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Polichtchouk, I., Shepherd, T. G. ORCID: https://orcid.org/0000-0002-6631-9968 and Byrne, N. J. (2018) Impact of parametrized nonorographic gravity wave drag on stratosphere-troposphere coupling in the northern and southern hemispheres. Geophysical Research Letters, 45 (16). pp. 8612-8618. ISSN 0094-8276 doi: 10.1029/2018GL078981 Available at https://centaur.reading.ac.uk/78395/

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To link to this article DOI: http://dx.doi.org/10.1029/2018GL078981

Publisher: American Geophysical Union

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL078981

Key Points:
- Parametrized nonorographic gravity wave drag (NOGWD) substantially affects modeled stratosphere-troposphere coupling in both hemispheres
- The nature of stratosphere-troposphere coupling is different in the two hemispheres
- The SH tropospheric semiannual oscillation can be eliminated by increased NOGWD and so cannot be explained through purely tropospheric processes

Supporting Information:
- Supporting Information S1

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Citation:
Polichtchouk, I., Shepherd, T. G., & Byrne, N. J. (2018). Impact of parametrized nonorographic gravity wave drag on stratosphere-troposphere coupling in the Northern and Southern Hemispheres. *Geophysical Research Letters*, *45*, 8612–8618. https://doi.org/10.1029/2018GL078981

Received 30 MAY 2018
Accepted 27 JUL 2018
Accepted article online 6 AUG 2018
Published online 21 AUG 2018

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Impact of Parametrized Nonorographic Gravity Wave Drag on Stratosphere-Troposphere Coupling in the Northern and Southern Hemispheres

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Abstract The impact of parametrized nonorographic gravity wave drag (NOGWD) on the stratosphere-troposphere dynamical coupling in atmospheric models is relatively unexplored. Using the European Centre for Medium-Range Weather Forecasts Integrated Forecast System, we find that changes in NOGWD strength have a substantial impact on the tropospheric eddy-driven jet (EDJ) in both hemispheres, but the sense of the impact is opposite in the two hemispheres. In the Northern Hemisphere the impact occurs via changes in the amplitude and persistence of stratospheric anomalies. In the Southern Hemisphere it occurs instead via differences in the sensitivity of the EDJ to a given stratospheric anomaly, arising from changes in the seasonal cycle leading up to the polar vortex breakdown. Increasing NOGWD eliminates the springtime phase of the Southern Hemisphere tropospheric semiannual oscillation, resulting in a more equatorward annual-mean EDJ and showing that the semiannual oscillation cannot be explained entirely from tropospheric mechanisms.

Plain Language Summary The parametrization of the drag exerted by unresolved nonorographic gravity waves (NOGWD) in atmospheric models is highly uncertain but is known to be of first-order importance in the representation of stratospheric and mesospheric circulation. Because stratospheric variability affects tropospheric circulation, NOGWD might be expected to affect the troposphere as well. This question is explored using an atmospheric model. We find that increasing the strength of NOGWD weakens the impact of stratospheric variability on the tropospheric midlatitude jet in the Northern Hemisphere but strengthens the impact in the Southern Hemisphere. Beyond being relevant to quantifying the importance of NOGWD and the relationships between model biases, the experiments shed light on the different nature of stratosphere-troposphere coupling in the two hemispheres, an important topic in atmospheric dynamics. They also show that the tropospheric Southern Hemisphere semiannual oscillation in surface pressure cannot be explained entirely from tropospheric mechanisms, as is usually assumed.

1. Introduction

A growing body of evidence suggests the importance of stratospheric polar vortex variability for tropospheric predictability on seasonal and subseasonal time scales in both hemispheres (e.g., Baldwin & Dunkerton, 2001; Byrne & Shepherd, 2018; Douville, 2009; Seviour et al., 2014; Sigmond et al., 2013; Son et al., 2013). In the Northern Hemisphere (NH), the main source of stratospheric polar vortex variability is stratospheric sudden warmings (SSWs), which typically precede an equatorward shift of the eddy-driven jets (EDJ) and therefore have a signal in the tropospheric annular modes (e.g., Baldwin & Dunkerton, 2001; Hitchcock & Simpson, 2014; Karpechko et al., 2017). In the Southern Hemisphere (SH), the stratospheric polar vortex variability is mainly associated with interannual variability in the seasonal cycle leading up to the springtime polar vortex breakdown: Anomalously strong polar vortex years, which tend to have an anomalously late vortex breakdown, are associated with a stronger poleward shift of the EDJ in September–November and a delay in the equatorward EDJ shift in early summer (Byrne et al., 2017; Byrne & Shepherd, 2018; Hio & Yoden, 2005; Seviour et al., 2014). Thus, for skillful tropospheric predictability in these periods it is pertinent that numerical weather and climate prediction models are able to faithfully represent stratospheric dynamics and stratosphere-troposphere dynamical coupling in both hemispheres.

