RESEARCH ARTICLE
10.1029/2018JD028537

Sudden Stratospheric Warming Formation in an Idealized General Circulation Model Using Three Types of Tropospheric Forcing

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Abstract  Tropospheric heating perturbations and topography are used to create Northern Hemisphere winter-like stratospheric variability in an idealized atmospheric general circulation model. Wave 1 and wave 2 heating perturbations as well as wave 2 topography are used. With appropriate choices of amplitudes, the three forcings produce reasonable sudden stratospheric warming (SSW) frequencies. It is found that large numbers of both split and displacement sudden warmings occur when the model is forced by heating perturbations, regardless of the wave number of the forcing. This is different from the wave 2 topographic forcing, which produces almost only splits. We use the results of the three model runs to investigate the extent to which SSWs are caused by anomalous tropospheric wave fluxes. We find that SSWs in this model can form both as a direct result of anomalous tropospheric wave activity and due to internal stratospheric processes which alter the propagation of tropospheric wave flux into the stratosphere and that the fraction of the two mechanisms is similar to that of the observed atmosphere for all three forcings. We further investigate the circulation differences associated with splits and displacements and find that splits and displacements have different zonal mean surface signatures when the model is forced by wave 1 heating.

1. Introduction

Sudden stratospheric warmings (SSWs) are the dominant sources of variability in the Northern Hemisphere winter stratosphere, but exactly how SSWs are caused is not fully understood. SSWs have traditionally been thought to be caused by the breaking of unusually large upward propagating planetary-scale waves originating in the troposphere (Matsuno, 1971), but more recent research has indicated that the state of the stratosphere plays a crucial role in SSW formation. Birner and Albers (2017) showed that SSWs and SSW-like events found in reanalysis data often occur without any preceding strongly anomalous tropospheric wave activity and that most anomalous tropospheric wave events have very small impacts on stratospheric circulation. The authors claimed that the climatological wave activity propagating from the troposphere is enough to cause SSWs and that whether SSWs happen or not depends on the state of the stratosphere. That SSWs can occur without anomalous tropospheric wave activity has also been found in idealized general circulation models (GCMs) with suppressed tropospheric variability (Scott & Polvani, 2004; 2006). Furthermore, Hitchcock and Haynes (2016) found that the evolution of the stratospheric mean state during SSWs is crucial in determining the upward fluxes of wave activity during the warming and that wave amplification during SSW onset was reduced by about 50% when variations in the stratospheric zonal mean state were suppressed in an idealized GCM.

SSWs are typically thought of as two types of events: vortex displacements (wave number 1 events) and vortex splits (wave number 2 events). SSWs in the observed atmosphere are roughly equally distributed between splits and displacements, and some authors have found the two types to be dynamically distinct (Charlton & Polvani, 2007). Some studies have found that splits and displacements have different impacts at the surface (e.g., Mitchell et al., 2013; Szevour et al., 2013), while other authors argue that differences in surface impacts following splits and displacements are not consistent for different classifications, and that a large number of events is required to distinguish the different responses (Maycock & Hitchcock, 2015).
In order to obtain a Northern Hemisphere winter-like stratosphere in an atmospheric GCM, one needs to create planetary-scale waves in the model. Stationary planetary waves can be forced by large-scale topography (Charney & Eliassen, 1949), land-sea heating contrasts (Smagorinsky, 1953), and the nonlinear interactions of synoptic scale eddies (Scinocca & Haynes, 1998). A way to produce Northern Hemisphere-like stratospheric wave activity commonly used in the literature is to use topography as a wave maker (e.g., Gerber & Polvani, 2009; Sheshadri et al., 2015; Taguchi & Yoden, 2002). Topography provides a simple way to tune the wave number and amplitude of tropospheric planetary-scale waves, and the regimes of stratospheric variability that result from the chosen forcing can then be explored. Gerber and Polvani (2009) added topography to the idealized GCM used by Polvani and Kushner (2002) and found that SSW frequencies similar to those of the observed Northern Hemisphere could be produced when running the model under perpetual winter conditions and with wave number 2 (wave 2) topography. These SSWs were all vortex splits. Gerber and Polvani (2009) found that the most Northern Hemisphere winter-like behavior occurred with wave 2 topography and amplitudes ranging from 2,500 to 3,500 m. They also found that with increasing amplitude of wave number 1 (wave 1) forcing the polar vortex went from being strong to destroyed, with no SSW regime in between. Other authors have produced SSWs in models with wave 1 topographic forcing, both under perpetual winter conditions (Taguchi et al., 2001) and with a seasonal cycle (Taguchi & Yoden, 2002). Martineau et al. (2018) varied the stratospheric temperature profile in the same dry dynamical core model used by Polvani and Kushner (2002) and Gerber and Polvani (2009) and found that SSWs were produced with both wave 1 and wave 2 topographic forcing.

