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The Antarctic ozone hole and the Northern Annular Mode: A stratospheric interhemispheric connection

D. Rind,[1] J. Jonas,[2] S. Stammerjohn,[1,3] and P. Lonergan[2]

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[1] The S.H. ozone hole deepened into the mid-1990s, while the Northern Annular Mode (NAM) became more positive. Both effects have since stabilized. We investigate a possible connection with modeling experiments of a S. H. spring ozone hole, and also year-round ozone loss in both polar regions. The S.H. ozone hole results in a more positive NAM-like phase extending down to the surface. Reduced vertical stability increases S.H. tropospheric wave energy flux into the stratosphere which drives a residual circulation with relative subsidence over the Southern pole and upwelling and reduced planetary wave energy flux at Northern high latitudes. The results suggest that similar trends in the Southern Ozone hole and the NAM over the last 20 years may be more than just a coincidence, although other factors undoubtedly influence the Northern high latitude circulation. **Citation:** Rind, D., J. Jonas, S. Stammerjohn, and P. Lonergan (2009), The Antarctic ozone hole and the Northern Annular Mode: A stratospheric interhemispheric connection, *Geophys. Res. Lett.*, *36*, L09818, doi:10.1029/2009GL037866.

1. Introduction

[2] In a recent article [*Rind et al.*, 2008], our modeling experiments showed how solar-influenced planetary wave-driven perturbations in the S.H. winter stratosphere could affect the extratropics of the Northern summer hemisphere, including the troposphere. This interhemispheric connection is different from that normally discussed for the stratosphere, for which the anti-phase relationship between polar and tropical regions has been emphasized (e.g., tropical cooling coinciding with mid-winter polar stratospheric warming events [*Fritz and Soules*, 1970]). For tracer and mass transports, the Lagrangian circulation from summer to winter pole above about 30 km is well-established [e.g., *Dunkerton*, 1978]. In this paper we discuss another example of a stratospheric interhemispheric connection, in this case perturbations associated with the Antarctic ozone hole, and its relationship to the NAM (Northern Annular Mode).

[3] There have been numerous studies relating the S.H. ozone hole to the more positive phase of the Southern Annular Mode (SAM) over the past several decades [e.g., *Thompson and Solomon*, 2002; *Gillett and Thompson*, 2003]. Most of the future global warming experiments for AR4 produce a more positive SAM, with both the ozone hole and global warming contributing [e.g., *Miller et al.*, 2006; *Intergovernmental Panel on Climate Change*, 2007], although some recent work has suggested a reversal of the summer SAM index in the 21st century as the ozone recovers [*Perlwitz et al.*, 2008; *Son et al.*, 2008].

[4] The importance of the N.H. ozone hole for the more positive phase of the Northern Annular Mode (NAM) has received less attention. Due to greater planetary wave activity in this hemisphere, the polar cyclone is not as isolated, and the ozone hole tends to be weaker and more variable; furthermore, it develops in the spring, so it would not be expected to influence the winter circulation. Nevertheless, a more positive winter NAM (and the corresponding North Atlantic Oscillation) developed between 1979 and the mid-1990s (e.g., http://www.ldeo.columbia.edu/res/pi/NAO/). It has since shown little trend, although 8 of the last 13 years have been positive. The S.H. ozone hole has had a similar change with time – minimum values decreased in general from 1979 to 1994, with leveling off since then [e.g., *Global Ozone Research and Monitoring Project*, 2007, chapter 4] (see http://ozonewatch.gsfc.nasa.gov/), following the trend in stratospheric chlorine associated with the Montreal Protocol. The S.H. ozone hole occurs during N.H. fall, a time-frame, at least, when it could conceivably influence the N.H. winter circulation.

[5] The overall similarity in trends between these two geographically disparate phenomena may simply be a coincidence, or related to some other common cause(s) (such as global warming). However, the model experiments discussed below suggest there may be a more direct connection.

