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Key Points:

- Changes in the stratospheric mean flow cause a shift in the tropospheric jet
- Planetary waves have an important influence on the magnitude of the jet shift
- The jet shift results from the interaction between the planetary- and synoptic-scale waves

Supporting Information:

- Supporting Information S1

Correspondence to:
K. L. Smith,
ksmith@ldeo.columbia.edu

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The role of planetary waves in the tropospheric jet response to stratospheric cooling

Karen L. Smith[1] and Richard K. Scott[2]

[1]Division of Ocean and Climate Physics, Lamont-Doherty Earth Observatory, Palisades, New York, USA, [2]School of Mathematics and Statistics, University of St. Andrews, St. Andrews, UK

Abstract An idealized general circulation model is used to assess the importance of planetary-scale waves in determining the position of the tropospheric jet, specifically its tendency to shift poleward as winter stratospheric cooling is increased. Full model integrations are compared against integrations in which planetary waves are truncated in the zonal direction, and only synoptic-scale waves are retained. Two series of truncated integrations are considered, using (i) a modified radiative equilibrium temperature or (ii) a nudged-bias correction technique. Both produce tropospheric climatologies that are similar to the full model when stratospheric cooling is weak. When stratospheric cooling is increased, the results indicate that the interaction between planetary- and synoptic-scale waves plays an important role in determining the structure of the tropospheric mean flow and rule out the possibility that the jet shift occurs purely as a response to changes in the planetary- or synoptic-scale wave fields alone.

1. Introduction

Many recent studies indicate that colder stratospheric conditions may result in a climatological shift in the position of the tropospheric jet to higher latitudes [e.g., *Sigmond et al.*, 2004; *Thompson et al.*, 2011; *Previdi and Polvani*, 2014, and references therein]. The effect was illustrated most convincingly by *Polvani and Kushner*, 2002 [2002, hereafter PK02] using a simplified general circulation model (GCM) in which the polar cooling was prescribed through a simple control parameter. A critical level of cooling was found, beyond which the latitude of the jet shifted abruptly poleward by about 10°. The dynamical mechanism responsible for the shift, however, is incompletely understood.

In seeking to understand the coupling processes, it is useful to decompose the stratospheric and tropospheric flows conceptually into mean and wave components and further decompose the latter into planetary and synoptic-scale components. As discussed in *Plumb* [2010], the planetary wave component has a relatively deep structure, while the synoptic waves are confined to the troposphere. The issue of coupling may be posed in terms of the link between the stratospheric mean flow, $\bar{u}_S$, and tropospheric mean flow $\bar{u}_T$, possibly mediated by a planetary wave field u'_0, present throughout both stratosphere and troposphere, and a synoptic wave field u'_1 mostly in the troposphere.

Song and Robinson [2004] suggest that $\bar{u}_S$ has a direct, but small, effect on $\bar{u}_T$ through downward control that is subsequently amplified by resulting changes to u'_1 and the associated eddy momentum flux convergences in the region of the tropospheric jet. However, they also found that this amplification is weaker when planetary waves are artificially damped in the stratosphere. In transient experiments with a perturbed stratospheric potential vorticity distribution, *Smy and Scott* [2009] illustrated that the tropospheric response to a stratospheric planetary wave anomaly could be much larger than the response to a zonally symmetric anomaly of comparable amplitude. Finally, *Yang et al.* [2015] examined the seasonal response to an ozone depletion-like perturbation in an idealized atmospheric model and found that the contribution of planetary waves was key to understanding the downward migration of the stratospheric anomaly.

While these results suggest that u'_0 may play an important role in any eddy feedback mechanism, the relative roles of synoptic and planetary-scale waves and their interaction with the tropospheric mean flow remain unclear [*Kunz and Greatbatch*, 2013]. For example, the extent to which the added stratospheric wave damping in *Song and Robinson* [2004] may have a direct influence on the tropospheric mean flow is far from obvious.

The aim of the present paper is to test the importance of planetary waves in the tropospheric response to polar stratospheric cooling in as clean as possible an experimental setting.

