

Are recent Arctic ozone losses caused by increasing greenhouse gases?

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Received 25 June 2013; revised 1 August 2013; accepted 6 August 2013; published 27 August 2013.

[1] It has been suggested that the Arctic ozone losses observed in recent years might be a manifestation of climate change due to increasing greenhouse gases. We here offer evidence to the contrary, by focusing on the volume of polar stratospheric clouds (V_{PSC}), a convenient proxy for polar ozone loss whose simplicity allows for easily reproducible results. First, we analyze the time series of V_{PSC} in three reanalysis data sets and find no statistically significant trends in V_{PSC} —nor changes in their probability density functions—over the period 1979–2011. Second, we analyze V_{PSC} in a stratosphere-resolving chemistry-climate model forced uniquely with increasing greenhouse gases following the A1B scenario: here too, we find no significant changes in V_{PSC} over the entire 21st century. Taken together, these results strongly suggest that the sporadic high ozone losses in recent years have not been caused by increasing greenhouse gases. **Citation:** Rieder, H. E., and L. M. Polvani (2013), Are recent Arctic ozone losses caused by increasing greenhouse gases?, *Geophys. Res. Lett.*, 40, 4437–4441, doi:10.1002/grl.50835.

1. Introduction

[2] It is well established that man-made ozone-depleting substances (ODS) are the primary cause of stratospheric ozone depletion [Molina and Rowland, 1974; Rowland and Molina, 1975]. Since the detection of the Antarctic ozone hole in the 1980s [e.g., Farman et al., 1985], the evolution of the Earth's ozone layer, especially at high latitudes, has received much attention. Notably, the Montreal Protocol and its amendments have led to a significant decline in the stratospheric burden of ODS [World Meteorological Organization (WMO), 2011], and the decline in ODS has had a measurable effect on column ozone [Mäder et al., 2010; WMO, 2011]. Furthermore, state-of-the-art chemistry-climate models consistently project ozone levels to recover to pre-1980 values in the second half of the 21st century [e.g., SPARC-CCMVal, 2010].

[3] In light of this, the Arctic ozone losses during winter 2010/2011 came somewhat unexpected [Manney et al., 2011,

hereinafter M11], although previous WMO/UNEP (United Nations Environment Programme) Ozone Assessment Reports highlighted the possibility of severe Arctic ozone depletion in particularly cold winters. The 2010/2011 event, referred to as the “first Arctic ozone hole” [e.g., Garcia, 2011; Sinnhuber et al., 2011; M11], has received much attention in the literature, with several studies providing a highly detailed picture of the chemical and dynamical state of the Arctic atmosphere during that winter [e.g., Adams et al., 2012; Lindenmaier et al., 2012; Pommerau et al., 2013; Sinnhuber et al., 2011; M11]. One key question, however, remains unanswered: Are such extreme Arctic ozone losses, which appear to have occurred more frequently in recent decades, a manifestation of climate change due to increasing greenhouse gases?

[4] The aim of this paper is to answer this question. We do so by studying the evolution of lower stratospheric temperatures: these are crucial to the formation of polar stratospheric clouds (PSCs) which are of central importance for stratospheric ozone depletion in polar winter [e.g., Peter, 1997; Solomon, 1999]. In particular, the volume of air that is colder than the threshold for PSC formation (hereinafter V_{PSC}) is a widely used and convenient proxy for polar ozone depletion [Rex et al., 2004, hereinafter R04]. In the last several decades, an upward trend in the evolution of V_{PSC} has been reported [WMO, 2011], with a new record approximately every 5 years, leading to the popular notion that “the coldest Arctic winters are getting colder” [e.g., Rex et al., 2006, hereinafter R06], possibly as a consequence of increasing greenhouse gases. But is this really so?

[5] In this paper, we carefully analyze V_{PSC} in three different reanalysis data sets and find no statistically significant changes in recent decades. We also analyze the output of a chemistry-climate model forced uniquely with increasing greenhouse gases from 1960 to 2100 and again find no trends in V_{PSC} over that entire period. From these facts, we conclude that it is premature to interpret recent large Arctic ozone losses as a signal of Arctic climate change induced by increasing greenhouse gases.