2. Experiments

[6] The standard experiment ("Southern Seasonal") incorporated an ozone hole into the 4 × 5, 53 layer version of the GISS Global Climate Middle Atmosphere Model 3 [*Rind et al.*, 2007]. In order to maximize its impact, an extreme ozone hole was used, with all ozone removed from 147–67 mb during S.H. spring. We also include an experiment in which all ozone is removed from the same region in the N.H. during its spring ("Northern Seasonal"), and one in which ozone is removed over both poles throughout the year (Both Poles Year-Round, BPYR). We run each experiment for 15 years with specified sea surface temperatures at climatological values to emphasize the stratospheric forcing in these experiments; the results are shown below, as differences from a control run (with climatological ozone) run for an equal amount of time, omitting the first three years to allow for soil moisture equilibration. As an additional check on the significance of the results, we subsequently ran 15

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[1] NASA Goddard Institute for Space Studies, New York, New York, USA.

[2] Center for Climate Systems Research, Columbia University, New York, New York, USA.

[3] Now at Ocean Sciences Department, University of California, Santa Cruz, California, USA.

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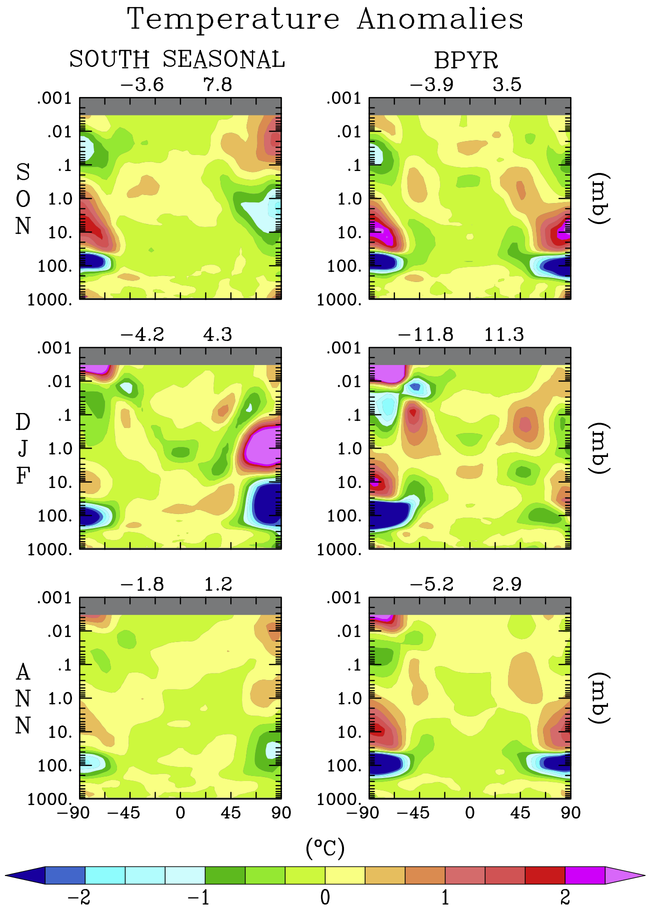

Figure 1. Zonal average temperature changes for Sept-Nov, Dec-Feb and the annual average for the Southern Seasonal and BPYR simulations. Maximum and minimum values are indicated above each plot.

additional years, and also reran the experiment with some differences in physics. Through a total of 50 years of simulations, the pattern of the results remained the same, though there was some variation in the magnitude of the response. We conclude that the results shown below are robust for this model, although at least some model-dependency may be expected.

3. Results

[7] Shown in Figure 1 are the temperature anomalies for Sept–Nov and Dec–Feb as well as the annual average in two of the experiments. As expected, the Southern Seasonal run (Figure 1, left) features S.H. lower stratospheric cooling which extends into the summer; despite the extreme nature of the ozone hole used, the seasonal temperature change for Sept–Nov is actually slightly less than the observed trend [*Thompson and Solomon*, 2002], for dynamic reasons discussed below. The year-round experiment (Figure 1, right) has substantial cooling in all seasons and hence a greater annual average effect. What was not expected, however, was that the N.H. response was quite strong during the S.H. spring and especially summer season in Southern Seasonal (and even evident on the annual average) – stronger, in fact, than when the N.H. ozone hole was prescribed for Dec–Feb season in the BPYR experiment. In contrast, there is little S.H. response in the Northern Seasonal experiment (not shown).

[8] The S.H. polar temperature response is significant at greater than the 99% level. The N.H. polar response has a significance level varying between 90–95% depending on the exact location; a similar significance is found for the 100 mb heights, discussed below.

