We thank the reviewers for their helpful comments. We have addressed the issues raised by the reviewers to the best of our abilities. In particular, we have included more dynamical metrics as suggested by Referees 2 and 3 to strengthen our discussion of the potential mechanisms of the results studied here. We have corrected or clarified some statistical testing, also suggested by Referees 2 and 3. We have moved several figures to supplementary material at the suggestion of Referees 1 and 3 and have pared down discussion of these figures in the text. This has led to a more succinct presentation of our results.

We provide detailed replies to referees, with referee comments in bold and within angle brackets and our responses and changes below.

Replies to Referee 1

<<

There is some inconsistency in the terminology to describe the two simulations.

>>

We have corrected Figures 2, 3, 8, and 10 to use CHEM and NOCHEM, as is used in the rest of the paper.

<<

The referencing to the sub-figures (in the caption, and also in main text) should be made with a/b/c labels, not top/middle/bottom.

>>

We have corrected this throughout the text and in figure captions.

<<

Overall, the paper has a lot of figures (15) with many of them showing insignificant differences. I think the presentation could become even clearer and more focussed on the main messages if the number of figures was somewhat reduced.

>>

We thank the reviewer for this recommendation. We have moved 5 of the original figures to supplementary material (now Supplementary Figures 1, 2, 4, 5, and 6), mainly those showing insignificant differences, and have tightened discussion of these figures.

The reviewer also included several technical comments; we have corrected typos or wording accordingly.

Replies to Referee 2

<<

Line 16: I'd be careful about the word "induce" here (maybe instead: "associated with"). For example, Ivy et al. 2017 states that causality is difficult to determine, as ozone could just be a proxy for dynamical effects.

>>

We agree and have followed the referee's recommended wording. See Lines 15-16.

Line 15-16: "Ozone extremes have also been shown to be associated with springtime surface anomalies in the Northern Hemisphere."

<<

Line 18: greater interannual variability of what? Also, in general it's a little tricky in these first few sentences of the introduction to understand if the focus is on the role of man-made ozone depletion or on the role of ozone extremes in general (regardless of the presence of CFCs).

Line 21-22: Particularly for the NH, where it's rarely cold enough for PSCs to form, what is the relative role of heterogeneous chemistry versus decreased mixing with mid-latitude air? I would expect mixing (or lack of it) to play a significant role.

>>

We have clarified the use of "interannual variability." We intended the focus of this introduction to be on the role of ozone extremes in general, and have rewritten this paragraph to make this clearer, though some mechanisms specific to the presence of CFCs are still present (i.e. episodic ozone depletion events such as 2011). We agree with the referee about the role of mixing and have included discussion of this mechanism. See updated discussion on Lines 18-24.

Lines 18-24: "Polar cap ozone anomalies are strongly related to interannual variability in stratospheric polar vortex strength, which is larger in the Northern Hemisphere than the Southern Hemisphere. This is a result of the larger amplitudes of upward-propagating planetary waves, which perturb the stratospheric circulation. Years with low wave activity tend to correspond to a stronger vortex and a weaker Brewer-Dobson Circulation (BDC), resulting in weaker ozone transport from the tropics into the poles and decreased mixing across the vortex edge, as well as enhanced formation of polar stratospheric clouds, which contribute to increased springtime destruction of ozone. Years with high wave activity correspond to a weaker vortex and a stronger BDC, with stronger ozone transport from the tropics and increased mixing (Newman et al., 2001)."

<<

Line 62: I'm not sure what is meant by "via its interannual variation".

>>

We have rephrased this sentence. See Lines 62-63.

Lines 62-63: "Due to the larger sample size, climatological ozone distribution, and constant forcings, this set of simulations more clearly separates the impact of ozone's interannual variation on stratosphere-troposphere coupling."

<<

Line 80: It would be good to be more explicit about what else is prescribed; given that you are using year-2000 conditions, for example, how are CFCs dealt with? (are they the same fixed value in each simulation? Also, do you think you need to be in a time period of peak CFCs to see the results that you get here? If true, that seems like an important point to make, especially as ozone is now slowly recovering.

>>

Alongside ozone , CFCs (CFC-11 and CFC-12), methane (CH_4), nitrous oxide (N_2O), and CO_2 are prescribed at year 2000 conditions in the NOCHEM (SC-WACCM) simulation. Other fields that are prescribed in this run are NO, atomic and molecular oxygen (O and O_2), following Smith et al. (2014). In the CHEM experiment, we use the same year 2000 conditions for all radiatively active gases, but ozone is calculated interactively, instead of being specified. We clarify this point on Line 82 and Lines 84-85. We speculate about the role of CFCs in Lines 122-127.

Lines 81-85: "In the NOCHEM simulation, ozone concentrations (and other radiatively active atmospheric constituents, including CFCs) are prescribed using zonally symmetric, monthly mean, seasonal climatology computed from the WACCM integration. These zonally symmetric monthly ozone fields are read into SC-WACCM and interpolated linearly to the day of the year. More details can be found in Smith et al. (2014). Hence, both CHEM and NOCHEM strictly impose identical year 2000 forcings for all radiatively active species, and only differ in their treatment of ozone."

Lines 122-127: "The same is not the case in Smith et al. (2014), where the vortex under constant year 1850-conditions was found to be of similar strength with interactive and specified chemistry. The difference in strength of the vortex with interactive vs. specified chemistry is then partially related to forcings used (year 2000 in this study, 1955-present historical in Haase and Matthes (2019), and 1955-2005 historical in Neely et al. (2014)); this suggests a potential relationship to CFCs. The details of this will be investigated in a further study, but this may be related to lower ozone variability in the absence of CFCs (Calvo et al., 2015)."

<<

Line 81: Could some of the differences seen in the results be due to using zonally-symmetric prescribed ozone, since during SSWs in particular the flow is very asymmetric? Could this also help explain why there is a larger difference in interactive vs prescribed for SSWs compared

to SPVs (where the flow is very zonal)?
>>

Yes, this is very possible. There is some indication that the differences in midwinter SSWs are partially related to zonally-symmetric ozone; Haase and Matthes (2019) found lower differences when prescribing ozone asymmetrically, though it did not erase all interactive vs. prescribed differences. We have added discussion of this and why we still consider zonally-symmetric prescribed ozone in Lines 86-91.

Lines 86-91: "One might consiser specifiying non-zonally symmetric ozone (Haase and Matthes, 2019), but that comes at cost of a major physical incosistency between the polar vortex and the ozone field: in other words the exteme ozone years in the model will not correspond with the unperturbed vortex years. More importantly, the vast majority of climate models in CMIP specificy zonally symmetric stratospheric ozone, including within CMIP6 (Keeble et al., 2019): hence the zonally-symmetric specified ozone case is the one of most interest in terms of evaluating the impact of interactive ozone chemistry."

<<

Line 92-93: Might also mention that surface impacts in March could be different than in mid-winter, as the NAO itself is changing in spatial structure from its winter to summerstate.
>>

Yes, this is quite plausible. We have added a mention of this on Lines 99-100.

Lines 99-100: "We consider March events separately from December-February events due to different shortwave heating behavior, model bias in March SSW frequency (too frequent SSWs in our model), and different NAO structure in early spring compared to winter."

<<

Line 99: Is there any sensitivity to your results if you use a different threshold, such as 43 m/s? If you use a non-absolute metric like NAM, can you better examine differences in Dec-Feb versus March SPVs? It would be nice to be able to compare to Ivy et al. results, for example.
>>

We redid key parts of the analysis using the 41.2 m/s threshold from Tripathi et al. 2015. This adds 10 more SPV events in NOCHEM and 11 more events in CHEM, so there is little change to the frequency results. There was also little change to the SLP results. We agree that a non-absolute metric would allow for better study of strong vortex events in March; for consistency with the rest of this work and the most standard SSW metrics, in the paper we only consider an absolute metric. See clarification on Line 108.

Line 108: "Results are not sensitive to using a 41.2 m/s threshold as in Tripathi et al. (2015)."

<<

Line 105, and throughout: when you use the two-sided two-sample t-test, what are the sample sizes used (is it just the number of events)? If it's the latter, this seems valid for, e.g., Figure 3. But I wonder about Figure 1 in particular where you are showing daily data; in this case, what is the sample size for CHEM vs NOCHEM and does it take into account auto-correlation of the daily time series?
>>

The sample sizes used are indeed the number of events. In later figures (Figure 3 and following), this is the number of the type of SSW/SPV under consideration. In Figure 1, it is the number of years in the simulation. At each time/latitude point in Figure 1, we consider 200 samples from each of CHEM and NOCHEM, treating each year of the simulation as independent. While consecutive days in the simulation are auto-correlated, each t-test conducted here is on samples that we can treat as independent. The results of t-tests on consecutive days do have some correlation due to auto-correlation of the daily time series, but so do results of t-tests at adjacent latitude points due to spatial auto-correlation in the data. Because each individual t-test is on independent samples, and each t-test uses disjoint data, we do not correct for time or spatial auto-correlation. This may lead to over-confident significance test in Fig.1, but we believe that the core result of the paper (i.e. a generally stronger vortex in CHEM than NOCHEM) is not affected, as explained next.
<<

Line 119: this difference seems extremely small given the large internal variability of the polar stratosphere zonal winds so I'm surprised that it's significant; how is significance assessed? Does it take into account auto-correlation of daily time series?
>>
We thank the reviewer for their question about how significance was assessed in the polar stratospheric zonal winds. We were not properly accounting for auto-correlation of the daily time series here. While the figure still shows daily winds (to better show the extreme values), we test significance by considering average winds over each winter (DJFM) in the simulations. The average zonal mean zonal wind from one winter to the next is independent, so we can treat these winters as independent samples and use a Welsh's t-test. A two-tailed t-test gave a p-value of 0.023, so the difference is small but significant (due to the large sample size in each simulation). We have added a discussion of this issue on Lines 131-134.

Line 131-134: "To determine whether this is statistically significant, we consider the average zonal mean zonal winds over each winter and treat the winters as independent. A two-sample, two-tailed Welsh's t-test of DJFM average winds in CHEM and NOCHEM yields a p-value of 0.023, so the difference, though small, is significant at a 95% level."

<<
Line 123: Given that the climatology is different in these two simulations, I wonder if it's worth also checking the statistics of a non-absolute metric like the NAM, to see if the variance/PDF of the NAM changes.
>>
The variances of the daily 10 hPa NAM distributions in DJF are similar: 2.42 in NOCHEM and 2.32 in CHEM (with both averages 0 by design). There are some minor differences in the PDFs, but they are much more similar overall than are the zonal mean zonal wind distributions.

<<
Line 125: You might mention in this paragraph how well the overall (Nov-Mar) SSW frequency compares with reanalysis, as the Dec-Feb value seems low (75/200 = 0.38).
>>
We have added a comment based on this suggestion near Lines 150-152.

Lines 150-152: "We note that both of these frequencies, around 5.5 events per decade, are on the lower end of what is seen across reanalyses (Butler et al., 2017; Cao et al., 2019) but very well within the spread among state-of-the-art chemistry-climate models (Ayarzagüena et al., 2018)."

<<
Line 132-133: I wonder also if this is because the CP07 definition is somewhat problematic with regards to the arbitrary April 30 cutoff for SSWs. Events in March essentially only have to pass a 10-day return to westerlies criteria (before April 30) to be counted as an SSW; when stricter criterion is used to separate these events from the final warming, some of them drop out (Butler and Gerber 2018).
>>
Using the stricter criterion used in Butler and Gerber 2018, we find 20 fewer SSWs in CHEM; 19 of those removed are during March. We also find 20 fewer SSWs in NOCHEM; 15 of those removed are during March. This more stringent criterion would still give us 13 NOCHEM vs. 20 CHEM March SSWs, still a very notable difference. We hypothesize that this is due to the stronger vortex in the climatology and the resulting later breakdown of the vortex (giving more "room" for springtime SSWs to happen).

Under the weaker CP07 criterion used in the paper, we can see the vortex recover more strongly following a March SSW in CHEM than in NOCHEM in the wind time series shown in Figure 9. The vortex isn't particularly strong in either case (and it's clear why the stricter criterion removes so many events!), but there's a meaningful difference in CHEM and NOCHEM in the aftermath of SSWs here.

<<
Line 170, 187: Is it possible to demonstrate that there is an increase in dynamical forcing? This is mentioned several times as the mechanism but it's not shown that thisis true.

>>

We have added a plot of the meridional eddy heat flux at 100 hPa, averaged between 40° and 80° N around the SSW central date as a new Figure 6, as well as a discussion of this figure. This is just a diagnostic, but it does indicate slightly stronger dynamical forcing in CHEM compared to NOCHEM, at least for midwinter SSWs. See discussion on Lines 189-194.

Lines 189-194: "The increased dynamical heating in CHEM could be related to greater wave activity necessary for an SSW to occur with a stronger mean vortex state. Figure **??** shows the eddy heat flux over 40-80° N over time in CHEM and NOCHEM. This is stronger by about 2 mK/s just before the central date in CHEM than in NOCHEM, indicating stronger wave forcing in CHEM. The CHEM and NOCHEM means are at the upper and lower bounds of the other's confidence intervals, respectively. Further, the zonal mean zonal winds at 10 hPa and 60° N around the central date of the SSW (shown in Figure **??**) are both stronger prior to the event and more easterly following the central date in CHEM than in NOCHEM."

<<

Line 175-180: Can you explain further the vertical/temporal structure in the shortwave heating differences (Figure 5 and Figure 6)? Is it related to the vertical structure of ozone after the SSW?

>>

Yes, they are related. In fact, the SW differences are entirely originated by the CHEM run (interactive ozone), as the NOCHEM run shows no SW heating anomalies around SSWs, due to the prescribed ozone climatology. We have added a reference for the vertical structure of ozone after the SSW with a similar structure to the shortwave heating here on Lines 200-201.

Lines 200-201: "The structure in height and time is related to integrated effects of the ozone anomalies following the SSW, which show a similar structure (Kieswetter et al., 2010)."

<<

Line 198-199: so is it weaker SSWs (which doesn't seem true, see next comment below) than in DJF or weaker stratosphere-troposphere coupling or both? This seems easy enough to check. Another possibility is that the surface response in spring is just not as strong/significant as the NAO evolves to a summer state.

Line 215: True, but it's worth noting that the magnitude of the dynamical heating for March SSWs and DJF SSWs is about the same (at least on visual comparison). Does this imply that the March SSWs are not dynamically weaker than the DJF SSWs? (this seems to be stated on line 256). The minimum zonal wind reversal in Figure 7 and Figure 11 looks roughly equivalent, but the DJF SSWs start from a stronger westerly climatology. Again, it might be nice to show a dynamical metric here as well.

>>

The meridional eddy heat flux anomaly leading up to a March SSW in the CHEM simulation is lower than that seen leading up to DJF SSWs, which does suggest a dynamically weaker SSW in that case. The differences in NAM descent indicate a generally weaker stratosphere-troposphere coupling following March SSWs, as compared to DJF SSWs. So, both seem to be at play here. We have added discussion of different surface response due to seasonality as suggested, on Lines 218-220, and Lines 228-229.