2. Data and Methods

[6] We follow the original approach of R04 and compute V_{PSC} using daily temperatures at 30 and 50 hPa, from three reanalysis data sets: NASA–Modern Era Retrospective Analysis for Research and Applications (NASA-MERRA) [e.g., Rienecker et al., 2011], European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim [Dee et al., 2011], and National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) [e.g., Kalnay et al., 1996; Kistler, 2001]. Note that these reanalyses have different horizontal resolutions: $0.5^\circ \times 0.66^\circ$ for NASA-MERRA, $1.5^\circ \times 1.5^\circ$ for ERA-Interim, and $2.5^\circ \times 2.5^\circ$ for NCEP-NCAR.

Additional supporting information may be found in the online version of this article.

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0094-8276/13/10.1002/grl.50835

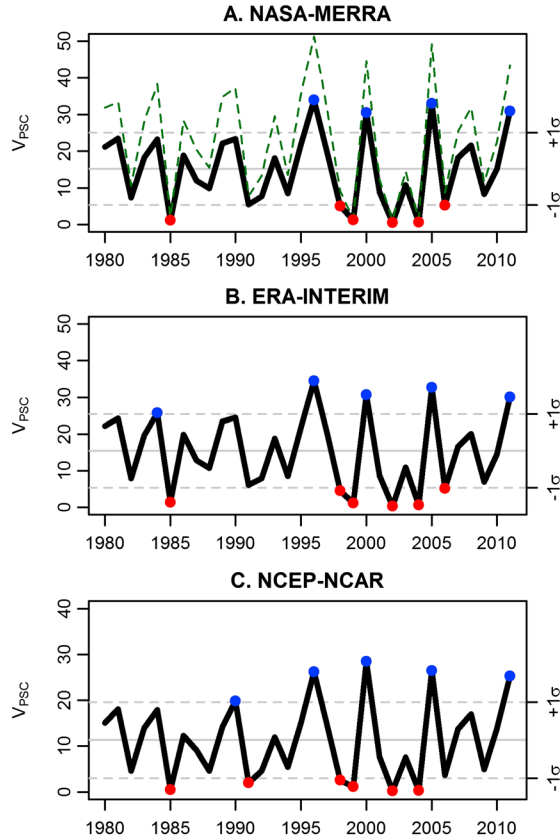


Figure 1. Black lines represent extended wintertime V_{PSC} (10^6 km^3) in 1979/1980–2010/2011 for the (a) NASA-MERRA, (b) ERA-Interim, and (c) NCEP-NCAR reanalysis data sets. Blue (red) points represent the years where V_{PSC} is outside of plus (minus) 1 standard deviation (dotted grey lines) of the 1979/1980–2010/2011 mean (solid grey lines). The green curve in Figure 1a represents unscaled V_{PSC} from M11.

[7] For each day, V_{PSC} is computed by first identifying the grid cells north of 60°N whose temperatures T fall below the critical threshold for nitric acid trihydrate (NAT) formation. Following *Hanson and Mauersberger* [1988], we use $T_{\text{NAT}} = 193.61 \text{ K}$ at 30 hPa and $T_{\text{NAT}} = 195.59 \text{ K}$ at 50 hPa. Next, we calculate the total PSC area (A_{PSC}) by summing the areas of all grid cells with $T < T_{\text{NAT}}$. Finally, following R04, we obtain V_{PSC} from A_{PSC} using the expression

$$V_{\text{PSC}} = [0.8 \times A_{\text{PSC}}(50 \text{ hPa}) \text{ km}^2 + 0.2 \times A_{\text{PSC}}(30 \text{ hPa}) \text{ km}^2] \times 5.06 \text{ km} \quad (1)$$

[8] From these daily values, we obtain the mean value of V_{PSC} for each Arctic winter by averaging over the extended season 16 December to 15 April. To test robustness, we have also computed V_{PSC} for the shorter season 16 December to 31 March and found no significant differences.