[9] The zonal wind response for the Dec–Feb is compared for the Southern Seasonal and BPYR experiments in Figure 2. The Southern Seasonal experiment actually has stronger zonal wind increase in the Northern (than Southern) Hemisphere, despite the lack of ozone hole in the North. As will be shown below, this is also the result of a ‘dynamic’ feedback. Note that in general the west wind increases extend down to the surface. The BPYR run, with an ozone hole in the North, actually has only a very weak polar west wind increase in the lowermost stratosphere, consistent with its weak temperature response in that season.

[10] Shown in Figure 3 are the N.H. 100 mb and 500 mb height anomalies for the winter season, as well as the sea level pressure (SLP) changes. A more positive NAM-like response is found in the Southern Seasonal experiment at

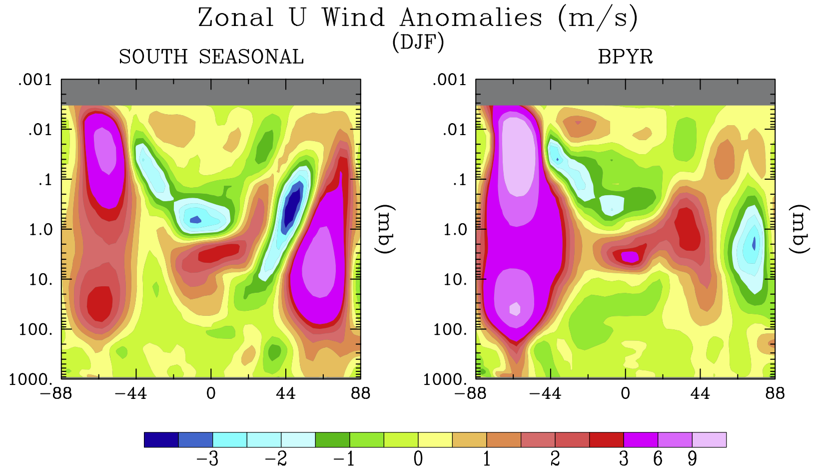

Figure 2. Zonal wind changes for Dec-Feb in Southern Seasonal and BPYR runs.

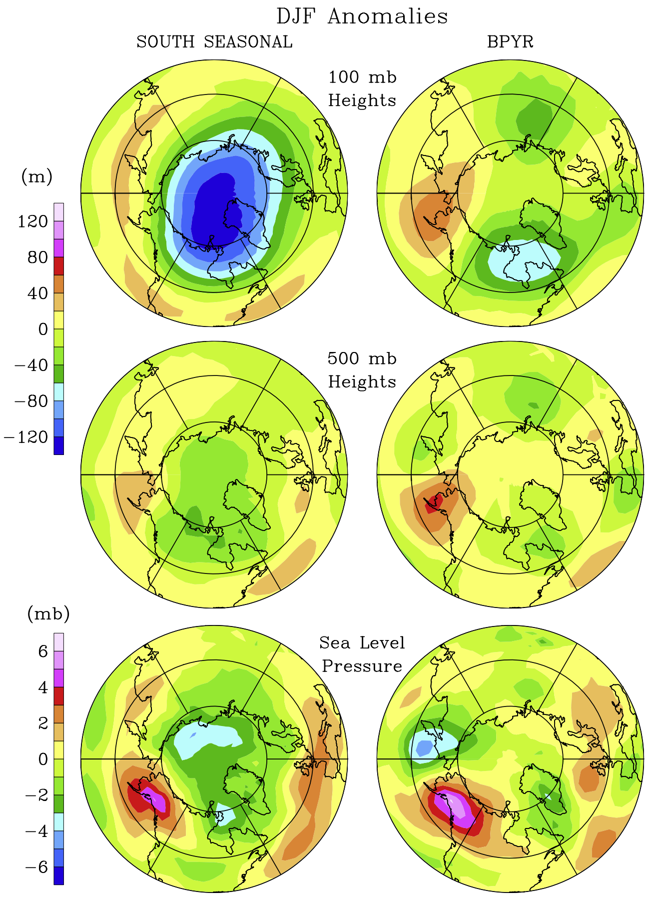

Figure 3. Change in N.H. 100 mb ht, 500 mb ht and sea level pressure during Dec-Feb in the Southern Seasonal and BPYR experiments.

both stratospheric and tropospheric levels than in the BPYR experiment with its N.H. ozone hole as well. The 100 mb height change reaches 95% significance over Greenland, and generally 90–95% over the polar region. Note that the magnitude of the SLP change, 2 to 4 mb in the polar region, is a sizable fraction of the observed trend (~4.5 mb) from 1969–2000 [*Ostermeier and Wallace*, 2001]. The N.H. 500 mb height change is actually ~60% of that found in observations for the S.H. linear trend [*Thompson and Solomon*, 2002].