Sheshadri et al. (2015) used a model based on that of Gerber and Polvani (2009) and investigated its behavior when run with a seasonal cycle and different types of topographic forcings. An important difference between the Gerber and Polvani (2009) and Sheshadri et al. (2015) models was the transition between tropospheric and stratospheric equilibrium temperatures: The transition occurred at 200 hPa for Sheshadri et al. (2015) compared to 100 hPa for Gerber and Polvani (2009). Sheshadri et al. (2015) found that 4,000-m wave 2 topography yielded a SSW frequency of 0.62 SSWs/year: a very close match to the 0.61 SSWs/year they found in reanalysis data for the years 1958 through 2013. Like Gerber and Polvani (2009), they also found that the wave 2 topographic forcing only produced split SSWs. Unlike Gerber and Polvani (2009), Sheshadri et al. (2015) found that wave 1 forcing produced both splits and displacements, although they were unable to find an amplitude of wave 1 forcing that produced a realistic SSW frequency. The highest SSW frequency they obtained with wave 1 forcing was 0.1 SSWs/year. Martineau et al. (2018) also found that SSWs were less common with wave 1 topographic forcing compared to wave 2 forcing. They obtained splits and displacements with both wave 1 and wave 2 topographic forcing, although Martineau et al. (2018) also found that wave 1 forcing favored displacements while almost all SSWs with wave 2 forcing were splits.

Scott and Polvani used idealized models to argue that SSWs and similar extreme stratospheric events can be caused by the state of the stratosphere, without anomalous tropospheric forcing. They used time-independent wave 1 tropospheric heating sources (Scott & Polvani, 2004) as well as wave 1 and wave 2 geopotential perturbations (Scott & Polvani, 2006) to create SSW-like events in an idealized atmospheric GCM where the tropospheric variability was suppressed. While their results show that SSWs can occur as long as climatological tropospheric forcing of wave number 1 or 2 exists, the results of Gerber and Polvani (2009) and Sheshadri et al. (2015) indicate that both the frequency and type of SSWs can be heavily dependent on the wave number of the tropospheric forcing.

In this paper we investigate the extent to which SSWs in this model are forced by anomalous tropospheric wave fluxes and if the results are sensitive to the forcing used or the type of SSW produced. The results are compared to the observational results of Birner and Albers (2017). We begin by presenting a method to simulate Northern Hemisphere winter-like stratospheric variability with diabatic heating instead of topography. We run an adapted version of the model used by Gerber and Polvani (2009) and Sheshadri et al. (2015) with tropospheric heating perturbations as a substitute for topography. The model is run under perpetual Northern Hemisphere winter conditions with both wave 1 and wave 2 heating perturbations, and the results are compared to those of a perpetual winter version of the setup used by Sheshadri et al. (2015). We use two different split and displacement classifications to show that, unlike in the topographically forced run, both wave 1 and wave 2 tropospheric heating produce large numbers of both splits and displacements. The SSW classifications are also tested on European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)-Interim reanalysis data for validation purposes. We analyze the anomalous wave fluxes associated with SSWs by separating the vertical Eliassen-Palm (EP) flux around splits and displacements into wave number components.
We find that SSWs in this model form both as a direct result of anomalous tropospheric wave activity and due to internal stratospheric processes which alter the propagation of tropospheric wave flux into the stratosphere and that the processes by which splits and displacements are formed are different when wave 1 heating is used. We also find that the fraction of SSWs forced by tropospheric wave flux anomalies exceeding two standard deviations is comparable to the fraction found in observations. Furthermore, we analyze the polar cap geopotential height anomalies around splits and displacements and find that splits and displacements have different surface signatures when the model is forced by wave 1 tropospheric heating.

The model setup as well as SSW definition and classifications are described in section 2. In section 3 we compare the climatologies of the model runs with wave 1 and wave 2 heating perturbations to that of the perpetual winter version of the Sheshadri et al. (2015) setup. Section 4 details the SSW statistics of the runs and the ERA-Interim data, while in section 5 we look at the vertical wave 1 and wave 2 EP flux anomalies around SSWs. The analysis of geopotential height anomalies associated with splits and displacements can be found in section 6. We present our conclusions in section 7.

2. Methods

Both model results and reanalysis data are analyzed in this paper. The reanalysis data come from the ERA-Interim Project (Dee et al., 2011) and contains four times daily observations from 1 January 1979 to 31 October 2016. Daily mean values of relative vorticity, zonal mean wind, and geopotential height were used. Section 2.1 below describes the simplified atmospheric GCM that was used to model the Northern Hemisphere winter stratosphere. The methods used to identify and classify SSWs are outlined in the second part of this section.

2.1. Model Setup

The model is an adapted version of the one used by Polvani and Kushner (2002). It is dry and hydrostatic, with T42 resolution in the horizontal and 40 vertical $\sigma$ levels, where $\sigma = p/p_s$, and $p_s$ is surface pressure. Newtonian relaxation to a zonally symmetric equilibrium temperature replaces radiation and convection schemes. Following Sheshadri et al. (2015), the transition between stratospheric and tropospheric conditions occurs at 200 hPa. The equations for the equilibrium temperature can be found in Polvani and Kushner (2002). $\epsilon$ is an asymmetry parameter in the equation for tropospheric equilibrium temperature, and unlike Polvani and Kushner (2002) and Sheshadri et al. (2015) we chose a value of $\epsilon = 0$ K to keep the tropospheric equilibrium temperature symmetric about the equator. Polvani and Kushner (2002) and Sheshadri et al. (2015) used $\epsilon = 10$ K (which makes the Northern Hemisphere troposphere colder), but that resulted in unrealistically long annular mode time scales in the troposphere, especially in the absence of topography (Sheshadri et al., 2015). With $\epsilon = 0$ K the annular mode time scales are reasonable in the absence of topography or heating perturbations (Sheshadri & Plumb, 2017). Unlike Sheshadri et al. (2015), our simulations did not include a seasonal cycle but were run under perpetual Northern Hemisphere winter conditions.

