

Impact of the stratosphere on tropospheric climate change

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[1] The atmospheric circulation response to CO₂ doubling in various versions of an atmospheric general circulation model (AGCM) without a well-resolved stratosphere (“low-top” model), is compared to the response in a version of the same AGCM with a well-resolved stratosphere (“high-top” model). The doubled CO₂ response of the “best-tuned” (i.e. operational) low-top model version is significantly different from that in the best-tuned high-top model version. Additional experiments show that this difference is not caused by the model lid height, but instead can be mainly attributed to differences in the settings of parameterized orographic gravity-wave drag which control the strength of the zonal wind in the mid- to high-latitude lower stratosphere and the mean sea-level pressure distribution. These findings suggest a link between the strength of the winds in the mid- to high-latitude lower stratosphere and tropospheric annular mode responses, and have implications for how to proceed with high-top low-top model intercomparisons. **Citation:** Sigmond, M., J. F. Scinocca, and P. J. Kushner (2008), Impact of the stratosphere on tropospheric climate change, *Geophys. Res. Lett.*, 35, L12706, doi:10.1029/2008GL033573.

1. Introduction

[2] It is well known that the troposphere influences the stratosphere through angular momentum transfer mediated by upwardly propagating planetary and gravity waves. In recent years, evidence has mounted for a downward influence of the stratosphere on the troposphere, apparently through interactions of planetary waves with the mean flow [e.g., *Song and Robinson*, 2004]. It has also been suggested that such two-way interactions have implications for climate change studies. For example, *Scaije et al.* [2005] showed that the tropospheric response to global warming is sensitive to zonal wind changes in the lower stratosphere. The potential for this downward influence raises the more practical question of how high a climate model domain needs to extend in order to correctly represent such effects, and to produce reliable tropospheric climate-change predictions. These are relevant questions given that most climate models used for climate prediction currently include a poor representation of the stratosphere [*Cordero and Forster*, 2006; *Kushner et al.*, 2007].

[3] Several modeling studies have investigated the requirement of a “well-resolved” stratosphere for the produc-

tion of reliable tropospheric climate-change predictions. For example, [*Shindell et al.*, 1999] have argued that a well-resolved stratosphere is required to reproduce observed tropospheric circulation trends, in particular that part of the trend that projects positively onto the Northern Hemisphere Annular Mode (NAM) [*Thompson and Wallace*, 2000]. Other studies have found that such positive NAM responses arise in global warming simulations in the absence of a well-resolved stratosphere [*Fyfe et al.*, 1999; *Gillett et al.*, 2002]. Such conflicting results highlight the subtle nature of the problem and the inherent difficulty in designing experiments meant to isolate the impact of the stratosphere on questions of tropospheric climate change.

[4] In this letter we revisit the question of whether or not a well-resolved stratosphere is needed for general circulation models (GCMs) to produce reliable tropospheric climate-change predictions. To this end, we compare the doubled CO₂ warming response of operational versions of a comprehensive atmospheric general circulation model (AGCM) with and without a well-resolved stratosphere (hereafter referred to as ‘high-top’ and ‘low-top’ model versions, respectively). The simulations are run with prescribed sea-surface temperatures (SSTs) and sea ice, which allows us to focus on the atmospheric response in the absence of ocean and sea-ice feed-backs [*Sigmond et al.*, 2007]. The comparison reveals inconsistent annular mode responses to global warming between the high- and low-top models, mirroring the results of some previous studies. Additional analysis, however, shows that this inconsistency does not represent a straightforward example of stratospheric influence, because it is found to arise primarily from inconsistent physical parameterization settings between the high- and low-top models. When the parameter settings are made consistent, we are able to make more definitive conclusions regarding the impact of the stratosphere on tropospheric climate change.

2. Methodology, Model and Experiments

[5] We employ different high-top and low-top versions of the CCCma third generation atmospheric general circulation model (AGCM3) [*McFarlane et al.*, 2005; *Scinocca et al.*, 2008]. AGCM3 is employed as the standard low-top model in this study (hereafter referred to as the LOW model). It has 32 levels from the surface up to 1 hPa, and is essentially identical to that used for the Intergovernmental Panel on Climate Change Fourth Assessment Report. For the standard high-top model (hereafter denoted as the HIGH model), we use the Canadian middle-atmosphere version of AGCM3, often referred to as CMAM [*Scinocca et al.*, 2008]. It has 71 levels from the surface up to 0.0006 hPa (100 km) and is essentially identical to the version used for

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the 2006 WMO Ozone Assessment [e.g., *Eyring et al.*, 2006].