[11] As the effect is initiated in S.H. spring, we show in Figure 4 the September–November vertical EP flux change for the Southern Seasonal and BPYR runs along with the change in EP flux stratospheric divergence. In the S.H. increased upward EP fluxes from the troposphere (13% increase through the 100 mb level) are associated with increased tropospheric eddy kinetic energy (EKE) (of some 5%) and result in a 30% EKE increase in the stratosphere; increased EKE generation is due to the reduced vertical stability associated with ozone hole cooling. An increase of tropospheric EKE of this magnitude associated with lower stratospheric ozone decrease has occurred consistently in different versions of the GISS model [e.g., *Rind et al.*, 2005]. (Note that this is a response *to the ozone hole*, and is not to be confused with the observed relationship of weaker EP fluxes helping *to produce* a stronger ozone hole.) The increased EP flux is associated with more poleward eddy heat transport, which helps limit the lower stratospheric cooling seen in Figure 1.

[12] The increased flux leads to S.H. stratospheric EP flux convergence (Figure 4), which amplifies the residual circulation (by ~20%), producing relative downwelling at high Southern latitudes. [Again this is not to be confused with the residual circulation in the winter preceding S.H. spring, where an amplified residual circulation is associated with warmer temperatures and a positive springtime ozone anomaly]. The high latitude Southern warming at mid-stratosphere levels is the result of both subsidence associated with this circulation change, and absorption by ozone of longwave terrestrial radiation that used to be absorbed by ozone at lower levels.

[13] The key aspect is that the circulation change extends into the N.H. with relative upwelling at high northern latitudes (Figure 5). The residual circulation change thus helps initiate cooling in the Northern polar stratosphere (Figure 1), while the resulting stronger west winds (Figure 2) reduce upward wave propagation (Figure 4) and poleward sensible heat transport (not shown) in this hemisphere, amplifying the cooling. The influence works its way downward in the stratosphere from N.H. fall to winter (Figure 1) due to wave-mean flow interactions, as seen with other stratospheric perturbations (e.g., solar perturbations [*Kodera and Kuroda*, 2002]). Therefore the N.H. polar response is initially driven from the S.H. polar region. This interhemispheric response is absent for the S.H. in the Northern Seasonal experiment presumably due to the lack of sufficient planetary wave energy in the S.H. to amplify it.

[14] The reason why the N.H. NAM-like response is actually greater during Dec–Feb with only the southern ozone hole than with ozone holes in both hemispheres is that when a northern ozone hole is present it too increases the eddy kinetic energy in the troposphere (as it did in the S.H.), with greater upward EP fluxes into the stratosphere and stratospheric EP flux convergences (Figure 4, right). This then acts to counteract the influence from the S.H. by increasing the N.H. residual circulation as well, with greater low latitude upwelling (Figure 5).

4. Discussion

[15] While the relationship discussed above is clear in the modeling experiments, can any of it be verified from observations? The residual circulation magnitude is highly correlated with the driving wave energy fluxes. We use vertical EP flux data through 100 mb level from the ERA40 and NCEP reanalyses, in the region 45S–75S (http://www.awi.de/de/forschung/fachbereiche/klimawissenschaften/atmosphaerische_zirkulationen/projects/candidoz/ep_flux_data/).

[16] In the model experiments, the initial dynamic forcing arises from increased vertical EP fluxes at S.H. upper mid-high latitudes in response to the presence of the Antarctic ozone hole. For the months of Sept–Nov, from the mid 1950s (prior to the ozone hole) through 2001, ERA40 and NCEP data show that the EP flux through the 100 mb level increased, with a correlation with increasing time of 0.54 (ERA40) and 0.65 (NCEP), both significant at the 99% level. On the absolute level, fluxes associated with S. H. polar total ozone less than 150 DU averaged 25% higher

