past half century. This issue is important, in part, because of its possible linkage to the vertical structure of trends induced by increasing greenhouse gases (GHGs). At low latitudes, climate models suggest larger temperature trends aloft than at the surface [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007], but establishing an observational benchmark for comparison with models has proven challenging [*Santer et al.*, 2008; *Allen and Sherwood*, 2008], owing to large uncertainties in radiosonde and satellite data [*Karl et al.*, 2006].

[3] *Cordero and Forster* [2006] suggested that some of the upper tropospheric discrepancy between models and observations could be attributed to stratospheric ozone depletion. Contrasting models with and without depletion – from the Coupled Model Intercomparison Project (CMIP3) – they showed that the latter are unable to produce the observed cooling in the tropical lower stratosphere (see *Randel et al.* [2009] for a recent review of the observations). Unfortunately, in addition to ozone depletion, a mix of other forcings were included by the different CMIP3 modeling groups (black carbon, volcanic aerosols, dust, etc), making the exercise not entirely conclusive. To address this, *Forster et al.* [2007] considered the effect of ozone alone, and documented how its depletion yields a clear cooling trend in the tropical lower stratosphere. However, this result was reached using a so-called "fixed dynamical heating" (FDH) radiative-convective model. Hence the possibility remains that, in the presence of interactive dynamics, those results might be substantially altered.

[4] In this paper we overcome the limitations of these earlier studies, by revisiting and extending the model integrations of *Polvani et al.* [2011]. On the one hand, the forcings in our model – ozone, GHGs and sea surface temperatures – are unambiguously specified, both in isolation and in combination, in order to be able to draw clear cause-and-effect relationships. On the other hand, unlike the earlier FDH calculations, the atmospheric circulation is here allowed to respond to the forcings in a consistent way, since a comprehensive general circulation model (GCM) is used. Furthermore, by using an IPCC-class model in which the ozone field is prescribed, i.e. not computed as in chemistry-climate models, we are able to decouple the lower-stratospheric upwelling trends from the ozone trends, and thus shed new light on the interplay between these quantities and their ultimate contribution to the observed temperature trends in the second half of the 20th century.

[5] Contrasting time-slice integrations with forcings at year-1960 levels against year-2000 levels, we confirm that ozone depletion at low-latitudes is able to substantially cool the lower stratosphere, with the cooling signal reaching a maximum between 50 and 70 hPa; we also find, in

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Table 1. The CAM3 Integrations Analyzed in This Study, and Their Respective Forcings[a]

Integration Number	Integration Name	O_3 (Year)	GHGs (Year)	SSTs (Average Epoch)
1	REFERENCE	1960	1960	1952–1968
2	OZONE	2000	1960	1952–1968
3	GHG&SST	1960	2000	1992–2008
4	ALL	2000	2000	1992–2008
5	ONLY SST	1960	1960	1992–2008
6	NO-SST	2000	2000	1952–1968
7	TROP-OZONE	2000[b]	1960	1952–1968
8	POLAR-OZONE	2000[c]	1960	1952–1968

[a]For the REFERENCE integration, all forcings are set at the year 1960. For the other integrations, some forcings are taken from the year 2000, as indicated. The first four integrations are identical to those analyzed in *Polvani et al.* [2011].

[b]For the TROP-OZONE integration the ozone field is set at year 2000 levels between of 35°S and 35°N, and left at 1960 levels elsewhere.

[c]For the POLAR-OZONE integration the ozone field is set at year 2000 levels between 50°S and the South Pole, and left at 1960 levels elsewhere.

agreement with previous studies, that the ozone induced cooling is largely confined above 120 hPa. In addition, our GCM integrations demonstrate that the tropical cooling trends associated with ozone depletion are much larger than those associated with increasing greenhouse gases, a fact previously reported but perhaps not widely appreciated. Finally, the seasonal structure of the ozone induced stratospheric cooling in our model integrations matches remarkably well the observed trends over the last several decades, suggesting that these observed trends are directly related to the depletion of ozone which, in turn, is likely caused by an accelerating Brewer-Dobson Circulation, itself driven by increasing GHGs [see, e.g., *Butchart et al.*, 2006], as we will describe in detail below.

[6] The paper is laid out as follows. In Section 2 we review the characteristics of the model used in this study, and present the model integrations we have performed and the different forcings used in each one. In Section 3 we illustrate how our model integrations confirm and extend the results of previous studies, and clarify the dominant role of ozone depletion on tropical lower-stratospheric temperature trends, in particular as it emerges from analyzing the seasonal cycle of the response. In Section 4 we contrast the respective roles of ozone depletion and GHG increases in affecting temperature and vertical velocity trends, and discuss our findings in the light of the closely related study of *Lamarque and Solomon* [2010]. In Section 5 we conclude by highlighting the importance of reliable ozone fields for an accurate determination of tropical temperature trends in model projections.

2. Methods

[7] The model integrations discussed here are performed with the Community Atmospheric Model (CAM), version 3 [*Hurrell et al.*, 2006], which we run in "time-slice" configuration (i.e. all forcings are constant in time, except for the seasonal cycle). Very briefly: all integrations are 50 years long, at spectral T42 horizontal resolution, with 26 standard hybrid vertical levels, and model top at 2.2 hPa (hence with a poorly resolved stratospheric circulation). For further details the reader is referred to *Polvani et al.* [2011].