Parametrized nonorographic gravity wave drag (NOGWD) is known to be important for tuning stratospheric dynamics in climate resolution models (e.g., McLandress et al., 2013; Scheffler & Pulido, 2015, 2017). Recently, Polichtchouk et al. (2018) have shown that it continues to be important even in a relatively high resolution model: Using the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) at T255L137 resolution, they found that decreasing NOGWD results in an increase in amplitude and persistence and a decrease in frequency of the SSWs in the NH, and a delay in the final warming date in the SH.

Thus far, the impact of NOGWD on stratosphere-troposphere dynamical coupling has not been examined. Therefore, the aim of this study is to quantify the impact of NOGWD on the ability of stratospheric vortex variability to influence the tropospheric EDJ in both hemispheres, using a high-resolution model. Three questions are addressed: (i) What is the impact of NOGWD amplitude on the annular modes in the NH following SSWs? (ii) Does the NOGWD amplitude impact the ability of stratospheric vortex variability to influence the EDJ in the SH spring? and (iii) What is the impact of NOGWD amplitude on the seasonal evolution of the EDJ in the SH? Using the IFS, it is shown that the effects of parametrized NOGWD on the stratosphere-troposphere dynamical coupling are opposite in the two hemispheres, due to the different nature of polar vortex variability in the two hemispheres, and that the seasonal evolution of the SH EDJ is influenced by NOGWD in the spring and summer seasons. Thus, beyond their implications for atmospheric modeling, the results shed light on the nature of stratosphere-troposphere coupling in the two hemispheres.

2. Data and Methods

Twice daily outputs from an ensemble of eight 4-year global simulations (spanning the years 2004–2014 and giving 32 nonindependent years of data) with IFS (model cycle 43R1) at T255L137 resolution (in the horizontal, grid spacing of ∼80 km; in the vertical, grid spacing of ∼350 m at 100 hPa, coarsening to ∼ 1.5 km at 1 hPa) are analyzed. To assess the impact of NOGWD on stratosphere-troposphere coupling, three simulations are performed with different NOGWD launch spectrum amplitude: (1) the default amplitude of 3.75 mPa; (2) a reduced amplitude of 1 mPa; and (3) an increased amplitude of 14 mPa. The launch height is at 450 hPa, but most of the flux is deposited in the middle atmosphere (see Figure 1 in Polichtchouk et al., 2018). The NOGWD parameterization in the IFS follows Scinocca (2003). The detailed description of the simulation setup and the motivation behind these NOGWD amplitude perturbations can be found in Polichtchouk et al. (2018). Henceforth, all simulations using the default NOGWD amplitude are referred to as *CTRL*, the reduced NOGWD amplitude as *REDUCED*, and the increased NOGWD amplitude as *INCREASED*.

An annular mode index for each pressure level from 10 to 1,000 hPa is defined as follows: A daily anomaly of the zonal-mean daily mean geopotential height is first calculated by removing a daily 90-day low pass filtered climatology for each run. An area-weighted polar cap averaged (60°–90°N/S) geopotential height anomaly is then constructed. The annular mode index defined in this way is highly correlated with the more commonly used Empirical Orthogonal Function-based index (Baldwin & Thompson, 2009). For the NH, northern annular mode (NAM) index composites are constructed about the SSW central date. A SSW is defined by the World Meteorological Organization to occur when the daily mean zonal-mean zonal wind at 10 hPa and 60°N becomes easterly between November and March. For the SH, composite time series of daily mean zonal-mean zonal wind (denoted by $[u]$) are constructed for the weakest and the strongest vortex years. The latter are defined as follows. First, the largest positive and largest negative values of the daily southern annular mode (SAM) index at 30 hPa are computed for each year (running from June to June). The upper tercile of the largest positive values identifies what we call the 11 weakest vortex years, and the lower tercile of the largest negative values (i.e., the most negative) identifies the 11 strongest vortex years. Any overlapping years in these terciles are excluded. Because of the strong autocorrelation of the SAM index in the stratosphere, this method identifies years where the SAM index tends to have a persistent anomaly throughout the spring-summer period (Byrne & Shepherd, 2018). The EDJ is defined by vertically averaging zonal-mean daily mean zonal wind between 1,000 and 250 hPa (denoted by $< [u] >$), and the jet latitude index is defined as the latitude of the maximum of $< [u] >$ in the SH. For comparison with the observations, similar diagnostics are also computed for the ECMWF ERA-Interim reanalysis (Dee et al., 2011) between 1979 and 2017.