[6] The HIGH and LOW models represent best tuned operational versions of AGCM3. “Best-tuned” here means that adjustable model parameters have been independently optimized, bearing in mind the operational purpose of each model version. Specifically, the LOW model version was tuned to simultaneously reduce tropospheric wind biases and mean-sea-level pressure biases related to the global mass distribution. The tuning of the HIGH model version focused primarily on reducing stratospheric wind biases, in order to obtain wintertime polar temperatures that would be cold enough for polar stratospheric clouds to form. Obtaining sufficiently low temperatures in this region was essential for using this model to investigate polar ozone chemistry in climate change simulations. This tuning was accomplished by adjusting parameters that controlled the strength and elevation of parameterized orographic gravity-wave drag (GWD) in the HIGH relative to the LOW model version. A detailed discussion is given by *Scinocca et al.* [2008, section 3].

[7] In order to more cleanly isolate the effect of a well-resolved stratosphere on the climate change response, we develop a third configuration of AGCM3 designed to be a lowered version of the HIGH model. This is essentially accomplished by eliminating all levels above 10 hPa in the HIGH model. The resulting model configuration will be referred to as the LOWERED model. It has 41 levels with a lid at 10 hPa and retains the same time step and spatial resolution of the HIGH model. The non-zonal sponge that is used in the vicinity of the lid in the HIGH model is eliminated in the LOWERED model, since experiments showed a significant reduction of wind and temperature biases near the sponge region. In both the HIGH and LOWERED model, parameterized gravity-wave momentum flux that reaches the lid is deposited in the uppermost model layer. This is done for both the orographic [*Scinocca and McFarlane*, 2000] and non-orographic [*Scinocca*, 2003] parameterized gravity waves, and appears to be a necessary condition for the LOWERED model to produce a realistic climatology (T. A. Shaw et al., manuscript in preparation, 2008).

[8] We obtain the CO₂ doubling response by doubling the atmospheric CO₂ concentration, and by perturbing the SST with a seasonally varying perturbation field, while keeping the sea-ice field fixed to the control run values. The SST perturbation field is based on coupled atmosphere-ocean GCM global warming simulations and represents the SST change in the doubled CO₂ world. (Specifically, we use the ensemble average of the difference between the 2090–2099 and 1990–1999 averaged SSTs in the A1B scenario of the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) experiments. The models used to construct the ensemble average are BCCR-BCM2.0, CCCma CGCM3.1(T63), CNRM-CM3, CSIRO-Mk3.0, ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, GISS-EH, GISS-ER, INGV-SXG, IPSL-CM4, MIROC3.2(medres), MRI-CGCM2.3.2, PCM and UKMO-HadCM3 (see <http://www-pcmdi.llnl.gov> for documentation for these models).) All model versions are run at T63 horizontal resolution and analyzed over an equilibrated period of 40 years. In the rest of this letter, the

doubled CO₂ response refers to the difference between the climatology of the doubled CO₂ run and the climatology of the control run.

3. Results

[9] A common approach for assessing the benefit of including a well-resolved stratosphere for (tropospheric) climate-change predictions is to compare the climate change response of the best-tuned low-top model with that of the best-tuned high-top model. We here follow this approach by comparing the doubled CO₂ responses of the HIGH and LOW models. We find that the HIGH and LOW models display a very distinct warming response in the Northern Hemisphere. Figures 1a and 1b show the HIGH and LOW model responses to CO₂ doubling of the December–January–February (DJF) mean sea level pressure (MSLP). The differences are immediately apparent: while the HIGH model response is dominated by a meridional dipole of decreasing pressure in the polar region and increasing pressure at mid-latitudes (similar to a positive NAM response), the LOW model response is dominated by a deepening of the Aleutian low. The area-weighted spatial correlation coefficient north of 45°N (hereafter denoted as r_{45-90N}) between the HIGH and LOW model responses is very low (0.38). From very similar results, *Shindell et al.* [1999] concluded that a well-resolved stratosphere is necessary to obtain an annular-mode type response for future tropospheric climate. Indeed the most obvious difference between the HIGH and LOW models is their difference in stratospheric resolution, and so a reasonable hypothesis would be that the difference between the HIGH and LOW models reflects stratospheric influence. However, as discussed in section 2, several other differences between the HIGH and LOW models exist. For a cleaner comparison we thus examine the climate response in the LOWERED model, with identical parameter settings to the HIGH model, but with a 10 hPa lid.

