Reply

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Cohen et al. (2005, hereafter CESGS) have several related reactions to our paper (Limpasuvan et al. 2004, hereafter LTH). First, they focus on the tropospheric precursor signals in our composite map analysis of sudden stratospheric warmings (SSWs). Second, they call attention to previous work on the potential role of Eurasian snow cover in forcing or helping to sustain annular mode variations in the troposphere and stratosphere.

In Fig. 9 of LTH, we show 1000-, 250-, and 50-hPa composite geopotential height anomaly charts for the Northern Hemisphere during the onset, growth, mature, decline, and decay phases of SSWs based on key dates derived from the leading principal component time series of zonal wind anomalies at 50 hPa. Each of the phases is on average about 2 weeks long, so the total cycle from onset to decay is about 2.5 months. The main feature of interest in Fig. 9 of LTH is that the 1000-hPa signal is better defined after the stratospheric event than before and that it is at least as persistent after the event as the accompanying stratospheric anomalies. The structures of the anomalies in the stratosphere and troposphere during and after the mature stage are very similar to the Northern Hemisphere annular mode (NAM; i.e., the North Atlantic Oscillation and Arctic Oscillation).

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It has been long established from diagnostic and modeling studies that stratospheric warming events are driven by waves originating in the troposphere (e.g., Reed et al. 1963; Matsuno 1971; Schoeberl 1978), but the idea that stratospheric warmings can induce long-lasting responses in tropospheric weather is relatively new (Baldwin and Dunkerton 1999). The structure and amplitude of annular mode variability in the Northern and Southern Hemispheres can be simulated in models with fixed surface conditions and without stratospheres (Limpasuvan and Hartmann 2000). Annular modes appear then to be natural internal modes of variability driven largely by wave–mean flow interaction in the troposphere (Lorenz and Hartmann 2001; Lorenz 2003). Nonetheless, annular mode variability seems to capture much of the interaction between the stratosphere and the troposphere on long time scales (Thompson and Wallace 1998). Another point of LTH is that, while persistent tropospheric signals appear to occur in association with stratospheric warmings, the shifts in the tropospheric circulation are driven by eddies with much shorter zonal scales than the planetary waves that drive the stratospheric warming in the first place.

Some apparently statistically significant (using a priori statistics) structures do appear in the troposphere during the onset stage, and these are the focus of CESGS. While these features are interesting, we do not have a framework with which to interpret them, or an a priori reason to expect the particular structures found. Also the patterns found in the onset phase do not persist or transition naturally to the patterns found in the growth phase. For these reasons, in LTH, we chose not to interpret these structures.

We are aware that stratospheric warmings are preceded by anomalous planetary wave forcing in the troposphere. However, we can think of three reasons why it would be surprising to find a coherent precursor pattern in the tropospheric circulation. First, stratospheric warmings are associated with an enhanced upward wave flux associated with planetary waves of zonal wavenumbers 1 or 2, but the specific geographic source of these waves may vary considerably from one warming episode to the next. Second, the waves that give rise to sudden warmings are traditionally attributed to topography or land–sea thermal contrasts, and it is unclear whether a localized source in the lower troposphere is capable of generating waves with sufficiently long wavelengths to perturb the stratospheric flow. Finally, the occurrence and characteristics of stratospheric warmings are particularly sensitive to the preexisting state of the stratosphere (McIntyre 1982), and thus the same pattern of planetary wave flux may only occasionally give rise to a stratospheric warming, and very different tropospheric planetary wave patterns may induce warmings if the stratosphere is properly preconditioned.

CESGS suggest that the upper-right panel in Fig. 9 of LTH supports their hypothesis that the initiation of changes in the NAM comes from Eurasian snow cover anomalies occurring earlier in the year. The pattern in that panel has high pressure over Europe and low pressure over Alaska and Canada. No signal appears over Siberia, as in the reference suggested by CESGS (Cohen et al. 2001). The correspondence between the anomalies in our onset phase and the structure of anomalies suggested for snow-cover-driven anomalies is not great. While Kuroda and Kodera (1999) show precursory upward wave fluxes over Eurasia (their Fig. 3), the primarily wave structure they find in the troposphere through their singular value decomposition (SVD) between zonal wind and vertical eddy flux is over the Atlantic Ocean sector (their Fig. 2).

CESGS also refer to Gong et al. (2003), who compute the response to Eurasian snow cover anomalies using a global climate model to compute the response to differences in Siberian snow cover corresponding to the extreme years of 1976 and 1988 (high and low snow, respectively). The model shows an increase in vertical wave activity flux over Siberia in the vicinity of the snow anomaly and a slight decrease in the intensity of the polar night jet ($\sim$4 m s^{-1} at 10 hPa). While this response may indeed be significant, it is small, and we believe it is likely that many other factors are more important. Moreover, on the time scales of months and seasons of interest here, signals are communicated globally and it is difficult to localize the causes of flow patterns that are strongly interconnected across the hemisphere.

Snow cover depends strongly on the current and preceding weather patterns and surface temperature, so a simple correlation between snow cover and weather anomalies does not necessarily imply that snow cover is forcing weather. Although the snow cover anomalies in September–October–November (SON) appear to presage changes in flow conditions that occur in December–January–February (DJF), it is possible that both are responding to other factors that simply have a long time scale. For example, the response to SST anomalies will be different in each season, even if the SST anomalies remain constant. An example would be an ENSO warm event, which might have a long-lasting and slowly varying SST signature to which the extratropics responds very differently during fall than winter. A persistent anomaly may express itself as early snowfall in Eurasia during SON but, after the snow cover has reached its seasonal maximum in DJF, manifest itself as an anomaly in the annular mode structure. The annular mode anomaly follows the snow cover anomaly in time but is not forced by it.

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