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The surface impacts of Arctic stratospheric ozone anomalies

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Abstract

In the Arctic stratosphere, total column ozone in the spring can vary, from year to year, by as much as 30%. This large interannual variability, however, is absent from many present-generation climate models, in which the prescribed seasonal cycle of stratospheric ozone includes, at best, smooth multi-decadal trends. We here investigate the extent to which interannual variability in Arctic stratospheric ozone is able to affect the surface climate of the Northern Hemisphere extratropics. We do this by contrasting pairs of model integrations with positive and negative springtime ozone anomalies, using a simple yet widely used climate model. For ozone anomaly amplitudes somewhat larger than the recent observed variability, we find a significant influence on the tropospheric circulation, and the surface temperatures and precipitation patterns. More interestingly, these impacts have very clear regional patterns—they are largest over the North Atlantic sector—even though the prescribed ozone anomalies are zonally symmetric. However, confirming other studies, for ozone anomaly amplitudes within the observed range of the last three decades, our model experiments do not show statistically significant impacts at the surface.

S Online supplementary data available from stacks.iop.org/erl/9/074015/mmedia

Keywords: Arctic stratospheric ozone, stratosphere–troposphere coupling, climate models, North Atlantic oscillation

(Some figures may appear in colour only in the online journal)

1. Introduction

Much research on stratospheric ozone over the last few decades has focused on its dramatic chemical depletion in the Antarctic springtime, caused by anthropogenic emissions of chlorofluorocarbons (World Meteorological Organization (WMO) 2011). The Antarctic ozone hole has become an annual feature in austral spring and, while confined to the Antarctic region, it has been linked to atmospheric circulation shifts that reach from the high latitudes well into the subtropics, and directly affect the surface climate. The broad and profound effects of Antarctic ozone depletion on the climate of the Southern Hemisphere have been extensively reviewed (Thompson *et al* 2011, Previdi and Polvani 2014).

The situation in the Arctic is quite different. On the one hand, the multi-decadal ozone loss associated with anthropogenic emissions of ozone depleting substances have been much smaller in the Arctic than in the Antarctic (World Meteorological Organization (WMO) 2011). The cause of this is well understood. Upward propagating planetary wave amplitudes are larger in the Northern Hemisphere, and their breaking in the stratosphere maintains the winter/spring Arctic polar cap considerably warmer than in the Antarctic. These warmer temperatures inhibit the formation of polar stratospheric clouds, and the accompanying chlorine

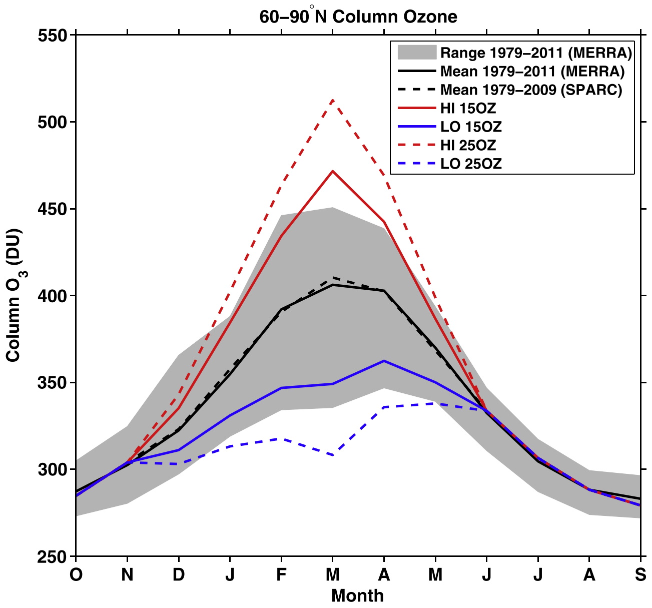

Figure 1. Climatological mean (solid black curve) and range (gray shading) for MERRA total column Arctic ozone (vertically integrated from 500–1 hPa) as a function of month, for the 1979–2011 time period, in Dobson Units (DU). The dashed black curve shows the climatological mean of IGAC/SPARC ozone for 1979–2009. Red and blue curves indicate anomalously strong and weak synthetic ozone forcings, respectively; the solid curves are for ±15% anomalies (15OZ), the dashed ones for ±25% anomalies (25OZ).

activation and heterogeneous chemical reactions that cause the dramatic springtime ozone depletion observed over the South Pole.

