Observed connection between stratospheric sudden warmings and the Madden-Julian Oscillation

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[1] The effect of the Madden-Julian Oscillation (MJO) on the Northern Hemisphere wintertime stratospheric polar vortex and major, mid-winter stratospheric sudden warmings (SSWs) is evaluated using a meteorological reanalysis dataset. The MJO influences the region in the tropospheric North Pacific sector that is most strongly associated with a SSW. Consistent with this, SSWs in the reanalysis record have tended to follow certain MJO phases. The magnitude of the influence of the MJO on the vortex is comparable to that associated with the Quasi-Biennial Oscillation and El Niño. The MJO could be used to improve intra-seasonal projections of the Northern Hemisphere high latitude circulation, and in particular of the tropospheric Northern Annular Mode, at lags exceeding one month. **Citation:** Garfinkel, C. I., S. B. Feldstein, D. W. Waugh, C. Yoo, and S. Lee (2012), Observed connection between stratospheric sudden warmings and the Madden-Julian Oscillation, *Geophys. Res. Lett.*, *39*, L18807, doi:10.1029/2012GL053144.

1. Introduction

[2] It is now well established that variability of the wintertime stratospheric polar vortex can influence tropospheric weather and climate [*Baldwin and Dunkerton*, 1999; *Polvani and Kushner*, 2002; *Limpasuvan et al.*, 2004]. Perhaps the most extreme example of polar stratospheric variability occurs when the polar vortex completely breaks down, whereby zonal winds change from strong (>50m/s) westerlies to easterlies in the span of one week. Such events are known as stratospheric sudden warmings (SSWs), and are preceded by a burst of wave activity from the troposphere into the stratosphere [*Matsuno*, 1971]. A SSW can influence jets in the troposphere, and in particular lead to the negative phase of the Northern Annular Mode (NAM), in the weeks or months following an event and thereby impact surface climate [*Baldwin and Dunkerton*, 2001; *Polvani and Waugh*, 2004; *Limpasuvan et al.*, 2004]. It is therefore important to understand the factors that control variability of the polar vortex on intra-seasonal timescales.

[3] A long list of studies have suggested that at least some variability of the Northern Hemisphere stratospheric polar vortex is linked to variability in the North Pacific region (hereafter, NP). Specifically, during an El Niño winter, mid-tropospheric geopotential heights are anomalously low in the NP, and these teleconnections with the midlatitudes have been linked with a weakened polar vortex [*Garfinkel and Hartmann*, 2008; *Bell et al.*, 2009; *Ineson and Scaife*, 2009; *Garfinkel et al.*, 2010, 2012]. In addition, part of the mechanism by which enhanced October Eurasian snowcover leads to a weakening of the early winter polar vortex appears to be a downstream low anomaly in the NP [*Hardiman et al.*, 2008; *Garfinkel et al.*, 2010]. Anomalously cold sea surface temperatures in the North Pacific Ocean also appear to weaken the polar vortex [*Hurwitz et al.*, 2011, 2012]. The mechanism by which the NP signal is communicated upwards appears to be constructive interference of a low anomaly in the Northwest Pacific with the climatological stationary trough [*Garfinkel and Hartmann*, 2008; *Nishii et al.*, 2009; *Garfinkel et al.*, 2010; *Smith et al.*, 2010]. In contrast, blocking in the western NP (i.e., a ridge) leads to a strengthened polar vortex [*Woollings et al.*, 2010].

[4] Recently, *Yoo et al.* [2012] found that the Madden-Julian Oscillation (hereafter, MJO), which is the dominant mode of intraseasonal variability in the tropics [*Madden and Julian*, 1994], can lead to Arctic surface temperature anomalies. While not discussed in their paper, they also find a connection between the MJO and the stratosphere. Their Figure 6 shows that about 10 days after the MJO passes its phase with reduced (enhanced) convection over the western Pacific (Indian) Ocean (phase 1 as defined by *Wheeler and Hendon* [2004]), warm anomalies are established in the polar lower stratosphere. In contrast, anomalous cooling occurs in the stratosphere about 10 days after MJO phase 5, which has convective anomalies of opposite sign to that of phase 1. In addition, *Cassou* [2008], *L'Heureux and Higgins* [2008], and *Lin et al.* [2009] connect the MJO and the Northern Annular Mode (hereafter, NAM) at time scales of up to 2 weeks.