2. Methods

2.1. Model

We use a simplified GCM (SGCM) that solves the dry, hydrostatic, primitive equations, forced with a Newtonian relaxation of temperature to a prescribed, zonally symmetric and time-independent, equilibrium temperature profile, T_{eq}. It has been used in numerous studies of stratosphere-troposphere coupling [PK02; *Kushner and Polvani*, 2004; *Reichler et al.*, 2005; *Gerber and Polvani*, 2009; *Chan and Plumb*, 2009; *Smith et al.*, 2010; *Domeisen and Plumb*, 2012; *Domeisen et al.*, 2013; *Garfinkel et al.*, 2013; *Yang et al.*, 2015]. In this study, all model parameters, including T_{eq}, are the same as those used in PK02 and *Kushner and Polvani* [2004].

In this model, the meridional position of the eddy-driven jet is sensitive to the mean strength of the polar vortex [PK02; *Gerber and Polvani*, 2009; *Garfinkel et al.*, 2013], controlled by a single parameter, γ, the temperature lapse rate over the winter pole in the equilibrium temperature profile.

The poleward jet shift found in the original PK02 study is larger than that found in more recent studies which introduce refinements to aspects of the model configuration [*Gerber and Polvani*, 2009; *Smith et al.*, 2010; *Jucker et al.*, 2013; *Sheshadri et al.*, 2015]. The differences have been shown to arise as a consequence of the fluctuation dissipation theorem and what are now thought to be unrealistically long annular mode timescales in the original model [*Chan and Plumb*, 2009; *Gerber and Polvani*, 2009]. Here we use the original model configuration to take advantage of the larger jet shift, which enables a more robust analysis of the dynamical processes involved. It seems plausible that the same dynamical processes are at play in the weaker jet shifts obtained in models with more realistic annular mode timescales.

We run our model integrations with 40 hybrid sigma pressure vertical levels (model lid height of 0.02 hPa), a horizontal resolution of T42, and a time step of 800 s. Additional model details are given in PK02 and *Kushner and Polvani* [2004].

2.2. Experiments

We perform four series of experiments, labeled C (= control), T (= truncated), T′ (= truncated with modified T_{eq}), and B (= bias corrected). First, we complete five experiments with the standard SGCM with varying polar vortex strength ($\gamma = 0$, 2, and 4) and varying seasonal asymmetry ($\epsilon = 0$ and 10; PK02). This series, hereafter denoted by C, represents our control series. Second, to isolate the influence of planetary-scale waves on the tropospheric jet, we perform a second series of experiments, series T, in which we truncate the SGCM such that only zonal wave numbers 4 and higher ($k \geq 4$) are resolved in a manner complementary to that of *Domeisen and Plumb* [2012].

It turns out, however, that the truncation results in changes to the climatology that make a direct comparison with the fully resolved model problematic (see below). To obtain climatological states with the truncated model that are closer to those of the control, we perform a third series of experiments with the truncated SGCM, series T′, using a modified equilibrium temperature profile. Specifically, we modify T_{eq} in the troposphere only such that the tropopause temperature T_T in equation (A3) of PK02 has the form

$$T'_T(p_T) = T_T(p_T)\left(2 - \cos^2\frac{\phi}{4.5}\right) \tag{1}$$

where p_T is the tropopause pressure. The original T_{eq} and the modified T'_{eq} are shown in Figures 1a and 1b and Figure 1c, respectively, for the case $\epsilon = 10$ and $\gamma = 0$.

Finally, we employ an alternative technique to correct the climatological basic state when only wave numbers 4 and higher are resolved [*Domeisen et al.*, 2013]. We follow the methodology of *Kharin and Scinocca* [2012] and *Simpson et al.* [2013] and perform three pairs of nudged- and bias-corrected experiments. This technique involves relaxing or “nudging” the truncated SGCM integrations toward the control climatology with a relaxation timescale of 24 h and saving the relaxation tendencies for vorticity, divergence, and temperature every 6 h.