[10] Figure 1c shows the DJF MSLP doubled CO₂ response in the LOWERED model. The close correspondence of this response to the HIGH model response (Figure 1a) is striking: both are dominated by a meridional dipole that is similar to a positive NAM pattern ($r_{45-90N} = 0.91$). The similarity between the HIGH and LOWERED model responses suggests that the well-resolved stratosphere is not responsible for amplifying the annular mode response in the HIGH model compared to the LOW response. It appears that differences in the HIGH and LOW model response are due to differences in model settings and/or physics, and not related to the presence or absence of a well-resolved stratosphere. This result also implies that a strong tropospheric annular mode response to global warming does not necessarily require the presence of a well-resolved stratosphere, hereby supporting the conclusions of *Gillett et al.* [2002] and *Fyfe et al.* [1999].

[11] We are still left with the question of precisely which aspects of the different model and physics settings in the LOW model are responsible for altering the warming response. Relative to the HIGH and LOWERED versions, the LOW model employed a larger time step, lower vertical resolution above roughly 500 hPa, a different type of upper sponge layer, different settings for the parameterized oro-

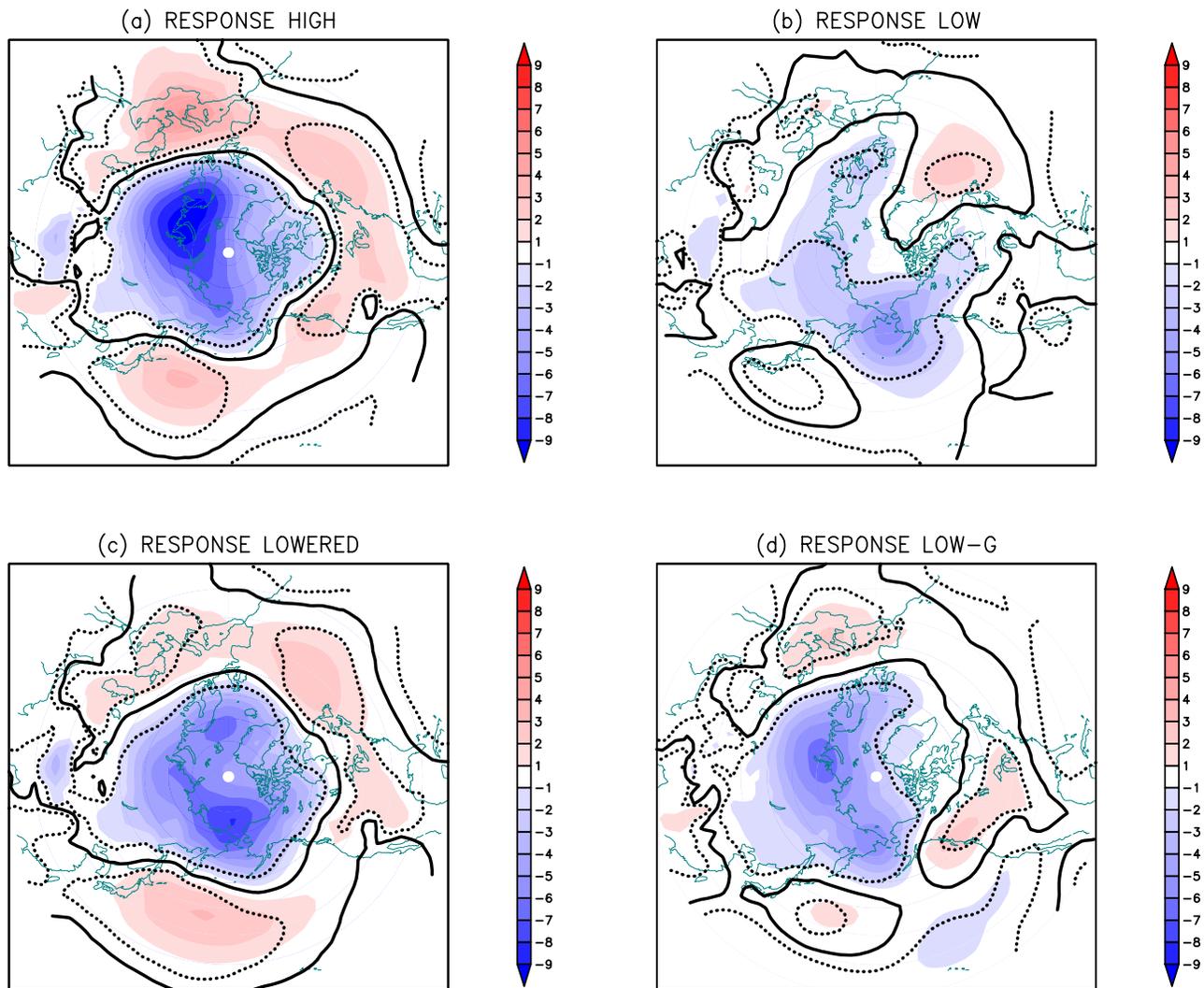


Figure 1. The doubled CO_2 response of the DJF MSLP in (a) the HIGH model, (b) the LOW model, (c) the LOWERED model, and (d) the LOW-G model (in *hpa*). The black solid line denotes the zero contour line, and the dotted line denotes statistical significance at 95% level (according to a standard *t*-test).

graphic gravity waves, and no parameterization for non-orographic gravity-wave drag [Scinocca *et al.*, 2008]. One clue to the critical difference is illustrated in Figures 2a and 2b which show the DJF zonal-mean zonal wind of the control climate for the HIGH and LOW models respectively. The zonal winds in the lower stratosphere at mid to high latitudes in the LOW model are weak relative to the HIGH (and LOWERED) model and to the observed winds in this region. We shall refer to this LOW-model bias as the “weak-wind bias”.