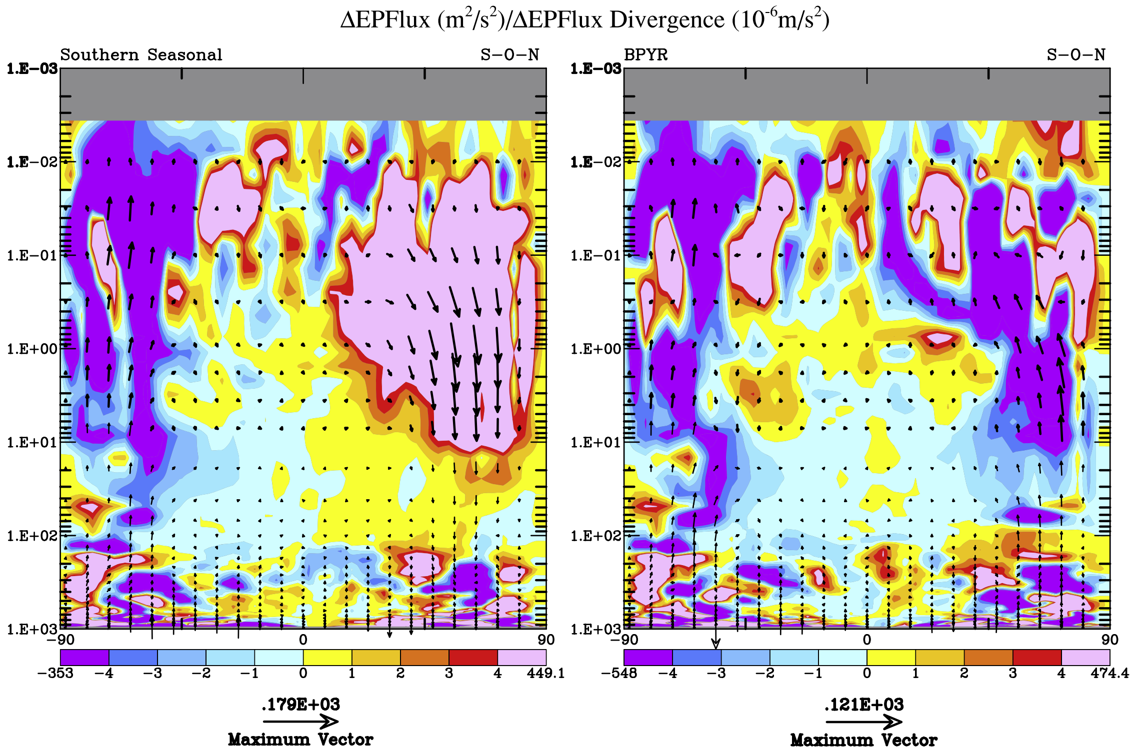

Figure 4. Change in EP flux (arrows) and change in EP flux divergence (colors) in the Southern Seasonal and BPYR experiments for Sept-Nov.

(ERA40) or 37% higher (NCEP) than those with total ozone greater than 200 DU. There are anecdotal relationships as well between EP fluxes and strong ozone hole values (e.g., the largest EP flux value for this season occurs in 1994, the year with the minimum ozone hole and the least ozone mass). The increased EP flux would be expected to drive a stronger residual circulation. However, the quality of S.H. EP flux data is somewhat questionable, and the introduction of satellite data at about the same time as the ozone hole started to develop raises the possibility of bias. Given such uncertainties, these results are suggestive of an increase in