On the other hand, the year-to-year temperature variability is much larger in the Arctic than in the Antarctic stratosphere (Randel 1988). This, again, is related to planetary waves. Extreme wave breaking events—known as Stratospheric Sudden Warmings—occur approximately every other year in the Arctic (Charlton and Polvani 2007), but have only occurred once in the Antarctic (Newman and Nash 2005). These events greatly affect stratospheric temperatures and transport, directly impacting ozone levels in springtime (Tegtmeier *et al* 2008). Hence in Arctic winters with weak wave driving and no sudden warmings, the stratosphere becomes extremely cold and experiences reduced poleward ozone transport, resulting in large observed springtime ozone minima. The latest instance occurred in March 2011, when Arctic ozone levels fell to their lowest recorded levels, on par with levels observed in the Antarctic (Manney *et al* 2011).

This large interannual variability in Arctic ozone is depicted in figure 1, which shows the seasonal cycle of the mean (solid black line) and the range (gray shading) of total column ozone in Dobson Units (DU), averaged over the Arctic polar cap (60–90° N) and over the 1979–2011 period. Note that the range of interannual variability is roughly 30% of the 400 DU mean value in the month of March (see also figure 1 of Müller *et al* 2008).

Whether this large year-to-year variability in Arctic stratospheric ozone is able to affect the surface climate of the Northern Hemisphere extratropics is currently unknown. Answering this question is the goal of this study. As we will show below, Arctic ozone anomalies can have a significant influence on extratropical Northern Hemisphere surface climate in spring, although the range of variability over the observational period (1979–2011) is insufficient to produce a statistically significant surface signal in the simplest experimental setup used here (a low-top, atmosphere-only climate model, with only zonally symmetric ozone forcings).

2. Methods

2.1. The model

The climate model used in this study is the Community Atmosphere Model version 3 (CAM3; Collins *et al* 2006). CAM3 is run at T42 horizontal resolution (approximately a 2.8° × 2.8° grid in latitude and longitude) and with 26 hybrid sigma-pressure vertical levels, 8 of which are located above 100 hPa. As with many present-generation climate models, CAM3 has a coarse representation of the stratospheric circulation and no interactive stratospheric chemistry. The reason for using such a model is simple: we are not here interested in understanding (or, even less, simulating) the complex interplay between ozone concentrations and the stratospheric circulation. Rather, we seek to determine whether year-to-year stratospheric ozone anomalies in the Arctic polar cap are able to affect tropospheric and surface climate over the Northern Hemisphere. Hence, a climate model in which ozone levels can be directly specified, such as CAM3, is a better tool than a model in which ozone needs to be interactively computed, as the latter offers less direct control over the ozone concentrations.

Furthermore, as reported in table 2 of Polvani *et al* (2011), the CAM3 response of the atmospheric circulation to stratospheric ozone losses in the Southern Hemisphere compares very well with the mean response of the models that participated in the Stratospheric Processes and their Role in Climate (SPARC)/Chemistry Climate Model Validation project, phase 2 (CCMVal2). Hence, this model is suitable for investigating the question at hand. Lastly, recall that most current generation models, notably the vast majority of those participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor *et al* 2012), incorporate the effects of ozone on climate by just prescribing ozone as a external forcing (Eyring *et al* 2013), exactly as we do here: hence our methodology is completely germane to that of the CMIP5 project.

2.2. The forcings

We run CAM3 with specified sea surface temperatures and sea ice concentrations (SSTs for short) as lower boundary conditions. These are given as a repeating seasonal cycle, without any long-term trends, obtained by averaging the HadISST data (Rayner *et al* 2003) over the 30-year period 1979–2009. Hence, by construction, there in no interannual variability in SSTs in any of the CAM3 integrations analyzed here: this is done to focus on the variability associated with stratospheric ozone anomalies alone.