[8] Our model integrations require three distinct forcings: (i) ozone, (ii) greenhouse gases (CO_2, CH_4, N_2O), and (iii) sea-surface temperatures and sea-ice concentrations (SSTs). We take the ozone fields from the AC&C/SPARC [*Cionni et al.*, 2011], the well mixed GHGs from the SRES A1B scenario [*Nakicenovic et al.*, 2000], and the SSTs from the Hadley Centre data set [*Rayner et al.*, 2003]. Except for SSTs, each of these forcings is specified either from the year 1960 (the reference configuration) or the year 2000 (the forced configuration). For SSTs we use 17-year means, constructed by averaging ± 8 years around the year 1960 or 2000, to avoid picking up unwanted signals due to ENSO events. Chlorofluorocarbons (CFC-11 and -12) concentrations are treated as in *Polvani et al.* [2011].

[9] We note, parenthetically, that the ozone trends in the AC&C/SPARC dataset are primarily derived from observations covering the time period 1979–2005, and then extended backwards in time using a regression onto a stratospheric chlorine proxy [*Cionni et al.*, 2011]. This is justified over the majority of the stratosphere (where chlorine is a dominant forcing), but perhaps less so in the tropical lower stratosphere (where ozone is highly sensitive to upwelling changes, which models suggest are likely due to greenhouse gas increases).

[10] With that caveat, let us now focus on the integrations discussed in this paper, which are listed in Table 1. The first four integrations are exactly those analyzed in much detail in *Polvani et al.* [2011], which we have renamed here for greater clarity: for integration 1 all forcings are set at year 1960 values (this is the REFERENCE integration), while for integrations 2–4 either ozone, or GHGs and SSTs, or all three set at year 2000 values. The next two integrations are performed to bring out the role of SSTs: in integration 5 we only change SSTs to year 2000 values (keeping GHG and ozone fixed at 1960 levels), and the complementary forcing set is used in integration 6. The last two integrations (7 and 8) are used to understand the relative contribution of polar versus tropical ozone, as described below. Throughout the paper, all integrations are referred to by name, as given in Table 1, and we use the term "response" to designate the difference between any one of our forced integration and the REFERENCE one; this difference is then divided by