[12] The zonal-mean zonal wind warming response in the HIGH and LOW models are respectively illustrated in Figures 2c and 2d. It is clear that the difference between the HIGH and LOW model circulation response is not limited to the surface, but extends throughout the entire vertical column. In particular, the mid-latitude zonal wind response is much stronger in the HIGH model than in the LOW model. Large differences are also apparent in the high-latitude stratosphere. The zonal-mean zonal wind warming response for the LOWERED model (Figure 2e) shows that the close correspondence between the HIGH and

LOWERED model is maintained throughout the entire vertical domain.

[13] The weak-wind bias in the LOW model is found to be most sensitive to the settings of the parameterized orographic gravity waves, which differed between the LOW and HIGH model versions. This key sensitivity is verified by creating a new LOW model version (referred to here as LOW-G), in which the settings for the parameterized orographic waves are made identical to those in the HIGH and LOWERED models. This modification results in the elimination of the weak-wind bias in the LOW-G model’s control climate (not shown). Strikingly, we find that this modification to the orographic GWD settings also changes the warming response. In Figures 1d and 2f, which illustrate the warming response for MSLP and for zonal-mean zonal wind, we see that there is now a much closer correspondence between the LOW-G and HIGH model circulation responses at the surface (MSLP $r_{45-90N} = 0.86$) and through the stratosphere and troposphere. Although there remain differences between the LOW-G and HIGH climate responses, related to the additional model differences iden-