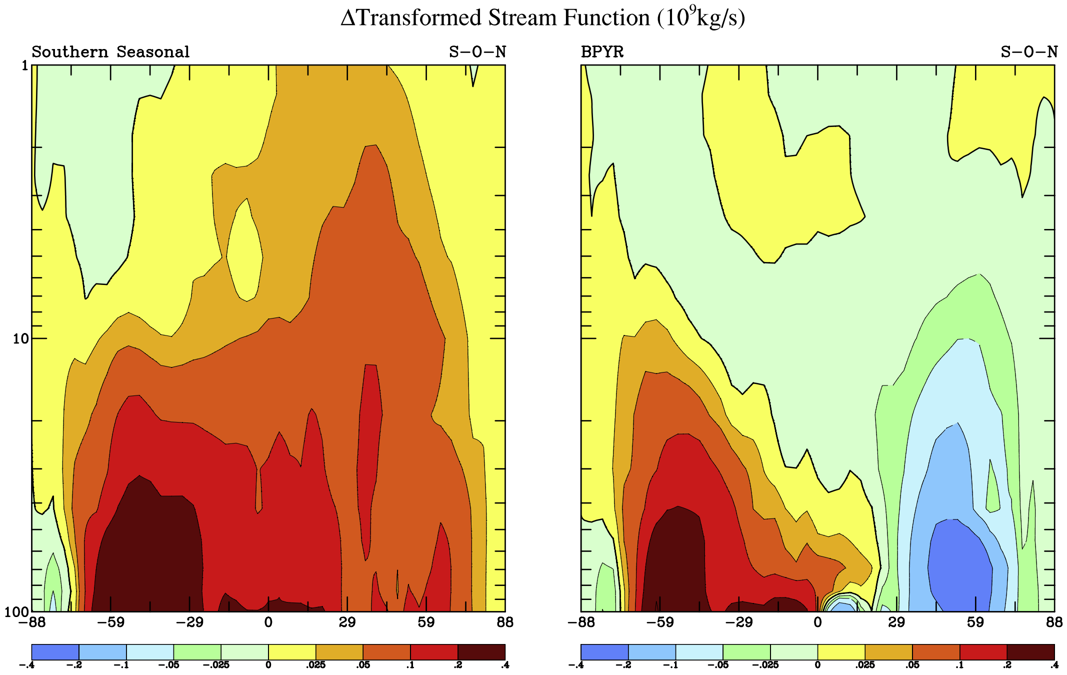

Figure 5. Change in Sept-Nov stratospheric residual circulation in the Southern Seasonal and BPYR experiments. Positive values indicate relative counter-clockwise circulation change in the plane of the figure.

S.H. EP flux in response to the ozone hole but not conclusive.

[17] The model experiments further suggest that in response, a weaker residual circulation should arise in the N.H., with a more positive NAM, and reduced vertical EP fluxes. From 1979–2000 there did seem to be a negative trend in vertical EP fluxes during January–February [*Randel et al.*, 2002], consistent with the periods of greater ozone holes, colder temperatures, and a more positive NAM [e.g., *Fusco and Salby*, 1999]. The polar stratosphere in the 1990s was quite cold [e.g., *Pawson et al.*, 1998], which for the most part was a time period without a major mid-winter stratospheric warming. Of course such circumstances may well have other influences, including natural forcing (solar, volcano), global warming and natural variability, all contributing to variations in the NAO/NAM [*Shindell et al.*, 1999; *Fyfe et al.*, 1999; *Rauthe et al.*, 2004; *Rind et al.*, 2005]. Hence the correlation of events in the two hemispheres could be fortuitous. Nevertheless, these experiments suggest that the S.H. ozone hole could be one additional influence. Another possible indication is that *Randel et al.* [2002] found little correlation between N.H. planetary wave EP fluxes and polar ozone during the Sept–Nov time period (in contrast to their winter results), which may suggest a S.H. influence on the N.H. stratospheric circulation was also operative.

[18] One other possible interpretation is that the connecting link is not through the stratosphere but via the troposphere. The S.H. ozone hole produces a more positive SAM, with lower pressure at high southern latitudes. This could initiate a change of mass within the troposphere, potentially affecting the N.H. sea level pressure distribution, and then other altitudes. However, one might expect the mass changes to be offsetting, as in the experiments of *Rind et al.* [2001] - not decreases at high latitudes in both hemispheres as in these experiments.

[19] The results have several implications. One is that the future of the S.H. ozone hole during the 21st century may be relevant for the future NAM in both the stratosphere and troposphere. In addition, they are an example of how stratospheric changes may influence the troposphere, in this case far removed from the original forcing. Since the tropospheric polar connection arises in response to stratospheric circulation changes, the results suggest that including a full stratosphere could be important for future tropospheric predictions. This suggestion has been made previously but from completely different perspectives, emphasizing northern tropospheric response to planetary wave propagation within that hemisphere [*Shindell et al.*, 1999] or gravity wave drag parameterizations [*Sigmond et al.*, 2008]. These results suggest an influence arising from circulation changes driven from the S.H. amplified by planetary wave feedback in the N.H.

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J. Jonas and P. Lonergan, Center for Climate Systems Research, Columbia University, New York, NY 10025, USA.

D. Rind, NASA Goddard Institute for Space Studies, New York, NY 10025, USA. (drind@giss.nasa.gov)

S. Stammerjohn, Ocean Sciences Department, University of California, Santa Cruz, CA 95064, USA.