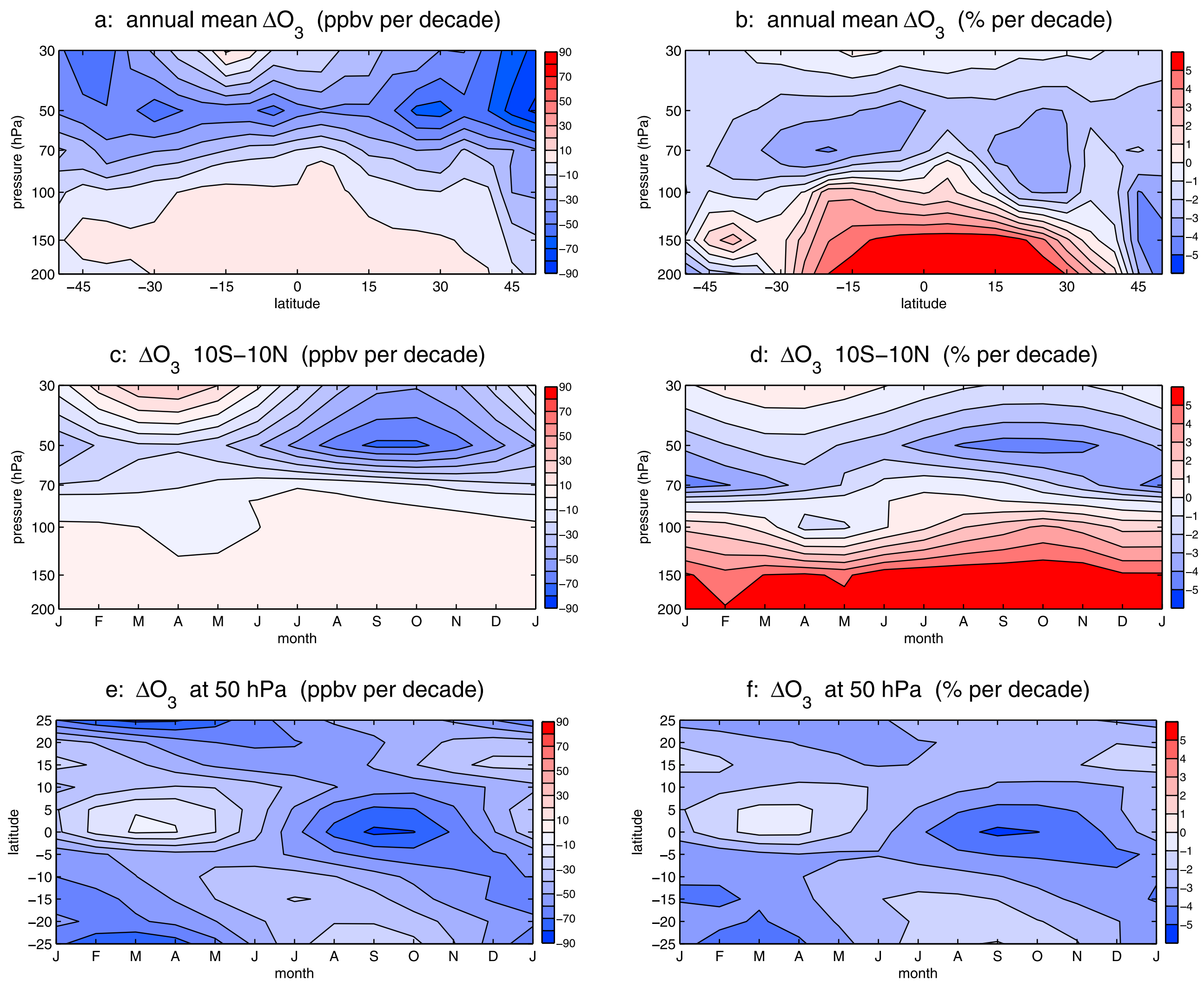

Figure 1. (left) Difference 2000–1960 in AC&C/SPARC ozone (ΔO_3) in ppbv/decade and (right) percentage/decade. (a and b) Annual mean ΔO_3. (c and d) Seasonal cycle of ΔO_3 vs height, averaged 10°S–10°N. (e and f) Seasonal cycle of ΔO_3 vs latitude, at 50 hPa. Values per decade are computed by dividing the actual 1960–2000 differences by 4; percentage values are similarly computed, relative to 1960 values.

4 = (2000 − 1960)/10, so as to express the answer as a trend (per decade), for easy comparison with previous studies.

3. Results

[11] Before presenting model results, we illustrate the latitudinal and vertical structure of the ozone forcing that we use in our model. Figure 1a shows the annual mean difference between 2000 and 1960, in ppbv/decade, in the AC&C/SPARC ozone data set: as expected, the bulk of the depletion is located in the lower stratosphere, between 30 and 100 hPa, with the maximum around 50 hPa. We also plot the same quantity in units of percent per decade in Figure 1b, for direct quantitative comparison with the forcing used in *Forster et al.* [2007, Figure 2a]. Similar trends, of the order of 2–4% per decade, are also found in the new combined SHADOZ/SAGE data set [see *Randel and Thompson*, 2011, Figure 8a].

[12] The accompanying tropical temperature response ΔT – due not only to local but also possibly to global ozone depletion via dynamical changes – is shown in Figure 2a, where hatching is used to indicate statistical significance. Note the robust cooling in the lower stratosphere, of the order of −0.4°K/decade, between 50 and 70 hPa. The structure of our model response is very similar to the one shown in Figure 2b of *Forster et al.* [2007], computed with a single column FDH model.

[13] In Figure 2b, one can see that the lower-stratospheric temperature response to the combined increase of GHGs and SSTs is considerably smaller, in amplitude, than that due to ozone depletion (with a statistically insignificant cooling of only about −0.1°K/decade in our model). This fact has been previously noted [see, e.g., *Ramaswamy et al.*, 2006, Figure 3b]. Furthermore, the response to the individual forcings appears to be largely additive: contrast the response in

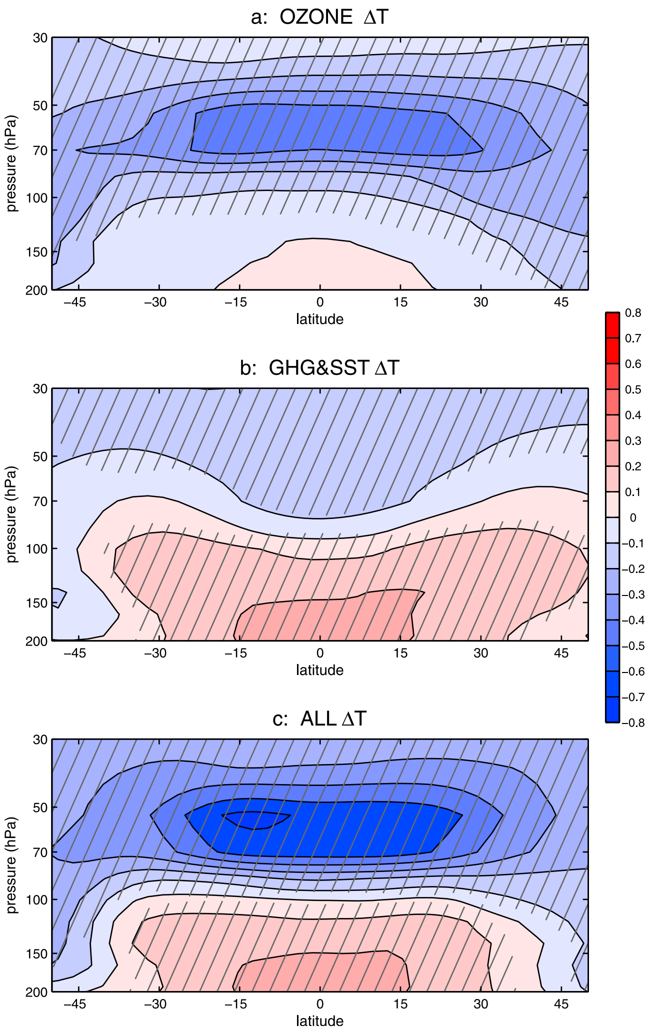

Figure 2. Annual mean model temperature response (ΔT), in K/decade, for the (a) OZONE (b) GHG&SST and (c) ALL integrations. In all cases (ΔT) is defined as the difference from the REFERENCE integration. Hatching denotes a statistically significant response, at the 95% confidence level, computed from the interannual variability of the REFERENCE integration with a simple *t*-test.

the ALL integration (Figure 2c) with the one in the panels immediately above.