[5] In this study, we expand on these results and demonstrate a statistically significant connection between the MJO and the stratospheric polar vortex, and subsequently the tropospheric NAM, at lags exceeding a month.

2. Methods and Data

[6] We use the daily multivariate MJO index that is described in *Wheeler and Hendon* [2004] (available at http://cawcr.gov.au/staff/mwheeler/maproom/RMM/index.htm). The MJO is considered as being active when the amplitude of the MJO index exceeds 1.5 (as in *Yoo et al.* [2012]),

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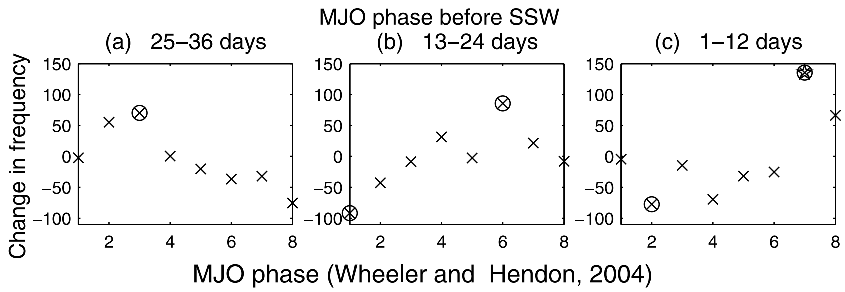

Figure 1. Change in frequency of each MJO phase preceding SSWs as compared to the climatological frequency during the extended boreal winter. Circles indicate results significant at the 90% level, and stars indicate results significant at the 95% level, by a 2-tailed Monte Carlo test. See Section 2 for the details of the calculation.

which corresponds to 37% of the days in our extended-boreal-winter dataset (i.e., November through March). The results are not sensitive to a reasonable change of this threshold (e.g., 1.0 or 2.0).

[7] To examine the response to the MJO, we use NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) [*Rienecker et al.*, 2011] reanalysis. We focus our analysis on the extended boreal winter from 1979 to 2011. April and May dates (i.e., after the polar stratospheric final warming) are removed when computing the lagged response to the MJO. The seasonal cycle is removed at each grid point by subtracting a low pass-filtered daily climatology. No smoothing or bandpass filtering has been applied to isolate the subseasonal signal unless otherwise indicated, but when bandpass filtering is used, we apply a 9th order Butterworth filter with cutoffs at 10 days and 100 days to the data before creating our composites.

[8] Only major, midwinter SSWs (i.e., the zonal wind at 10 hPa, 60 N reverses) are considered. The SSW dates are taken from Table 1 of *Cohen and Jones* [2011]. A total of 23 SSW events are included, with the first being on 22-February-1979 and the last on 9-February-2010. The area weighted average of anomalies from 65N and poleward, is referred to as *polar cap height anomalies.* Polar cap height anomalies are used to track NAM variability at all vertical levels; at each vertical level, we normalize by the wintertime standard deviation, so that we show the NAM in units of standard deviations. *Baldwin and Thompson* [2009] find that the NAM events identified by anomalous polar cap height and by an EOF-based definition of the NAM are nearly identical.

[9] The following Monte Carlo test is used to determine the statistical significance of the connection between the MJO and SSW. The extended boreal winter is divided into 12-day intervals (corresponding to the 12-day intervals displayed in Figure 1). Twenty-three intervals are randomly selected (corresponding to the 23 SSW events) and the frequency of each MJO phase during the active MJO dates is computed. Then, by performing the Monte Carlo procedure 2,000 times, we end up with 8 PDFs corresponding to each of the eight MJO phases, with each PDF containing 2,000 values of the frequency of occurrence for that MJO phase. (The 8 PDFs are distinct because certain MJO phases occur most often [cf. *Yoo et al.*, 2011, Figure 2].) Finally, the frequency of occurrence preceding the SSWs for each MJO phase is compared with the PDFs from the 2,000 calculations to determine the statistical significance.