Lines 218-220: "Three factors could contribute to this: weaker SSWs, weaker stratosphere-troposphere coupling, both discussed below, and a shorter NAM decorrelation timescale in March than in DJF (Baldwin et al., 2003; Simpson et al., 2011), which would result in weaker anomalies at the surface when averaged over several weeks."

Lines 228-229: "The eddy heat flux show in Figure S3, however, shows weaker wave forcing preceding only the CHEM (not the NOCHEM) March SSWs compared to those in DJF."

<<

Line 246-247: I'm not sure it was ever explained clearly why the interactive chemistry simulation has a stronger basic state of the polar vortex.

>>

This is correct. We have reworded based on this comment and a similar one from Referee 3 so that this sentence no longer implies a mechanism. See Lines 273-274.

Lines 273-274: “The climate model results presented here show an important relationship between interactive ozone, the climatological state of the stratospheric polar vortex, and the Euro-Atlantic surface impacts of midwinter SSWs.”

We have also made phrasing and figure labeling changes based on the referee’s technical comments. We have added clearer tick marks to Figure 1 and edited figure labels throughout to be consistent with the text. The suggested phrasing changes have been incorporated throughout.

Replies to Referee 3

<<

General comments: No relevant results are found for March SSWs or for strong vortex events.

>>

We agree with the referee that there are no significant differences, but a lack of difference is a result. This null result is very much worth reporting here, given its implications. For example, we wish to discuss March SSWs (1) and the frequency of SSWs (2). The lack of significant differences in March SSWs is a relevant finding, as it challenges the expectation that ozone would have a larger signal in late-winter/spring (given the larger SW feedback in those months). The weak impact of ozone chemistry on the modeled SSW frequency is another key ”no result”, since it implies that interactive chemistry may not be needed to simulate a realistic SSW frequency in high-top models (possibly, the vertical resolution and model lid are more important parameters for this metric). We also challenge the referee’s view concerning the strong vortex events: the vortex decay in the lower stratosphere 40-50 days after the onset of these events is slower in CHEM than NOCHEM, as discussed in Line 260-262; this means that extreme vortex events are longer-lived when ozone is interactive. Even though these effects are not directly relevant for surface climate, they have implications for our understanding of these dynamical events in the stratosphere.

<<

I find the new findings incremental. The results are basically reproducing those from Haase and Matthes (2019), using the same models but with longer runs and different external forcing.

>>

We politely disagree with the referee concerning the degree to which these results are ”incremental” over Haase and Matthes (2019; hereafter H&M19). First, we use time-slice experiments with constant forcings for the year 2000, whereas H&M19 use transient boundary conditions. Second, we have a 4x larger sample size in both CHEM and NOCHEM runs (200 years vs 50 years in H&M19). Third, we impose a climatological ozone distribution, whereas H&M19 impose a transient ozone. Fourth, we explore the effects in both polar vortex extremes, i.e. SSWs and strong vortices, whereas H&M19 only focus on the former. Finally, while we independently cofirm some of the results in Haase and Matthes (2019), we also report that some of their findings are not robust.

Owing to the larger sample size and cleaner model set-up (1+2), we are able to show that interactive ozone *does not affect* the modeled SSW frequency integrated over the extended winter (DJFM), which is in contrast with H&M19. We also think that our set-up (3) more cleanly isolates the effect of interactive ozone, as imposing a climatological ozone distribution in NOCHEM which does not contain any (dynamically induced) inter-annual variations is a more consistent way of removing the effects of ozone variability on the dynamical state of the stratosphere, as noted on Line 63. Lastly, we explore a wider range of vortex extremes, thereby broadening the results in H&M19 concerning the importance of interactive chemistry for simulating stratospheric vortex variability and stratosphere-troposphere coupling.

<<

General comments: This is essentially a comparison between two different models, one that has been exhaustively tuned at NCAR to provide the best possible climatology and variability (CHEM), and one that has been “downgraded” by specifying the evolution of ozone and other species (NOCHEM).

>>

We fear the reviewer's view of SC-WACCM is a misconception. The WACCM Specified Chemistry (SC-WACCM) model is officially supported and scientifically validated by NCAR and it can be run using prescribed ozone in the same fashion as other models used for CMIP6 (Keeble et al., 2020). Under preindustrial conditions, it was thoughtly tested, and the stratospheric dynamics and stratosphere-troposphere coupling in WACCM and SC-WACCM were shown to be very similar across a wide variety of metrics (Smith et al., 2014). These features make it appropriate to pair these two to study the contributions in a model of interactive chemistry and transport. There is nothing "downgraded" in SC-WACCM: the ozone specification is SC-WACCM is identical to the one implemented by the vast majority of CMIP5 and CMIP6 models. Hence, it is of great interest to document how WACCM and SC-WACCM differ, in order to understand how interactive ozone chemistry affects climate variability.

<<

Line 18. Interannual variability of what?

First paragraph of section 3.1. It should be good to at least speculate about a mechanism to explain the stronger westerlies in CHEM. In the light of the given comparisona against Haase and Matthes and Smith et al, are high CFC concentrations needed to get this result?

Line 168-169. "(...) perhaps because of greater wave activity necessary for an SSW to occur with a stronger mean vortex state (...)". The authors provide no proof of this,but it should be easy to check.

Figure 6. Please consider removing this figure, it does not really add much to the manuscript.

Conclusions, first sentence. This has not beens shown, at least to my understanding. A mechanism behind the circulation differences between CHEM and NOCHEM has not been provided, nor have the authors discriminated between the effects of ozone chemistry and the effects of transport of ozone during SSWs.

Line 253-254. It is a speculation that CHEM needs stronger wave forcing to drive SSWs, it has not been proven. Please modify this sentence accordingly.

Please refer to individual figure panels using the labels a, b, c, etc. and not top-right etc.

>>

We have already addressed all these comments in response to Referees 1 or 2. See above. In short, we added results for a wave forcing diagnostic (eddy heat flux at 100 hPa), and also explored changes in downwelling velocities.

We also tested the robustness of this result (stronger vortex in CHEM than NOCHEM) by comparing the vortex strength in the set of transient historical simulations documented in Neely et al. (2014). These are 10 ensembles with interactive (WACCM) or specified ozone (SC WACCM), as monthly and daily climatologies. Again, we found the same results, suggesting a stronger vortex with interactive ozone in late-winter/spring, indicating that this effect is robust. Nonetheless, the details of the relationship to CFCs will be investigated in a follow-up study using more models. We have added a brief discussion of this in the text where we discuss the differing vortex climatologies in CHEM and NOCHEM, i.e. Lines 81-85 and 122-127.

<<

Line 119. I find it surprising that a 1.7 m/s difference be statistically significant, given the large interannual variability in the strength of the westerlies. But letting aside the statistics, how physically meaningful might this difference be?

>>

We have added further detail on the statistical testing here (see response to Referee 2). In terms of physical meaning, this difference seems to be related to a final warming date that is on average a week later (a large difference compared to variability) and large differences in numbers of SPVs and late winter SSWs (through the later final warming date). Figure 7 also shows a stronger vortex leading up to a midwinter

SSW central date in CHEM than in NOCHEM, which is related to the strength of the SSW itself. So this mean state difference, while small, does seem to have physical meaning.

<<

In line 153 it is stated that Fig. 3 reveals the surface impacts of SSWs. In the beginning of the following paragrah it is addressed whether the results of Fig.3 are due to SSWs. Please consider presenting first Fig. 4, and then Fig. 3 (or revise the way the story line is presented).

>>

We agree with the reviewer that this was unclear. We have reworded for a more coherent storyline.

Line 171-172: "To determine whether the differences at the surface following SSWs in CHEM and NOCHEM are a result of differences in the events in the stratosphere, we calculate the Northern Annular Mode (NAM) for each simulation."

<<

Line 163. I am not so sure about this. The positive T signal in Fig. 5a appears at positive lags, generally after the peak of the warming. Without further analysis, this might well be interpreted as a slower temperature recovery in the aftermath of SSWs in CHEM than in NOCHEM.

>>

While the bulk of the positive temperature signal is at positive lags, it does appear at negative lags too; we have added a better marker of the central date (0 lag) to make this clearer in Fig. 5.

<<

An alternative explanation of stronger dynamical heating in CHEM could be that having a stronger jet in the mid-stratosphere generally implies a stronger vertical gradient of temperature over the pole (see Fig. 3b In Haase and Matthes). And a given w* anomaly, under a stronger temperature vertical gradient, would produce a stronger dynamical heating.

>>

We thank the referee for their insightful comment. We calculated $\overline{w}^*$ using daily data but found no difference between CHEM and NOCHEM near the onset of SSWs, so the alternate explanation here (larger vertical temperature gradient) seems a plausible part of the dynamical mechanism. However, the details are still unclear and will be the subject of follow-up work involving more models. This is discussed on Lines 189-197.

Lines 189-197: "The increased dynamical heating in CHEM could be related to greater wave activity necessary for an SSW to occur with a stronger mean vortex state. Figure 6 shows the eddy heat flux over 40-80° N over time in CHEM and NOCHEM. This is stronger by about 2 mK/s just before the central date in CHEM than in NOCHEM, indicating stronger wave forcing in CHEM. The CHEM and NOCHEM means are at the upper and lower bounds of the other's confidence intervals, respectively. Further, the zonal mean zonal winds at 10 hPa and 60° N around the central date of the SSW (shown in Figure 7) are both stronger prior to the event and more easterly following the central date in CHEM than in NOCHEM. However, the residual vertical velocity (not shown) is similar leading up to SSWs for CHEM and NOCHEM, so it is possible that the increased dynamical heating is a result of a stronger vertical temperature gradient related to the stronger vortex (associated with a colder pole)."

<<

Figure 5. It would be good to include the temperature tendency to better understand the effects and timing of the dynamical heating (please be explicit, is this w*dt/dz, TEM formalism?), and the radiative heating. Also, please include in the caption the latitude band considered.

>>

This is dynamical heating as model output, which represents the temperature tendency computed by the dynamical core. Hence, it is not the TEM formalism, but it should be fairly close to the TEM approximation (w*dT/dz). As indicated above, the dynamical heating following the TEM formalism will be more thoroughly studied in follow-up work involving more models. Lastly, we have added the latitude band ($60-90^\circ$ N) to the caption as suggested.

<<

Line 170-172. So would it be possible to discriminate the fraction of the stronger long-wave cooling that comes from having reached higher temperatures, from the fraction that comes from having larger ozone concentrations? This would tell us the importance of the accumulation of ozone over the pole during SSWs to the recovery of the vortex.

>>

This is an interesting question, but it would require running the radiation scheme offline to fully account for the ozone impacts on the LW. This is unfortunately unfeasible at present, but it could be studied in the future.

<<

Lines 183-190. The study of De La Camara et al also shows results on changes of polar ozone during SSWs using a similar version of WACCM as the one used here.

>>

We have reworded the references to this study to acknowledge both the reanalysis and model-based results reported in De La Camara et al. See Lines 205-207 and 209-210.

Lines 205-207: "We see a sharp increase in ozone in the 15 days leading up to the central date, reaching a peak of on average about 40 Dobson units above climatology just after the central date, similar to that seen in reanalysis and a similar model by De La Cámara et al. (2018)."

Lines 209-210: "This ozone anomaly is consistent with total ozone column in reanalysis and a similar model (De La Cámara et al., 2018) and the smaller ozone depletion in years with early SSWs observed by Strahan et al. (2016)."

<<

Line 200. Please take into account that NAM decorrelation timescales are shorter in March-April than in winter (Simpson et al. 2011), which may help understand the weaker persistence of surface anomalies after March SSWs.

>>

We thank the reviewer for noting this; we have added it to the discussion. See Lines 218-220.

Lines 218-220: "Three factors could contribute to this: weakerSSWs, weaker stratosphere-troposphere coupling, both discussed below, and a shorter NAM decorrelation timescale in March than in DJF (Baldwin et al., 2003; Simpson et al., 2011), which would result in weaker anomalies at the surface when averaged over several weeks."

<<

I am unsure whether it is worth keeping section 3.4, but 4 figures to only show a very weak signal seems excessive.

>>

We have moved two of the four figures to the supplementary material. However, as stated above, we believe that the insignificant difference here is worth documenting and discussing.

The effect of interactive ozone chemistry on weak and strong stratospheric polar vortex events

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Abstract. Modeling and observational studies have reported effects of stratospheric ozone extremes on Northern Hemisphere spring climate. Recent work has further suggested that the coupling of ozone chemistry and dynamics amplifies the surface response to midwinter sudden stratospheric warmings (SSWs). Here, we study the importance of interactive ozone chemistry in representing the stratospheric polar vortex and Northern Hemisphere winter surface climate variability. We contrast two simulations from the interactive and specified chemistry (and thus ozone) versions of the Whole Atmosphere Community Climate Model, designed to isolate the impact of interactive ozone on polar vortex variability. In particular, we analyze the response with and without interactive chemistry to midwinter SSWs, March SSWs, and strong polar vortex events (SPVs). With interactive chemistry, the stratospheric polar vortex is stronger, and more SPVs occur, but we find little effect on the frequency of midwinter SSWs. At the surface, interactive chemistry results in a pattern resembling a more negative North Atlantic Oscillation following midwinter SSWs, but with little impact on the surface signatures of late winter SSWs and SPVs. These results suggest that including interactive ozone chemistry is important for representing North Atlantic and European winter climate variability.

1 Introduction

The climate impacts of stratospheric ozone extremes, particularly Antarctic ozone depletion, have been widely studied (Previdi and Polvani (2014) and references therein). While the effects are clearer and larger in the Southern Hemisphere~~due to greater ozone depletion~~, ozone extremes have also been shown to ~~induce~~ be associated with springtime surface anomalies in the Northern Hemisphere ~~(Calvo et al., 2015; Ivy et al., 2017)~~(Smith and Polvani, 2014; Calvo et al., 2015; Ivy et al., 2017).

~~The weaker ozone depletion in the Northern Hemisphere is partially due to greater interannual variability~~ Polar cap ozone anomalies are strongly related to interannual variability in stratospheric polar vortex strength, which is larger in the Northern Hemisphere than the Southern Hemisphere. This is a result of the larger amplitudes of upward-propagating planetary waves, which perturb the stratospheric circulation. Years with low wave activity tend to ~~a~~ correspond to a stronger vortex and a weaker Brewer-Dobson Circulation (BDC), resulting in weaker ozone transport from the tropics into the poles and decreased mixing across the vortex edge, as well as enhanced formation of polar stratospheric clouds, which contribute to increased springtime destruction of ozone. Years with high wave activity correspond to a weaker vortex and a stronger BDC, with stronger ozone transport from the tropics and ~~temperatures too high for polar stratospheric clouds to form~~increased mixing (Newman et al., 2001).