[14] The additivity of the response to the different forcings is more immediately striking in Figure 3a, where we show vertical profiles averaged from 30°S to 30°N, for direct quantitative comparison with *Cordero and Forster* [2006]. The response in the ALL integration (solid black curve) almost perfectly overlaps the sum of the responses of the OZONE and GHG&SST integrations (dashed black curve). We also note that the amplitude of our ALL response (approximately half a °K/decade around 50 hPa) compares very well with the trends computed by the CMIP3 models which did include ozone depletion [see *Cordero and Forster*, 2006, Figure 9], even though our results come from "time-slice" integrations. However, the distinct maximum around 70–50 hPa – associated with ozone forcing in our model integrations – is not as prominent in the observations (see, e.g., Figure 11 of *Haimberger et al.* [2008] and Figure 15 of *Randel et al.* [2009]). This feature is likely due to the AC&C/SPARC ozone we have used, and also possibly to an inadequate representation of the stratospheric circulation in our model.

[15] Note how the response to what is usually referred to as climate change (red curve), i.e. the combination of increasing GHG and SSTs, is composed of two distinct parts: a warming in the troposphere, peaking between 300 and 150 hPa, and a cooling in the stratosphere, increasing with height above 100 hPa. The specific role of SSTs is brought out in Figure 3b: it is clear that with SST forcing alone (red dashed curve) the response only reaches up the tropopause (and perhaps a little beyond). Conversely, no response is seen in the troposphere when no SSTs forcing is applied (red dash-dotted curve). All of this is in line with the widely held belief that, in the troposphere, the vertical structure of tropical temperatures is largely controlled by SSTs, as temperatures at low latitudes tend to follow moist adiabatic lapse rates [*Wallace*, 1992; *Sobel*, 2010].

[16] We next address the question of whether low-latitude (as opposed to polar) ozone depletion is responsible for the lower-stratospheric cooling in our model. The answer is perhaps not immediately obvious, as recent work has shown that the impact of the ozone hole over the South Pole can be detected deep into the subtropics [*Kang et al.*, 2011]. As one can see in Figure 3c, when ozone depletion is confined to be between 55°S and the South Pole only a minuscule tropical response is seen (dash-dotted blue curve). Conversely, when ozone depletion is confined to ±35° about the equator (dashed blue curve), a very clear cooling results, and it is very close to that when ozone depletion is applied at all latitudes (solid blue curve). From this we deduce that *tropical* lower-stratospheric ozone is responsible for the response shown in Figure 2a. Note that this fact does *not* imply that tropical ozone itself is not linked to other dynamical processes (e.g. the tropical upwelling component of the Brewer-Dobson circulation). But it does imply that tropical temperature changes are directly related to tropical ozone changes. In other words, unless tropical ozone is depleted, lower stratospheric cooling is not seen in our model integrations (cf. Figure 2b).

[17] This simple fact becomes even clearer when one considers the seasonal cycle of the tropical temperature response to the various forcings, paying special attention to ozone depletion. We start by noting that the observed 1960–2000 trends in tropical lower-stratospheric ozone exhibit a very clear seasonal cycle. The vertical and latitudinal structure of this cycle is shown, for the AC&C/SPARC ozone, in Figures 1c–1f. The key point of that figure is that the bulk of ozone depletion around 50 hPa takes place during the second half of the year, from June to January, with a maximum in September/October and a minimum in March/April.

[18] With this in mind, observe now the vertical structure of the seasonal cycle of the tropical temperature response in the OZONE, GHG&SST and ALL integrations, shown in Figure 4. It is clear that the seasonal cycle of the response in the ALL integration is due to ozone depletion, and not increasing GHGs or SSTs. We encourage the reader to directly compare our model response in Figure 4a with the radiosonde trends in Figure 1 of *Free* [2011], which also show a maximum at 50 hPa between July and February, and minimum between March to June. A robust seasonal cycle,