Similarly, all well-mixed greenhouse gas concentrations (namely CO_2, CH_4, N_2O, CFC-11 and CFC-12, which are given by spatially uniform values in CAM3) are specified to be the 1979–2009 averages from the Historical and Representative Concentration Pathway 4.5 (RCP4.5) scenarios (Meinshausen *et al* 2011); these concentrations are identical in all the integrations analyzed here. The only forcing in our model that is varied is stratospheric ozone, which we discuss next.

We start considering the IGAC/SPARC ozone database (Cionni *et al* 2011). As already mentioned, this ozone database was used by the majority of the CMIP5 models, and includes observational data up to 2009 (this is why we have decided to define our climatology only up to that year). The seasonal cycle of total column IGAC/SPARC ozone, averaged over the period 1979–2009 over the polar cap, is shown by the dashed black line in figure 1. The crucial point, of course, is that nearly all interannual ozone variability is absent from the IGAC/SPARC ozone database—see, for instance, figure 3, of Cionni *et al* (2011)—since it was constructed by simple linear interpolation following a decadal averaging of the data.

To add interannual variability we turn to re-analyses. Specifically, we here use the Modern-Era Retrospective analysis for Research and Applications (MERRA; Rienecker *et al* 2011). We use the MERRA ozone for 1979–2011, so that the large 2011 Arctic ozone minimum is included. First, we confirm that there are no major differences between the MERRA and IGAC/SPARC ozone climatologies. As shown by the solid black line in figure 1, the MERRA total column ozone differs very little from the IGAC/SPARC.

Next, we construct synthetic ozone forcings meant to roughly match the extent and seasonal cycle of the interannual variability, shown by the gray shading in figure 1. This is done by adding simple anomalies to the climatological IGAC/SPARC curve: these anomalies are chosen to peak in March at a given amplitude (either positive or negative), and linearly diminish to zero in November and June. Spatially, the anomalies are confined above 300 hPa and north of 60° N, diminishing to zero in the vertical (below 500 hPa) and in the horizontal (south of at 50° N) with linear weighting functions.

Choosing the anomaly amplitude to be 15% yields the red and blue pair of solid curves in figure 1, corresponding to years with relatively high and low ozone concentration, respectively. Note how these curves roughly span the 1979–2011 range of internal variability, which is why the value of 15% was chosen. To explore larger values of variability (as might possibly occur in future years), we also construct a high/low pair of ozone forcing with 25% amplitude, shown by the dashed red/blue curves in figure 1. Note that these synthetic ozone fields, while built to have realistic temporal and spatial structure, are outside the observed range of Arctic ozone variability and are not meant to 'simulate' any particular event, or any one year; they are simply meant to serve as possible upper and lower ranges of interannual variability, to be used in the idealized integrations described below.

For completeness, the meridional and vertical structure of the anomalies is shown in figure S1 of the supplementary material, available at stacks.iop.org/erl/9/074015/mmedia, for the 15% ozone case. We emphasize that all stratospheric ozone forcings in this paper are *zonally symmetric*, a very important point to which we will return in the discussion section below.

2.3. The integrations

We have performed a set of five time-slice integrations with CAM3, each 100 years long. We use the term 'time-slice' to indicate that, in each integration, all forcings depend on time only via the seasonal cycle, but do not change from year to year. The first integration uses the climatological, 1979–2009 mean, IGAC/SPARC ozone; we call this the 'control run.' The other four integrations, each 100 years long, consist of two pairs, each with a high ozone (HI) and low ozone (LO) member. The first pair, labeled HI 15OZ and LO 15OZ, is forced with the 15% ozone anomalies (solid red/blue curves in figure 1); the second pair, labeled HI 25OZ and LO 25OZ is forced with the 25% ozone anomalies (dashed red/blue curves in figure 1).

In all figures below, the results are presented as the difference of the 100-year means between the LO and HI ozone integrations, for both the 15OZ and 25OZ cases. We refer to this as 'the response to ozone anomalies.' The statistical significance of the response is determined by using a simple Student's *t*-test. Model output for the 100-year integrations is at monthly resolution, but we also save 20-years of daily output for each run.