We then rerun the truncated SGCM with the time mean, zonal mean relaxation tendencies applied as a bias correction, series B. Unlike the nudged integrations, which are tightly constrained by the relaxation, the bias-corrected integrations permit the resolved waves to interact naturally with the background flow. The bias

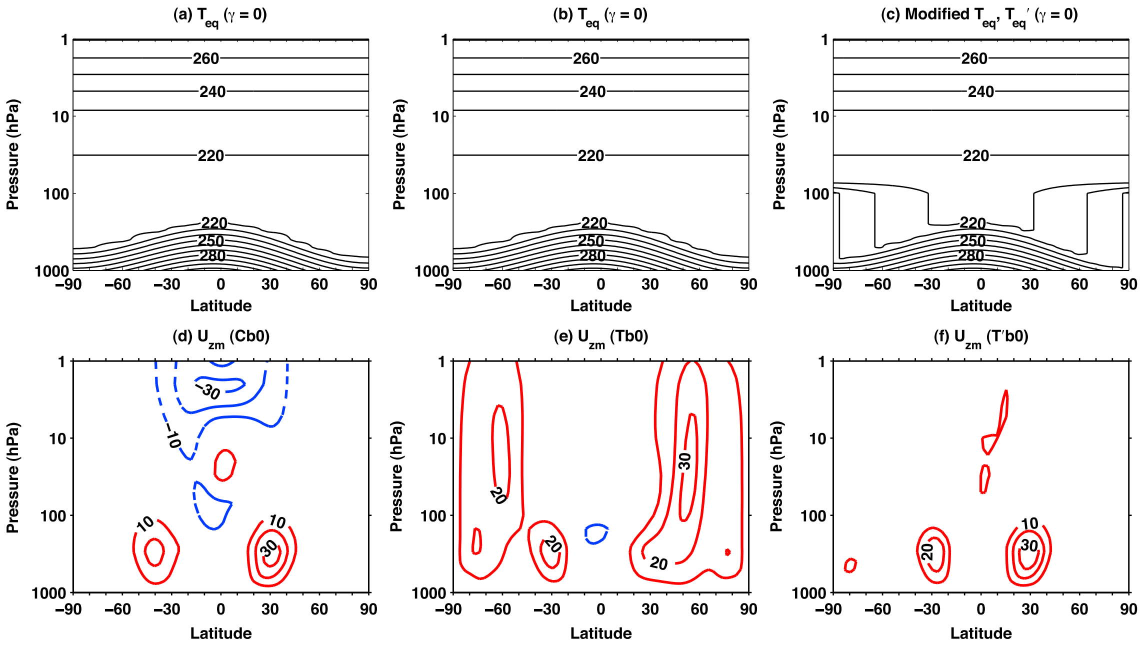

Figure 1. (a and b) Equilibrium temperature T_{eq} and (c) modified equilibrium temperature T_{eq} as a function of latitude and pressure. (d–f) Corresponding climatological zonal mean zonal winds for $\gamma = 0$ in (Figure 1a) the full model with all waves resolved (Cb0) and (Figures 1b and 1c) the truncated model (Tb0 and T′b0).

correction can be interpreted as a stationary forcing that is specifically constructed to represent the effects of the unresolved planetary waves in the truncated model. The underlying assumption is that the interaction between the planetary- and synoptic-scale waves is small; in the limit that the interaction goes to zero, applying the bias correction to the truncated SGCM would recover the control climatology.

To test the robustness of our results, we repeat the bias-corrected experiments by varying seasonal asymmetry (ϵ) in the equilibrium temperature profile. In the following, each integration is denoted by the series, value of ϵ ($\epsilon = 0$ or 10 denoted by a or b, respectively) and value of γ ($\gamma = 0, 2$, or 4); thus, Ca2 is the control run with $\epsilon = 0, \gamma = 2$, etc. We restrict attention to those values of ϵ that exhibit large jet shifts [*Chan and Plumb*, 2009].

All experiments are integrated for at least 5000 days. See Table 1 for the complete list of model experiments and main parameter values.