3. Results: Northern Hemisphere

Figure 1 shows composites of the NAM index time series following SSWs for ERA-Interim and for simulations with different NOGWD. All composites display the characteristic downward propagation of the NAM

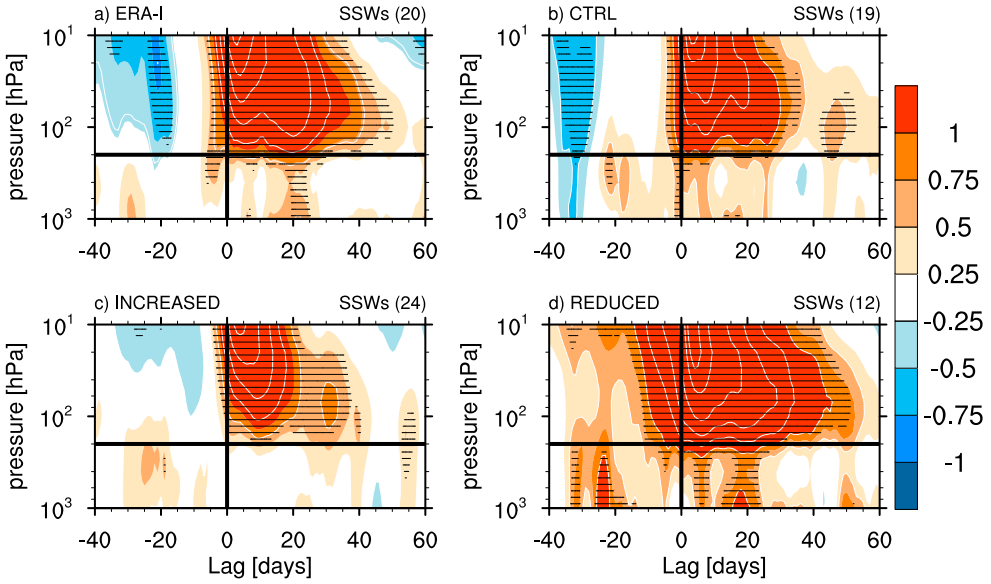

Figure 1. Composites of the NAM index (unit: standard deviation) centered on the SSW central date in (a) ERA-Interim, (b) CTRL, (c) INCREASED, and (d) REDUCED. Shading interval is 0.25 standard deviations, and contour interval is 0.5 standard deviations. The number in parentheses above the panels shows the number of SSWs in each case. Hatching means different from 0 at 5% significance level. The thick black vertical line shows the central date, and the horizontal line the 200 hPa level.

signal (e.g., Baldwin & Dunkerton, 2001). The CTRL composites, in particular, closely resemble the signal in ERA-Interim, indicating that the IFS is able to adequately represent this aspect of NH stratosphere-troposphere coupling. It is clear that reducing NOGWD increases the propagation of NAM anomalies to the surface, while increasing NOGWD has the opposite effect. This can be understood straightforwardly via the effect of NOGWD on SSWs: As can be seen in Figure 1 (see also Figure 10 and discussion in Polichtchouk et al., 2018), reducing NOGWD increases the amplitude and persistence of SSWs and, therefore, the NAM index. As has been demonstrated in previous studies, longer-lived and stronger stratospheric vortex anomalies are associated with a stronger tropospheric impact (Hitchcock et al., 2013; Kodera et al., 2016; Runde et al., 2016). Moreover, it is clear from Figure 1 that reducing NOGWD amplifies the NAM anomalies in the lower stratosphere/upper troposphere immediately following the central date (cf. Figures 1c and 1d). Karpechko et al. (2017) found that a larger NAM index in the lower stratosphere during the first few days following the central date is associated with a larger surface impact. Thus, reducing NOGWD increases the NAM index in the lower stratosphere, leading to a larger surface impact, with the opposite effect from increasing NOGWD. That the nature of the coupling itself is unchanged is shown by the fact that if SSWs with similar NAM index in the middle to lower stratosphere are selected from the INCREASED and REDUCED cases, the surface impact is similar in both experiments (see the supporting information). It should be noted that the variance of surface NAM anomalies is largely unchanged between the different cases (37 m for ERA-Interim, 40 m for CTRL, 38 m for INCREASED, and 40 m for REDUCED), such that a larger relative value for REDUCED in Figure 1 really does mean a larger impact on the troposphere. It should also be noted that no significant difference is evident in the time of year that SSWs occur with NOGWD changes: The change in the median and mean central date from the CTRL with increase or decrease in NOGWD is less than 2 weeks, which is well within the standard deviation of the central date for each simulation.