[9] For the modeling component of this study, daily values of T were not available. However, daily A_{PSC} was archived, albeit only at 50 hPa. In view of this, we use the simpler expression

$$V_{\text{PSC}^*} = [0.8 \times A_{\text{PSC}}(50 \text{ hPa}) \text{ km}^2] \times 5.06 \text{ km} \quad (2)$$

[10] We are aware that this simplification affects the absolute magnitude of V_{PSC} ; however, since A_{PSC} at 50 hPa is multiplied by a much larger coefficient (see equation (1) above), this simplification does not affect the overall pattern or robustness of the results. In fact, we have compared V_{PSC} and V_{PSC^*} in the NASA-MERRA reanalysis: Figure S1a in the supporting information shows that the two quantities are very tightly related, the latter being consistently smaller, on average, by 25%. We also note that in a number of recent studies [e.g., *Tilmes et al.*, 2006; M11], V_{PSC} was further scaled by the volume of the polar vortex. Here we decided to analyze unscaled V_{PSC} as there are many possible ways to define the vortex, and such scaling adds, in our view, unnecessary complexity to the simple formulation given in equation (1). In fact, we have compared scaled and unscaled V_{PSC} for NASA-MERRA and found that the correlation is very high (0.92).

3. Evidence From Reanalyses

[11] The time series of extended winter time V_{PSC} , which was computed using equation (1) over the period 1979/1980–2010/2011, is shown in Figure 1 for each of the three data sets we have analyzed. Contrasting the abscissa on the individual panels, one can see that the actual magnitude of V_{PSC} varies considerably among the three reanalyses, with NASA-MERRA and ERA-Interim being roughly 30% larger than NCEP-NCAR. Such differences have been documented before and are directly related to the individual temperature biases in the data sets. *Manney et al.* [2003], for instance, contrasted six different reanalyses and found that the areas of low temperatures in the lower stratosphere can differ by as much as 50% among different products, with NCEP-NCAR, in general, being the warmest, as confirmed in Figure 1. Hence, NCEP-NCAR should be used with much caution in detailed polar process studies.

[12] More importantly, however, Figure 1 reveals a remarkable agreement in the year-to-year variability of V_{PSC} among the three reanalysis data sets. The correlations among the three time series in Figure 1 are extremely high, ranging from 0.95 (between ERA-Interim and NCEP-NCAR) to 0.99 (for NASA-MERRA and ERA-Interim). This strong agreement among different data sets, combined with the extreme simplicity of the underlying method used here for computing V_{PSC} , makes our results very robust.

[13] The first result to be gathered from Figure 1 is that no trend in V_{PSC} is immediately discernible over the 32 year period for which reliable data are available from multiple data sets. To confirm this, we have computed trends in several different ways and found nothing that is statistically significant on a rigorous test level (i.e., 95%). Specifically, we have computed the trend over (1) the entire time series, (2) the first and second halves separately, and (3) 5 year and 3 year maximum and minimum values. The p values for all of these are reported in Table S1: no trends are significant on a 95% level.

[14] Next, we focus on the “extreme” years, as these have received the most attention in the previous literature. These years are the key piece of evidence behind the suggestion that “the coldest winters are getting colder” [e.g., R06]. We start by objectively defining the “coldest winters” as those for which the V_{PSC} values are more than 1 standard deviation above the mean (computed over each of the 1979/1980–2010/2011 time series). These coldest winters are