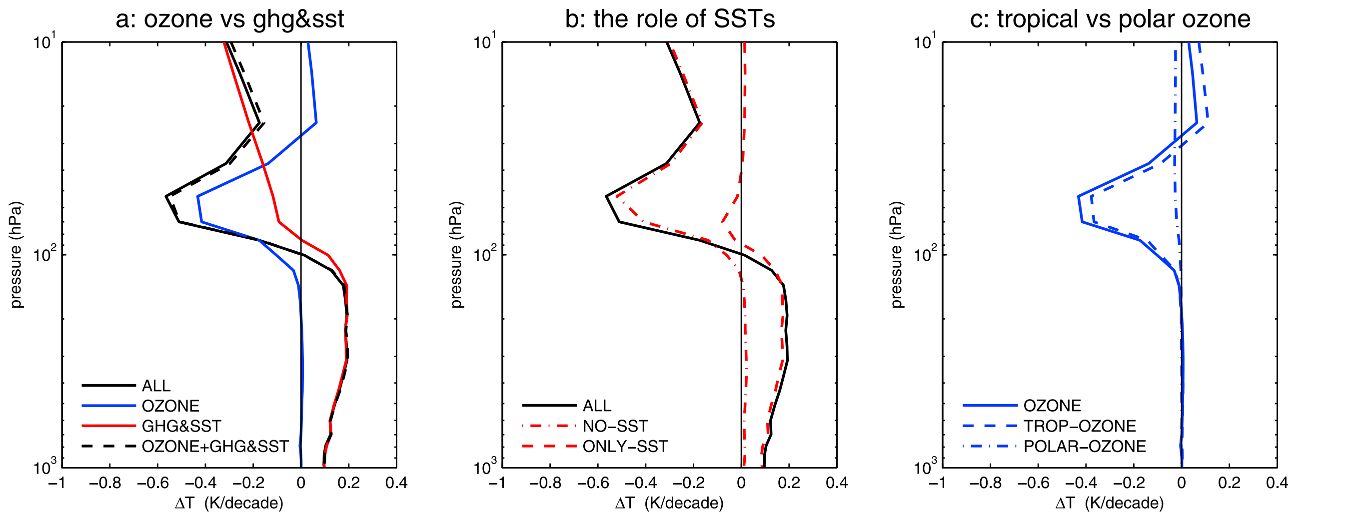

Figure 3. Annual mean model temperature response (ΔT), averaged 30°S–30°N, in K/decade, for different model integrations, as indicated in the legends. The thin, vertical, solid, black line marks the zero response.

very similar to that shown in Figure 4a, was found in the six different radiosonde data sets analyzed by *Free* [2011]. Such strong similarity leaves little doubt that ozone depletion is likely the dominant cause of the observed tropical lower-stratospheric temperature trends in recent decades. The cause for ozone depletion at these low latitudes is discussed in the next section.

[19] A similar conclusion can be reached from the latitudinal structure of the seasonal cycle of the response, shown in Figure 5. Figure 5a, for the ALL integration, can again be directly compared Figure 2 of *Free* [2011] (which shows radiosonde trends) as well as Figure 2a of *Fu et al.* [2010] (which shows trends from channel 4 of the Microwave Sounding Unit (MSU); see also Figure 11 of *Randel et al.* [2009]). In the tropics, both sets of observations show significant cooling from July to February, although the MSU amplitudes are smaller than those in the radiosondes, as noted by *Free* [2011]. These observed low-latitude trends are very similar to the ones shown in Figure 4a, although our model integrations were not set up to "simulate" any specific set of observations, but rather to examine seasonal and latitudinal structure due to the different forcings. (We note, in passing, that several high-latitude features seen in Figure 5a also appear in the MSU trends, but none of them is statistically significant except the one associated with the ozone hole in Austral spring). The remarkably good agreement, in spite of differences in the time periods between the model forcings and the observations (and the fact that ours are time-slice integrations), suggests that the signature of ozone depletion on tropical temperature trend seasonality is indeed robust.

4. Discussion

[20] *Lamarque and Solomon* [2010] (hereafter LS10) have recently reported results that are highly germane to the ones we have just presented. In this section we discuss those

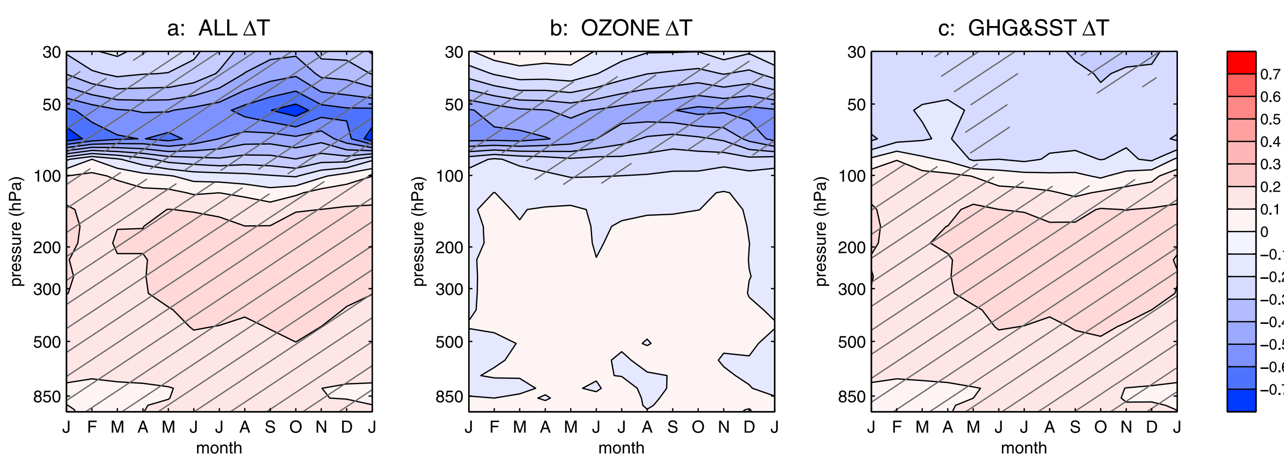

Figure 4. Seasonal cycle of the model temperature response (ΔT) as a function of height, averaged over 10°S–10°N, in K/decade. As in Figure 2, ΔT is defined as the difference from the REFERENCE integration: (a) ALL, (b) OZONE and (c) GHG&SST response. Hatching indicates statistical significance, as in Figure 2.