4. Results: Southern Hemisphere

The impact of NOGWD on the ability of the 11 strongest and 11 weakest vortex years to influence the EDJ in the SH is now discussed. Figure 2 shows differences in September to December monthly mean $[u]$ between strong and weak vortex years for ERA-Interim (top row) and each NOGWD simulation (second, third, and fourth rows). In strong vortex years the strengthening and the poleward shift of the EDJ is stronger in the months leading up to the vortex breakdown event and the equatorward transition in the summer is delayed (Byrne & Shepherd, 2018). Thus, different from the SSWs in the NH, EDJ anomalies in the spring and summer SH cannot

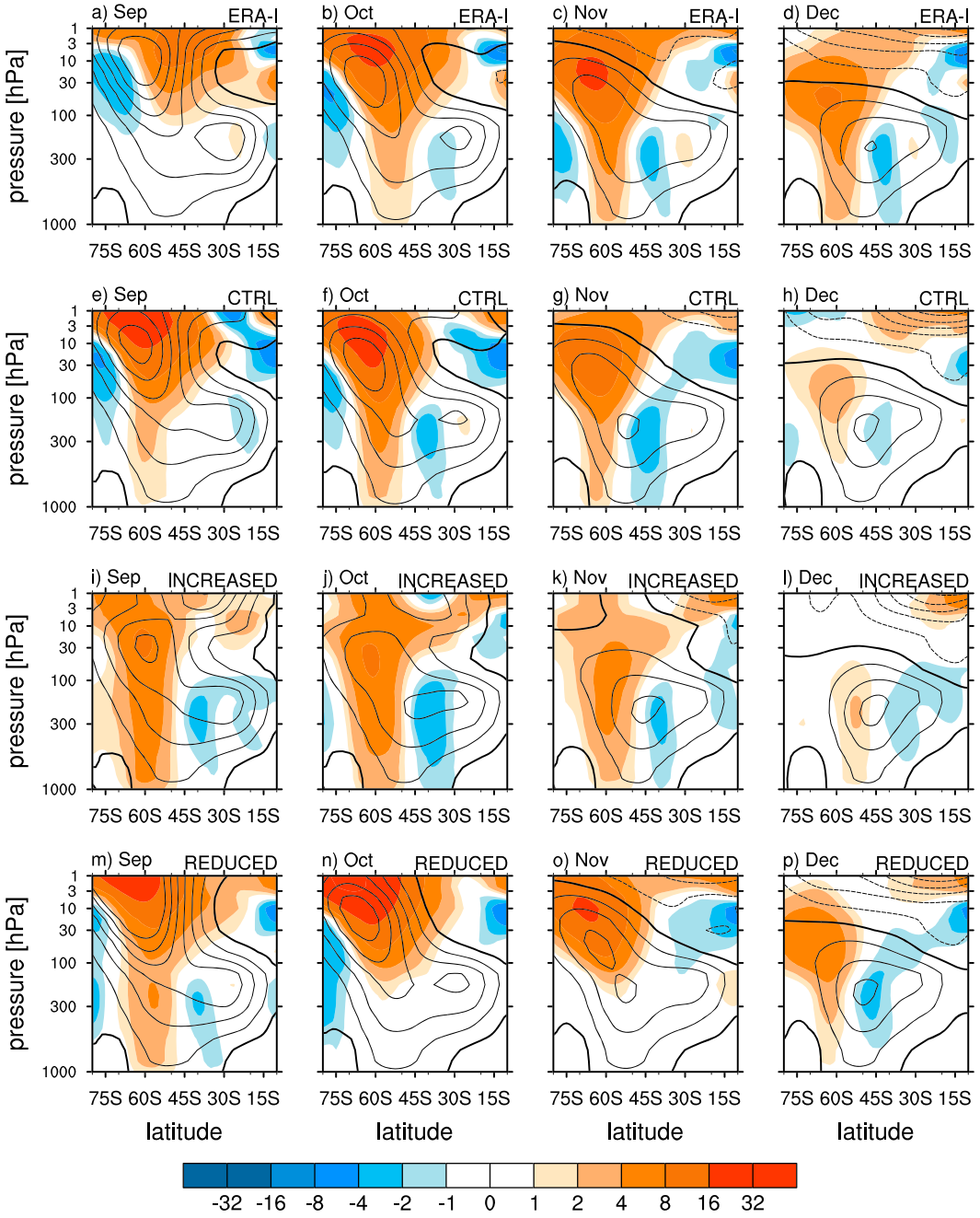

Figure 2. Monthly mean [*u*] (contours, in m/s) and differences in [*u*] between strong and weak vortex years (shading) for September–December for (a)–(d) ERA-Interim, (e)–(h) CTRL, (i)–(l) INCREASED, and (m)–(p) REDUCED. Contour interval for [*u*] is 10 m/s. Negative [*u*] contours are dashed, and the zero contour is drawn with double thickness. Note the nonlinear contour interval for shading.