These processes are well-represented in fully interactive chemistry-climate models (Strahan and Douglass, 2004). However, such models are computationally expensive compared to the more common ones, in which stratospheric ozone is simply prescribed. A number of studies have explored the importance of interactive ozone chemistry on model representations of coupled stratosphere-troposphere variability. Smith and Polvani (2014) and Karpechko et al. (2014) found little impact of stratospheric ozone extremes on surface climate in the Northern Hemisphere using prescribed zonal mean monthly mean ozone fields. However, Calvo et al. (2015) found robust surface impacts associated with stratospheric ozone extremes using an interactive chemistry-climate model, suggesting the potential importance of this coupling. Further model studies are needed to disentangle the effects of ozone from those of polar vortex variability.

While the effect of polar stratospheric clouds on ozone is mainly seen in the spring when sunlight returns to the region, the variability of the polar vortex can result in wintertime ozone anomalies which may have surface impacts. The most extreme states of the polar vortex are sudden stratospheric warmings (SSWs) and strong polar vortex events (SPVs). Leading up to an SSW, dynamical forcing disrupts the stratospheric circulation, eventually resulting in a reversal of zonal mean zonal wind throughout much of the polar stratosphere. SSWs have surface effects for the two months following, particularly a negative North Atlantic Oscillation and cold anomalies over much of Northern Eurasia. SPVs, as the result of a lack of planetary wave activity, are not dynamical events in the same way as SSWs (Limpasuvan et al., 2004, 2005) but may still have surface impact (a positive NAO) (Baldwin and Dunkerton, 2001).

For the dynamical reasons described above, SSWs and SPVs tend to be associated with the occurrence of positive and negative stratospheric ozone anomalies, respectively. About two weeks prior to an SSW, the BDC accelerates, resulting in adiabatic warming of the stratosphere and enhanced isentropic eddy transport of ozone and thus increased ozone concentration over the pole (De La Cámara et al., 2018). SPVs are similarly accompanied by an anomalously weak BDC because of the lack of planetary wave activity and thus an anomalously low transport of ozone, as well.

Because they affect both stratospheric ozone and the NAO in the troposphere, extreme vortex events offer an ideal case in which to study wintertime surface impacts of ozone chemistry. Haase and Matthes (2019) studied the impact of interactive versus prescribed ozone on SSWs, as well as their ~~their~~ surface effects, in simulations of the recent past (1955-present) in an earth system model. They compared results of a simulation with interactive ozone to those of a simulation with ~~ozone prescribed~~ prescribed ozone. This prescribed ozone was given daily (with no averaging/climatology) from ~~the~~ a single historical interactive chemistry simulation. They found a stronger climatological vortex in the interactive chemistry simulation, and this was associated with a decreased SSW frequency. Further, SSWs were followed by stronger and more persistent surface anomalies in the simulation with interactive chemistry. These results suggest important surface impacts of ozone chemistry. However, their simulation was relatively short (64 winters), and the historical period they simulated includes long-term trends in ozone that may affect the results. Also, their method of prescribing ozone means that the ozone in the specified chemistry simulation was associated with dynamical variability of the interactive chemistry run, and that variability was inconsistent with the dynamical state of the specified chemistry model.

Building on the study of Haase and Matthes (2019), we here study interactions between ozone chemistry and polar vortex variability by analyzing SSWs, SPVs, and their surface impacts in two 200-year timeslice simulations with fully interactive and prescribed chemistry versions of a model. Using 200-year timeslices provides us with a large sample size of SSW and SPV events without long-term ozone trends, and we prescribe ozone based on the ozone climatology from the 200 years of the interactive chemistry simulation. ~~This~~ Due to the larger sample size, climatological ozone distribution, and constant forcings, this set of simulations more clearly separates the impact of ozone~~on the~~'s interannual variation on stratosphere-troposphere coupling~~, via its interannual variation~~. While we do not see decreased SSW frequency with interactive chemistry, we confirm Haase and Matthes (2019)'s results on the vortex climatology and response to midwinter SSWs. We further find that there is little surface effect of interactive ozone chemistry immediately following SPVs or March SSWs. However, SPVs show long-lasting effects on stratospheric ozone, with anomalies 1-2 months after the central date of a similar magnitude to those caused by midwinter SSWs.

The paper is organized as follows. Section 2 describes the model, simulations, and methodologies. Section 3 addresses our results on the impacts of interactive chemistry, considering the stratospheric mean state, midwinter SSWs, March SSWs, and SPVs. We conclude the paper with a discussion of these results.

2 Methods

In this study, we analyze model integrations performed with the Whole Atmosphere Community Climate Model, Version 4 (WACCM4), one atmospheric component of the Community Earth System Model (CESM1) (Marsh et al., 2013). WACCM4 is an interactive chemistry-climate model with a horizontal resolution of 1.9° in latitude and 2.6° in longitude, 66 vertical levels, and a model top at 5.1×10^{-6} hPa (140 km). Northern Hemisphere stratospheric variability, such as the frequency and dynamical features of SSWs, are accurately simulated in WACCM4 (Marsh et al., 2013).

We perform two model integrations, both 200-year-long timeslice integrations with forcings at constant year-2000 values to avoid long-term trends in ozone. One model integration uses the fully interactive chemistry scheme in WACCM4 (Kinnison et al., 2007). We refer to this simulation as the CHEM simulation in the analysis. The other uses the "Specified Chemistry" version of WACCM, known as SC-WACCM (Smith et al., 2014). ~~In the SC-WACCM~~ We refer to this prescribed chemistry simulation as the NOCHEM simulation in the analysis. In the NOCHEM simulation, ozone concentrations (and ~~a few~~ other radiatively active atmospheric constituents, ~~e.g. CH_4~~including CFCs) are prescribed using zonally symmetric, monthly mean, seasonal climatology computed from the WACCM integration. These zonally symmetric monthly ozone fields are read into SC-WACCM and interpolated linearly to the day of the year. More details can be found in Smith et al. (2014). ~~Using the climatology to specify ozoneminimizes the effect of ozone extremes in particular years of the interactive chemistry simulation on results of the simulation with prescribed chemistry. We refer to this prescribed chemistry simulation as the NOCHEM simulation in the analysis.~~ Hence, both CHEM and NOCHEM strictly impose identical year 2000 forcings for all radiatively active species, and only differ in their treatment of ozone. The use of climatological ozone fields in NOCHEM removes the effect of extreme ozone variations on the climate system. One might consiser specifiying non-zonally symmetric ozone (Haase and Matthes, 2019), but that comes at cost of a major physical incosistency between the polar vortex and the ozone field: in other words the exteme ozone years in the model will not correspond with the unperturbed vortex years. More importantly, the vast majority of climate models in CMIP specificy zonally symmetric stratospheric ozone, including within CMIP6 (Keeble et al., 2020): hence the zonally-symmetric specified ozone case is the one of most interest in terms of evaluating the impact of interactive ozone chemistry.

We identify SSWs in the model output following the definition in Charlton and Polvani (2007a) (see the corrigendum Charlton-Perez and Polvani (2011)). We define an SSW as a reversal of zonal mean zonal wind at 60° N and 10 hPa from westerly to easterly during November through March, with the central date being the first day of easterly zonal mean zonal winds. No later date can be a central date until the winds have been westerly again for at least 20 days, and the winds must return to westerly for at least 10 consecutive days before April 30 (thus discarding stratospheric final warmings). This definition is optimal for identifying SSWs, as described by Butler and Gerber (2018). We focus on SSWs occurring in December-February and in March. We consider March events separately from December-February events due ~~both~~ to different shortwave heating behavior~~and to~~, model bias in March SSW frequency (too frequent SSWs in our model), and different NAO structure in early spring compared to winter.

To the best of our knowledge, there is no standard definition of an SPV. Different methods have been used in the literature (Limpasuvan et al., 2004; Tripathi et al., 2015; Scaife et al., 2016; Beerli and Grams, 2019). We here follow the definition used in Scaife et al. (2016) and Smith et al. (2018), designed to be analagous to the Charlton and Polvani (2007a) SSW definition and to result in a similar number of events in reanalysis. We define an SPV as zonal mean zonal wind at 60° N and 10 hPa reaching 48 m/s or higher (westerly) during November through March, with the central date being the first day of zonal mean zonal winds above 48 m/s. No later date can be a central date until the winds return below 48 m/s for at least 20 consecutive days. We focus on SPVs occurring in December-February, due to low event frequency in November and March. A separate analysis reveals that results are not sensitive to using a 41.2 m/s threshold as in Tripathi et al. (2015).

The results we present here are based on composites of daily model output for climate variables, with composites centered around SSW or SPV central dates.

For composites from either CHEM or NOCHEM simulations, we calculate significance using a Monte Carlo test based on 5000 randomly chosen central dates. We also consider the difference in CHEM or NOCHEM composites, denoted CHEM-NOCHEM; for these, we calculate significance from a two-sided two-sample t-test.

3 Impact of interactive chemistry

3.1 Stratospheric mean state and extreme events

We first consider the effect of interactive chemistry on the mean state of the stratosphere by examining the climatological Northern Hemisphere 10 hPa zonal mean zonal wind (Figure 1). We find stronger westerlies in CHEM than in NOCHEM in the vortex formation stage (September and early October) and in the latter half of winter (January-April), between 60° − 80° N. In line with this, we also find weaker downwelling in winter in the upper latitudes in CHEM than in NOCHEM (not shown).

This relative strength in CHEM in late winter also corresponds to a delayed final warming by 7 days on average~~(not shown)~~. These results are consistent with those found by Haase and Matthes (2019). ~~The same is~~ Similar results are found using six 1955-2005 historical integrations of WACCM and SC-WACCM (with ozone specified monthly or daily from the WACCM climatology) from Neely et al. (2014) (not shown), further indicating that this feature is robust. This is not the case in Smith et al. (2014), where the vortex under constant year 1850-conditions was found to be of similar strength with interactive and ~~specified chemistry~~prescribed ozone. The difference in strength of the vortex with interactive vs. ~~specified chemistry is then partially~~ prescribed ozone chemistry may be related to forcings used (year 2000 in this study, ~~and~~ 1955-present historical in Haase and Matthes (2019) ~~).~~ and Neely et al. (2014), but 1850 in Smith et al. (2014)); lower ozone variability in the absence of CFCs (Calvo et al., 2015) might limit the effects of any ozone-dynamics feedbacks, the details of which will be investigated in a further study.

Because we identify extreme stratospheric events using zonal mean zonal winds at 10 hPa and 60~~° N~~ ° N (U1060) (Charlton and Polvani, 2007a; Butler and Gerber, 2018), we next examine the mean state and variability of this quantity in CHEM and NOCHEM. Figure 2 shows the two distributions of U1060 in December through March. The average difference in DJFM between CHEM and NOCHEM is about 1.7 m/s~~, a small but statistically significantdifference; Figure 1 indicates that this difference is larger in January through March~~. To determine whether this is statistically significant, we consider the average zonal mean zonal winds over each winter and treat the winters as independent. A two-sample, two-tailed Welsh's t-test of DJFM average winds in CHEM and NOCHEM yields a p-value of 0.023, so the difference, though small, is significant at a 95% level. The CHEM distribution also has a longer right tail~~. This~~ , which is consistent with the polar vortex being stronger overall with interactive chemistry. It also indicates that we should expect more SPVs in CHEM than in NOCHEM. While there are fewer days of weak westerlies (0-20 m/s) in CHEM than in NOCHEM, the numbers of days of easterlies are similar, so we expect less of a difference in SSW frequency between the two simulations.

Indeed, this is what we find when we calculate the frequencies of weak and strong vortex events in the CHEM and NOCHEM simulations (Table 1). We consider December-February (DJF, midwinter) and March (late winter) separately for two reasons. First, the ozone impacts in midwinter are different from those in late winter/early spring, as shortwave effects become important in spring. Second, our model is biased in March, with too many SSWs compared to reanalysis, a feature also seen in more recent versions of this model (Gettelman et al., 2019). We see 1.4 March SSWs per decade in NOCHEM and 1.95 March SSWs per decade in CHEM compared to 0.87-1.1 per decade in the reanalysis (Butler et al., 2017).

The stronger vortex in midwinter in the CHEM simulation might lead us to expect fewer DJF SSWs in CHEM than in NOCHEM. We do see a decrease of about 10% in DJF SSWs with interactive chemistry compared to specified chemistry, but this decrease is far from being statistically significant. In contrast, in March, we see more SSWs in CHEM than in NOCHEM, potentially related to the later breakdown of the vortex.

Haase and Matthes (2019) consider the overall (November-March) number of SSWs. They report a decrease in overall SSWs with interactive chemistry of around 30%. In contrast, for November-March, we find ~~a slight increase in SSWs of about 2% (from~~ virtually no difference in SSWs (109 events ~~to~~ vs 111, not shown) ~~from prescribed chemistry to interactive chemistry.~~ in CHEM and NOCHEM. We note that both of these frequencies, around 5.5 events per decade, are on the lower end of what is seen across reanalyses (Butler et al., 2017; Cao et al., 2019) but very well within the spread among state-of-the-art chemistry-climate models (Ayarzagüena et al., 2018).

We now consider SPV frequency. The increase in DJF SPV frequency from NOCHEM to CHEM is about 29%. This is unsurprising given the stronger vortex in CHEM overall. With our definition of SPVs, the number of March strong vortex events (in either simulation) is too small for a robust statistical analysis. This is because of the weaker vortex in March compared to DJF; a much larger anomalous vortex strength would be necessary to reach 48 m/s. Because of the low number of such events, we do not further study March SPVs and thus discard them from the analysis.

We now examine DJF SSWs, March SSWs, and DJF SPVs separately in each of the following three sections.

3.2 Midwinter sudden stratospheric warmings

We start by focusing on the surface impacts of SSWs, seeking to document any differences between the CHEM and NOCHEM simulations. After noting the impact of the events on the surface, we then consider how any differences in those impacts arise aloft.

Figure 3 shows composite surface level pressure anomalies in the first and second months (top and bottom respectively) following December-February SSWs in CHEM (left, 75 events) and NOCHEM (middle, 67 events), as well as the difference between the two (right). We see a strong and significant pattern resembling a negative North Atlantic Oscillation (NAO) in the first month following SSWs in both CHEM and NOCHEM, and in both cases this negative annular mode persists through the second month following the event. There is minimal difference between the two simulations in the first 30 days, with the CHEM simulation having only a slightly stronger signal. However, the difference is statistically significant and strongly projects onto the NAO 30-60 days after the central date. This indicates that the surface signature of SSWs is stronger and more persistent in CHEM than in NOCHEM.