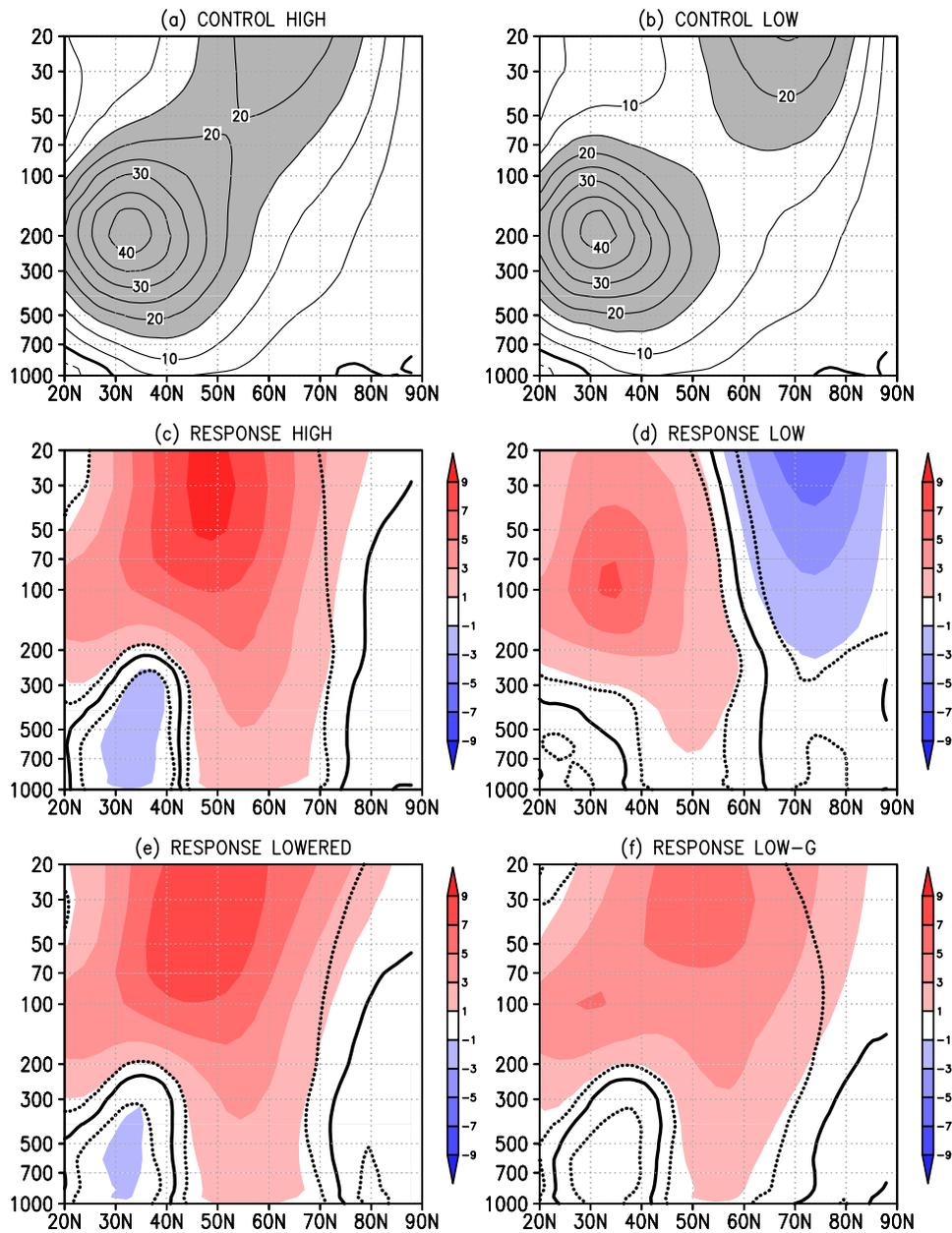


Figure 2. The DJF zonal-mean zonal wind in the control climate in (a) the HIGH model and (b) the LOW model and the doubled CO_2 response of DJF zonal-mean zonal wind (in ms^{-1}) in (c) the HIGH model, (d) the LOW model, (e) the LOWERED model, and (f) the LOW-G model. In Figures 2a and 2b, the contour interval is 5 ms^{-1} , and areas where the zonal wind exceeds 15 ms^{-1} are shaded. In Figures 2c–2f, the solid line denotes the zero contour line, and the dotted line denotes statistical significance at 95% level (according to a standard t -test).

tified earlier in this section, the primary sensitivity is to the orographic gravity-wave settings. In summary, these results indicate that the different warming response in the HIGH and LOW models is mainly a consequence of different settings of the orographic GWD parameterization.