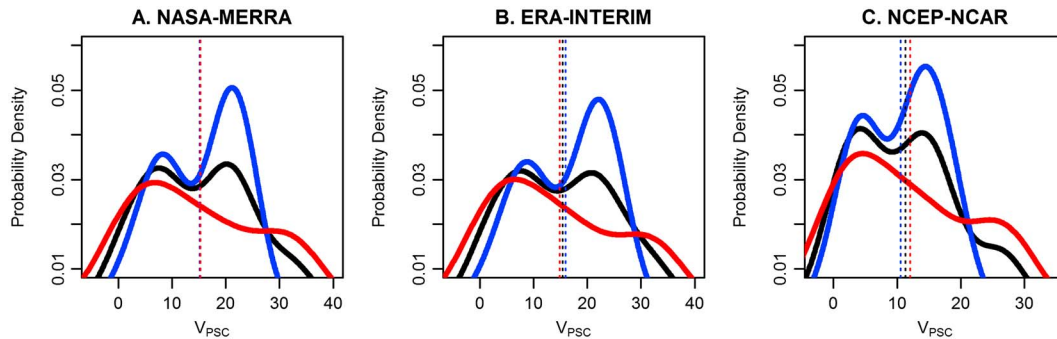


Figure 2. Probability density plots of extended wintertime V_{PSC} (10^6 km^3) for the 1979/1980–2010/2011 (black), 1979/1980–1994/1995 (blue), and 1995/1996–2010/2011 (red) time periods as computed from the (a) NASA-MERRA, (b) ERA-Interim, and (c) NCEP-NCAR reanalysis data sets. The colored dotted lines mark the respective mean values of the individual time periods. Probability densities are calculated using the “density” function with a “Gaussian” kernel from the standard “stats” package in the statistical software R. The statistical properties of the kernel (K) are determined by $\sigma^2(K) = \text{int}(t^2 K(t) dt)$, which is always equal to 1 (and hence the bandwidth is the standard deviation of the kernel) and $R(K) = \text{int}(K^2(t) dt)$.

highlighted, for each reanalysis, by the blue dots in Figure 1. It is abundantly clear that no visible positive trends exist in these coldest winters, in any of the reanalyses here presented. It seems that extremely cold winters are more frequent in the second half of the record (see below), but note that the actual ranking of the coldest winter is not robust across the reanalyses. For instance, the winter of 1999/2000 is the coldest in NCEP-NCAR (Figure 1c), but it is clearly not the coldest in the other two reanalyses. More importantly, we see no evidence for a steady and monotonic increase in V_{PSC} for the coldest winters, such as, e.g., the one shown in the 2010 Ozone Assessment Report [WMO, 2011, Figure 2-16] or in R04 and R06. The explanation for this major qualitative difference, we suggest, lies in the fact that while our V_{PSC} time series originate from individual, and therefore internally consistent, reanalysis products, the earlier studies have merged possibly inconsistent data sets. Specifically, the V_{PSC} time series analyzed in R04 and R06 were constructed by combining radiosonde data for the presatellite era with ECMWF operational analyses after 1979. We note that the latter alone have undergone significant changes in the assimilation scheme and the number of assimilation levels in 1997 and again in 1999 [Pommerau et al., 2013]. Furthermore, Figure 1 shows that not only the coldest winters but also the warmest winters (red dots) appear to be more frequent in the second half of the record. If indeed the coldest winters are getting colder as a consequence of climate change induced by increasing greenhouse gases, the naive expectation would be that the entire stratosphere would be cooling, and thus, the warmest winters should be less frequent in recent decades: Figure 1 testifies to the contrary.

[15] Although robust trends are clearly absent from the time series in Figure 1, the fact remains that the majority of extreme winters—both cold and warm—are found in the second half of the record, and this occurs robustly across all three reanalyses. The visual impression one gets from Figure 1 is that perhaps, a regime shift occurred around 1995, so that extreme winters have become more frequent since. In order to test whether this impression is in fact statistically significant, we carefully compare the first and second halves of the time series.

[16] Specifically, in Figure 2, we show the probability density functions of V_{PSC} for the entire time period (black), the first half of the record (1979/1980–1994/1995, blue), and

the second half (1995/1996–2010/2011, red); for clarity, each reanalysis is shown in a different panel. The blue and red curves appear quite different, at first glance. To determine if this difference is statistically significant, we apply two standard statistical tests. First, we use a Kolmogorov-Smirnov (KS) test, the standard nonparametric test for the equality of continuous one-dimensional probability distributions. The results of the KS test are that the probability distributions do not differ significantly from each other in any of the three reanalysis data sets (all p values > 0.7). Second, we use a more conservative test that assigns greater weight to the tails. A k -sample Anderson-Darling (ADK) test, a standard rank test without restrictive parametric model assumptions for the equality of continuous one-dimensional probability distributions [e.g., Scholz and Stephens, 1987], confirms the results of the KS test. Given the highly insignificant p values of the KS and ADK tests, we conclude that the samples in the first and second halves of the record are stemming from the same overall probability distribution. In simpler terms, events found after 1995 could have occurred before 1995 with equal probability, and vice versa. This result also holds if different (and shorter) time windows are compared (not shown here).

[17] We conclude this section by emphasizing that our results are highly insensitive to the precise definition of V_{PSC} . For instance, M11 used seven isotropic surfaces in the lower stratosphere (390, 410, 430, 460, 490, 520, and 550 K) to calculate V_{PSC} . One might ask whether such complexity is needed. The green dashed line in Figure 1a shows the V_{PSC} computed by M11: while the absolute numbers are consistently higher than the ones obtained from the original R04 definition (as one would expect from simply adding more vertical levels), the correlation between the green and black lines is very high (a value of 0.98, as illustrated in Figure S1b).