To determine whether ~~these anomalies originate in~~ the differences at the surface following SSWs in CHEM and NOCHEM are a result of differences originating in the stratosphere, we calculate the Northern Annular Mode (NAM) for ~~CHEM and NOCHEM~~each simulation. We use a method similar to that of Gerber et al. (2010) and Gerber and Martineau (2018); the detailed procedure is in Appendix A. We show the results of the NAM calculations in Figure 4. The CHEM and NOCHEM composites around SSWs have comparable NAM anomalies in the stratosphere around the central date, but in the CHEM simulation the negative anomaly persists more strongly in the lower stratosphere beyond 40 days after the central date. The CHEM-NOCHEM difference shows that this change in persistence with interactive chemistry is significant at the 95% level. There is also more descent of the anomaly to the surface in the CHEM simulation, especially at about 30 days after the central date.

This difference in descent is also seen in the CHEM-NOCHEM temperature anomalies (Figure 5~~top left~~a). The warming in the stratosphere associated with the onset of the SSW is larger with interactive chemistry. This stratospheric temperature anomaly then descends more strongly through the stratosphere and troposphere in the CHEM simulation than in the NOCHEM simulation.

We investigate the processes leading to these changes in more detail by examining the dynamical, longwave, and shortwave heating terms. The greater warming throughout the stratosphere is due to increased dynamical heating (~~top right~~Figure 5b) in CHEM compared to NOCHEM, ~~perhaps because of greater wave activity necessary for an SSW to occur with a stronger mean vortex state,~~ as the higher temperature with interactive chemistry is also associated with a longwave cooling response (~~bottom left~~Figure 5c). The higher stratospheric ~~tempertaures~~ temperatures result in greater longwave emission. The increase in dynamical forcing also corresponds to increased ozone transport. Ozone is a longwave emitter, so the increased dynamical forcing could directly account for part of this longwave cooling difference, as well.

The increased dynamical heating in CHEM could be related to greater wave activity necessary for an SSW to occur with a stronger mean vortex state. Figure 6 shows the eddy heat flux over 40-80° N over time in CHEM and NOCHEM. This is stronger by about 2 mK/s around the central date in CHEM than in NOCHEM, indicating a slightly stronger wave forcing in CHEM. The CHEM and NOCHEM means are at the upper and lower bounds of the other's confidence intervals, respectively. Further, the zonal mean zonal winds at 10 hPa and 60° N around the central date of the SSW (shown in Figure 7) are both stronger prior to the event and more easterly following the central date in CHEM than in NOCHEM. However, the residual vertical velocity anomalies leading up to SSWs is nearly identical for CHEM and NOCHEM (not shown), so the increased dynamical heating in CHEM might be a result of a stronger vertical temperature gradient related to the stronger vortex in this simulation (associated with a colder polar stratosphere).

In DJF, the dynamical heating and the longwave heating are the dominant temperature tendency terms. There is also a significant shortwave heating response (~~bottom right~~Figure 5d), but in midwinter it is an order of magnitude smaller than the other terms, owing to the absence of incoming solar radiation to polar night. The structure in height and time is related to integrated effects of the ozone anomalies following the SSW, which show a similar structure (Kiesewetter et al., 2010). The importance of the shortwave response increases the later in winter the SSW events occurs. We illustrate this in Figure ~~??, showing the difference in shortwave anomalies between~~ S1, showing much stronger differences in CHEM and NOCHEM ~~for SSWs occurring in December, January, and February separately. There is very little difference in shortwave heating anomalies in CHEM compared to NOCHEM for December SSWs , with no difference greater than 0.05 K/day. The difference increases in January , with differences between 0.125 and 0.15 K/day in the upper stratosphere 20-30 days after the central date, but this is still small compared to the dynamical heating and longwave terms. Much stronger differences are seen for February SSWs, with CHEM-NOCHEM differences throughout the upper stratosphere following the central date of comparable magnitude to the differences in longwave heating anomalies of approximately 0.3 K/day.~~ shortwave anomalies for February SSWs than for December or January events.

Finally, we examine the anomaly in total ozone column around the central date of the SSW (Figure 7) in the CHEM simulation. ~~The figure also shows the zonal mean zonal wind to illustrate the corresponding evolution of the vortex.~~ We see a sharp increase in ozone in the 15 days leading up to the central date, reaching a peak of on average about 40 Dobson units above climatology just after the central date, similar to that seen in reanalysis and a similar model by De La Cámara et al. (2018). This ozone anomaly results from transport due to the greater dynamical forcing in CHEM noted earlier. Following the central date, anomalies of about 20 Dobson units persist for up to 3 months following the central date. This ozone anomaly is consistent with total ozone column in reanalysis ~~reported by De La Cámara et al. (2018) and~~ and a similar model (De La Cámara et al., 2018) and the smaller ozone depletion in years with early SSWs observed by Strahan et al. (2016).

3.3 March sudden stratospheric warmings

We now turn to the March SSWs. Figure 8 shows the composite sea level pressure anomalies for CHEM and NOCHEM, as well as the CHEM-NOCHEM difference, for each of the first two months following the central date. Both simulations again show a negative NAO-like pattern in the two months following the SSW. There are some regions with significant difference between CHEM and NOCHEM in the first thirty days, but the pattern does not project strongly onto the NAO. Also, there is very little difference between the two composites in the second thirty days after the central date.

The surface responses seen following March SSWs, in both models, are weaker and less persistent than those following DJF SSWs, and the areas of strong or significant low or high anomalies are smaller. ~~This indicates either weaker SSWs~~Three factors could contribute to this: weaker SSWs, weaker stratosphere-troposphere coupling, and a shorter NAM decorrelation timescale in March than in DJF ~~or weaker stratosphere-troposphere coupling~~(Baldwin et al., 2003; Simpson et al., 2011), resulting in weaker anomalies at the surface when averaged over several weeks. The differences between surface impacts of SSWs in CHEM and NOCHEM are also weaker for March SSWs. Thus, ~~ozone chemistry~~ interactive ozone seems much less important for the surface effects of March SSWs than for DJF SSWs.

Considering the NAM in these simulations as shown in Figure ~~??~~S2, we see negative NAM anomalies at the surface in both the CHEM and NOCHEM simulations, consistent with the negative NAO-like pattern seen in the Figure 8. There is a stronger signal in the troposphere in the CHEM compared to NOCHEM March SSW simulations at around 15-20 days after the central date, which may correspond to the surface pressure differences.

~~As for the surface plots, the NAM anomalies again~~ The NAM anomalies suggest that March SSWs in both CHEM and NOCHEM are weaker overall than the DJF SSWs; the stratospheric NAM anomalies are smaller and less significant. The eddy heat flux show in Figure S3, however, shows weaker wave forcing preceding only the CHEM (not the NOCHEM) March SSWs compared to those in DJF. Stratosphere-troposphere coupling also seems weaker compared to that seen for DJF SSWs. Further, the difference in ~~this~~ the NAM descent between CHEM and NOCHEM is less strong and persistent than the difference ~~in NAM signals seen in the troposphere~~ seen after midwinter SSWs.

Soon after the central date for March SSWs, the NAM signal in the stratosphere is weaker with ~~interactive chemistry than with specified chemistry~~CHEM than NOCHEM, in contrast to the midwinter SSW case. This difference appears to arise from the temperature and heating anomalies (Figure ~~??~~S4). The lower stratosphere is only briefly and weakly warmer in CHEM compared to NOCHEM. Shortwave heating seems to be dominant in the temperature response to March SSWs, with the CHEM-NOCHEM difference in temperature anomalies (Figure ~~??a~~S4a) largely following the difference in shortwave heating anomalies (Figure ~~??d~~S4d). This is in contrast to the DJF SSWs, where the shortwave heating had little effect, and dynamical heating was dominant.

Finally, we note that unlike the DJF SSW case, the ozone anomaly for March SSWs does not persist after the event (Figure 9). This is related to the seasonal breakdown of the vortex, seen in the wind ~~curve~~curves. Because these are late winter SSWs, the second month following the central date is near the expected stratospheric final warming date; ~~in our simulations,~~ the winds return to easterly about 50 days ~~on average~~ after the March SSW central date. The ozone anomaly returns to 0 Dobson units as the vortex breaks down. The maximum ozone anomaly is also about half the size of the maximum anomaly seen in DJF, consistent with the weaker nature of the March SSW events overall.

3.4 Midwinter strong polar vortex events

Finally, we turn our attention to strong polar vortex (SPV) events in DJF. While less extensively studied than SSWs, SPVs also impact surface climate. Baldwin and Dunkerton (2001) suggest that strong polar vortex events can have surface signals comparable to but opposite in sign to those following SSWs, and Smith et al. (2018) found effects of Northern Hemisphere SPVs on spring and summer Arctic sea ice.

In the thirty days following the SPV central date, we see a pattern reminiscent of a weakly positive NAO in both CHEM and NOCHEM (Figure 10). This positive NAO-like pattern appears stronger in CHEM than in NOCHEM, but not significantly so. There is very little difference from climatology at the surface in the second month after the event in either of the simulations. This minimal difference using interactive versus specified ozone compared to the difference seen with SSWs may be related to the more zonal nature of SPVs. We specify ozone in a zonally-symmetric way, which is much more consistent with the vortex seen in an SPV than in an SSW.

The NAM anomalies following SPVs in CHEM and NOCHEM (Figure ~~??~~S5) have similar strength (and opposite sign) in the stratosphere to those following midwinter SSWs, but they have much weaker downward propagation, consistent with an only weakly positive NAO. The difference between the NAM anomalies in CHEM and NOCHEM confirms a more positive NAM in mid-to-lower troposphere in the first month following the SPV central date with interactive chemistry, but again, this difference is not significant and does not reach the surface.

These minimal differences in surface pressure and NAM are consistent with the ~~lack of differences in~~ similarity in the evolution of stratospheric temperature and ~~temperature tendencies~~heating rates in CHEM and NOCHEM, shown in Figure ~~??. A small shortwave heating difference is expected in midwinter, but the longwave and dynamical heating differences are also much smaller than for midwinter SSWs.~~ S6. The only large and significant difference is in stratospheric temperature~~is~~, 40-60 days following the SPV central date, when the stratosphere is colder with interactive chemistry. This is after zonal mean zonal winds have returned to typical levels and is thus likely related to the stronger mean state of the stratospheric polar vortex with interactive chemistry compared to specified chemistry. ~~However, this does not affect the surface.~~

The zonal mean zonal winds in CHEM and NOCHEM around the SPV central dates further confirm that there is little difference in the strength of these events between CHEM and NOCHEM; the winds follow nearly identical trajectories from 30 days before to 30 days after the central date. We also see a weaker ozone anomaly following SPVs than following SSWs, with a maximum absolute anomaly of about 30 Dobson units compared to 40 (Figure 11). The ozone decrease following SPVs is also much more gradual than the increase seen in DJF SSWs. This is consistent with the fact that SPVs are not strong and sudden dynamical events in the way that SSWs are. As with DJF SSWs, though, the anomaly does persist for three months after the central date.

4 Conclusions

The climate model results presented here show an important ~~contribution of interactive ozonechemistry to~~ relationship between interactive ozone, the climatological state of the stratospheric polar vortex~~and to~~ , and the Euro-Atlantic surface impacts of midwinter SSWs. However, ozone chemistry has minimal impact on the surface effects of March SSWs and of midwinter SPVs, despite long-lasting total ozone column anomalies in the latter case. Furthermore, in contrast to the results reported by Haase and Matthes (2019), we do not find significantly fewer SSWs with interactive chemistry, despite the stronger climatological polar vortex. ~~We~~ However, we do find more frequent SPVs~~, however~~.

The stronger polar vortex mean state with interactive ozone chemistry also affects the surface signature of SSWs. ~~Stronger~~ A possible mechanism is that stronger wave forcing is necessary for an SSW to occur, and the resulting negative NAM propagates to the surface more strongly, as well. This result is also consistent with that reported by Haase and Matthes (2019), though the effects documented here are weaker. In extending this work to consider March SSWs, we found that while the same stronger dynamical forcing is present, the influence of the shortwave heating term in late winter/early spring results in a stratospheric temperature difference of opposite sign, and with little difference at the surface following March SSWs between interactive chemistry and specified chemistry simulations. We also find minimal impact on midwinter surface effects of SPVs~~; the~~ . However, we do see persisting negative ozone anomalies ~~associated with SPVs instead have an~~ that can have an important effect in spring (Ivy et al., 2017).

Previous work (Smith and Polvani, 2014; Calvo et al., 2015; Ivy et al., 2017; Lin et al., 2017; Rieder et al., 2019) has shown the importance of ozone for the stratospheric polar vortex and surface springtime climate variability. Haase and Matthes (2019) further suggested that feedbacks among chemistry and dynamics are important for accurately capturing the response at the surface to SSWs, one of the major drivers of North Atlantic and European winter climate variability. By running longer simulations allowing for a ~~clean~~ cleaner quantification of the impact of interactive ozone, we find that these feedbacks are important for representing impacts of midwinter SSWs. However, we do not find similar importance for describing surface response to March SSWs or DJF SPVs. Our results suggest that including interactive ozone chemistry may have a sizable impact on N.Atlantic and European winter and spring climate variability in models.

Finally, we note that while we have only focused on winter SSWs and SPVs, stratospheric final warmings also have tropospheric effects (Black et al., 2006; Ayarzagüena and Serrano, 2009; Wei et al., 2007; Hardiman, 2011; Thieblemont et al., 2019; Butler et al., 2019). Those effects are dependent on the timing of the final warming, with earlier final warmings resulting in surface effects more like those seen following SSWs (Ayarzagüena and Serrano, 2009; Li et al., 2012). Interactive chemistry may thus also affect the representation and surface signature of stratospheric final warmings in models; this will be investigated in a follow-up study.

Data availability. All model results are stored and available on the High Performance Storage System (HPSS) at the National Center for Atmospheric Research (NCAR).

Author contributions. GC and LMP designed the model experiment. JO, GC, and LMP decided on the analysis, and wrote the paper. GC carried out the model simulations. JO performed the data analysis and produced the figures.

Competing interests. The authors declare that they have no conflict of interest.

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Appendix A

We calculate the NAM using a method similar to that of Gerber et al. (2010) and Gerber and Martineau (2018). The specific procedure is as follows:

1. We average model output to find a time series of daily, zonal mean geopotential height $Z(t,\lambda,p)$ as a function of time t, latitude λ, and pressure p.

2. For every day and pressure level, we remove the global mean geopotential height $\bar{Z}^{\mathrm{global}}(t,p)$. This helps to remove the global changes so that the index instead mainly captures meridional differences or shifts (Gerber et al., 2010). (While not the case for the simulations used in this study, this step would remove much of the global warming signal if it were present.)

3. For each day, latitude, and pressure level, we remove the average for that calendar day over the whole period; that is, we remove the climatology to find an anomalous height.

4. For each day, latitude, and pressure, we remove the linear trend over the period.

5. For each day and pressure level, we compute a polar cap average. Here we are interested in the NAM, and we take the average from 65-90°N. This is a proxy for the annular mode as shown in Baldwin and Thompson (2009).

6. We multiply by -1 so that a positive polar cap geopotential height anomaly yields a negative NAM, for consistency with the convention of Thompson and Wallace (1998).