3. Results

We start by considering the ozone induced response on the polar cap-averaged geopotential height (ΔZ_{pcap}), for the 15OZ and 25OZ cases, shown in figures 2(a) and (b), respectively. As noted by Baldwin and Thompson (2009), Z_{pcap} is highly correlated with the Northern Annular Mode (NAM) index, and thus ΔZ_{pcap} is a simple measure of the NAM response to the stratospheric ozone forcing in our integrations. Also, recall that in the stratosphere a positive NAM anomaly (corresponding to negative Z_{pcap} anomalies) indicates an anomalously cold and strong vortex, whereas in the troposphere a positive NAM indicates a poleward shift of the mid-latitude jet.

As seen in figure 2, both pairs of integrations show statistically significant (shaded) negative ΔZ_{pcap} in the springtime stratosphere, corresponding to a colder and stronger polar vortex in the LO relative to the HI ozone integration. Although the difference in the ozone forcings begins in December (figures 1 and S1), the statistically significant effect of ozone anomalies on the circulation does not occur until spring, when the Arctic region emerges from polar night; lower ozone concentrations then cause a colder stratosphere,

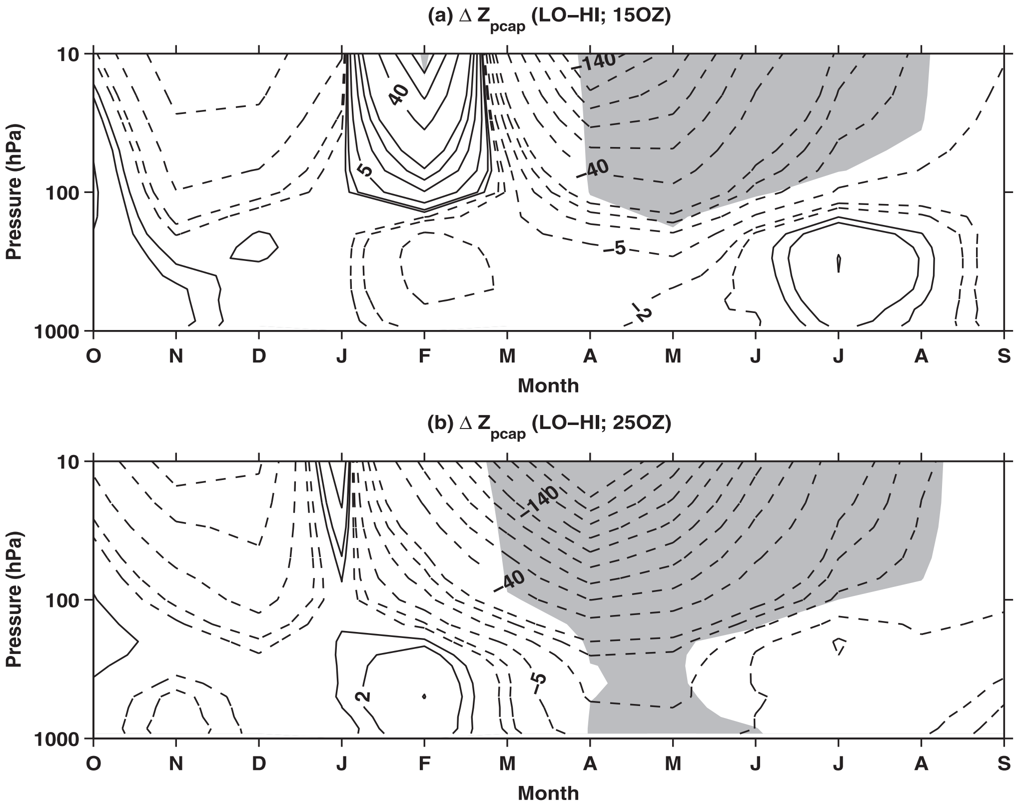

Figure 2. The response to stratospheric ozone changes, as seen in polar cap averaged geopotential height (Z_{pcap} (m)) as a function of month and pressure for the (a) 15OZ case and (b) the 25OZ case. Contour interval is [...–40,–20,–15,–10,–5,–2,–1,1,2,5,10,15,20,40,...]. Solid and dashed contours indicate positive and negative values, respectively. Gray shading indicates a statistical significance of the response, at the 95% level.

and hence a smaller geopotential, as a consequence of the reduced absorption of incoming short-wave radiation by the ozone layer.