[10] When the respective phases are displayed in Figure 1, we normalize by the climatological distribution of phases because certain MJO phases (e.g., phase 3 and 7) occur most often [cf. *Yoo et al.*, 2011, Figure 2]. The normalization used is 100 $\frac{F_{SSW,p,g} \quad F_{climatology,p}}{F_{climatology,p}}$, where $F_{climatology,p}$ is the number of active days with MJO phase p during the period of record. $F_{SSW,p,g}$ is computed as follows: suppose C_{SSW,p_g} is the number of days with MJO phase p at a lag g before SSWs, then $F_{SSW,p,g} = C_{SSW,p,g} \quad \frac{\sum_p F_{climatology,p}}{\sum_p C_{SSW,p,g}}$. Hence, a change in frequency of 100% corresponds to a doubling in the frequency of occurrence of a particular MJO phase prior to SSW events as compared to climatology.

[11] A Student's-t test is used to evaluate the statistical significance of the anomalies associated with a composite of active MJO events. When we calculate the degrees of freedom, a consecutive series of, e.g., MJO phase-3 days that is separated by at least seven days from any other MJO phase-3 day is considered as one unique degree of freedom.

3. Results

[12] We first examine the phase of the MJO preceding SSWs. The change in frequency of each MJO phase for three different periods preceding SSWs (25–36, 13–24, and 1–12 days before the SSWs) as compared to the climatological distribution of MJO phases is shown in Figure 1. It is clear that phases 7 and 8 are preferred during the 12 days preceding SSWs (Figure 1c). During days 13 to 24 before SSWs, MJO phases 4, 6, and 7 are preferred, while during days 25 to 36 before SSWs, MJO phases 2 and 3 are preferred (Figures 1a and 1b). The lag between MJO phases 3 and 7 is consistent with the 30–60 day periodicity of the MJO. This effect is statistically significant for many phases. The results are not sensitive, in a qualitative sense, to discriminating between displacement or split SSWs (described in *Charlton and Polvani* [2007]), or to distinguishing between El Niño or La Niña SSW. The key point is that the potential for predictability extends back as far as one month: if a MJO phase 2 or phase 3 is occurring, the probability that a SSW will occur in one month is apparently increased.

[13] The weak stratospheric vortex anomaly following MJO phase 3 eventually reaches the troposphere (Figure 2a). During the fourth week after MJO phase 3, there is a rapid weakening of the polar vortex in the middle and upper stratosphere. In the ensuing two weeks, the signal propagates into the lower stratosphere, and by day 50 it reaches the

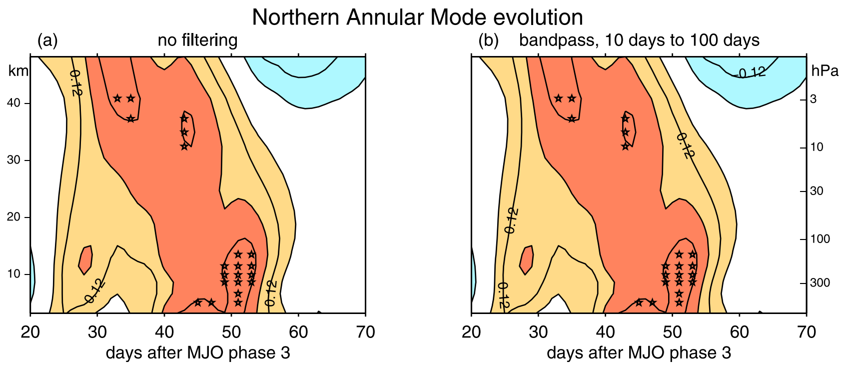

Figure 2. Evolution of normalized polar cap height (i.e., the NAM) after MJO phase 3 as a function of altitude regardless of whether a SSW has occurred. The contour interval is 0.06 standard deviations. (a) No filtering has been applied to the NAM index; (b) a bandpass filter has been applied before composites are created in order to isolate the subseasonal signal. Anomalies statistically significant at the 95% level by a Student's-t test are indicated with stars. See Section 2 for the details of the calculation and the bandpass filter.