Finally, we have also tested the robustness of our results by repeating several experiments truncating the SGCM to retain zonal wave numbers 6 only, 4–6 only, and 6 and higher only. The results for these experiments are qualitatively similar to the wave number 4 and higher truncation results. They will not be discussed further but indicate that our conclusions are not sensitive to the precise truncation applied.

3. Results

3.1. Modified T_{eq}

Figure 1d shows the climatological zonal mean zonal wind as a function of latitude and pressure simulated by the SGCM for the control experiment Cb0 ($\epsilon = 10, \gamma = 0$). The corresponding climatology in the truncated experiment Tb0 is shown in Figure 1e. Significant departures from the control experiment are clear: because of the lack of planetary-scale waves, the truncated model fails to simulate an adequate Brewer-Dobson circulation and, therefore, does not simulate a positive meridional temperature gradient in the upper troposphere/lower stratosphere region. In the control experiments, this temperature gradient acts to close off the tropospheric jets via thermal wind balance. In contrast, in the truncated experiments the tropospheric jets continue into the stratosphere and are only decelerated by the sponge layer at the model lid.

The differences between the truncated and control climatologies make it difficult to determine whether the sensitivity of the position of the tropospheric jet to changing the polar vortex strength results from the influence of planetary waves or from the configuration of the climatological state itself. The differences motivate the choice of a modified temperature equilibrium, T'_{eq} defined in section 2.2: with this choice, the climatology

Table 1. List of Model Experiments[a]

Experiment	Zonal Wave Numbers Resolved (k)	Seasonal Asymmetry (ϵ)	Polar Vortex (γ)	Integration Length (days)	Jet Latitude (deg)
Ca2	all k	0	2	8,000	36
Ca4	all k	0	4	8,000	44
Ba2	$k \geq 4$	0	2	8,000	25
Ba4	$k \geq 4$	0	4	8,000	25
Cb0	all k	10	0	5,000	30
Cb2	all k	10	2	10,000	**31**
Cb4	all k	10	4	10,000	**44**
Tb0	$k \geq 4$	10	0	5,000	48
T′b0	$k \geq 4$	10	0	5,000	29
T′b2	$k \geq 4$	10	2	5,000	28
T′b4	$k \geq 4$	10	4	5,000	29
Bb2	$k \geq 4$	10	2	10,000	**25**
Bb4	$k \geq 4$	10	4	10,000	**27**

[a] Experiments beginning with C, T, T′, and B indicate those performed with the control, truncated, truncated with modified T_{eq}, and the bias-corrected model configurations, respectively. Zonal wave numbers resolved (k, wave numbers resolved), seasonal asymmetry (ϵ), and polar vortex strength (γ) are varied across experiments. The jet latitude is defined as the latitude of maximum time mean zonal mean vertically averaged (1000–100 hPa) zonal wind rounded to the nearest degree. The jet latitude for the original PK02 integrations and corresponding bias-corrected experiments are in bold.

obtained in the truncated model is qualitatively similar to that of the control model; compare Figures 1d and 1f. We proceed therefore to compare the experiments Cb and T′b for different values of polar cooling γ.

Figures 2a and 2c show the zonal mean zonal wind profiles for the control experiment with T_{eq} and $\gamma = 2$ (experiment Cb2) and the truncated experiment with T'_{eq} and $\gamma = 2$ (experiment T′b2). The structure of the zonal wind in both the troposphere and the winter stratosphere are qualitatively similar in both experiments, with only a slight strengthening of the polar vortex in experiment T′b2. When we strengthen the polar vortex by increasing the polar lapse rate to $\gamma = 4$ (experiment Cb4, shown in Figure 2b), the tropospheric jet shifts poleward by roughly 10° in the control, as found by PK02. In contrast, there is almost no perceptible shift in jet position in the corresponding truncated experiment (experiment T′b4, shown in Figure 2d).