7. We normalize the index by its standard deviation at each pressure level.

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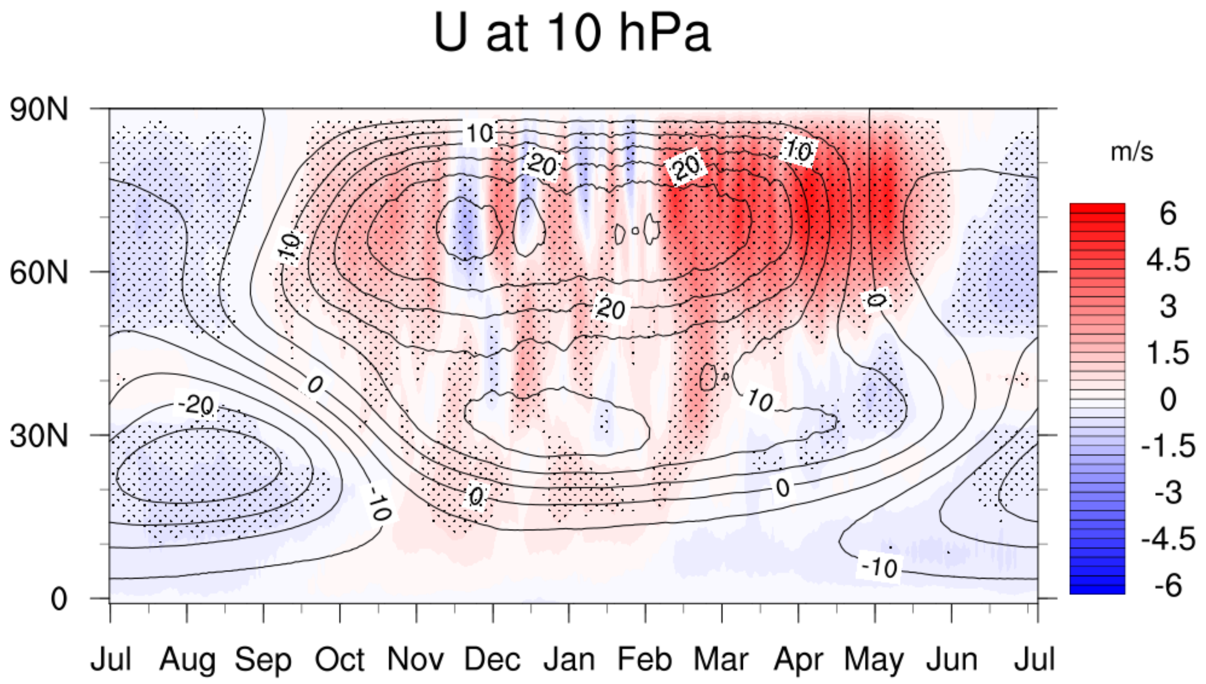

Figure 1. Latitude-time plot of zonal mean zonal wind at 10 hPa. Contours show NOCHEM values in m/s. Colored shading shows the difference CHEM-NOCHEM in m/s. Stippling indicates a significant CHEM-NOCHEM difference at a 95% level using a two-sample, two-tailed Welsh's t-test.

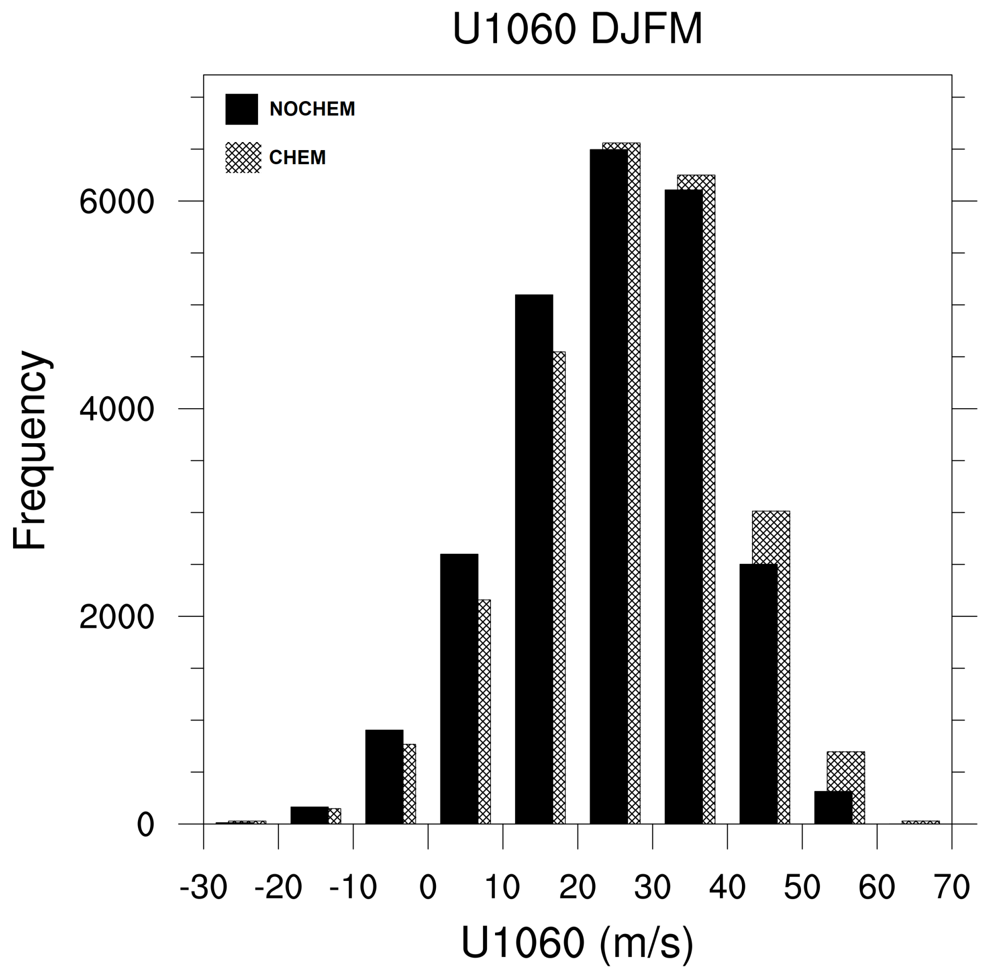

Figure 2. Histogram of daily values of zonal mean zonal wind at 10 hPa and 60°N in December-March for CHEM and NOCHEM. The mean ~~and standard deviation~~ of the CHEM and NOCHEM zonal mean zonal wind values are ~~26.5~~ 26.1 m/s and ~~12.9~~ 24.4 m/s ~~. For NOCHEM, these values are 25.0 m/s and 12.3 m/s~~ respectively. The ~~shift to a stronger vortex in~~ right tail of the CHEM ~~compared to NOCHEM~~ distribution is ~~statistically significant at the 95% level based on~~ longer, indicating more days of a ~~Kolmogorov-Smirnov test; the difference in means is significant at the 95% level based on a two-sample t-test~~particularly strong polar vortex.

	NOCHEM	CHEM	Percent Difference	p-value
Total Winters	200	200		
DJF SSW events	75	67	-10.7%	0.45
DJF SPV events	58	74	+29.3%	0.13
March SSW events	28	39	+39.3%	0.14
March SPV events	7	5	-28.6%	0.58

Table 1. Summary of sudden stratospheric warming (SSW) and strong polar vortex (SPV) events in 200-year year 2000 timeslices with and without interactive chemistry (CHEM and NOCHEM respectively). We separately consider the events occurring in December through February and those occurring in March. Reported p-values are based on a two-tailed two sample t-test (Charlton and Polvani, 2007b).

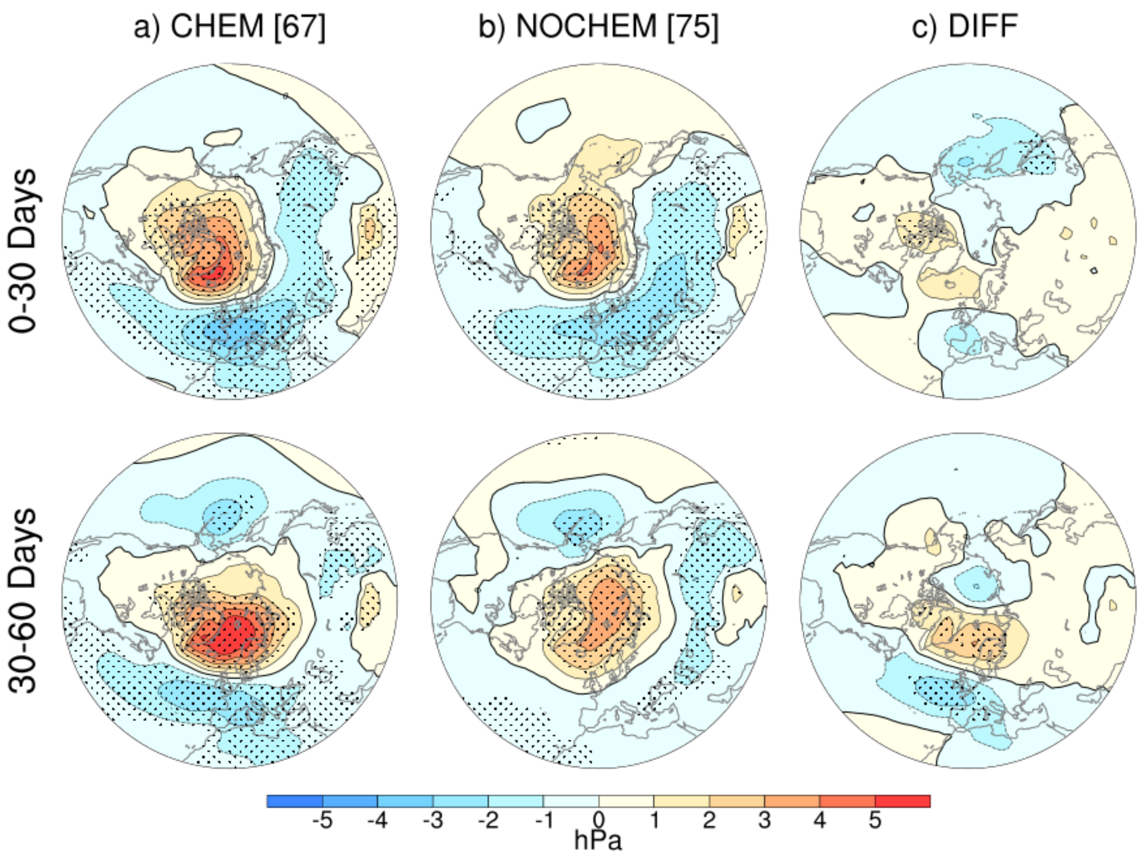

Figure 3. Composites of sea level pressure (SLP) anomalies (in hPa) in the 0-30 and 30-60 days following the central date of DJF SSWs in CHEM (WACCM, a) and NOCHEM (SC-WACCM, b) simulations, as well as the difference in the CHEM and NOCHEM composites (c). Significance at the 95% level using a Monte Carlo test (a,b) or a two-sided t-test (c) is indicated by stippling. The number of events included in each composite is noted in brackets above the figures.

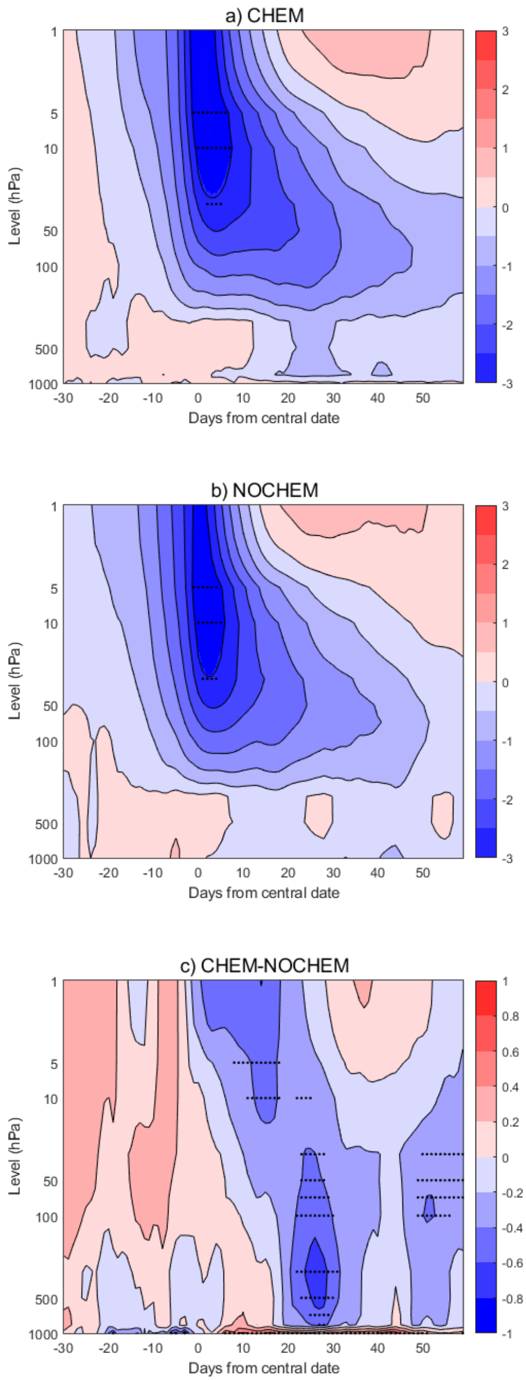

Figure 4. NAM anomaly composites around DJF SSW central dates in CHEM (~~top~~a), NOCHEM (~~middle~~b), CHEM-NOCHEM (~~bottom~~c). Stippling shows significance at the 95% level (with a Monte Carlo test for CHEM and NOCHEM and a two-tailed t-test for CHEM-NOCHEM). Contours are every 0.5 standard units for CHEM and NOCHEM and every 0.2 standard units for CHEM-NOCHEM.

