Triggering of sudden stratospheric warming in a stratosphere-mesosphere model by impulsive regional ozone perturbations

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Introduction

A number of natural phenomena affect the distribution of stratospheric ozone, in turn contributing to the variability of the atmosphere and climate. Solar proton events (SPEs) and transient luminous events (TLEs) are examples of impulsive processes that affect the chemistry of the stratosphere (e.g. [1] Jackman et al. 2004, [2] Arnone et al. 2008) on timescales from hours to days, in contrast to more gradual changes induced by the seasonal cycle or by anthropogenic emissions injected from the troposphere. Because of the non-linearities exhibited by stratospheric dynamics e.g. as sudden stratospheric warmings (SSWs), we investigate under what conditions the response to these impulsive perturbations can be amplified and contribute to the observed winter stratosphere variability. In this study we present the preliminary results of idealised impulsive SPE-like perturbation experiments performed on a radiative-dynamics model of the middle atmosphere. TLE perturbations require a coupled chemistry-dynamics approach and will be the subject of future work.

The model

We used an updated version of the original U.K. Met. Office StratosphereMesosphere Model (SMM) ([3] Austin and Butchart, 1992). The model was succesfully adopted in studying the dynamically driven winter Arctic stratosphere (e.g. [4] Gray et al., 2003). The SMM has 32 vertical levels equally spaced in logpressure with a resolution of 0.125 hPa (about 2 km), ranging from 316 to 0.03 hPa, and a horizontal resolution of 5×5 degrees. We forced the model at its lower boundary with NCEP/NCAR reanalysis geopotential heights from 1962 to 1984 to reproduce the natural variability induced by tropospheric planetary waves. Climatological distributions of trace gases used in the radiation scheme were from pre-ozone hole conditions.

Variability at the Arctic

The use of realistic lower boundary forcing induces a degree of planetary wave activity and temperature interannual variability in the model extra-tropical stratosphere which are in good agreement with those observed (ERA40). Under full lower boundary forcing (black line of Figure 1), SSWs realistically occur in many winters that have a weak vortex mode.

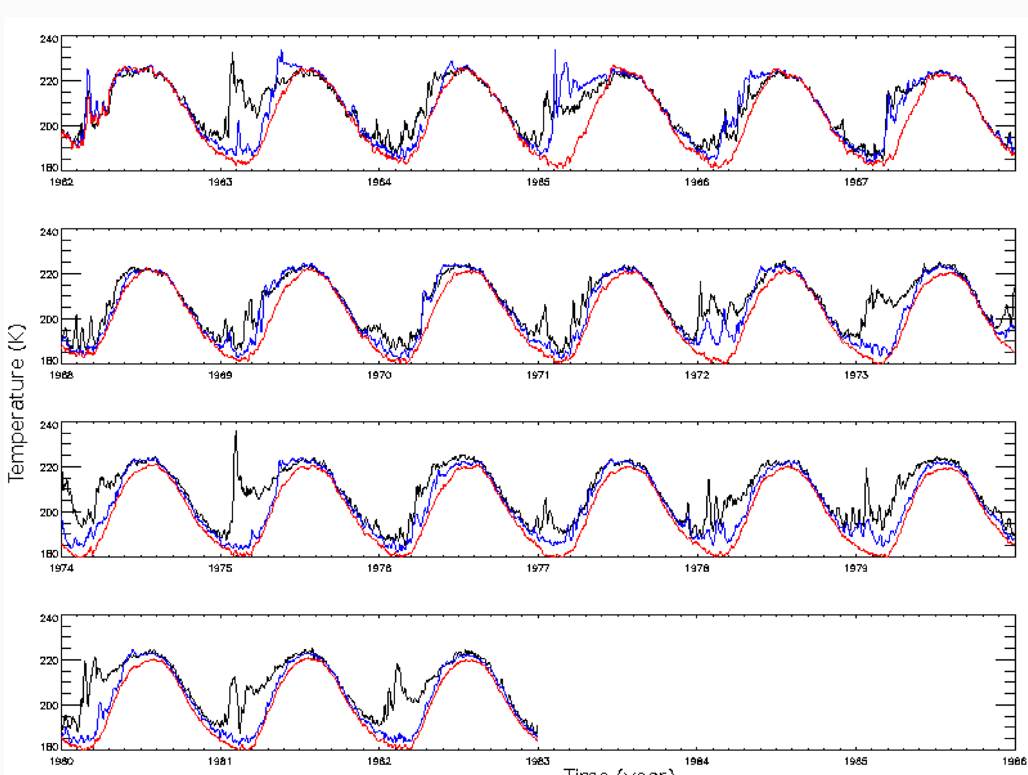

Figure 1: Time series of the Arctic temperature at 56 hPa. The experiment with a full amplitude of the lower boundary forcing (black) is shown together with that having 80% of the forcing (blue) and a 50% reduced one (red).