A tropospheric diabatic heating perturbation was added to the winter hemisphere to induce Northern Hemisphere winter-like wave activity. The format of the heating perturbation was

$$Q_0 (\lambda, \phi, p) = \begin{cases} q_0 \sin (m \lambda) \exp \left[ -\frac{1}{2} \left( \frac{\phi - \phi_0}{\sigma_\phi} \right) \right] \sin \left( \pi \frac{\log(p/p_0)}{\log(p_t/p_0)} \right), & p_t \leq p \leq p_0 \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where $\lambda$ is longitude, $\phi$ is latitude, $p$ is pressure, $q_0 = 6$ K/day, $m$ is the longitudinal wave number (1 or 2), $\phi_0 = 45^\circ$N, $\sigma_\phi = 0.175 \cdot 360 / (2\pi)$, $p_0 = 8.0 \cdot 10^4$ Pa, and $p_t = 2.0 \cdot 10^4$ Pa. Figure 1 shows the format of the heating perturbation at the longitude of maximum heating. The model was run with either wave number $m = 1$ or $m = 2$. The value of $q_0 = 6$ K/day was chosen because with $m = 2$ this heating amplitude produced a
SSW frequency similar to a perpetual winter version of the 4,000-m wave 2 topographic forcing model used by Sheshadri et al. (2015). The latter was found to produce a Northern Hemisphere winter-like frequency of SSWs when run with a seasonal cycle (0.62 SSWs per year during a 50 year run). Unlike the runs with tropospheric heating, there is a tropospheric asymmetry parameter $\epsilon = 10$ K in the model run with topographic forcing. Hereafter the tropospheric heating wave 1 run will be referred to as H1, the tropospheric heating wave 2 run as H2, and the 4,000-m wave 2 topographic forcing run as T2.

The model runs were 31,000 days long, and the first 1,100 days were discarded.

### 2.2. SSW Definition and Classification

We used the Charlton and Polvani (2007) definition of a SSW: a change from westerly to easterly zonal mean zonal wind at 60°N and 10 hPa. The first day on which this condition is fulfilled is considered the central date. No SSW can be identified without at least 20 consecutive days of westerly zonal mean zonal wind before the central date. This condition prevents the same SSW from counting as two different events because of short-term wind fluctuations. To make sure that final warmings are not counted as SSWs in the analysis of the ERA-Interim data, we used the same condition that Charlton and Polvani (2007) used: At least 10 consecutive days of westerly zonal mean zonal wind is required after the central date and before 30 April if the wind reversal is to be counted as a SSW; otherwise it is assumed to be the final warming.

Just like in Charlton and Polvani (2007) we looked at dates between 5 days before the central date and 10 days after to classify SSWs as splits or displacements. Unlike Charlton and Polvani (2007) we adopted a classification that is based on geopotential height and not absolute vorticity and that requires considerably fewer calculations. We considered daily wave 1 ($A_1$) and wave 2 ($A_2$) amplitudes of geopotential height at 10 hPa and 60°N, and if for any day in the specified range

$$A_2 - k \cdot A_1 \geq 0,$$

the SSW was considered a split. If those conditions were never fulfilled, the SSW was considered a displacement. This method is similar to the one used by Yoden et al. (1999), who also used wave amplitudes of geopotential height to classify SSWs. The parameter $k$ allows skewing the results toward more or fewer splits.

We tried values of $k$ ranging from 0.8 to 1.1 and settled on $k = 1.0$. This value of $k$ resulted in a split and displacement classification that produced ratios which were very similar to those obtained by manual inspection of 10 hPa absolute vorticity surfaces. This type of classification will be referred to as subjective analysis (SA),
after the expression used by Charlton and Polvani (2007). The SA consisted of looking at daily values of absolute vorticity at 10 hPa between 5 days before the central date and 10 days after and classifying the SSW as a split if during any day there were two distinct vortices of comparable magnitudes and horizontal extents.

3. Climatology of Model Runs

The zonal mean zonal winds and zonal mean temperatures for the thermally and topographically forced runs are shown in Figure 2. One prominent difference between the different types of forcing is the location of the tropospheric jet maximum. In the case of T2 (Figure 2c) the Northern Hemisphere tropospheric jet reaches a maximum around 29°N, while the runs with thermal forcing (Figures 2a and 2b) have the tropospheric jets maximized further poleward: around 43°N for H2 and 35°N for H1. This makes the separation between the tropospheric jet and polar night jet smaller for H1 and H2 compared to T2. The mean location of the tropospheric jet cannot be easily changed when using topographic forcing: Gerber and Polvani (2009) noted that the location of the jet maximum changed by less than 2° in latitude when varying the polar vortex strength.
under topographic settings that produced SSWs (see Figure 2b in their paper). Another model parameter that affects the mean location of the tropospheric jet in control runs without topography or anomalous heating is the hemispheric asymmetry parameter, but when changing the asymmetry parameter to values ranging from $\epsilon = -30$ K to $\epsilon = 30$ K in the presence of topography, we found that the mean position of the Northern Hemisphere jet did not change by more than a few degrees (results not shown). Instead, it seems the large topography itself is impeding any significant latitudinal shift of the jet. This is not the case in the thermally forced runs, where the jet position is not as strongly constrained.