be regarded as statistically stationary variability but rather represent a phase shift in the seasonal cycle (Byrne et al., 2017). Therefore, looking at the differences in [*u*] between weak and strong vortex years over the course of the seasonal cycle, as shown in Figure 2, is more insightful than examining *dripping paint* plots similar to Figure 1.

The difference in the tropospheric [*u*] between strong and weak vortex years is similar in CTRL and ERA-Interim, albeit the coupling is weaker in CTRL in the summer (cf. Figures 2d and 2h). This might be related to the missing ozone trend (e.g., Thompson et al., 2011) in the simulations. While the details in responses in Figure 2 differ between the different NOGWD simulations and ERA-Interim, the strong stratospheric vortex

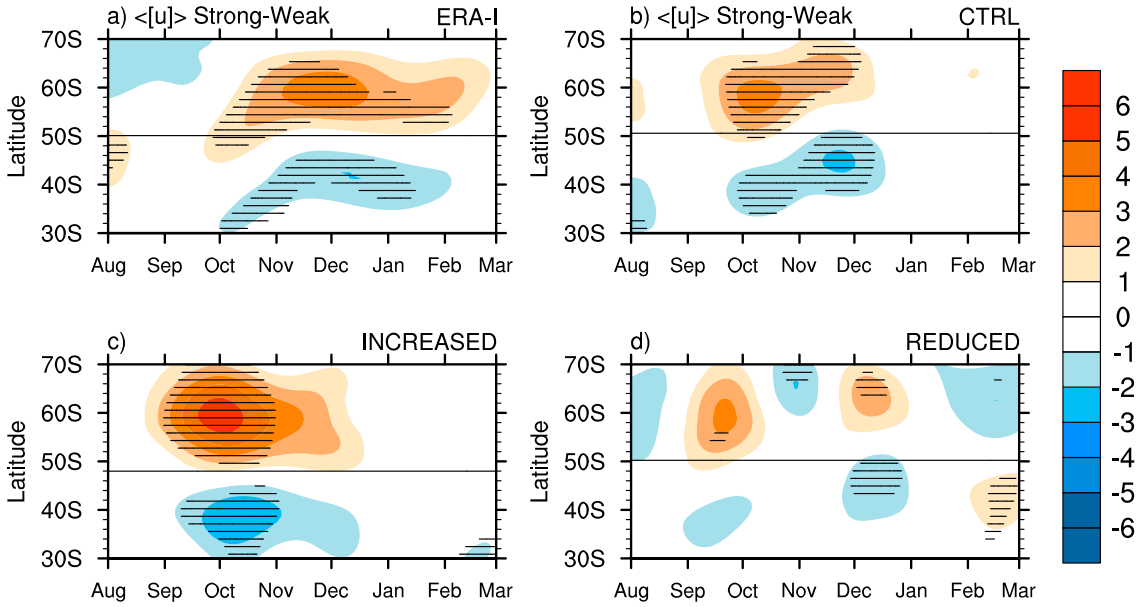

Figure 3. Difference in $< [u] >$ (shading, in m/s) between the 11 weakest and 11 strongest stratospheric polar vortex years for (a) ERA-Interim, (b) CTRL, (c) INCREASED, and (d) REDUCED. Hatching marks where the differences are significant at the 5% level. The horizontal line shows the annual mean eddy-driven jet latitude averaged over all years for each case.

years consistently produce a stronger and more poleward location of the EDJ compared to the weak vortex years. This suggests that the mechanism behind the stratosphere-troposphere coupling is similar in reanalysis and simulations.

