Supporting Information for
“Stratospheric control of planetary waves”

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Introduction

Text S1.

Supplementary Figure 1 shows the climatology (time mean) of the zonal mean, zonal winds in each of the control runs \(c1\), \(c8\), \(c30\), and \(c70\). The differences between these climatologies and the base run climatology are shown by the contour lines with an interval of 0.5 m s\(^{-1}\). This demonstrates that the effect of nudging the zonally symmetric component of the stratosphere to the climatological state of the base run has a minimal effect on the zonal mean basic state. The impact of the stratospheric nudging on the Northern Hemisphere troposphere amounts to less than a 0.25 m s\(^{-1}\) change in the tropospheric winds in all cases but \(c70\), where a dipolar anomaly of approximately 0.5 m s\(^{-1}\) corresponding roughly to a poleward shift of the jet. The changes are small relative to the internal variability of the winds; it is therefore unlikely that these changes will have a significant effect on the response of the system to the imposed anomalies. The fact that the tropospheric response seen in Fig. 2l closely resembles the composite response shown in Fig. 1c also confirms this claim.

Text S2.

Supplementary Figure 2a shows the vertical profile of the mid-latitude average of the standard deviation of the zonal mean zonal wind in the base run and in each of the con-

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control runs, plus one additional control run, c100, with $p_b = 200$ hPa and $p_t = 80$ hPa. The boundary of the nudging layer for each case is indicated by the colored lines. Within the nudging layer where the relaxation is at its full strength, the internal variability is strongly suppressed; the variability is reduced to a lesser degree even below $p_b$. To some extent this need not indicate anything artificial - if variability in the stratosphere is driving some component of variability in the tropospheric flow as our experiments have demonstrate, eliminating the stratospheric variability should remove this component from the tropospheric variability as well. Nonetheless this figure demonstrates that the nudging layer cannot be moved much below 90 hPa without substantially constraining the tropospheric flow. Figure S3b shows the same quantity but computed as the ensemble spread over the nudged runs relative to their respective control runs, averaged over days 15 to 60 following the central date. This spread agrees closely with the internal variability.

**Text S3.**

Supplementary Figure 3 shows plots equivalent to those in Fig. 2 but for two additional ensembles, s8w6h and s8w1d, nudged with alternative profiles of the relaxational timescale, specified using different values for the parameters in (2). In both cases $q = 4$, $p_b = 10$ hPa and $p_t = 3$ hPa. The first, s8w6h, is an ensemble of 600 integrations with $\tau_1 = 6$ h (Fig. S2a,c,e), while second, s8w1d, is an ensemble of 400 integrations with $\tau_1 = 1$ d (Fig. S2b,d,f). Differences in both cases are taken from a control run relaxed to $X_c$ with the corresponding nudging profile, but in the latter case the differences are taken from the time mean the control run, so they do not vanish at the onset of the integrations. These ensembles may be seen as corresponding to a profile intermediate between s1 and s8, though we discuss these plots relative to the latter.

In both cases the EP flux convergence near $p_b$ prior to the central date seen in Fig. 2b is no longer present. The strong anomalous divergence around the central date in Fig. 2b is reduced in these ensembles, and is weaker in s8w1d, consistent with the weaker vertical shear induced by the nudging. The descending region of anomalous convergence is still present, though again is somewhat weaker than in Fig. 2b. Nonetheless, the weakened vertical fluxes throughout the depth of the stratosphere, and the shift of the tropospheric jet seen in Fig. 2 are also present in these alternative ensembles; the mean jet shift in both cases is consistent with the uncertainty shown in Fig. 3c.
We conclude from these further integrations that the EP flux artifacts near $p_b$ are not playing a significant role in the evolution of the flow below the nudging layer.

Text S4.

Supplementary Figure 4 demonstrates that the amplification of the waves prior to stratospheric sudden warmings is fully recovered when the base run is restarted 30 ($m_{30c}$) or 20 ($m_{20c}$) days prior to the events. The panels show the evolution of the vertical EP flux in ensembles equivalent to $m_{30}$ and $m_{20}$ but with no stratospheric constraint, an as an anomaly from the evolution of the base run over the same period. Because the restarts are based on instantaneous output at a single timestep, the full information required by the leap-frog timestep used by the model to reproduce bit-for-bit evolution of the runs is not available, and this leads ultimately to diverging trajectories. However, this error growth only becomes significant well after the onset of the stratospheric event. This confirms that the effect demonstrated in Fig. 3a,b is in fact due to constrained stratospheric winds, not due to chaotic error growth.

Text S5.

Supplementary Figure 5 shows the effects of modifying the profile of the linear relaxation on the suppression of the wave amplification shown in Figs. 3ab. In each case an ensemble similar to $m_{30}$ or $m_{20}$ has been carried out. Panels a and b correspond directly to Figs. 3 a and b but for the nudging profile in (2) modified by setting $\tau_0 = 1$ d and $q = 4$; $p_b$ is set to 90 hPa and $p_t$ to 30 hPa. The weaker nudging strength has the expected effect of allowing for more amplification of the wave fluxes. Panel c shows an ensemble equivalent to $m_{30}$ but with $\tau_0 = 1$ d and $q = 4$; $p_b$ set to 200 hPa and $p_t$ to 80 hPa. Constraining the flow lower in the atmosphere has the effect of reducing the amplification of the wave fluxes.
Figure 1. The colored contours show climatological (time mean) zonal mean zonal winds from each of the four control runs. Differences between these climatologies and that of the base run are indicated by the contour lines, shown at intervals of 0.5 m s$^{-1}$. The zero contour is omitted. The horizontal lines indicate the nudging layer in each control run as in Fig. 2.
Figure 2. Vertical profile of the mid-latitude (30-60° N) average standard deviation of zonal mean zonal wind for (a) the internal variability of the control runs and (b) the ensemble spread of the nudged runs, relative to their respective controls. The internal variability of the base run is also shown in (a). For the nudged runs, the corresponding colored horizontal lines indicate the nudging layer in each control run as in Fig. 2.

Figure 3. Equivalent to Fig. 2b,f,i but using two alternate profiles of relaxation timescales. See supplementary text S3 for full description.
Figure 4. Evolution of the vertical EP flux in a control ensemble initialized from the base run (a) 30 days prior and (b) 20 days prior to the first four hundred sudden warming events. The fluxes are shown as an anomaly relative to the base run over the same periods.

Figure 5. Equivalent to Fig. 3a,b. but for alternative nudging configurations. See text S5 for full description.