Additionally, in figure 2 we note that the significant response in stratospheric Z_{pcap} persists throughout the summer in our model integrations. This response is clearly not a direct consequence of the radiative effects of ozone, as there is no difference between LO and HI ozone forcings from June to November. The negative ΔZ_{pcap} in summer, therefore, results from a delayed and less dramatic breakdown of the polar vortex during the spring, as the stratospheric circulation transitions from polar stratospheric westerlies to easterlies. In the LO integrations the final warming is delayed by approximately two weeks relative to the HI integrations (this is estimated from the daily output over 20 years and is roughly equivalent to one standard deviation of the interannual variability in the final warming date in this model; not shown). One could conjecture that because the vortex is stronger in spring in the LO ozone integrations, the same average amount of wave activity flux from the troposphere to the stratosphere results in a final warming that ultimately ends up with weaker easterlies.

The most interesting finding in figure 2, however, is that for ozone anomalies that span the observed range—the 15OZ case shown in panel (a)— the Z_{pcap} response is *not* statistically significant in the troposphere. This result is consistent with the findings of a concurrent study (Karpechko *et al* 2014) which uses a different methodology (focusing on the ozone anomalies in the spring of 2011, and using a stratosphere-resolving model) and also the work of Jackson *et al* (2013), who found no impact when assimilating Microwave Limb Sounder (MLS) ozone in the UK Met Office NWP model for the spring of 2011. Note that this negative result is not immediately obvious, as one might easily have expected some tropospheric impacts to follow from the large observed interannual range in column ozone over the Arctic.

The question then becomes: how extreme do Arctic stratospheric ozone anomalies need to be for a significant signal to be detected at the surface? As can be seen in panel (b) of figure 2, a 25% anomaly suffices. At that amplitude, we do find a statistically significant signal in ΔZ_{pcap} in the troposphere, in April and May. The effect of ozone anomalies in the springtime in the 25OZ case has the familiar characteristic of a zonal-mean stratosphere–troposphere coupling, with a positive tropospheric NAM anomaly (associated with a negative ΔZ_{pcap}), corresponding to a poleward shift of the mid-latitude jet, as noted above. It should be clear that this coupling to the troposphere is dynamical in nature: it is an *indirect* consequence of the difference in the stratospheric ozone forcing between the LO and HI integrations.

Since the statistically significant Z_{pcap} response is confined to the spring, for the remainder of the paper we restrict our analysis to the April-May time period. In figure 3, we show the zonal mean, April–May response in temperature