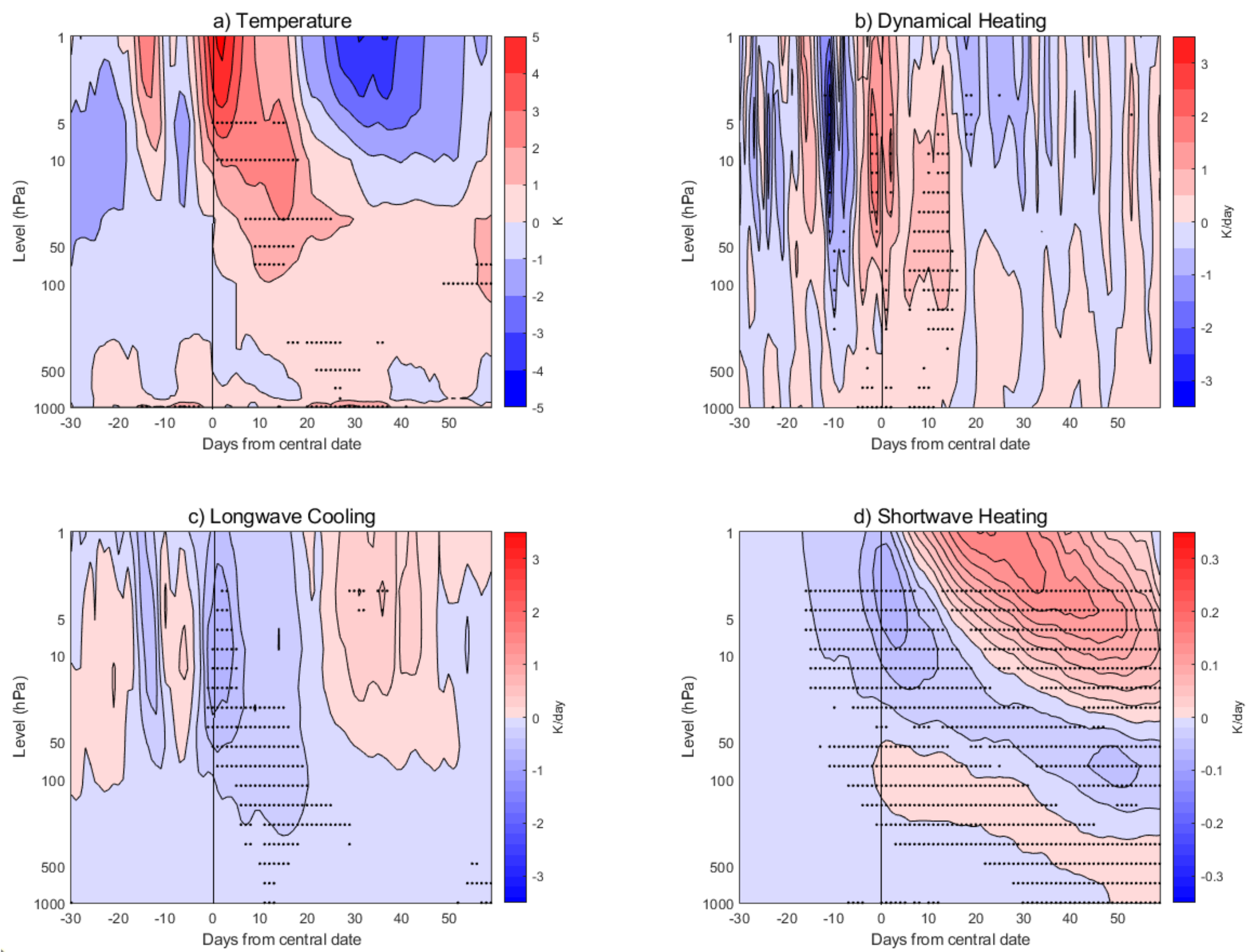

Figure 5. CHEM-NOCHEM differences in the temperature and heating anomalies over 60-90° N from -30 to +60 days around the SSW DJF central dates. ~~Top left~~(a): ~~temperature~~ Temperature anomalies. Contours are every 1 K. ~~Top right~~(b): ~~dynamical~~ Dynamical heating anomalies. Contours are every 0.5 K/day. ~~Bottom left~~(c): ~~longwave~~ Longwave heating anomalies. Contours are every 0.25 K/day. ~~Bottom right~~(d): ~~shortwave~~ Shortwave heating anomalies. Contours are every 0.02 K/day. Stippling shows significance at the 95% level under a two-tailed t-test.

~~CHEM-NOCHEM difference~~

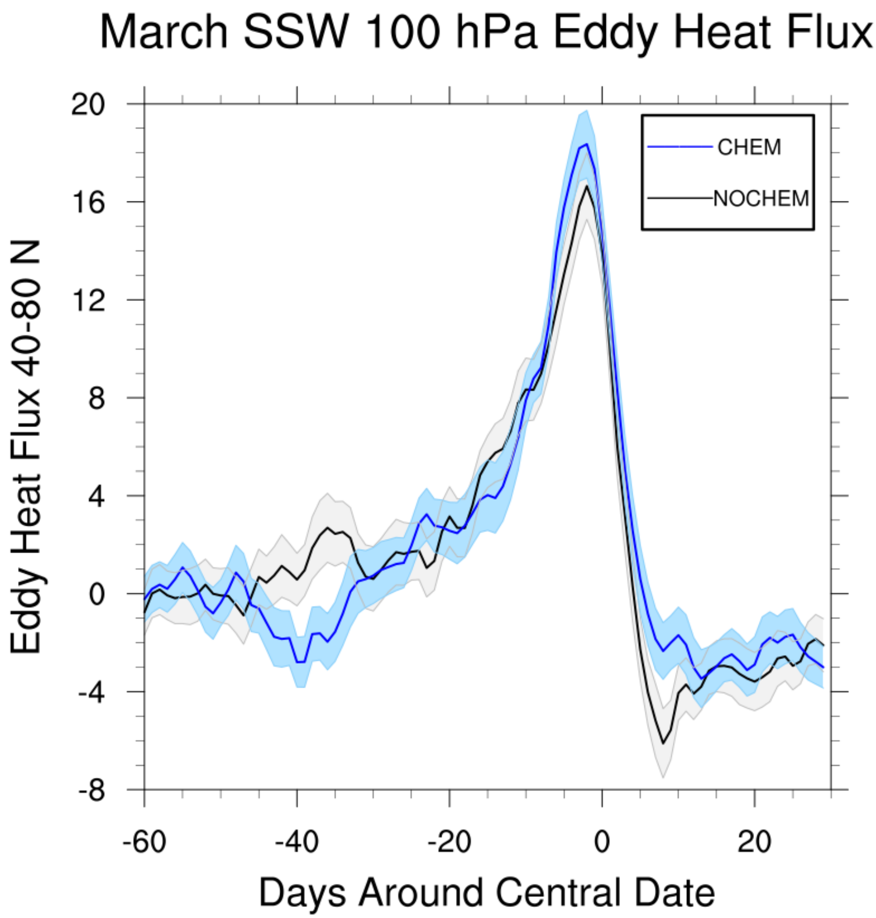

Figure 6. Eddy heat flux in ~~shortwave heating anomalies~~ mK/s over 40-80° N from ~~-30~~ -60 to +~~60~~ 30 days around the SSW DJF central dates. The CHEM average is in ~~December (top)~~blue, ~~January (middle)~~with confidence intervals shown in pale blue. The NOCHEM average is in black, ~~and February (bottom)~~with confidence intervals shown in gray.

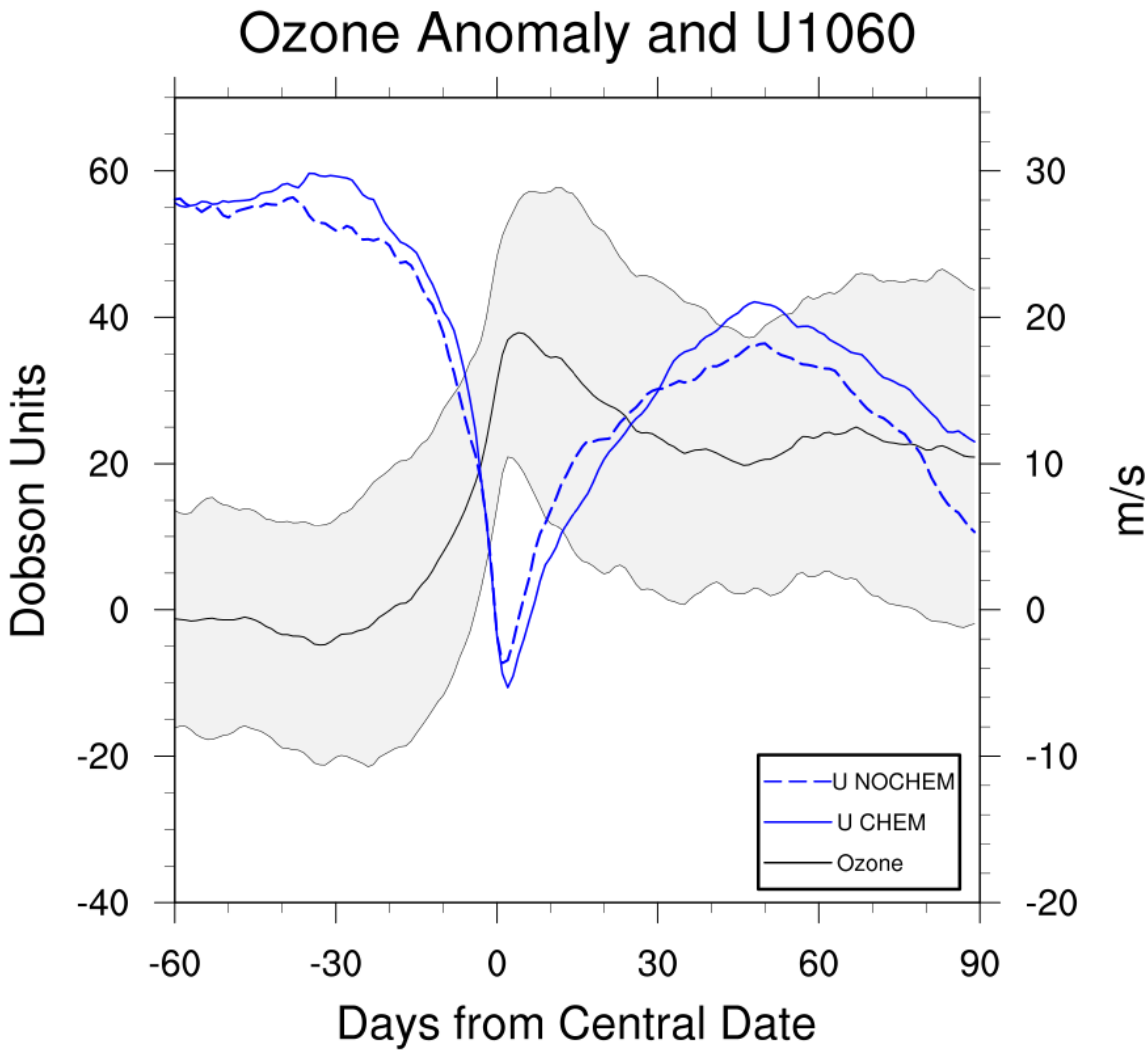

Figure 7. Composite of total column polar cap (over 60-90° N) ozone anomalies in Dobson units in the CHEM simulations and ~~composite~~ composites of zonal mean zonal wind at 60° N and 10 hPa in m/s from -60 to 90 days around the central date of DJF SSWs in CHEM ~~simulations~~and NOCHEM. The black line shows the mean total ozone column; 1σ from the mean is shaded. The blue solid and dashed ~~line~~ lines shows the mean U1060 in CHEM and NOCHEM respectively.

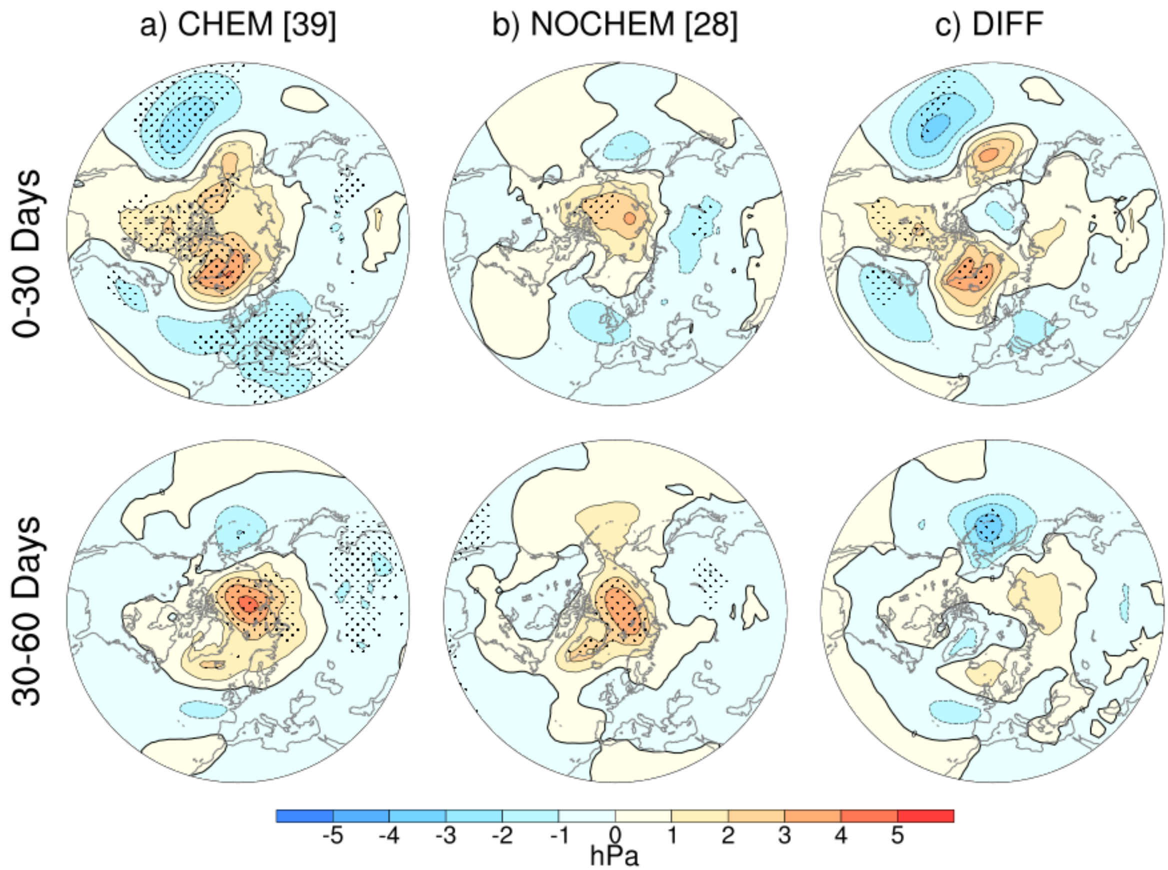

Figure 8. As in Figure 3, for March SSWs.