Another major difference between the topographically and thermally forced runs is the zonal mean zonal winds in the tropical tropopause and lower stratosphere. In the thermally forced runs the zonal mean zonal wind around 50 hPa and the equator is close to 0 m/s, and there are easterlies of magnitude around 20 m/s centered around 100 to 200 hPa and extending from 20°S to the northern midlatitudes. In T2 the easterlies are more symmetric about the equator and much weaker. There is also no stratospheric equatorial region in the T2 run where the zonal mean zonal wind approaches 0.

The polar night jet has a higher mean strength in T2 compared to the thermally forced runs: just below 60 m/s compared to about 55 m/s for H2 and just over 40 m/s for H1. The jet maximum occurs around 70°N for all runs.

The most prominent difference in the zonal mean temperatures between the different forcings can be found in the upper troposphere and lower stratosphere in the northern midlatitudes. While T2 has a slightly higher zonal mean temperature in that region compared to other latitudes at the same pressure levels (Figure 2f), the temperature is much higher in the thermally forced runs: about 20 K warmer for H2 (Figure 2e) and 40 K for H1 (Figure 2d) compared to T2.

Figure 3 shows the wave 1 and wave 2 components of the divergence of EP flux in the Northern Hemisphere for the three runs. Higher wave numbers do not contribute significantly to the overall divergence of EP flux in the stratosphere. The divergence of EP flux was calculated based on Edmon et al. (1980), and the equations were

$$F_\phi = -\cos \phi \frac{\partial u}{\partial \phi}.$$  \hspace{1cm} (3a)
$$F_p = f \cos \phi \frac{\partial v}{\partial p}.$$  \hspace{1cm} (3b)
$$\nabla \cdot \vec{F} = \frac{1}{r \cos \phi} \frac{\partial}{\partial \phi} \left( F_\phi \cos \phi \right) + \frac{\partial}{\partial p} F_p.$$  \hspace{1cm} (3c)

In the above equations $\phi$ is latitude, $p$ is pressure, $r$ is Earth’s radius, $f$ is the Coriolis parameter, $u$ and $v$ are zonal and meridional winds, respectively, and $\theta$ is potential temperature. Overbars denote zonal means, and primes deviations from the zonal mean. $F_\phi$ and $F_p$ are the meridional and vertical components of EP flux, respectively. $\nabla \cdot \vec{F}$ is the divergence of EP flux, and Figure 3 shows $\frac{1}{\cos \phi} \nabla \cdot \vec{F}$. This scaling makes the EP flux proportional to zonal acceleration.

The divergence of EP flux is similar between H1 and H2. There is strong wave 1 convergence in the lower stratospheric extratropics ($-9$ m/$s$ $r$day) and upper stratospheric high latitudes ($-4$ m/$s$ $r$day) in H1, and strong divergence ($7$ m/$s$ $r$day) poleward of about 75°N and above 10 hPa (Figure 3a). There is weak wave 2 convergence (around $-1$ m/$s$ $r$day) throughout most of the stratosphere, except poleward of about 65°N where there is convergence approaching 2 m/$s$ $r$day (Figure 3b). The wave 1 convergence and divergence in H2 (Figure 3c) is structurally similar but weaker by roughly a factor of 2 compared to that of H1 except in the lower stratosphere, where H2 does not have wave 1 convergence. The structure in wave 2 for H2 (Figure 3d) is also similar to that of H1 but about twice as large in the magnitude of convergence but with

| Data set         | H1       | H2       | T2       | ERA-Interim |
|------------------|----------|----------|----------|-------------|
| Total SSWs (SSWs per 100 days) | 199 (0.66) | 145 (0.48) | 127 (0.42) | 24 (0.42)   |
| Total splits (fraction), WAC  | 118 (0.59) | 108 (0.74) | 124 (0.98) | 12 (0.5)    |
| Total splits (fraction), SA     | 108 (0.54) | 104 (0.72) | 123 (0.97) | 13 (0.54)   |
| Agreement between WAC and SA, fraction  | 0.76  | 0.83  | 0.98  | 0.88        |

*Note. For ERA-Interim the SSWs are counted per 100 extended winter days (November through March). SSW = sudden stratospheric warming WAC = wave amplitude classification; SA = subjective analysis.*
less divergence. These results make sense in an intuitive way: When the model is forced with wave 1 heating there is more wave 1 activity compared to wave 2, and vice versa when the model is forced with wave 2.

The EP flux divergence for T2 is very different compared to that of H1 and H2. There is strong wave 1 EP flux divergence ($6 \text{ m} / (\text{s} \cdot \text{day})$) in the polar upper stratosphere (Figure 3e) and strong wave 2 convergence ($-7 \text{ m} / (\text{s} \cdot \text{day})$) poleward of 40°N (Figure 3f). This suggests that practically all wave breaking in the stratosphere of T2 is wave 2. Figure 3 seems to indicate that the wave number of the forcing in the T2 run has a strong impact on the wave activity in the stratosphere, while the wave number of the heating in the thermally forced runs has a comparatively small impact on the climatological stratospheric wave activity.

4. SSW Statistics

The SSW frequencies as well as split and displacement ratios are summarized in Table 1. The SSW frequencies of H2 and T2 were 0.48 and 0.42 SSWs per 100 days, respectively. These frequencies are very similar to the SSW frequency found in ERA-Interim reanalysis data ranging from 1 January 1979 to 31 October 2016: 0.42 SSWs per 100 extended winter days (November through March). In the case of H1 the heating amplitude was kept equal to that of H2 to compare the differences between wave 1 and wave 2 forcing, without any thought to matching the SSW frequency to T2 or reanalysis data. This resulted in a SSW frequency of 0.66 per 100 days for H1. There were no SSWs in a 10,900-day-long control run without tropospheric wave forcing.