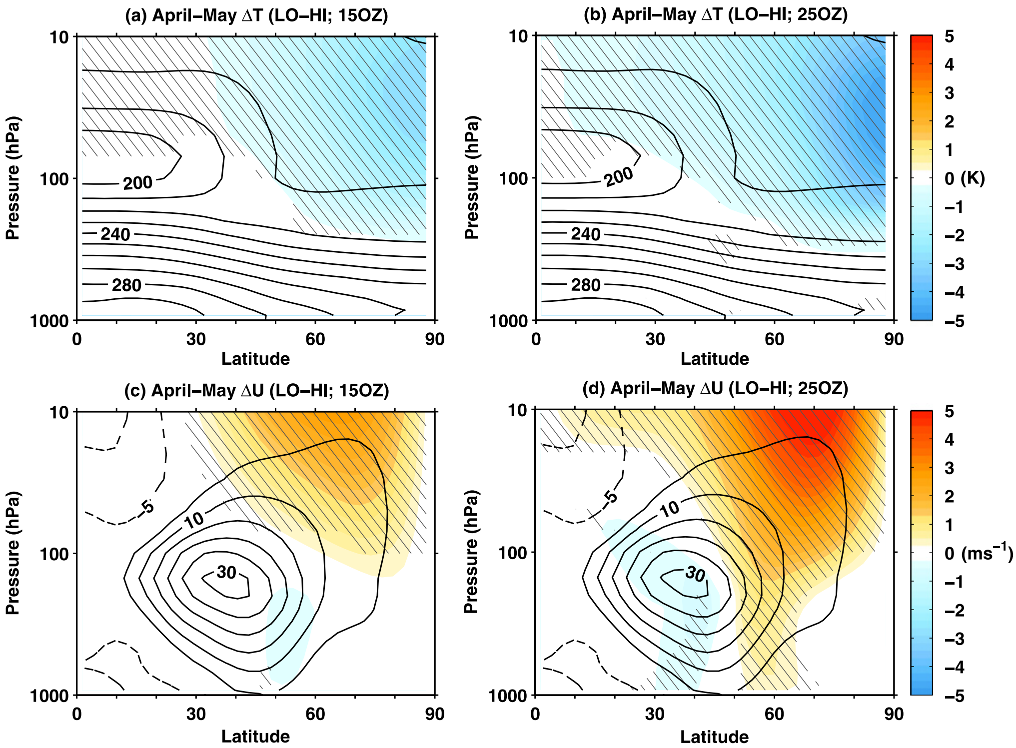

Figure 3. The April–May response to stratospheric ozone changes (shading), as seen in zonal mean temperature (K) and zonal wind (m s^{-1} as a function of latitude and height. (a) And (c) are for the 15OZ case and (b) and (d) are for the 25OZ case. The solid and dashed black contours show the positive and negative climatological zonal mean temperatures and zonal winds, respectively, from the control integration. The contour interval is 10 K for panels (a) and (b), and 5 m s^{-1} for panels (c) and (d). Hatching indicates a statistical significance of the response, at the 95% level.

(top) and zonal wind (bottom), for both the 15OZ (left) and 25OZ (right) cases. The black contours show the climatology (from the control run), the colors show the response, and the hatching shows regions where the response is statistically significant at the 95% level. As seen in panels (a) and (b), both the 15OZ and 25OZ cases show strong cooling in the stratosphere and in the upper troposphere. This cooling is primarily a direct radiative effect caused by the ozone anomalies, but is also amplified by dynamical cooling due to a reduction in wave driving associated with a stronger vortex (not shown).

Panels (c) and (d) of figure 3 show the zonal mean zonal wind response to ozone loss, for the 15OZ and 25OZ cases, respectively. In both cases we see an acceleration of the stratospheric zonal winds, which must result from the ozone induced changes in temperature. However, only the 25OZ case shows significant dynamical coupling between the stratosphere and the troposphere, and a resulting poleward shift of the mid-latitude tropospheric jet that reaches all the way to the surface. Contrasting the colors and the black contours in panel (d), it is clear that the maximum of the surface westerlies is shifted poleward when stratospheric ozone is anomalously low. This is perhaps not surprising, as a similar shift has been found in the Southern Hemisphere to occur on decadal time scales, albeit in a different season and as a consequence of increased ozone depleting substances, not as a consequence of natural variability.

Since a statistically significant surface response is absent in the 15OZ case, we will now focus on tropospheric diagnostics for the 25OZ case in the following figures. While most of our current understanding of the dynamical coupling between the stratosphere and the troposphere is based on a zonal mean perspective (e.g. the annular modes), focusing uniquely on the zonal mean quantities misses out on very significant regional features, which we present in figure 4. Panel (a) shows zonal wind response, at 500 hPa, as a function of latitude and longitude, for the 25OZ case. The largest significant response is found in the North Atlantic sector, where a coherent poleward shift of the mid-latitude jet is seen. Similar-signed signals also occur over the continents, and in the Pacific basin, but those are less significant. We emphasize that the tropospheric responses seen in figure 4 show a very high degree of zonal asymmetry, even though the ozone forcing anomalies in our model are zonally symmetric.