~~As in Figure 4, for March SSWs.~~

~~As in Figure 5, for March SSWs.~~

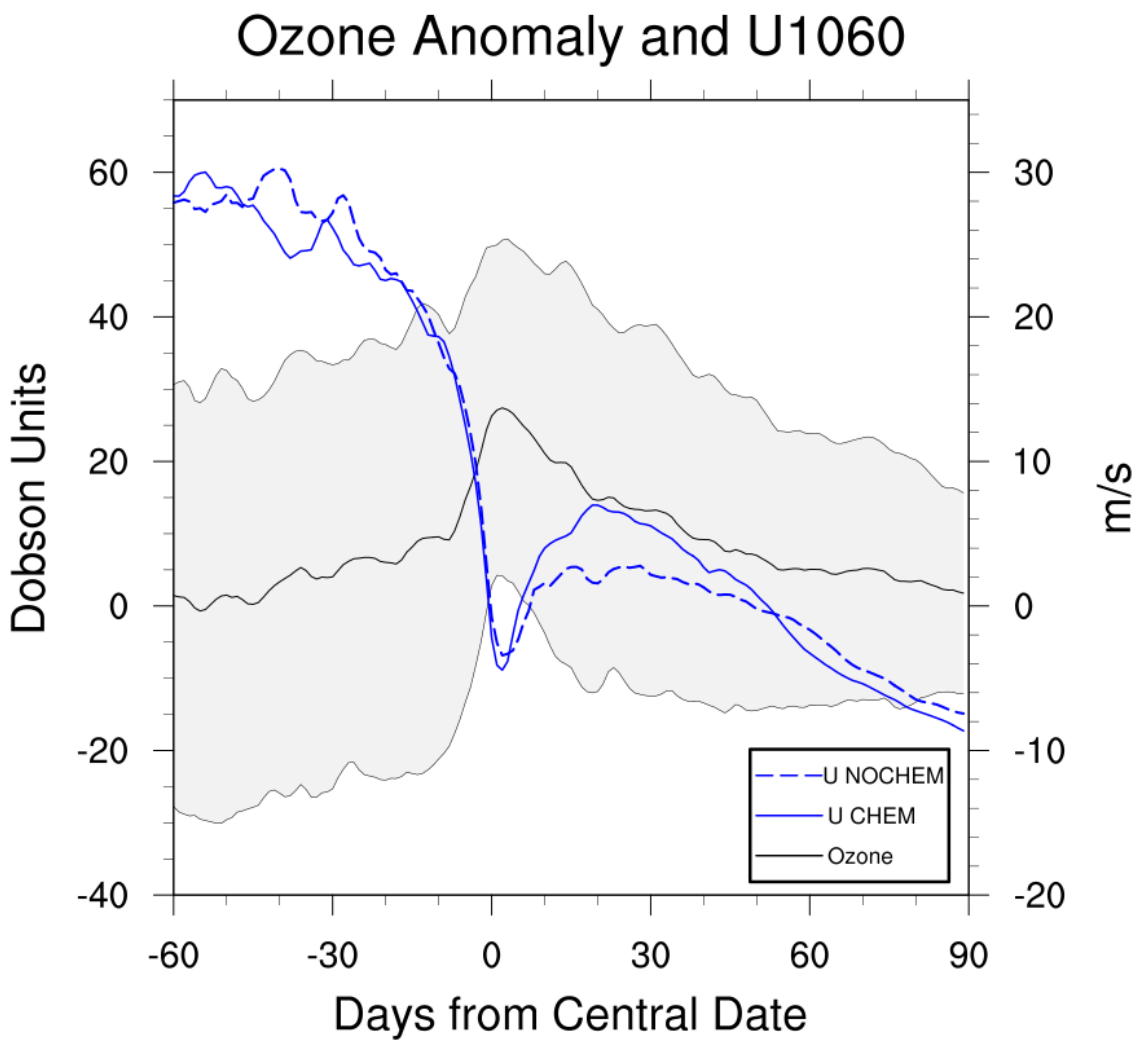

Figure 9. As in Figure 7, for March SSWs.

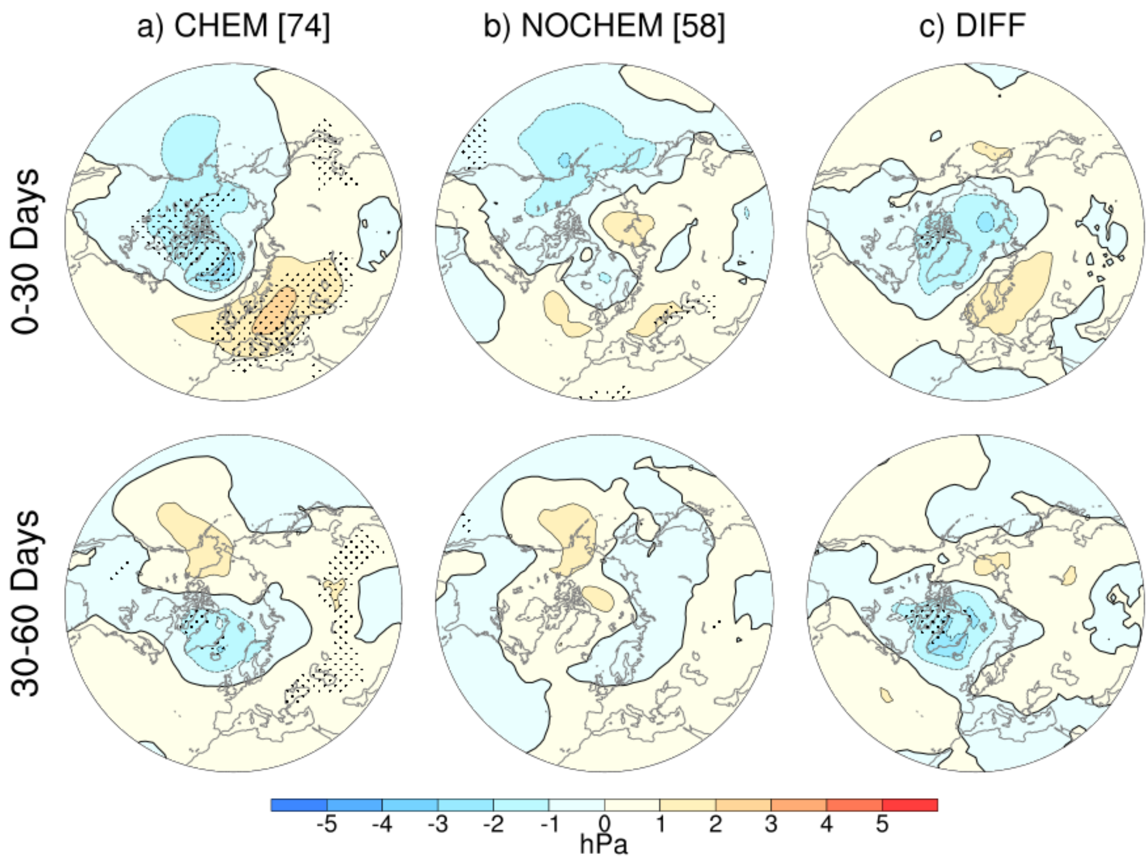

Figure 10. As in Figure 3, for DJF SPVs.

~~As in Figure 4, for DJF SPVs.~~

~~As in Figure 5, for DJF SPVs.~~

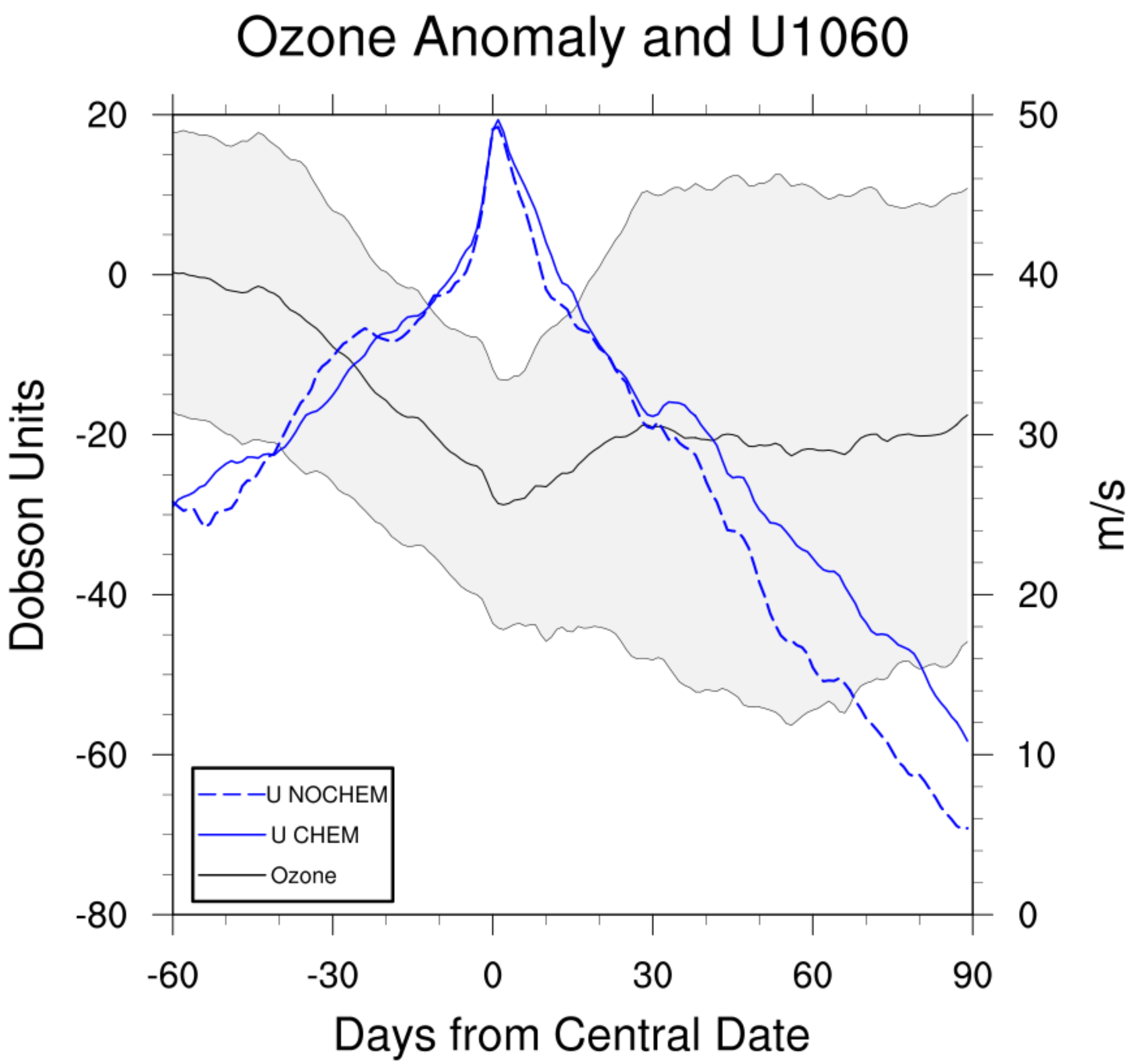

Figure 11. As in Figure 7, for DJF SPVs.

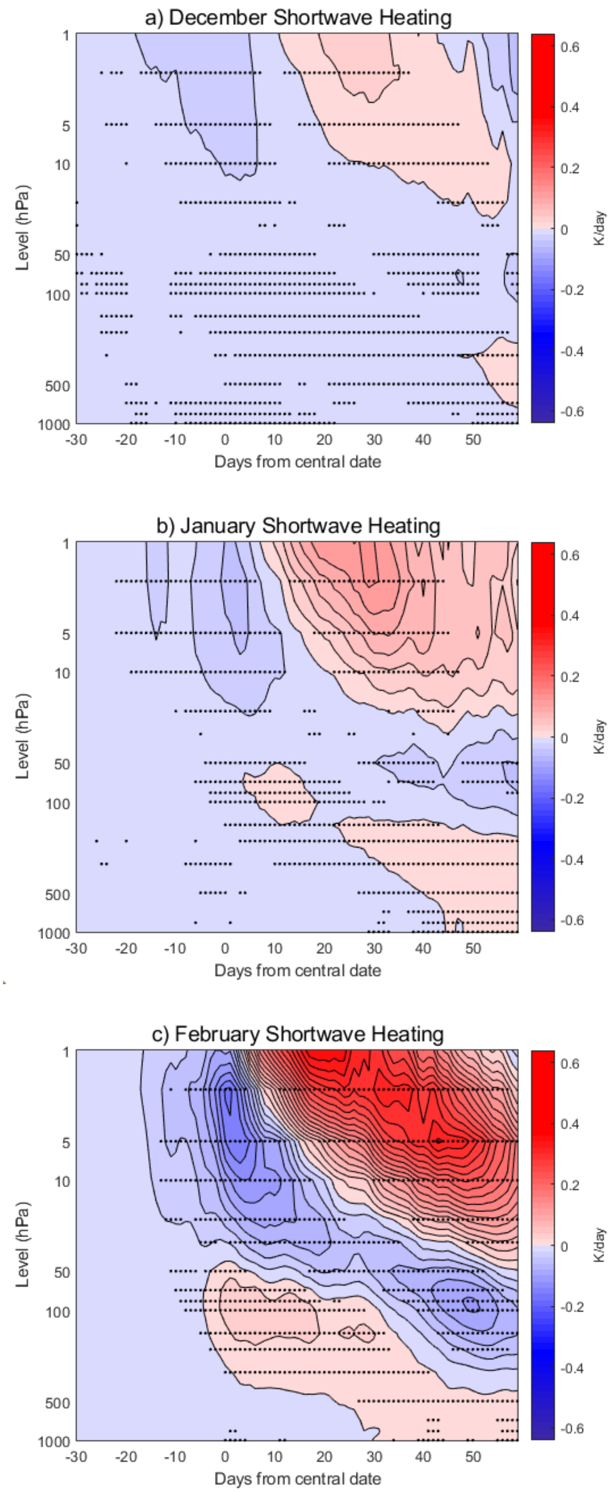

Figure S1. CHEM-NOCHEM difference in shortwave heating anomalies from -30 to +60 days around the SSW central dates in December (a), January (b), and February (c).

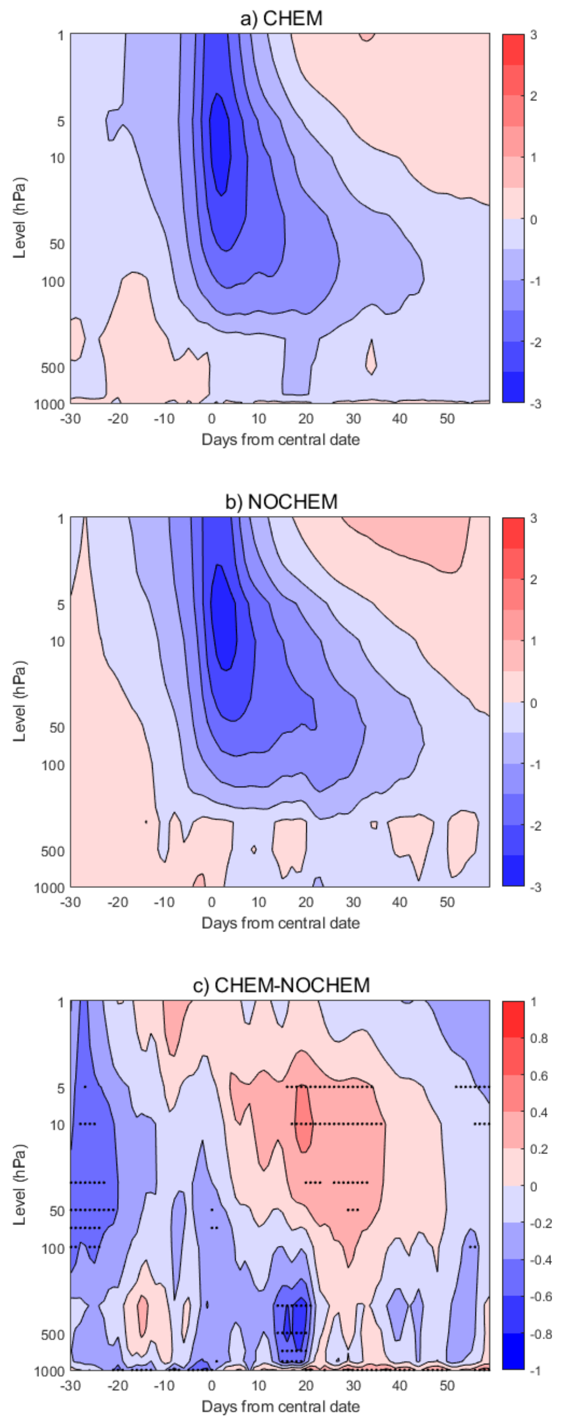

Figure S2. As in Figure 4, for March SSWs.