While the above result suggests a clear role for planetary waves in determining the tropospheric response to a colder polar stratosphere, firm conclusions are complicated by the fact that the climatological states in the two series are not exactly equal. In the truncated experiment T′b2, for example, the tropospheric jet is located at a lower latitude than the jet in the corresponding control experiment, Cb2, and it is conceivable that this difference alone is enough to account for the different behavior when γ is increased to 4. *Barnes et al.* [2011] demonstrated that lower latitude jets exhibit greater annular mode persistence, which may have an influence on the jet response to an increase in stratospheric cooling.

On the other hand, it is worth noting that *Chan and Plumb* [2009] found sensitivity of the jet position to the stratospheric state to be larger when the climatological position of the jet is at lower latitudes. That being the case, we would expect the jet position in the truncated model to be more sensitive to γ, not less, and we conclude that the difference between the full and truncated models observed here is unlikely to be due to differences in the $\gamma = 2$ climatological state alone.

3.2. Bias Correction

As a separate test that avoids the somewhat ad hoc modification of T_{eq} to obtain an appropriate climatology, we now employ the nudging and bias correction technique discussed in section 2.2. Supporting information Figure S1a shows the zonal mean zonal wind profile for the nudged integration (denoted by N) with $\gamma = 2$, $\epsilon = 10$ and only wave numbers 4 and higher resolved. If we compare supporting information Figure S1a with Figure 2a, we find that they are indistinguishable, illustrating that an integration with only wave numbers 4 and higher relaxed toward the corresponding control experiment is able to fully compensate for the lack of unresolved planetary waves. The same is true of the corresponding experiments with the $\gamma = 4$, shown in supporting information Figure S1c and Figure 2c.

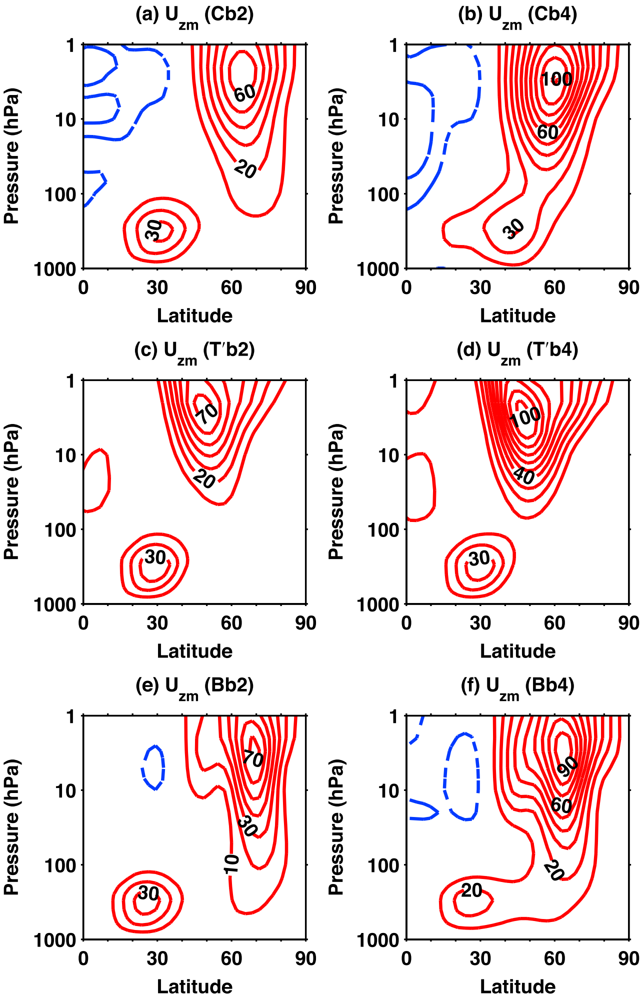

Figure 2. Time and zonal mean zonal winds as a function of latitude and pressure for experiments (a) Cb2, (b) Cb4, (c) T′b2, (d) T′b4, (e) Bb2, and (f) Bb4.