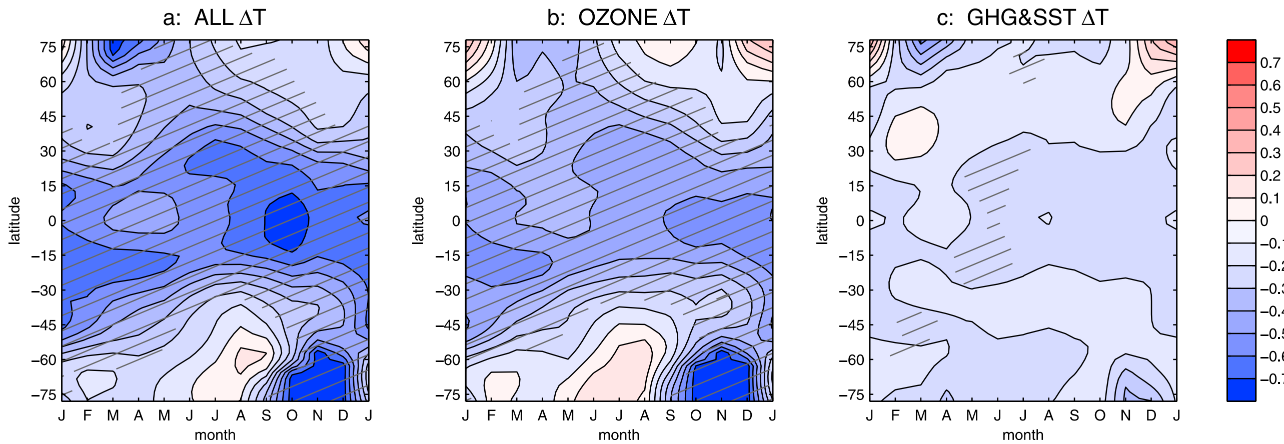

Figure 5. Seasonal cycle of the model temperature response (ΔT) as a function of latitude at 50 hPa, in K/decade. As in Figure 2, ΔT is defined as the difference from the REFERENCE integration: (a) ALL, (b) OZONE and (c) GHG&SST response. Hatching indicates statistical significance, as in Figure 2.

results in the light of our new findings, highlighting the differences between the two studies, and clarifying the new insights provided by the new integrations presented here.

[21] The key finding of LS10 was that ozone depletion in the tropical lower stratosphere in the last several decades is likely due to increasing GHGs, and not to the presence of chlorofluorocarbons (CFCs), as one might have naively guessed. That result was obtained by independently specifying concentrations of GHGs and CFCs, using a model similar to ours (CAM3), but with *interactive* tropospheric and stratospheric chemistry, plus a modified gravity wave scheme (to obtain a reasonable representation of the stratospheric circulation, while retaining a relatively low model top).

[22] Our new model integrations add two new insights to the findings of LS10. First, we have here shown that it is ozone depletion at low-latitudes that controls the tropical lower-stratospheric temperature trends in our model (cf. Figure 3c). If we only specify polar ozone depletion, no tropical temperature trends are observed in our model.