4. Evidence From Chemistry-Climate Model Integrations

[18] Having demonstrated that reanalyses show no evidence that “the coldest winters are getting colder” over the last 32 years, we now turn to analyzing model output. It is conceivable that the observational record is simply too short, but a clear climate signal would appear on a longer time scale

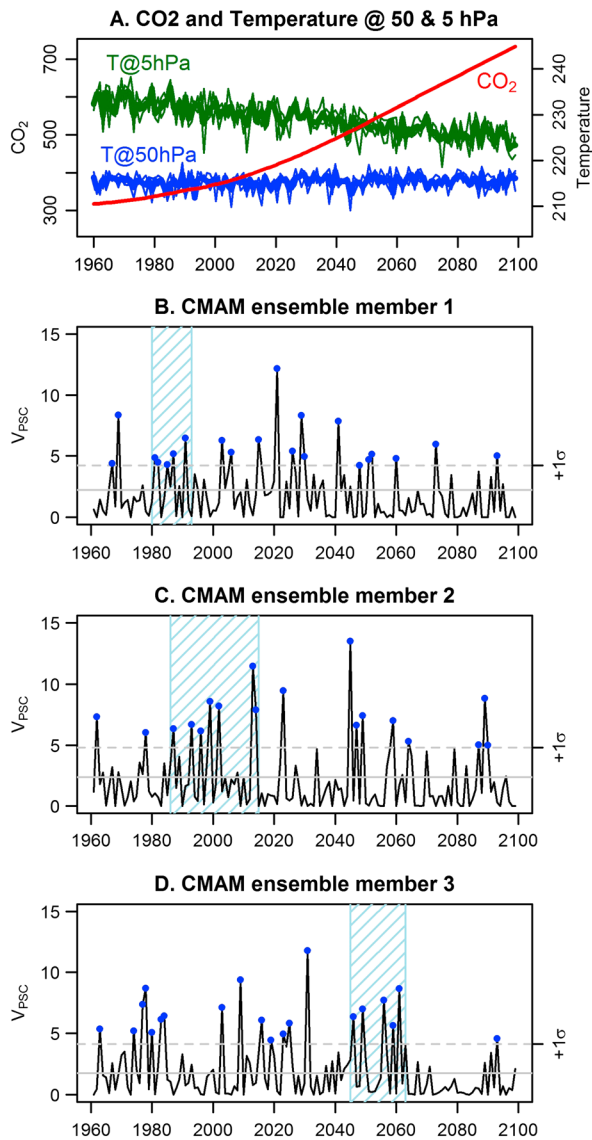


Figure 3. (a) Annual mean CO₂ concentration (ppm) (red) and mean wintertime (December–April) polar cap (60°N–90°N) temperatures (K) at the 50 (blue) and 5 (green) hPa levels, from the Canadian Middle Atmosphere Model (CMAM) ensemble under the SCN-B2b scenario (bold lines show ensemble averages; thin lines show individual ensemble members). (b–d) Extended wintertime V_{PSC^*} (10⁶ km³) (black solid line) from 1960/1961 to 2099/2100 in the three CMAM ensemble members under the SCN-B2b scenario. Blue points mark the years where V_{PSC^*} is outside of plus 1 standard deviation (dotted grey lines) of the 1979/1980–2010/2011 mean value (solid grey lines). Blue hashed boxes highlight periods with increasing patterns in V_{PSC^*} extremes.

with a larger greenhouse gas forcing. In the present context, what is needed are model runs with increasing greenhouse gases alone, to see if the coldest winters do indeed become colder (in the lower stratosphere) as a consequence of such an increase.