The relaxation tendencies generated in the nudging integrations are then applied to new truncated integrations as a bias correction. We should think of the relaxation tendencies as a representation of the effect of the missing planetary waves in the truncated model integrations, i.e., the additional force required to generate the same climatology in the truncated model integrations. The zonal mean zonal wind climatologies for these integrations are shown in Figures 2e and 2f (experiments Bb2 and Bb4): they represent the climatology that arises when only wave numbers 4 and higher are free to interact with the mean flow, but in the presence of the bias correction; in particular, all interactions involving planetary waves have been eliminated.

In Figure 2e, the zonal mean zonal wind profile of the bias-corrected integration has a tropospheric jet that is equatorward of the jet in the control experiments (Figures 2e and 2a, respectively). This already suggests that the behavior of the synoptic-scale waves is modified by the presence of planetary waves and that applying the bias correction to the truncated SGCM does not identically recover the control climatology. In the framework described in section 1, it appears that the evolution of the tropospheric synoptic waves, u'_1, are weakly modulated by the planetary waves, u'_0, specifically that in the absence of planetary waves, the synoptic-scale waves alone maintain the jet at a slightly lower latitude than otherwise.

Moreover, when the polar vortex is strengthened by increasing the lapse rate to $\gamma = 4$, as above, the tropospheric jet in the bias-corrected integration (experiment Bb4; Figure 2f) shifts poleward by only ~15% of the amount of the shift in the control experiment (experiment Cb4; Figure 2c). This suggests one of two conclusions: either (i) that the planetary waves themselves contribute directly to the tropospheric jet shift (interaction of u'_0 and $\bar{u}_T$) or (ii) that the presence of planetary waves modifies the behavior of the

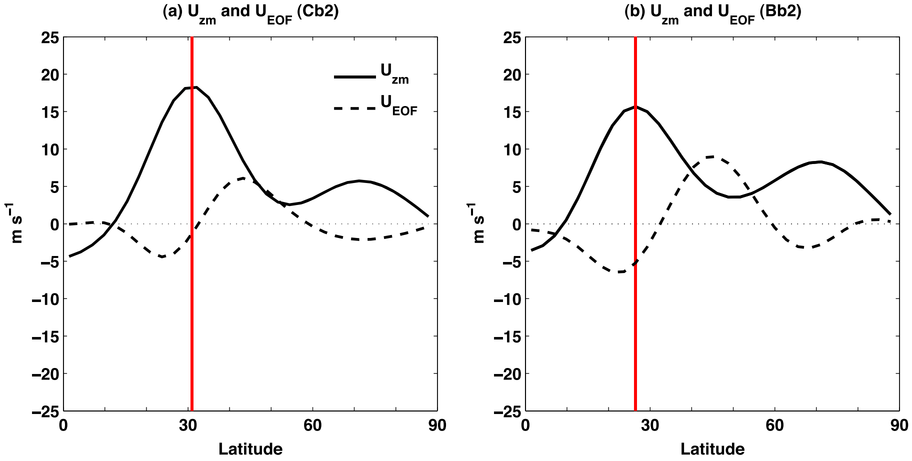

Figure 3. Vertically averaged (1000–100 hPa) zonal mean zonal wind (black solid curves) and the vertically averaged zonal mean zonal wind regressed on its leading mode of variability (black dashed curves) as a function of latitude for (a) experiment Cb2 and (b) experiment Bb2. Vertical red lines indicate the latitude of maximum vertically averaged zonal mean zonal wind.

synoptic-scale waves such that they have a stronger influence on the tropospheric jet position (interaction of u_0' and u_1' and subsequent interaction of u_1' and $\bar{u}_T$). By construction, our bias correction accounts for (i); thus, our integrations demonstrate that (ii), the interaction between the planetary- and synoptic-scale waves, is essential for the tropospheric jet shift response to polar stratospheric cooling.

We have tested the robustness of our results to the basic state configuration by running two additional pairs ($\gamma = 2$ and $\gamma = 4$) of control and bias-corrected experiments with varying seasonal asymmetry (ϵ) in the equilibrium temperature profile. The results are summarized in Table 1 showing the position of the maximum time mean zonal mean vertically integrated zonal wind for each pair of experiments. Two points are worth noting.