While T2 and H2 have similar SSW frequencies, T2 produces almost only splits while more than a quarter of the SSWs in H2 are displacements. H2 produced 145 SSWs in 30,000 days, and with the wave amplitude classification (WAC) described in equation (2), 108 of those were splits (74%). With SA the number of splits was 104 (72%). The two different classifications agreed with each other 83% of the time. Figure 4 shows the absolute vorticity at 10 hPa on the central date of two events from H2 that both classifications agreed were a split and a displacement, respectively. The split (Figure 4a) is typical of splits in H2 in that the two vortices formed immediately after the splits are usually located around longitudes 90° and 270° on the 10 hPa surface or about 45° east of the location of maximum heating. This is similar to the results of Matthewman et al. (2009), who in their analysis of reanalysis data found that there was little variation of longitudinal vortex position between individual SSWs, although they found this to be true for both splits and displacements.

The difference in fraction of splits between WAC and SA was somewhat larger for H1: 118 splits (59%) with WAC and 108 splits (54%) with SA. The agreement between classifications, 76%, was lower than for H2.

While Sheshadri et al. (2015) and Gerber and Polvani (2009) found that wave 2 topographic forcing produced only splits, we found three displacements (2%) with WAC and four (3%) with SA. The split and displacement distribution that we found in T2 is therefore more similar to the one obtained by Martineau et al. (2018), who also found that while wave 2 topographic forcing produced some displacements almost all SSWs were splits.

To make sure that our WAC classification was not only applicable to this model, we compared split and displacement ratios from the ERA-Interim data obtained using both WAC and SA. Out of the 24 SSWs in the data set, WAC classified 12 as splits compared to 13 using SA. The classifications agreed for 21 out of 24
Figure 5. Vertical wave 1 (a, c) and wave 2 (b, d) EP flux anomalies around displacements (a, b) and splits (c, d) in the H1 run, expressed in terms of standard deviations. The EP flux anomalies were averaged between 40°N and 80°N. Areas within green lines are statistically significant at a 95% confidence level. The contour interval is 0.25 standard deviations. EP = Eliassen-Palm.

5. Wave Fluxes Around Splits and Displacements

The climatological EP flux divergences of the three runs (Figure 3) indicate that wave 2 dominates the stratospheric wave activity in T2, while the stratospheric wave activity is less dependent on the wave number of the forcing in H1 and H2. This is also clear in the split and displacement ratios of the two runs, where both H1 and H2 produce large numbers of both splits and displacements while T2 produces almost only splits. To understand how the wave number of the tropospheric forcing relates to the split and displacement ratios, we analyzed vertical EP flux as a function of pressure and latitude around SSWs in the three runs. The wave 1 and wave 2 components of equation (3b) were calculated and then averaged between 40°N and 80°N and composited on the central dates of SSWs. The SSWs were divided into splits and displacements using WAC, and the fluxes around splits and displacements were composited separately. The time mean was subtracted, and the results are displayed in Figures 5–7 in terms of standard deviations. Versions of Figures 5–7 where the flux...
anomalies are expressed as numerical values instead of standard deviations can be found in the supporting information. The statistical significance was assessed with a t test.

The flux anomalies for H1 are shown in Figure 5. About 10 days before the central date of displacements there is a statistically significant wave 1 flux anomaly (Figure 5a) that reaches almost −2 standard deviations (hereafter SD). The anomaly is statistically significant far down in the troposphere, and the magnitude of the flux anomaly is largest near the surface (see Figure S1a in the supporting information) even though the standard deviation is larger in the stratosphere. It therefore seems that, on average, displacements in H1 are associated with a tropospheric wave 1 flux anomaly. There is a negative wave 2 anomaly confined to the stratosphere associated with displacements (Figure 5b), of a lesser magnitude and occurring on average about 5 days before the central date. The anomalies associated with splits are interesting: there is a negative wave 1 anomaly (Figure 5c) of slightly less than 1.5 SD in magnitude in the stratosphere, which forms about 10 days before the central date. On average, the tropospheric wave 1 flux associated with splits is smaller in both magnitude and vertical extent and shorter in duration compared to the tropospheric wave 1 anomaly during displacements. Once again the negative wave 2 anomaly (Figure 5d) forms about 5 days before the central date, with a magnitude of over 1 SD. Somewhat surprisingly, the wave 2 anomaly is smaller for splits compared to displacements. While the vertical EP flux anomalies are almost entirely confined to the stratosphere when expressed in terms of standard deviations, the magnitude of climatological EP flux is much larger in the troposphere than in the stratosphere. Therefore, splits in H1 are associated with a reasonably large tropospheric wave 1 flux anomaly, even though Figure 5c makes the anomaly look small (for comparison, see Figure S1c in the supporting information). Nevertheless, splits in H1 are on average associated with less anomalous tropospheric wave activity compared to displacements.