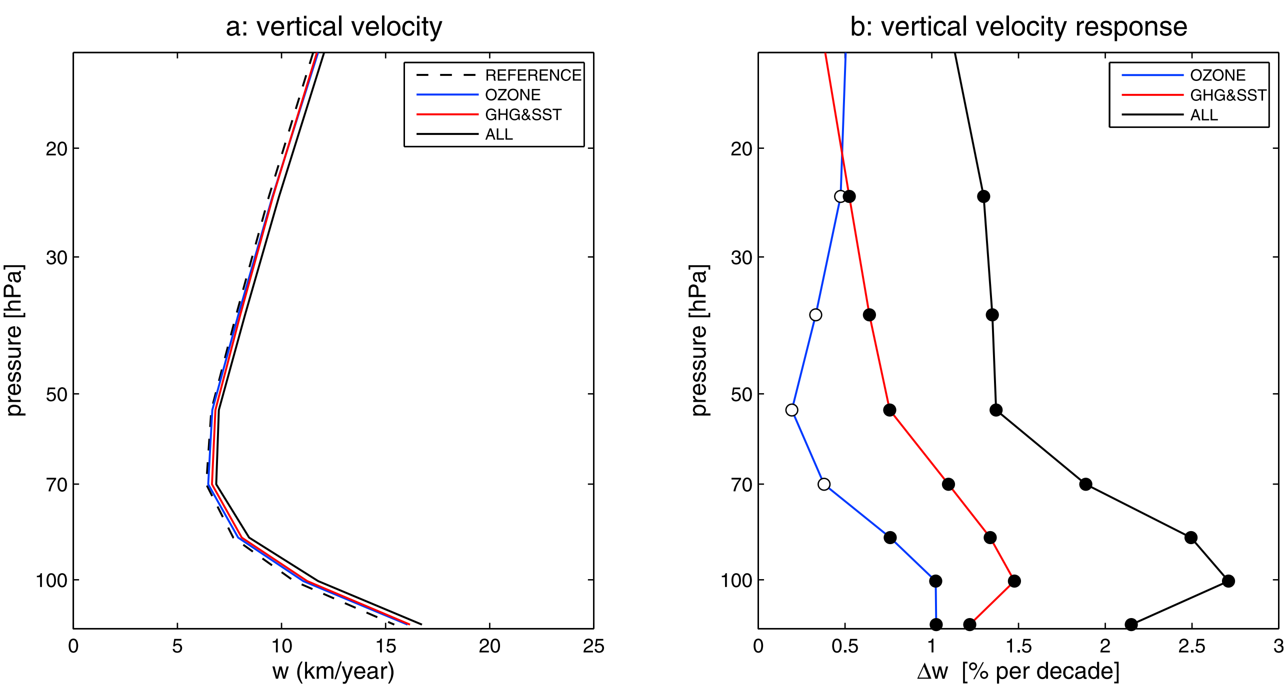

Figure 6. (a) Annual mean model vertical velocity w, averaged 20°S to 20°N, in km/year, for the REFERENCE, OZONE, GHG&SST and ALL integrations. (b) Annual mean model vertical velocity response Δw, averaged 20°S to 20°N, in percentage/decade, for the OZONE, GHG&SST and ALL integrations. The response is defined as the difference from the REFERENCE integration. In Figure 6b, filled dots indicate a statistically significant response; empty dots indicate the lack of statistical significance in the response; significance is evaluated from a simple Student t-test, using the 95% confidence level.

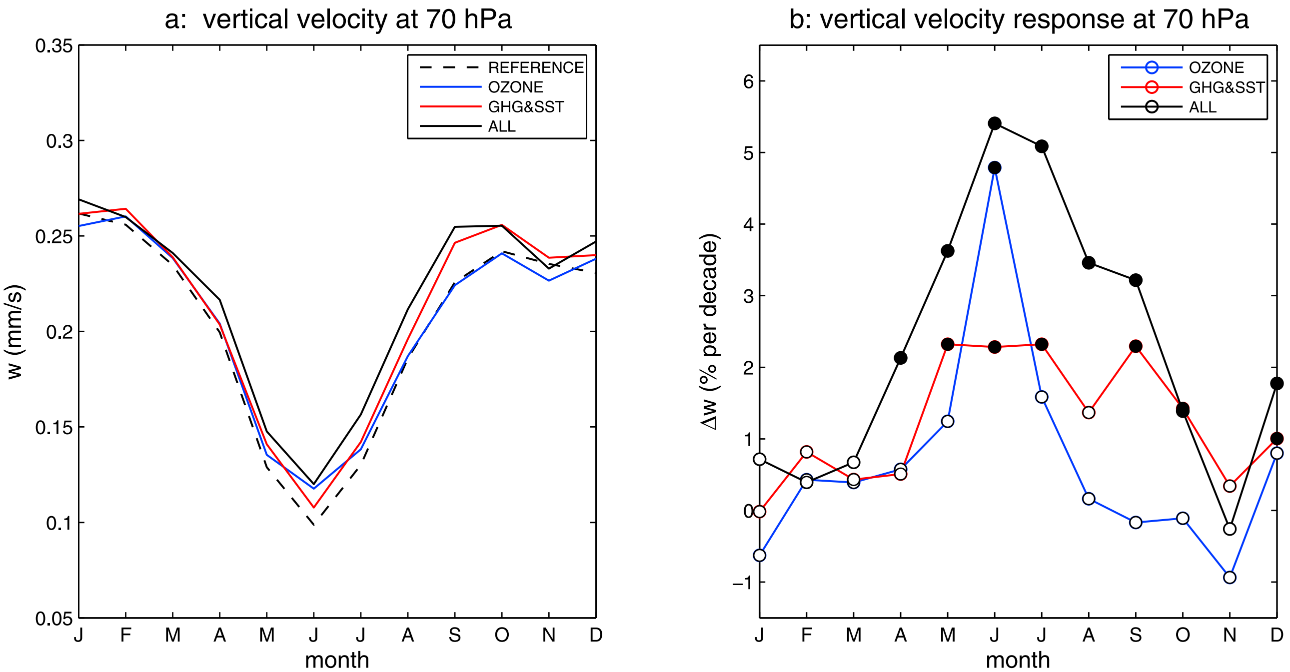

Figure 7. As in Figure 6, but for the seasonal cycle of (a) w and (b) Δw, at 70 hPa, averaged 20°S to 20°N.