The striking feature in Figure 2 is that the effect of NOGWD on the tropospheric EDJ anomalies is opposite to that in the NH, namely, that increasing NOGWD leads to stronger stratosphere-troposphere coupling in the SH, in the sense that the magnitude of the tropospheric anomaly between weak and strong vortex years is larger, averaged over the spring season. Moreover, different from the NH, the amplitude of the middle to lower stratospheric geopotential height anomalies is unchanged by NOGWD (i.e., the amplitude and the persistence is similar in the INCREASED and REDUCED cases). Thus, in the SH it is the sensitivity of the tropospheric circulation to a lower stratospheric anomaly that is larger in the increased NOGWD case.

Figure 3 further quantifies the impact of NOGWD on the ability of strong and weak vortex years to shift the seasonal cycle in the SH EDJ. The figure shows differences in $< [u] >$ between strong and weak vortex years in time-latitude cross sections. The characteristic dipole pattern in the response, with positive values poleward of and negative values equatorward of the annual-mean EDJ latitude, represent an early shift in spring and a late shift in summer of the EDJ in anomalously strong vortex years. Interestingly, NOGWD influences the timing of the stratosphere-troposphere coupling. Focusing on the hatched regions only in Figure 3, the coupling in December in the REDUCED case occurs later in the seasonal cycle than in the other simulations (cf. Figures 3b and 3c with Figure 3d). This later manifestation of stratosphere-troposphere coupling with a reduction in NOGWD is presumably due to the different seasonal cycle in the stratospheric polar vortex in the different NOGWD simulations: As NOGWD is reduced the vortex is stronger and the timing of the polar vortex breakdown is delayed (cf. second, third, and fourth columns in Figure 2). The stronger vortex in the REDUCED case means that the coupling is mostly centered around the time of the polar vortex breakdown in December.

The seasonal evolution of the SH EDJ is thought to be modulated by the stratospheric polar vortex (Bracegirdle, 2011; Byrne et al., 2017; Byrne & Shepherd, 2018; Hio & Yoden, 2005; Kuroda & Kodera, 1998). Given that NOGWD influences the strength and the seasonal evolution of the SH stratospheric polar vortex (see also Polichtchouk et al., 2018; Scheffler & Pulido, 2015, 2017) and the stratosphere-troposphere coupling, it is of interest to establish what impact NOGWD amplitude has on the EDJ itself. Figure 4 shows the seasonal evolution of the EDJ latitude index for ERA-Interim (in blue) and the simulations employing different NOGWD amplitude. Exact agreement of CTRL with ERA-Interim is not expected as the forcing employed in CTRL

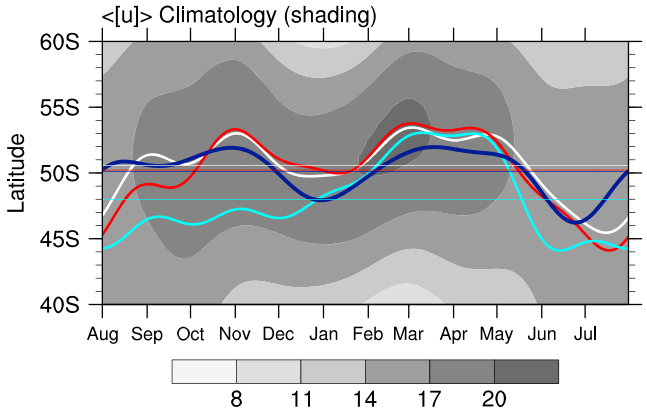

Figure 4. Climatology of $< [u] >$ (shading, in m/s) for the control run, and the eddy-driven jet latitude index for ERA-Interim (dark blue line), CTRL (white line), INCREASED (cyan line), and REDUCED (red line). The horizontal lines show the corresponding annual-mean jet latitude index. The fields are smoothed in time by retaining the first six Fourier components.

does not match that of the ERA-Interim period. Nevertheless, the EDJ in the CTRL simulation is quite realistic. In particular, it exhibits the tropospheric semiannual oscillation (SAO; van Loon, 1967) where the jet is strong and poleward of its mean position in the SH spring and autumn and weak and equatorward of its mean position in the SH summer and winter.