Figure 4(b) shows the response in sea-level pressure (SLP), again for the 25OZ cases. We find that a consistent positive NAM pattern, with a negative SLP response over the Arctic and a positive SLP response in mid-latitudes, accompanies large ozone losses. Regionally, figure 4(b) shows a significant SLP dipole pattern over the North Atlantic region, corresponding to a statistically significant positive phase of the North Atlantic Oscillation. Third, figure 4(c) shows the response in surface temperature, for the same case. This response is less robust than for zonal wind and SLP. The

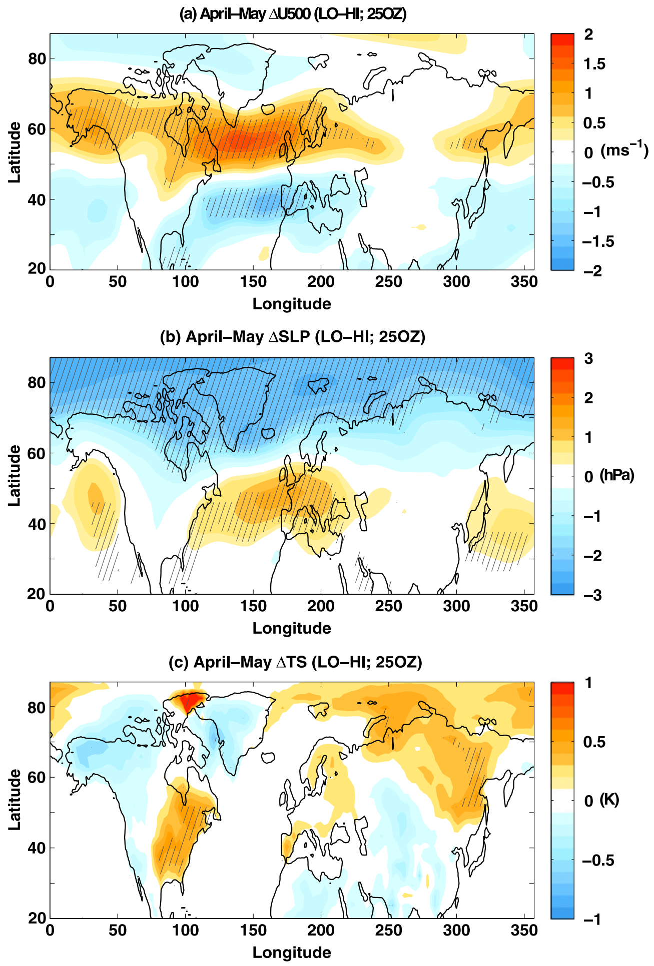

Figure 4. Regional April–May response to stratospheric ozone changes (shading) for (a) zonal wind at 500 hPa (U500 (m s^{-1}), (b) sea-level pressure (SLP (hPa)) and (c) surface temperature (TS (K)), for the 25OZ case. Hatching indicates regions of statistically significantly response at the 95% level.

strongest signal is found over Eastern North America, which shows a considerable warming when stratospheric ozone is anomalously low. This surface temperature response can be understood from the SLP response over the Atlantic: it results from the advection of more warm subtropical air from the Gulf of Mexico poleward. We also note significant warming in Eastern Siberia, associated with the high pressure center in the Pacific that advects maritime air inland.

Finally, focusing more closely on the North Atlantic region, where the largest circulation response is found, we illustrate a statistically significant shift in precipitation caused by the ozone anomalies. Averaging from 120 to 180° W, the precipitation response, given by the red line in figure 5(a), shows a clear dipole pattern, indicating a poleward shift (contrast the red line with the black line, which shows the climatology in the control run). figure 5(b) shows the corresponding response in zonal winds at 500 hPa averaged over the same longitudes: the similarity with panel (a) clearly shows that the poleward precipitation shift is directly associated with the jet shift.

4. Summary and discussion

Using time-slice integrations of an atmospheric GCM with prescribed ozone forcings, we have shown that Arctic stratospheric ozone perturbations comparable in magnitude to the year-to-year variations over the satellite era (roughly ±15% relative to the climatological mean) appear to be unable to significantly influence the surface climate of the Northern Hemisphere extratropics, at least in our experiments. This corroborates the findings of Jackson *et al* (2013), who showed no improvement in 31-day tropospheric forecast errors when observed ozone data was assimilated into the UK Met Office model, for the spring of 2011. Our result is also in agreement with the recent study of Karpechko *et al* (2014) who have similarly found, using a stratosphere-resolving GCM with specified zonally-symmetric ozone forcings, few surface impacts resulting from spring 2011 ozone perturbations alone. However, that study argues that, when combined with favorable SST anomalies, the ozone perturbation of the amplitude observed in 2011 can in fact have a significant impact on surface conditions.