troposphere. The tropospheric NAM (as defined in section 2) remains negative for the following three weeks. The surface Arctic Oscillation anomaly at a lag of 48 to 50 days as defined by NCEP/CPC (available at ftp://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.ao.index.b500101.current.ascii) is 0.65; this surface anomaly is statistically significant at the 95% level by a Student's-t test. A similar stratospheric NAM signal exists two to three weeks after MJO phase-7; however, the stratospheric anomaly does not significantly impact the tropospheric NAM (not shown; future work is necessary to understand why this may be). The timescale of the downward propagation is similar to that shown in *Baldwin and Dunkerton* [2001]. The NAM response to the MJO is qualitatively similar if we isolate the subseasonal signal by bandpass filtering (Figure 2b).

[14] In order to understand the source of the apparent connection between the polar vortex and the MJO, we compare the teleconnections of the MJO and the tropospheric precursors of SSWs in the NP (Figures 3a–3c). In the 20 days preceding SSWs, 500-hPa height anomalies are negative in the NP, as in *Garfinkel et al.* [2012] (Figure 3c). The NP height anomalies shortly after MJO phase 7 and one month after MJO phase 3 are similar to those preceding SSWs (Figures 3a and 3b), and these NP height anomalies are statistically significant at the 95% level (not shown). As the NP teleconnection of these MJO phases is collocated with the trough of the climatological planetary wave, it can lead, through constructive interference, to enhanced wave driving of the polar vortex [e.g., *Garfinkel et al.*, 2010]. Therefore, it is to be expected that the MJO can affect the polar vortex. The subsequent downward propagation of the signal from the stratosphere to the troposphere in response to a NP low anomaly is similar to that shown by *Garfinkel et al.* [2010] (see their section 5). Finally, we have examined extreme negative height anomalies in the NP as in *Garfinkel et al.* [2012], and results are consistent with what we show here (not shown).

[15] We summarize the influence of each phase of the MJO in the NP and on the polar stratosphere as a function of time in Figure 4. A range of MJO phases and lags influence the NP (Figure 4a) and the polar stratosphere (Figure 4b). The time evolution of the response is consistent with the periodicity of the MJO, and the lag between the tropospheric and stratospheric responses is consistent with Figure 2. Figure S1 in the auxiliary material shows that these anomalies are qualitatively similar if we isolate the subseasonal signal by bandpass filtering.[1] However, an apparent gap exists in the extratropics-MJO connection near a lag of 25 days before the connection re-emerges. Future work is therefore necessary in order to confirm that the observed connection between the MJO and the stratospheric polar vortex at lags exceeding one month is physical (as opposed to a statistical artifact). Nevertheless, we find a statistically significant connection

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053144.