Both splits and displacements in H2 are preceded by EP flux anomalies originating in the troposphere. During displacements there is a small, negative (less than 0.5 SD in magnitude) tropospheric wave 2 anomaly that starts about 15 days before the central date but disappears after around 5 days (Figure 6b). When the wave 2 anomaly disappears a negative tropospheric wave 1 anomaly is instead formed, reaching a magni-

Figure 6. Same as Figure 5 but for H2. Notice the increased range of the color bar for d.
Figure 7. Vertical EP flux wave 1 (a) and wave 2 (b) anomalies around splits in the T2 run, expressed in terms of standard deviations. Areas within green lines are statistically significant at a 95% confidence level. The contour interval is 0.25 standard deviations.

Amplitude exceeding 0.5 SD (Figure 6a). This wave 1 anomaly extends into the stratosphere, where the anomaly approaches $-1.5$ SD just before the central date. Centered around the central date of displacements is a stratospheric wave 2 anomaly of around $-1.5$ SD. There is a relatively large (up to 1 SD) positive wave 1 flux anomaly following the displacement that extends all the way to the upper troposphere.

The EP flux anomalies around splits in H2 show that the anomalous wave flux around splits is dominated by wave 2. A large negative EP flux anomaly starts to form about 12 days before the central date of splits (Figure 6d). The anomaly extends from the troposphere to the stratosphere, and while the magnitude of the tropospheric anomaly is small in terms of standard deviations, the absolute vertical EP flux anomaly is large (see Figure S2d in the supporting information). The magnitude of the negative anomaly exceeds 3 SD in the middle stratosphere around the central date. Positive anomalies of less than 0.5 SD can be found in the troposphere up to 20 days after the central date. In comparison, there is a small (less than 0.5 SD in magnitude) negative wave 1 anomaly preceding the split, with a modest vertical extent (Figure 6c). A weak (less than 0.5 SD) but statistically significant positive wave 1 flux anomaly follows the splits.

The EP flux anomalies around splits in T2 are found in Figure 7. Since almost all SSWs in T2 were splits, no meaningful statistics could be obtained for displacements, so the anomalies around displacements are not shown in Figure 7. Pressure levels below 450 hPa are unavailable for analysis due to the topography. Structurally the flux anomalies are very similar to those found in splits in H2. There are practically no wave 1 anomalies preceding the SSWs but positive anomalies following the events of up to 1 SD (Figure 7a). The wave 2 flux anomalies become statistically significant around 15 days before the central date, and they are larger in the troposphere than the stratosphere before the central date (Figure 7b). Just before the central date the negative wave 2 anomalies reach their largest magnitude of over 3 SD.

Birner and Albers (2017) found that 7 out of 28 SSWs (25%) in their reanalysis data set were preceded by lower tropospheric wave events. They defined a lower tropospheric wave event as a 10-day average upward EP flux at 700 hPa averaged between 45°N and 75°N that exceeded two standard deviations. They looked at both wave 1 and wave 2 fluxes. To complement Figures 5–7, we performed a similar analysis, where we searched

Table 2

| Data set | H1      | H2      | T2      |
|----------|---------|---------|---------|
| Displacements (fraction) | 26 (0.32) | 6 (0.16) | 2 (0.67) |
| Expected displacements (5th/95th percentiles) | 19 (1/24) | 8 (5/12) | —       |
| Splits (fraction) | 20 (0.17) | 26 (0.24) | 43 (0.35) |
| Expected splits (5th/95th percentiles) | 27 (22/32) | 24 (20/27) | —       |

Note. See text for details.
for the strongest 10-day average upward EP flux at 450 hPa averaged between 40°N and 80°N before each SSW in our data sets. The 10-day averages were calculated with center dates ranging from 20 days before the SSW to the central date. The pressure level of 450 hPa was chosen so that T2 could be included. Unlike Birner and Albers (2017) we did not separate the vertical EP flux into wave numbers for this analysis, since the average structure of the wave flux anomalies were already shown in Figures 5–7 and we are interested in the full flux around the events. We found that the number of SSWs preceded by vertical EP flux anomalies exceeding two standard deviations (2 SD) was 46 (23%) for H1 and 32 (22%) for H2. To assess the statistical significance of differences between splits and displacements, we produced 100,000 sets of random data for both H1 and H2, where each set contained a number of entries equal to the number of SSWs in the runs (199 and 145, respectively). The entries consisted of ones and zeros, where the number 1 represented a SSW forced by anomalous flux exceeding the threshold of 2 SD. Therefore, 46 out of 199 and 32 out of 145 entries were designated as ones. According to WAC there were 118 splits and 81 displacements in H1, and 108 splits and 37 displacements in H2. We randomly picked the corresponding numbers of splits and displacements from each data set. From the 100,000 data sets we could then find the 5th and 95th percentiles of splits and displacements that would be forced by anomalous vertical EP flux exceeding 2 SD if there was no difference between the forcing of splits and displacements. The results can be found in Table 2.

SSWs in both H1 and H2 are preceded by anomalous vertical EP flux exceeding 2 SD at about the same frequency as the number found by Birner and Albers (2017): 23% and 22% for H1 and H2, compared to 25%. Interestingly, there is no statistically significant difference between splits and displacements in H2, even though Figure 6 indicates that splits are on average preceded by strong wave 2 flux. This is likely due to the fact that displacements in H2 are on average preceded by both anomalous wave 1 and wave 2 flux, and even though the fluxes from the individual wave numbers are small on average their sums add up to a relatively strong total flux. Splits in H2, on the other hand, are on average not preceded by any significant tropospheric wave 1 flux. The fractions of splits and displacements in H1 that are preceded by anomalous flux exceeding 2 SD are different from each other at a 95% confidence level, with 32% of displacements and 17% of splits forced by such tropospheric wave flux anomalies. Like Figure 5 indicated, displacements in H1 are more likely to be forced by anomalous tropospheric wave 1 flux compared to splits. Given the small amounts of displacements in T2 we did not perform any statistical analysis for that model run, but we note that a large amount (35%) of SSWs in T2 are forced by flux anomalies exceeding 2 SD.