[19] As it happens, such runs were suggested as part of the Chemistry–Climate Model Validation Activity 2 (CCMVal-2) and were referred to as the “SCN-B2b scenario”: high-top models with interactive stratospheric chemistry were to be

integrated from 1960 to 2100 with only well-mixed greenhouse gases increasing as per the SRES A1B scenario, but with all other forcings kept fixed at 1960 levels [SPARC-CCMVal, 2010]. Unfortunately, only few such runs actually are available (as they were not made mandatory in CCMVal-2); for clarity of presentation, we focus here on an ensemble of three SCN-B2b runs performed with the Canadian Middle Atmosphere Model (CMAM), the only model for which an ensemble of such runs was available. The CMAM model and its SCN-B2b runs have been extensively documented [McLandress *et al.*, 2010, 2011] in the context of the ozone hole in the Southern Hemisphere. Here we shift the focus to the Arctic lower stratosphere and how it changes as a consequence of increasing greenhouse gases, keeping in mind that CMAM was also the only CCMVal-2 model with a fully coupled ocean, thus simulating the surface warming due to the greenhouse effect in an internally consistent way (all other CCMVal-2 models were run with specified sea surface temperatures).

[20] To set the stage, the red line in Figure 3a shows the CO₂ concentrations in these runs: note that the values more than double from 1960 to 2100. As a consequence of the increasing CO₂, the upper stratosphere cools, as one expects: this is illustrated by the green curve in the same figure, showing the 60°N–90°N polar cap temperature at 5 hPa, averaged over the three ensemble members (the individual members are the thin curves of the same color). However, the lower stratosphere is little affected by the increasing greenhouse gases: see how the blue curve, showing the lower stratospheric polar cap temperature at 50 hPa, is nearly flat. This is not a peculiar behavior of the CMAM model. It is well established that greenhouse gas cooling manifests itself primarily in the middle and upper stratosphere and is very small in the lower stratosphere; see, for instance, the classic study of Manabe and Wetherald [1967, Figure 16]. Furthermore, using a comprehensive general circulation model, Sigmond *et al.* [2004] explored the effects of CO₂ doubling on lower/middle stratospheric temperature and showed that the very small signal results from a cancellation between radiative cooling at upper levels and tropospheric dynamical heating.

[21] Since the lower stratospheric, polar cap, mean temperature carries no signature of the increasing greenhouse gases in the CMAM integrations, it is not surprising that the extreme temperatures show no trends as well (as documented for an earlier version of CMAM) [Hitchcock *et al.*, 2009]. In Figures 3b–3d, we plot the time series of V_{PSC^*} for each of the three CMAM ensemble members from 1960 to 2100. The blue dots show the coldest winters, i.e., those which fall outside 1 standard deviation of the 1979/1980–2010/2011 mean, as in Figure 1. There are clearly no meaningful trends in the blue dots, over the entire 140 year period. Nonetheless, one can easily identify multidecadal periods in which a sequence of coldest winters (blue dots) appears to be getting colder: these are highlighted with the blue hashing, to emphasize the fact that such periods are entirely fortuitous in these model runs.

5. Conclusion

[22] Over the 32 year period 1979–2011, three widely used reanalysis data sets show no trends in the volume of polar stratospheric clouds (V_{PSC}), when computed in a simple

and reproducible way from daily temperatures at two lower stratospheric levels. In addition, although high- V_{PSC} years appear to cluster after 1995, we find that the probability density distributions are not statistically different before and after that year. These findings are in agreement with the recent study of Pommerau *et al.* [2013], who document the absence of statistically significant trends in the amplitude of denitrification in early winter, renoxification of the vortex, vortex strength, or total ozone depletion, over the period 1994–2011. Furthermore, analyzing the output from a model forced solely with increasing greenhouse gases, we find no evidence of a temperature trend in the lower stratosphere, although CO₂ concentrations more than double over the length of those model runs. While these results come from a single model, they offer compelling evidence that greenhouse gases are unlikely to have a major effect on lower stratospheric temperatures in Arctic spring.

[23] **Acknowledgments.** H.E.R. acknowledges the support of the Swiss National Science Foundation (SNF) through fellowship grant PEZP2-134426. L.M.P. was partly supported by a grant from the U.S. National Science Foundation. The authors are grateful to Gloria Manney, Rolf Mueller, Thomas Peter, Tiffany Shaw, Ted Shepherd, and Susan Solomon for enlightening discussions on this topic. The authors also thank Gloria Manney and Zac Lawrence for A_{PSC} data from the NASA-MERRA Reanalysis and Charles McLandress for providing the CMAM data. The authors thank Markus Rex for detecting a plotting mistake in Figure 1c in an early draft of this paper.

[24] The Editor thanks Jean-Pierre Pommereau and an anonymous reviewer for their assistance in evaluating this paper.

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