[23] Second, and more importantly, by "decoupling" ozone depletion from circulation changes (as we have done here), we are able to elucidate the relative contribution of ozone depletion and increased tropical upwelling on the lower-stratospheric temperature response. To illustrate this, we plot in Figure 6a the annual mean vertical velocity w, averaged from 20°S to 20°N, for the four key integrations of our model; the corresponding response Δw, due to different forcings, is shown in Figure 6b. This figure is meant to be directly compared to Figure 1 of LS10: although ours is just an off-the-shelf version of CAM3, without interactive chemistry, the vertical velocities in our integrations, and their response to forcings, compare very favorably to the ones reported in that study.

[24] The key point to be gathered from Figure 6 comes from comparing the colored lines in Figure 6b. Note that the tropical upwelling response due to increased GHGs and SSTs (red line) is larger than the one due to ozone depletion (blue); the latter, in fact, is not even statistically significant above 80 hPa. In spite of this stronger upwelling, GHGs and SSTs are unable to induce a statistically significant response on lower-stratospheric temperatures, as already shown in Figures 4c and 5c. Conversely, while ozone depletion is unable to induce a statistically significant increase in vertical velocities, it causes a robust and significant cooling in the tropical lower stratosphere, peaking around 50 hPa. Our model results, therefore, suggest that the temperature trends in the tropical lower-stratosphere observed over the last half century are primarily associated with the in situ radiative effects due to ozone loss, and not with increased upwelling in that region. Nonetheless, it is quite likely that the ozone depletion itself is related to changes in upwelling: our work thus demonstrates how understanding temperature trends in this region is a complicated question.

[25] This conclusion is further strengthened by consideration of the seasonal cycle of the vertical velocity, illustrated in Figure 7. In Figure 7a we show the annual cycle of w at 70 hPa, averaged from 20°S to 20°N. Although our model does not have a fully resolved stratospheric circulation, this seasonal cycle compares well with observations. Contrast our Figure 7a with, for instance, Figure 2 of *Randel et al.* [2008]: both show that the seasonal cycle of w has a minimum in JJA and maximum in DJF. Next, consider the seasonal cycle of Δw, the vertical velocity response due to different forcings, shown in Figure 7b. Our model's response to ozone forcing (blue line) is only significant in June, and if a seasonal cycle in Δw exists at all, it would show a maximum in MJJ: this, however, is out of phase with the seasonal cycle of the lower stratospheric temperature response (see Figures 4b and 5b). The same is true for the ALL integration (black curve in Figure 7b), where the Δw is statistically significant for many months, but again is out of phase with the temperature response shown in Figures 4a and 5a.

[26] We close this discussion by emphasizing that we have no means of determining, at present, whether the seasonal cycle of Δw in our model integration bears any resemblance to observations, as no studies we are aware of have reported the seasonal cycle of the upwelling trends in the last several decades. Nonetheless, the fact that a "low-top" model without interactive chemistry, such as the one we have used here, is able to reproduce the observed seasonal cycle of tropical lower-stratospheric temperatures trends when forced with the observed ozone fields alone (specifically, the SPARC ozone from *Cionni et al.* [2011]), is compelling evidence for the key role of ozone depletion on tropical lower-stratospheric temperatures trends.

5. Conclusion

[27] In summary then, the results presented here suggests that increased upwelling is not the immediate cause of recent

tropical lower-stratospheric temperature trends: ozone depletion is. This, of course, begs the question: what is causing ozone depletion in the tropical lower-stratosphere? LS10 have argued that it is, precisely, an increased upwelling that is the likely culprit. It is well established that lower-stratospheric ozone is very tightly correlated to tropical upwelling; so much so, in fact, that "because there are no direct measurements of upwelling near the tropical tropopause … ozone observations can provide a sensitive measure of upwelling changes in the real atmosphere", as *Randel and Thompson* [2011] point out.

[28] That being the case, the next question must be: what is causing the increased upwelling? There is growing evidence that increased greenhouse gases are responsible for increased upwelling, via an accelerated Brewer-Dobson circulation. The recent observational study of *Fu et al.* [2010], which considers the seasonality of the observed trends as we have done here, concludes that these are "largely a response to changes Brewer-Dobson circulation". Our modeling results confirm this, but with the important, additional clue that ozone changes are the crucial link between the circulation changes and the temperature changes.

[29] Other evidence for the role of increasing GHGs in accelerating the Brewer-Dobson circulation comes from chemistry-climate models forced with a wide variety of scenarios [*Butchart et al.*, 2006; *Garcia and Randel*, 2008; *Butchart et al.*, 2010]. Such models, when forced with increasing GHGs, robustly show accelerated Brewer-Dobson circulations. However, the seasonal cycle of the tropical upwelling is often poorly simulated in such models [see, e.g., *Butchart et al.*, 2006, Figure 3], and the full seasonal cycle of the trends has yet to be reported in the literature.

[30] Last, we wish to stress the importance of using accurate and well documented stratospheric ozone fields in all modeling intercomparison projects, and of archiving such fields. This becomes increasingly important as ozone changes emerge as key players in past and future climate changes. The major role of stratospheric ozone depletion on the circulation and hydrology of the Southern Hemisphere is now well documented (see *Thompson et al.* [2011] for a comprehensive review). This paper shows that at low-latitudes too stratospheric ozone depletion plays an important role, notably as it relates to the knotty issue of tropical temperature trends [*Karl et al.*, 2006].

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