It seems that when SSWs are associated with tropospheric flux anomalies exceeding 2 SD the SSW is more likely to depend on the wave number of the forcing, with wave 1 forcing favoring displacements and wave 2 favoring splits. The results from H1 show that almost twice the fraction of displacements are associated with such anomalies compared to splits, and although the differences are not statistically significant in H2 there is an indication that this may be the case in that model setup as well, with the fraction associated with splits being 50% higher than that of displacements.

The fact that the fractions of SSWs forced by anomalous tropospheric wave flux exceeding 2 SD in the three model runs is similar to what Birner and Albers (2017) found in reanalysis data indicates that SSWs produced in this model may be formed by processes similar to those in the observed atmosphere. T2 has much too many splits compared to observations and can reasonably be expected to be least similar to observations in terms of SSW generation, but even in that model run about two thirds of SSWs occur without anomalous tropospheric wave flux exceeding 2 SD. This suggests that previous authors who have used this idealized GCM with topographic wave 2 forcing (e.g., Gerber & Polvani, 2009; Martineau et al., 2018; Sheshadri et al., 2015) may have produced SSWs for reasons similar to those in the observed atmosphere.

The choice of two standard deviations as a threshold for considering an SSW forced by tropospheric wave flux anomalies is high and somewhat arbitrary. However, even if the threshold is decreased to one standard deviation only 73%, 65%, and 76% of SSWs in H1, H2, and T2 reach this threshold. That a quarter to a third of SSWs in these runs occur without the tropospheric flux anomalies in a 21-day window reaching even one standard deviation indicates that a significant amount of SSWs occur without anomalous tropospheric forcing. These SSWs are therefore most likely caused by internal stratospheric processes, where the stratosphere allows a larger than usual amount of tropospheric wave flux to propagate into the upper stratosphere. Hitchcock and Haynes (2016) found that the evolution of the state of the stratosphere during SSW onset is crucial in
Figure 8. Geopotential height anomalies averaged from 65°N to 90°N and normalized by their standard deviations. The anomalies are composited on the central dates of displacement events (a, c) and split events (b, d) in H1 (a, b) and H2 (c, d), using wave amplitude classification. (e) The anomalies around splits in T2. Areas within green lines are statistically significant at a 95% confidence level. The contour interval is 0.25 standard deviations.
determining the wave flux during the event, and the results above further confirm the importance of the state of the stratosphere in SSW formation.

6. Differences in Polar Cap Height Following Splits and Displacements

In order to investigate the impacts of splits and displacements on tropospheric circulation in the model, we composited zonal mean geopotential height anomalies from 65°N to 90°N on the central dates of splits and displacements in H1 and H2 (using WAC) and on splits in T2. The anomalies were normalized by the standard deviations of geopotential height in the respective runs. Once again a t test was used to assess statistical significance at the 95% level. Figures 8c and 8d show the anomalies in H2 following displacements and splits, respectively. In both cases the anomalies are positive before and after the central date, and the anomalies last longer in the lower stratosphere compared to the upper stratosphere. There are tropospheric anomalies associated with both types of events, but in the case of splits the tropospheric anomalies seem to precede stratospheric anomalies of similar magnitude by about 20 days. The lower tropospheric anomalies associated with splits remain statistically significant for over 80 days following the central date, although the anomalies following displacements are slightly weaker and not statistically significant to the same extent. The largest tropospheric anomalies associated with splits approach 1 SD, but tropospheric anomalies barely exceed 0.5 SD for displacements. However, the difference between tropospheric anomalies associated with displacements and tropospheric anomalies associated with splits is only statistically significant at the 95% level between about 12 and 4 days before the central date, where the anomalies before splits are slightly stronger (assessed using a t test; not shown), so while both splits and displacements have statistically significant zonal mean surface impacts in H2, there is little evidence for splits and displacements having different zonal mean surface impacts with this forcing.

The difference between splits and displacements is larger for H1. Displacements (Figure 8a) are preceded by statistically significant negative anomalies of a magnitude over 0.5 SD that extend from the surface to the middle stratosphere, and following the central date there are no tropospheric anomalies. There are barely any negative anomalies preceding splits (Figure 8b), and there are positive anomalies approaching 0.5 SD following the central date. These tropospheric anomalies last from almost 20 days after the central date to about 80 days after the central date. Unlike H2, a t test reveals that the difference between splits and displacements is statistically significant at the 95% level throughout most of the troposphere (not shown). Although the zonal mean geopotential height anomalies around splits and displacements in H1 look very different, their tropospheric impacts are quite similar if the anomalies before the central date are compared with the anomalies following: In both cases the SSW changes the anomaly by about 0.5 SD. With this in mind it seems that the zonal mean geopotential height anomalies do not tell us much about the difference in tropospheric impact of splits and displacement but rather the state of the polar region before the events. It is possible that the state of the polar region may affect whether splits or displacements are produced in this model configuration, although it should be noted that Charlton and Polvani (2007) did not find significant polar cap temperature differences between splits and displacements in their reanalysis data set.