First, even with $\gamma=2$, the jet is located farther poleward in the control runs than in the corresponding bias-corrected runs, none of which permit a jet poleward of approximately 30°N. This is consistent with the possibility mentioned above that the interaction between synoptic- and planetary-scale waves generally results in a jet that is farther poleward. Second, there is essentially very little change in the jet position in response to a strengthened polar vortex in the bias-corrected integrations.

Our results clearly indicate the importance of the interaction between planetary- and synoptic-scale waves in the tropospheric response to stratospheric cooling. One might ask whether the weaker jet shift is associated with significantly shorter annular mode timescales in the bias-corrected experiments relative to the control experiments. We find that the timescales remain very long (~300 days), and although they change somewhat from one experiment to another, there is no systematic change (not shown).

More importantly, however, we find that truncating the planetary waves results in substantial changes to the leading mode of variability of the jet. When planetary waves are included, the leading mode of variability consists predominantly of a lateral shift of the jet. Figure 3a shows the time mean vertically averaged (from 1000 to 100 hPa) zonal mean zonal wind as a function of latitude for the Cb2 experiment along with the vertically averaged zonal mean zonal wind regressed onto its leading empirical orthogonal function (EOF). The EOF pattern clearly shows a shift of the jet about the time mean jet position.

On the other hand, when planetary waves are truncated, the leading mode of variability changes to a mixture of lateral shift and change in intensity [*Eichelberger and Hartmann*, 2007; *Barnes and Hartmann*, 2011]. Figure 3b shows the corresponding EOF from the bias-corrected experiment, Bb2, and clearly illustrates a pulsing of the time mean jet. Following fluctuation dissipation arguments, the response to stratospheric cooling in the absence of planetary waves projects less strongly onto a shift of the tropospheric jet.

4. Conclusions

The above results consistently indicate the necessary role of planetary-scale waves in the observed poleward shift of the tropospheric jet resulting from a cooler winter polar stratosphere. The use of a simplified model enables the design of relatively clean experiments, but we note that there may still be some ambiguity regarding the importance of the climatological basic state in the bias-corrected integrations: in particular, the removal of planetary waves results in modifications of the synoptic-scale wave evolution that alters the basic state in the bias-corrected integrations relative to the control integrations. Further work is therefore required to verify the robustness of our results to changes in the climatological basic state in more complex model configurations.

Bearing that in mind, in all cases when planetary waves are truncated, the jet forms at lower latitudes than in the control runs and, moreover, persists at low latitudes when polar stratospheric cooling is increased. Because of the nature of the bias-correction technique, we can infer that the interaction between planetary- and synoptic-scale waves must be a key component of the eddy feedback mechanism responsible for the coupling between stratospheric cooling and the tropospheric circulation. In particular, the results appear to rule out the possibility that the jet shift results from the direct modification of the tropospheric synoptic waves by mean flow changes in the stratosphere, even though the latter would be expected to have a nonlocal effect on waves throughout the depth of the atmosphere.

Our results are consistent with the results of *Song and Robinson* [2004], which noted the importance of stratospheric planetary waves in modulating the tropospheric mean flow response in time-averaged experiments. However, the artificial damping of planetary waves in the stratosphere only in those experiments may have other effects on the tropospheric mean flow, through, for example, additional secondary circulations or the modification of the propagation characteristics of planetary waves in the troposphere. Our results offer additional experimental evidence that avoids these issues. In addition, they are consistent with the transient experiments of *Smy and Scott* [2009] and, in particular, *Yang et al.* [2015], which points to the importance of the interaction between planetary- and synoptic-scale waves in the circulation response to an ozone depletion-like forcing.

A related truncation method to the one used here was used recently by *Domeisen et al.* [2013]. In transient experiments, they demonstrated the importance of synoptic-scale waves in the cause of the jet shift following individual stratospheric sudden warmings. Our results indicate that such an effect of the synoptic waves on the mean flow is crucially modulated by the planetary waves; in other words, the synoptic and planetary wave fields cannot be considered as acting separately on the mean flow but must be considered as part of a fully nonlinear system with wave-wave interactions across all scales.

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