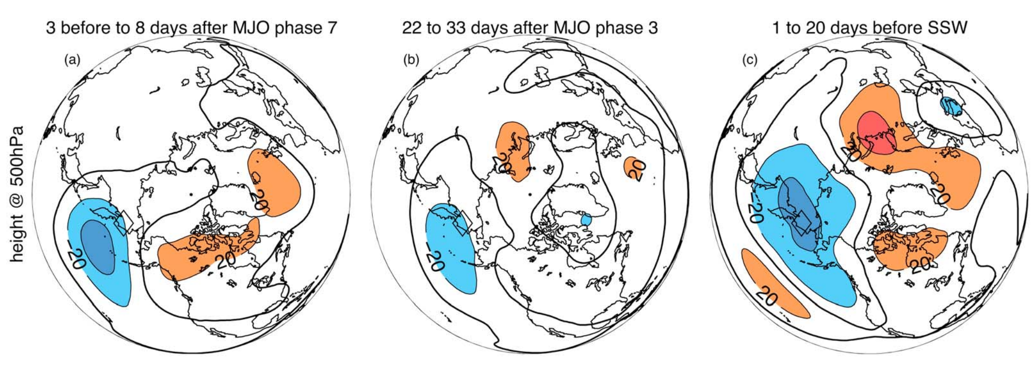

Figure 3. Anomalies in geopotential height at 500 hPa in MERRA in the extended boreal winter during a composite of MJO phases, and 1 to 20 days preceding sudden stratospheric warmings. The contour interval is 20 m. The zero line is thick.

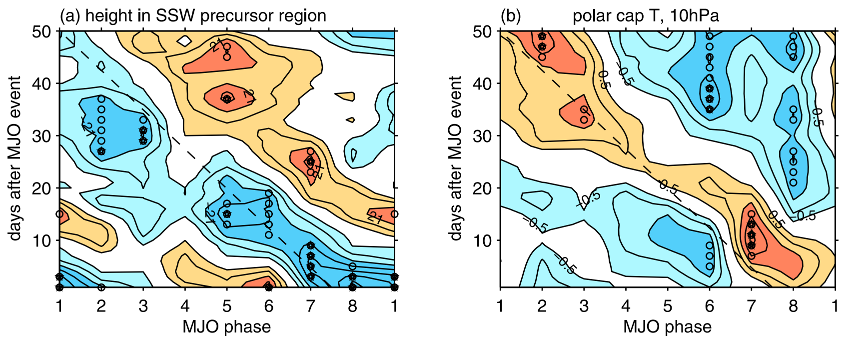

Figure 4. Summary of the response to each MJO phase in the (a) SSW precursor region (defined as the region 52.5 N–72.5 N and 155 E–185 E, the region in the North Pacific with the largest anomalies in Figure 3c), and in (b) polar cap temperature (area average from 65N and poleward) at 10 hPa. Note that negative values in Figure 4a indicate a deepened North Pacific trough. The dashed line is identical in Figures 4a and 4b and is intended to help one compare the timing of the responses in the troposphere and stratosphere. The contour interval is 7 m (Figure 4a) and 0.5 K (Figure 4b). Circles indicate results significant at the 90% level, and stars indicate results significant at the 95% level, by a 2-tailed Student's-t test.

between the MJO and the polar stratosphere at lags exceeding 40 days. This suggests that a physical mechanism might be present even at these long lags. Note that the polar stratospheric warming following MJO phase-1 visible in Figure 6 of *Yoo et al.* [2012] is weak (0.5 K in the 65N and poleward polar cap average) as compared to the response during other MJO phases. Finally, the difference in polar cap temperature anomalies during opposite MJO phases exceeds 4 K (Figure 4b), which is comparable to the effect associated with ENSO and the Quasi-Biennial Oscillation [*Garfinkel and Hartmann*, 2007].

4. Conclusions

[16] A strong connection has been shown to exist between the Madden-Julian Oscillation (MJO) and the Northern Hemisphere wintertime stratospheric polar vortex. SSWs in the reanalysis record tend to follow certain MJO phases, likely because the MJO influences the region in the North Pacific most strongly associated with tropospheric planetary wave driving. Similarly, the strength of the polar vortex is significantly modulated by particular MJO phases at specified lags, and the magnitude of the influence of the MJO on the polar vortex (4 K) is comparable to that associated with the Quasi-Biennial Oscillation and El Niño.