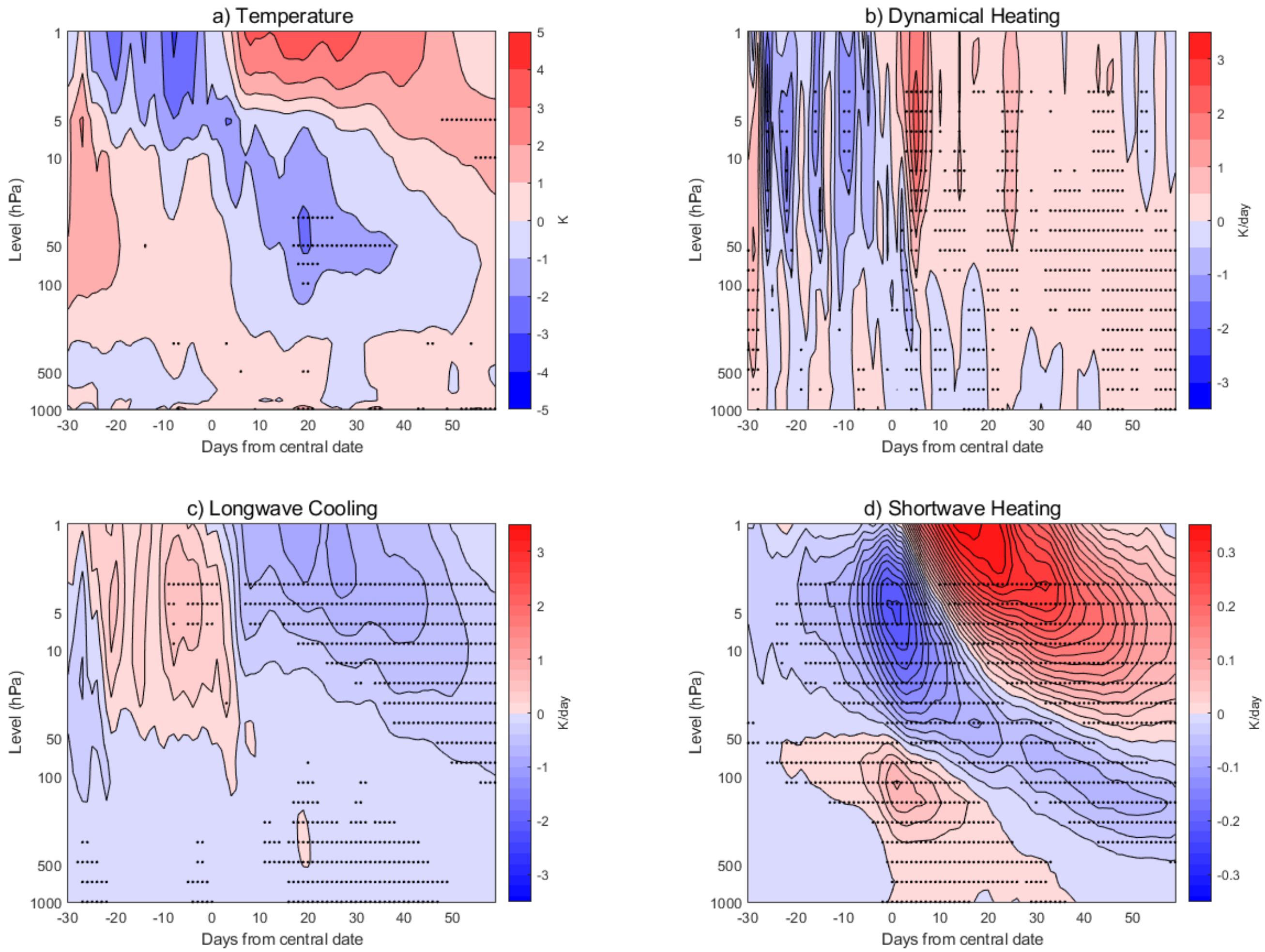

Figure S3. As in Figure 5, for March SSWs.

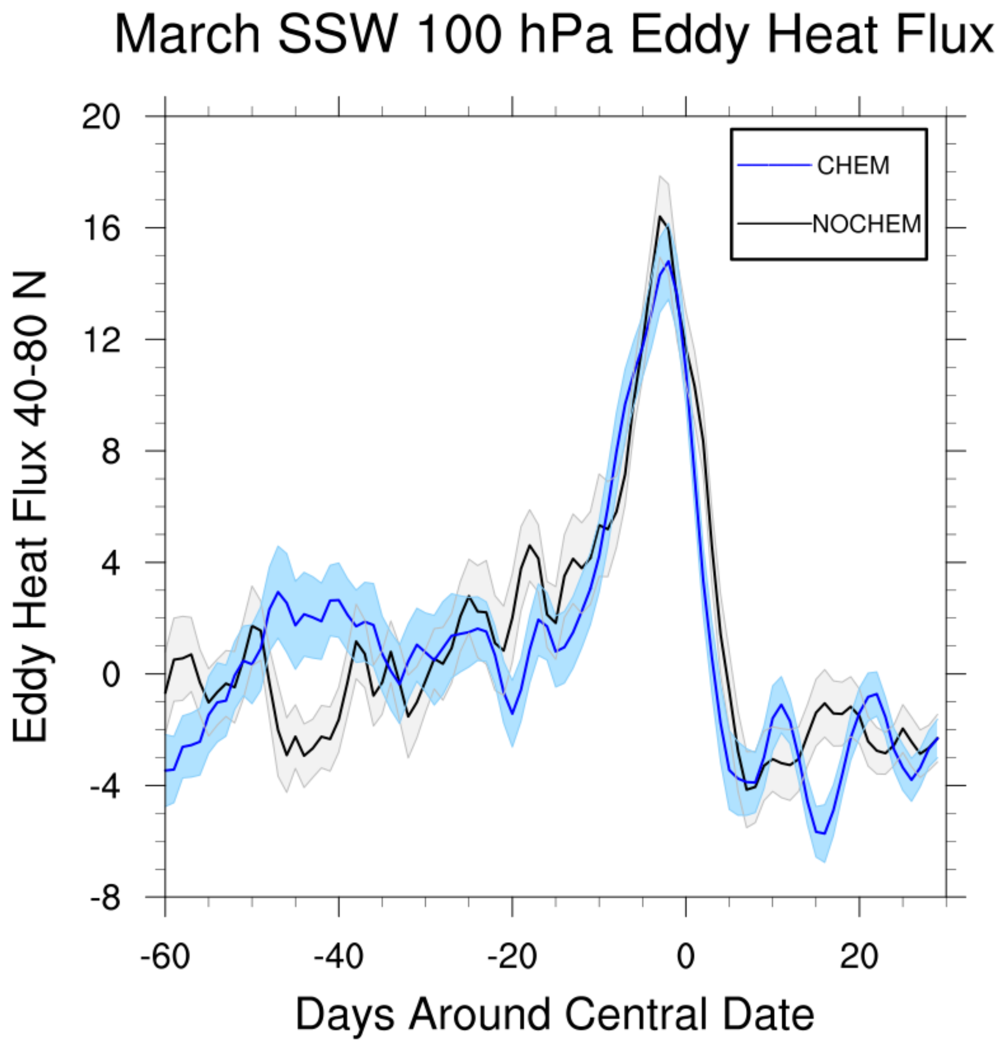

Figure S4. As in Figure 6, for March SSWs.

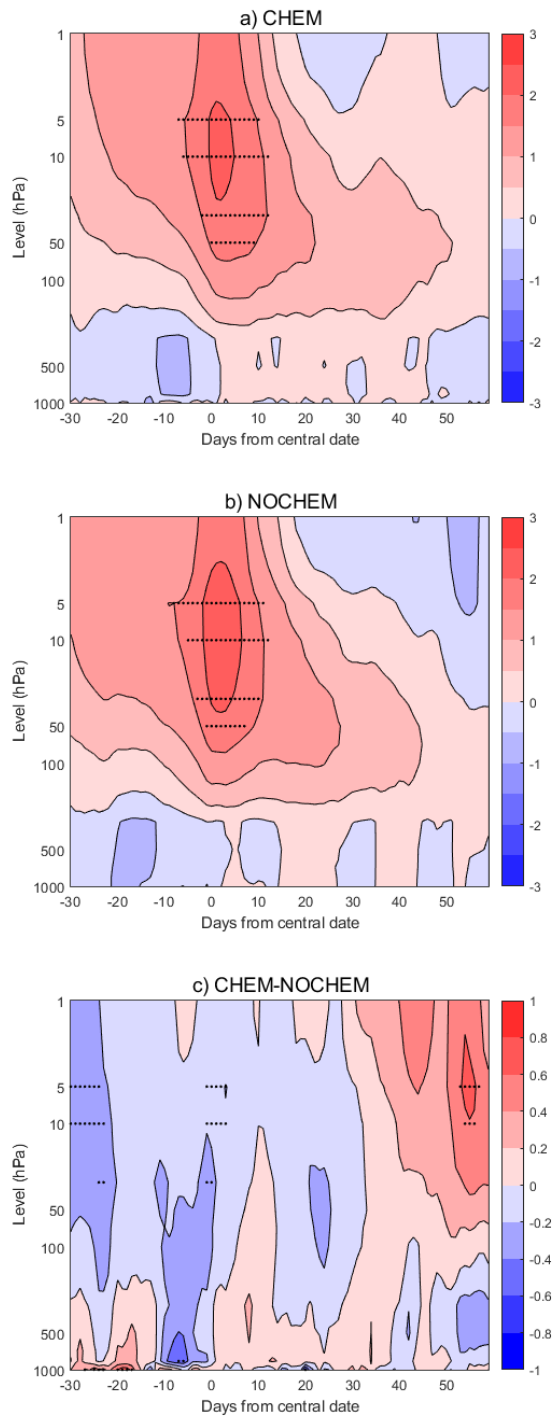

Figure S5. As in Figure 4, for DJF SPVs.

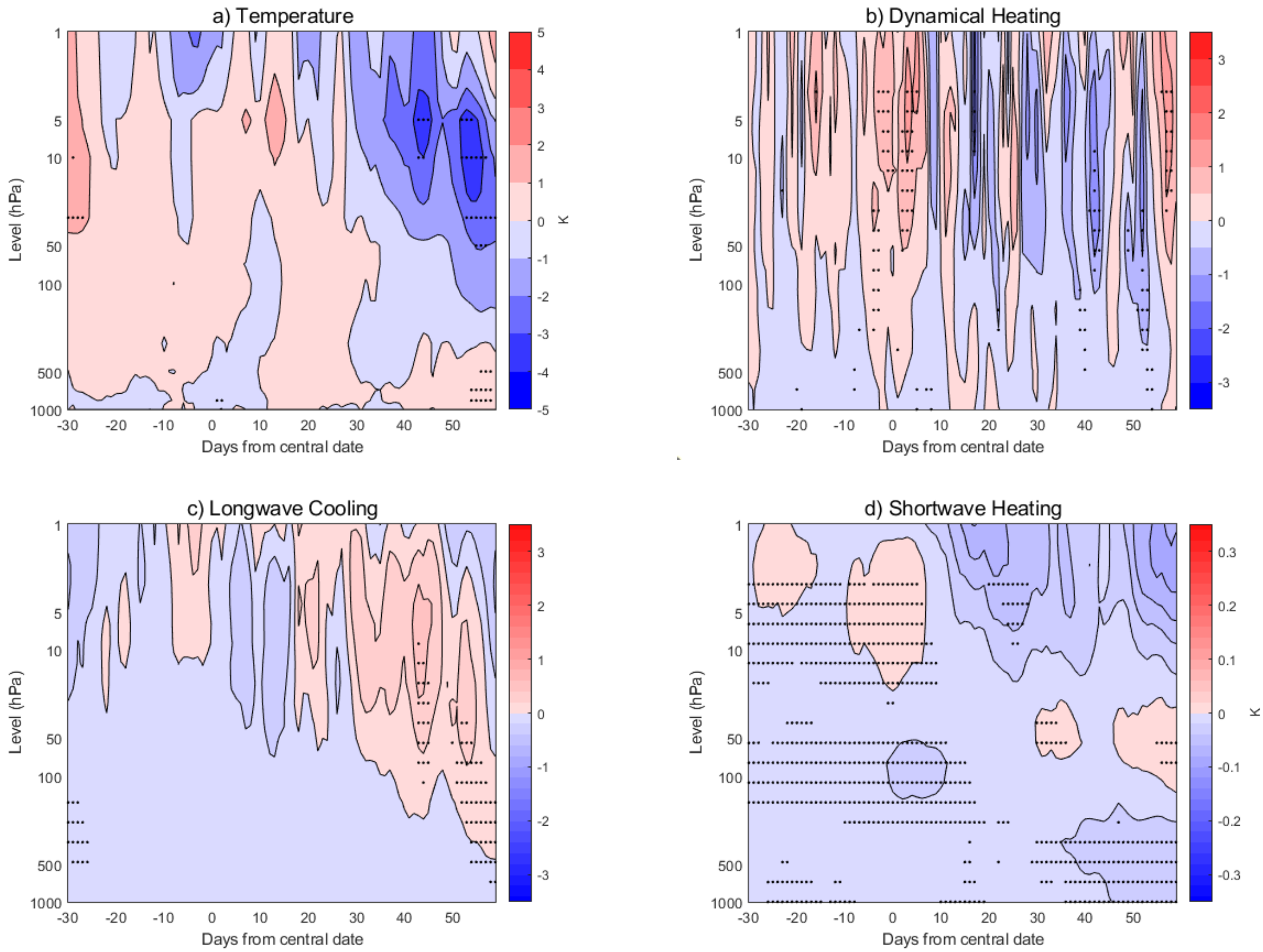

Figure S6. As in Figure 5, for DJF SPVs.