The impact of NOGWD on the seasonal evolution of the SH EDJ latitude index is now discussed. First, it is clear that increasing NOGWD shifts the EDJ equatorward (by $\sim$ 2.2°) in the annual mean compared to the CTRL and REDUCED cases. This equatorward shift is mostly due to equatorward EDJ displacement in August to January (cf. cyan with white and red lines in Figure 4). Indeed, the equatorward displacement in that period is so large that the SAO is absent in the INCREASED case. In particular, the EDJ does not transition poleward of its mean latitude in the early spring. This result supports the hypothesis advanced by Bracegirdle (2011) and Byrne and Shepherd (2018) that the SAO between September and February is influenced by the stratosphere.

5. Summary and Conclusions

Parametrized NOGWD, which mostly acts in the middle atmosphere and influences stratospheric dynamics, is shown to affect stratosphere- troposphere coupling in both hemispheres in a state-of-the-art atmospheric model run at comparatively high horizontal resolution, where much of the gravity wave activity is resolved rather than parameterized. However, the two hemispheres respond differently to altered NOGWD amplitude: Reducing NOGWD strengthens the impact of stratospheric variability on the tropospheric EDJ in the NH but weakens the impact in the SH. This difference arises due to the different causes of the variability in the two hemispheres. In the NH, stratosphere-troposphere coupling occurs mostly via SSWs, whose amplitude and persistence increase when NOGWD is reduced. In the SH, the coupling occurs via interannual variability in the seasonal cycle leading up to the polar vortex breakdown. In this case, increasing NOGWD modifies the seasonal cycle by weakening the vortex during the breakdown period and enhances the sensitivity of the tropospheric EDJ to a given lower stratospheric anomaly.

This study has the following conclusions, implications, and open questions:

1. The tropospheric NAM response to changes in NOGWD is consistent with our understanding of stratosphere-troposphere coupling: Reducing NOGWD increases the amplitude and the persistence of the lower stratospheric anomalies, leading to a stronger tropospheric response in the NH (Hitchcock et al., 2013; Karpechko et al., 2017; Kodera et al., 2016; Runde et al., 2016). In the SH, the seasonal cycle itself affects stratosphere-troposphere coupling. In contrast to the NH, changing NOGWD shifts the seasonal cycle in the SH stratosphere, leaving the amplitude and the persistence of the lower stratospheric anomalies largely unchanged.
2. NOGWD directly affects SSW life cycles and thereby controls the strength of the tropospheric response in the NH. It is therefore possible that the way different atmospheric models partition middle-atmosphere wave drag into parametrized nonorographic and orographic, and the resolved gravity wave contribution, can have an impact on stratosphere-troposphere coupling within a model. For example, NOGWD and parametrized orographic gravity wave drag have been shown to affect SSWs differently (McLandress et al., 2013).
3. In the SH, increasing NOGWD shifts the EDJ equatorward in the annual mean. The equatorward shift mostly occurs in the spring and summer seasons. This sensitivity has potential implications for the jet latitude biases in atmospheric models: If the annual-mean EDJ latitude biases occur in the spring season, this calls for more careful inspection of NOGWD formulation.
4. The stratospheric polar vortex evolution clearly influences the tropospheric SAO in the SH spring/summer season, corroborating the results in Bracegirdle (2011) and Byrne and Shepherd (2018). Previously, the SAO has been interpreted to result largely from contrasting seasonal evolutions of surface temperature over the Southern Ocean and the Antarctic regions (Karoly & Vincent, 1998). This study shows that those factors are themselves insufficient to cause the SAO, as the SAO disappears when the NOGWD is increased.

5. As NOGWD has an opposite effect on stratosphere-troposphere dynamical coupling in the two hemispheres, care must be taken when tuning a model using a global value for the flux amplitude, as is currently done in most numerical weather and climate prediction models. This assumption may need to be revisited.

Acknowledgments
The authors thank Peter Bechtold and Tim Stockdale for helpful discussions and the two anonymous reviewers for their insightful comments. The authors are supported by the *Understanding the atmospheric circulation response to climate change* (ACRCC, ERC advanced grant, 339390) project. This work used the computational facilities at ECMWF. ERA-Interim data are publicly available at the ECMWF website (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/).

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