[17] The MJO could lead to improved intra-seasonal predictions of the North Atlantic Oscillation (NAO) on timescales exceeding one month. Previous studies on the MJO/NAO connection [e.g., *Cassou*, 2008; *L'Heureux and Higgins*, 2008; *Lin et al.*, 2009] examined lead times up to 2 weeks, presumably assuming that the MJO-excited poleward propagating Rossby waves are confined to the troposphere. However, the results of this study allude to another route, with a longer period, involving poleward and *vertical* Rossby wave propagation, alteration of the stratospheric polar vortex, and then downward coupling to the tropospheric NAO. This physical mechanism is similar to that proposed by *Bell et al.* [2009] and *Ineson and Scaife* [2009] with regards to El Niño's effect on the NAO. However, future work is necessary to confirm the importance of this mechanism for the connection between the MJO and the polar vortex/NAM.

[18] Unfortunately, many comprehensive general circulation models (GCMs) do not generate a sufficiently realistic MJO [*Lin et al.*, 2006], and therefore likely fail to reproduce this connection. While "super-parametrized GCMs" are capable of simulating the MJO, the computational costs of running such a model are high [*Randall et al.*, 2003]. We speculate that an accurate simulation of MJO variability in future comprehensive models might lead to improved variability of the Northern Annular Mode in both the stratosphere and troposphere.

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References

Baldwin, M. P., and T. J. Dunkerton (1999), Propagation of the Arctic Oscillation from the stratosphere to the troposphere, *J. Geophys. Res.*, *104*(D24), 30,937–30,946.

Baldwin, M. P., and T. J. Dunkerton (2001), Stratospheric harbingers of anomalous weather regimes, *Science*, *294*(5542), 581–584.

Baldwin, M. P., and D. W. J. Thompson (2009), A critical comparison of stratosphere-troposphere coupling indices, *Q. J. R. Meteorol. Soc.*, *135*, 1661–1672.

Bell, C. J., L. J. Gray, A. J. Charlton-Perez, M. M. Joshi, and A. A. Scaife (2009), Stratospheric communication of El Niño teleconnections to European winter, *J. Clim.*, *22*, 4083–4096, doi:10.1175/2009JCLI2717.1.

Cassou, C. (2008), Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation, *Nature*, *455*, 523–527, doi:10.1038/nature07286.

Charlton, A. J., and L. M. Polvani (2007), A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks, *J. Clim.*, *20*, 449–469, doi:10.1175/JCLI3996.1.

Cohen, J., and J. Jones (2011), Tropospheric precursors and stratospheric warmings, *J. Clim.*, *24*, 6562–6572, doi:10.1175/2011JCLI4160.1.

Garfinkel, C. I., and D. L. Hartmann (2007), Effects of the El Niño-Southern Oscillation and the Quasi-Biennial Oscillation on polar temperatures in the stratosphere, *J. Geophys. Res.*, *112*, D19112, doi:10.1029/2007JD008481.

Garfinkel, C. I., and D. L. Hartmann (2008), Different ENSO teleconnections and their effects on the stratospheric polar vortex, *J. Geophys. Res.*, *113*, D18114, doi:10.1029/2008JD009920.

Garfinkel, C. I., D. L. Hartmann, and F. Sassi (2010), Tropospheric precursors of anomalous Northern Hemisphere stratospheric polar vortices, *J. Clim.*, *23*, 3282–3299.

Garfinkel, C. I., A. H. Butler, D. W. Waugh, and M. M. Hurwitz (2012), Why might SSWs occur with similar frequency in El Niño and La Niña winters?, *J. Geophys. Res.*, doi:10.1029/2012JD017777, in press.

Hardiman, S. C., P. J. Kushner, and J. Cohen (2008), Investigating the ability of general circulation models to capture the effects of Eurasian snow cover on winter climate, *J. Geophys. Res.*, *113*, D21123, doi:10.1029/2008JD010623.

Hurwitz, M. M., P. A. Newman, and C. I. Garfinkel (2011), The Arctic vortex in March 2011: A dynamical perspective, *Atmos. Chem. Phys.*, *11*, 11,447–11,453, doi:10.5194/acp-11-11447-2011.