In this paper we have shed light in a different direction, and shown that going from 15% to 25% amplitude, would be sufficient for stratospheric ozone anomalies to have a clear surface impact. For the larger amplitude ozone forcing, the direct cooling in the stratosphere drives a dynamically coupled stratosphere-troposphere response that projects onto the positive phase of the Northern Annular Mode (NAM) in the troposphere and at the surface. This result mirrors that of the Southern Hemisphere circulation response to the Antarctic ozone hole (e.g. Polvani *et al* 2011).

Furthermore, as shown in a number other studies dealing with stratosphere-troposphere coupled dynamics in the Northern Hemisphere (Scaife *et al* 2012, Shaw and Perlwitz 2013), we find that the tropospheric response to the larger ozone anomalies is most robust in the North Atlantic region. The reasons for the sensitivity in this region are not deeply understood at present, and might involve local transient eddy feedbacks (Eichelberger and Hartmann 2007). This regionalization of the tropospheric response to ozone anomalies is particularly surprising since, in our model experiments, the non-zonally-symmetric response results from zonally symmetric ozone forcing. This aspect has not been previously noted, and suggests that much previous work which has almost exclusively focused on the zonal mean response may have missed out on important regional features.

Finally, while conceding that a 25% anomaly in stratospheric ozone has not been observed to date, we recall that the present study has employed only the simplest possible forcing configuration, i.e., ozone anomalies that are, by construction, zonally symmetric. However, as shown in several recent studies (Peters *et al* 2014, Gabriel *et al* 2007, Waugh *et al* 2009, Gillett *et al* 2009, McCormack *et al* 2011), specifying non-zonal ozone forcings results in a much stronger surface response. Hence, it is not inconceivable that, even a 15% amplitude ozone anomaly, provided it be specified without zonal averaging, may result in a statistically significant surface signal. We will be reporting on this is in an

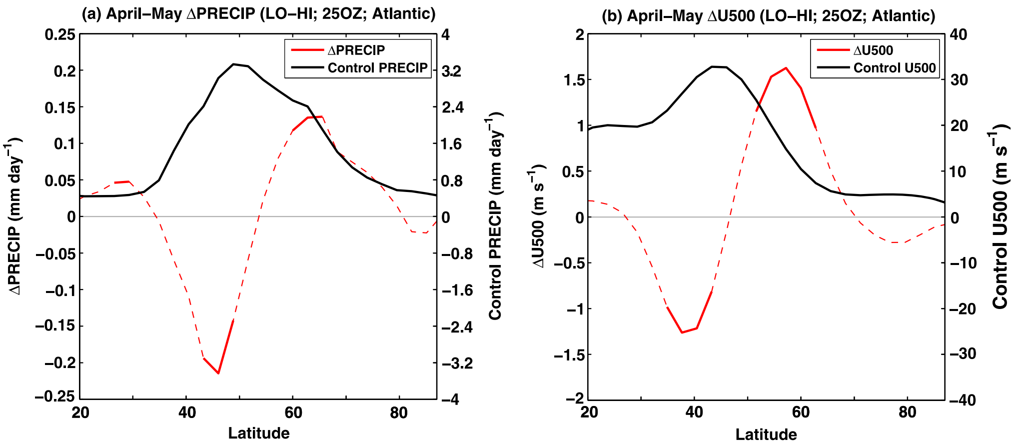

Figure 5. (a) Precipitation (mm day^{-1} and (b) zonal wind at 500hPa (U500 (m s^{-1})) response to stratospheric ozone changes (red curves), in April–May over the Atlantic, for the 25OZ case. The Atlantic region is defined as longitudes from 120–180° W. Solid sections of the red curves indicate latitudes where the response is significant, at the 95% level. The solid black curves show climatological fields, from the control integration.

upcoming study. In addition, as Arctic ozone concentrations are highly linked to transport, decoupling ozone from dynamics, as was done in this study and in most CMIP5 GCMs, may weaken the effects of ozone on surface climate.

Acknowledgments

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