Splits in T2 (Figure 8e) are not preceded by any tropospheric anomalies, and among the model setups it seems splits in T2 have the smallest impacts on polar geopotential height in the lower troposphere. While there are positive anomalies in the upper troposphere following the central date, the only significant lower tropospheric impacts can be found on the central date and between about 20 and 30 days following the splits, and they do not reach 0.5 SD.

The differences between tropospheric impacts of splits and displacements in H1 are similar to those found by Mitchell et al. (2013). They used ERA-40 reanalysis data and calculated the northern annular mode as the leading empirical orthogonal function of daily geopotential anomalies poleward of 20°N and looked at NAM anomalies associated with splits and displacements after subtracting the seasonal cycle. They found that negative NAM anomalies following displacements stopped at the tropopause, while negative NAM anomalies following splits could reach the surface and persist for around 60 days (Figure 4 in their paper). The structure of zonal mean geopotential height anomalies associated with splits and displacements in H1 are very similar
to the results obtained by Mitchell et al. (2013). It seems that the wave number of the forcing is important for the tropospheric response to SSWs in this model.

7. Conclusions
In this paper we have demonstrated that Northern Hemisphere winter-like stratospheric variability can be produced in an atmospheric GCM with tropospheric heating perturbations. When run with topographic wave 2 forcing (T2) this model produces almost only split SSWs, but we found that with tropospheric heating the model produces large numbers of both splits and displacements with both wave 1 (H1) and wave 2 forcing (H2).

We created a WAC of splits and displacements and showed that it compared favorably with SA of SSWs. Our classification compared less favorably with the one used by Charlton and Polvani (2007) when analyzing reanalysis data, and we overestimate the amount of splits with both SA and WAC compared to Charlton and Polvani (2007). We further showed that while H1 and H2 both cause splits and displacements, the ratio of splits and displacements for H1 is slightly more sensitive to the SSW classification, while the agreement between classifications for H1 is lower compared to H2.

We used the results of the three model runs (T2, H1, and H2) to investigate the extent to which SSWs are caused by anomalous tropospheric wave activity. We analyzed anomalous wave 1 and wave 2 vertical EP flux composed on splits and displacements, as well as the 10-day anomalous tropospheric vertical EP flux around each SSW. We found that in the case of splits in T2 and H2, the anomalous wave flux around the events is dominated by its wave 2 component. Displacements in H2 and H1 were associated with anomalous tropospheric wave 1 EP flux, but in the case of displacements in H2 the events were also preceded by anomalous tropospheric wave 2 flux. Splits in H1, however, were on average preceded by very little anomalous tropospheric EP flux, and the anomalous EP flux associated with the events seemed to be found mostly in the stratosphere. Birner and Albers (2017) found that only 7 out of 28 (25%) SSWs in reanalysis data were preceded by anomalous tropospheric EP fluxes exceeding two standard deviations. Our analysis of anomalous EP flux around individual events gave similar fractions of SSWs above this threshold: 23%, 22%, and 35% for H1, H2, and T2, respectively.

We also found that the fraction of displacements forced by strong, anomalous tropospheric wave fluxes was higher than splits in H1, at a 95% confidence level. We found no statistically significant difference in this fraction between splits and displacements in H2. When the threshold for anomalous vertical EP flux is lowered to one standard deviation a quarter to a third of SSWs do not reach this threshold, which strongly suggests that some of the observed SSWs are caused by internal stratospheric processes which alter the amount of tropospheric wave flux permitted to propagate into the stratosphere. It therefore seems that SSWs in this model can form as a result of both anomalous tropospheric wave activity and changes in the state of the stratosphere. The fact that the fraction of SSWs associated with strong tropospheric EP flux anomalies is similar to the fraction found in reanalysis data indicates that this model may be producing SSWs for reasons similar to those in the observed atmosphere. Apart from validating the mechanisms behind SSW formation in our model runs, this might also apply to other authors who have used versions of this model with topographic wave 2 forcing to produce SSWs (e.g., Gerber & Polvani, 2009; Martineau et al., 2018; Sheshadri et al., 2015).

Tropospheric polar geopotential height anomalies associated with splits were found to be different from those of displacements in H1 and similar in structure to anomalies found by Mitchell et al. (2013). Interestingly, the tropospheric effects of splits and displacements in H1, as measured by polar geopotential height anomalies preceding and following SSWs, were not very different. Instead, it seems the zonal mean geopotential height before displacements is lower compared to before splits, at a 95% confidence level. This indicates that the state of the polar region may have an influence on whether a split or displacement is formed in this model configuration. There were barely any statistically significant differences between splits and displacements in H2. It seems the wave number of the forcing is important for tropospheric anomalies associated with SSWs in this model, and especially displacements.

In this paper we investigated the formation of splits and displacements in a frequently used idealized atmospheric GCM by analyzing SSWs formed when using three different types of forcing. We found that while the ways SSWs form vary with the type of forcing used and type of SSW produced, the fraction of SSWs forced by anomalous tropospheric wave flux is relatively similar to the fraction previously found in reanalysis data, regardless of the type of forcing. We also found that the zonal mean surface signatures of splits and displacements were only different with one type of forcing but that the difference between the impacts of splits and
displacements is very small. Rather than splits and displacements having different impacts with this forcing, it seems more likely that the state of the polar region affects the type of SSW produced.

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