Hurwitz, M. M., P. A. Newman, and C. I. Garfinkel (2012), On the influence of North Pacific sea surface temperatures on the Arctic winter climate, *J. Geophys. Res.*, doi:10.1029/2012JD017819, in press.

Ineson, S., and A. A. Scaife (2009), The role of the stratosphere in the European climate response to El Niño, *Nat. Geosci.*, *2*, 32–36, doi:10.1038/ngeo381.

L'Heureux, M. L., and R. W. Higgins (2008), Boreal winter Links between the Madden Julian Oscillation and the Arctic Oscillation, *J. Clim.*, *21*, 3040–3050, doi:10.1175/2007JCLI1955.1.

Limpasuvan, V., D. W. J. Thompson, and D. L. Hartmann (2004), The life cycle of the Northern Hemisphere sudden stratospheric warmings, *J. Clim.*, *17*, 2584–2596.

Lin, H., G. Brunet, and J. Derome (2009), An observed connection between the North Atlantic Oscillation and the Madden-Julian Oscillation, *J. Clim.*, *22*, 364–380, doi:10.1175/2008JCLI2515.1.

Lin, J.-L., et al. (2006), Tropical intraseasonal variability in 14 IPCC AR4 climate models. Part I: Convective signals, *J. Clim.*, *19*, 2665–2690, doi:10.1175/JCLI3735.1.

Madden, R. A., and P. R. Julian (1994), Observations of the 40–50-day tropical oscillation—A review, *Mon. Weather Rev.*, *122*, 814–837, doi:10.1175/1520-0493(1994)122<0814:OOTDTO>2.0.CO;2.

Matsuno, T. (1971), A dynamical model of the stratospheric sudden warming, *J. Atmos. Sci.*, *28*, 1479–1494.

Nishii, K., H. Nakamura, and T. Miyasaka (2009), Modulations in the planetary wave field induced by upward-propagating Rossby wave packets prior to stratospheric sudden warming events: A case-study, *Q. J. R. Meteorol. Soc.*, *135*(638), 39–52, doi:10.1002/qj.359.

Polvani, L. M., and P. J. Kushner (2002), Tropospheric response to stratospheric perturbations in a relatively simple general circulation model, *Geophys. Res. Lett.*, *29*(7), 1114, doi:10.1029/2001GL014284.

Polvani, L. M., and D. W. Waugh (2004), Upward wave activity flux as a precursor to extreme stratospheric events and subsequent anomalous surface weather regimes, *J. Clim.*, *17*, 3548–3554.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski (2003), Breaking the cloud parameterization deadlock, *Bull. Am. Meteorol. Soc.*, *84*, 1547–1564, doi:10.1175/BAMS-84-11-1547.

Rienecker, M. M., et al. (2011), MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications, *J. Clim.*, *24*, 3624–3648, doi:10.1175/JCLI-D-11-00015.1.

Smith, K. L., C. G. Fletcher, and P. J. Kushner (2010), The role of linear interference in the annular mode response to extratropical surface forcing, *J. Clim.*, *23*, 6036–6050, doi:10.1175/2010JCLI3606.1.

Wheeler, M. C., and H. H. Hendon (2004), An all-season real-time multivariate MJO Index: Development of an index for monitoring and prediction, *Mon. Weather Rev.*, *132*, 1917–1932, doi:10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

Woollings, T., A. Charlton-Perez, S. Ineson, A. G. Marshall, and G. Masato (2010), Associations between stratospheric variability and tropospheric blocking, *J. Geophys. Res.*, *115*, D06108, doi:10.1029/2009JD012742.

Yoo, C., S. Feldstein, and S. Lee (2011), The impact of the Madden-Julian Oscillation trend on the Arctic amplification of surface air temperature during the 1979–2008 boreal winter, *Geophys. Res. Lett.*, *38*, L24804, doi:10.1029/2011GL049881.

Yoo, C., S. Lee, and S. B. Feldstein (2012), Mechanisms of extratropical surface air temperature change in response to the Madden-Julian Oscillation, *J. Clim.*, in press.