[14] Further tests suggest that the sensitivity of the climate change response to orographic gravity waves does not depend on the particular GWD scheme used. The same behavior of the warming response is recovered from simulations employing the *McFarlane* [1987] orographic scheme (not shown). GWD parameter settings that result in a weak-wind bias produce a warming response similar to the LOW

model, while settings that eliminate this bias produce a response more similar to the HIGH, LOWERED, and LOW-G models. This result suggests that the response to climate change can significantly depend on lower-stratospheric wind biases in the control climate, which are most sensitive to the settings for parameterized GWD.

4. Conclusions and Discussion

[15] In this study we have considered the impact of a well-resolved stratosphere on the tropospheric response to a CO_2 doubling. Employing operational versions of high-top

and low-top climate models, based on the same GCM, we have documented instances where the tropospheric circulation response to increasing greenhouse gases in Northern Hemisphere winter is inconsistent between the two model versions. This type of inconsistency has been interpreted as highlighting the importance of including a well-resolved stratosphere for tropospheric climate-change predictions [Shindell *et al.*, 1999].

[16] Here we have extended the analysis to include a carefully constructed lowered version of the high-top model (with its model lid at 10 hPa). The warming response in this lowered model closely matches that in the high-top version indicating that the initial inconsistency was unrelated to the presence or absence of a well-resolved stratosphere. Based on the lowered-model experiment, we conclude that the inclusion of a well-resolved stratosphere in the high-top model played little role in the production of the annular-mode type response. These findings suggest that conclusions regarding the role of the stratosphere drawn from previous studies with less controlled high-top low-top model comparisons [e.g., Shindell *et al.*, 1999] need to be reconsidered.

[17] In excluding the role of a well-resolved stratosphere, the lowered model experiment pointed to other inter-model differences as the explanation for the inconsistent warming response in the high- and low-top models. This inconsistency was shown to depend mainly on the use of different settings for the parameterized orographic gravity waves, which control the strength of the lower stratospheric wind. Thus, we find evidence of lower stratospheric influence on the tropospheric response, consistent with, for example, Scaife *et al.* [2005]. At the same time, we find that we do not need a model with a fully resolved stratosphere to capture this downward influence. A vertical model domain that extends up to the middle stratosphere appears to be sufficient to capture the influence of the stratosphere on tropospheric climate change.

[18] The findings of this study have some similarities to the recent results of Kodera *et al.* [2008], who investigated the impact of solar activity on the tropospheric response to increased greenhouse gases. A comparison of the surface response from that study with Figure 1 here, indicates a correspondence of the low-solar winters with basic states that include the weak-wind bias (low-top model) and high-solar winters with basic states that do not include the weak-wind bias (e.g. high-top and lowered-lid version). Possible mechanisms suggested by Kodera *et al.* [2008] involve differences in the Brewer-Dobson circulation response of the high- and low-solar periods to increasing greenhouse gases. Such differences were related to the strength of the zonal wind at stratopause level where the impact of solar variability maximizes. However, to the extent that the surface warming response induced by solar activity is similar to that induced by the (lower stratospheric) weak-wind bias, it can be argued that its origins may be unrelated to the (upper) stratospheric changes identified by Kodera *et al.* [2008]. This is an interesting possibility that requires further investigation.

[19] Our results illustrate the necessity for clean comparisons of low-top and high-top models. The sensitivity to gravity wave drag settings shows how subtle changes to model settings might confuse the interpretation of the differences between best-tuned high-top and low-top mod-

els. These considerations will provide useful input on future efforts to compare low-top and high-top models [Kushner *et al.*, 2007].

[20] The degree to which the atmospheric circulation response to climate change projects onto the NAM is a critical part of understanding and predicting the future evolution of the coupled ocean-atmosphere system. It is at present uncertain whether the long-term trend in the NAM will emerge to be positive, negative, or neutral [Overland and Wang, 2005; Cohen and Barlow, 2005]. This aspect of the response is one of the least robust aspects of model simulations of climate change [Miller *et al.*, 2006]. Our results suggest that at least part of this non-robustness stems from differences in orographic gravity wave drag settings among models. Future investigation aimed at understanding this key sensitivity will help to improve the fidelity of future regional climate predictions.

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