Reducing the forcing to 80% of the observed amplitude (blue line) strongly decreases the number of winters with SSWs, and a reduction down to 50% (red line) sets all model Arctic winters into a strong vortex mode with the disappearance of all SSWs, and a much colder mean temperature. In the range 80% to full planetary wave forcing some of the winters sets at the edge between a weak and strong vortex mode so that even small changes in the propagation of the waves can significantly alter the dynamical behaviour of the Arctic stratosphere.

Regional ozone perturbation

We studied the model response to a number of increasingly more complex constant-in-time ozone perturbations. In radiatively driven regions, uniform ozone reductions showed a linear temperature response when applied with a magnitude of the ozone reduction of less than 20%. In this linear-regime range, regional ozone perturbations imposed at different heights and latitude led to larger non-local dynamically driven changes because of the stronger local temperature gradients.

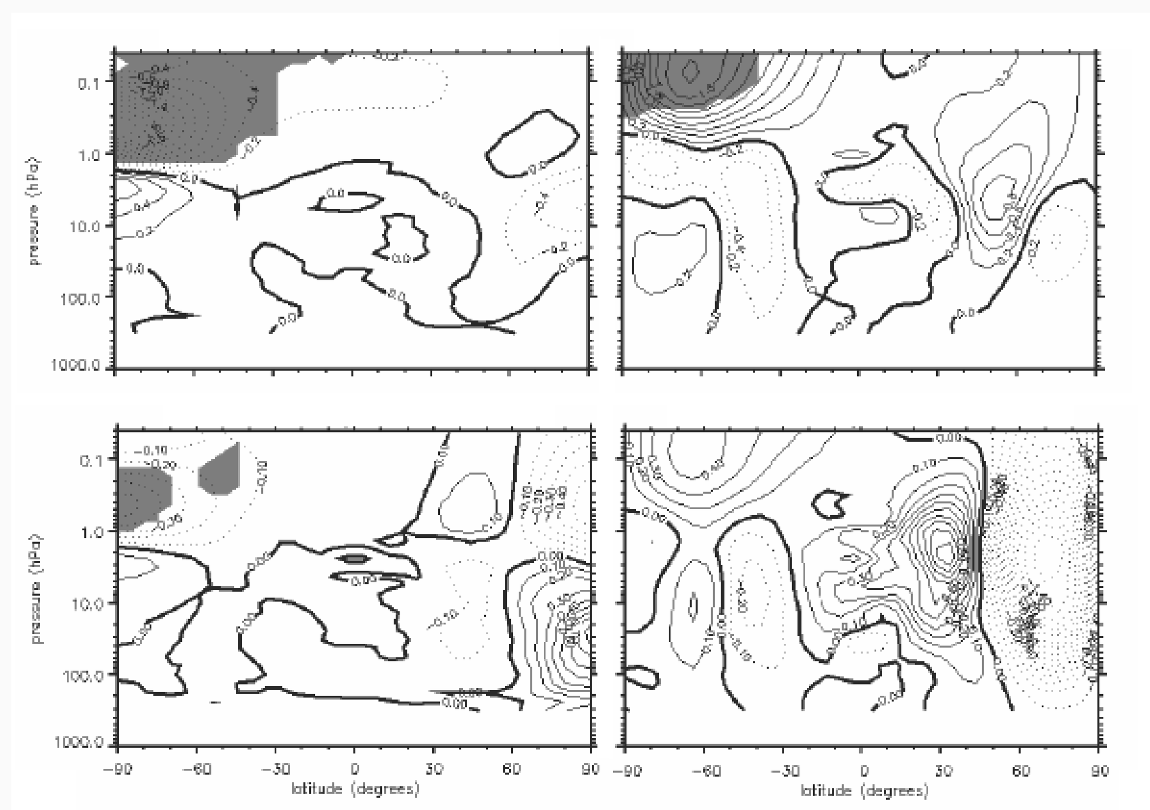

Figure 2: Temperature (left) and zonal wind (right) responses to a 10% polar stratopause ozone reduction applied constantly in time (top) or impulsively every 4 days (bottom). Statistically significant changes of the mean are shaded.

Applying an idealised SPE-like ozone reduction by 10% at the polar stratopause led to the winter temperature and zonal wind responses shown in figure 2 (top panels). Only the region above 1 hPa and south of 30 S showed a statistically significant shift of the mean (shaded areas). The winter Arctic showed only minor changes compared to the control experiment. Clearly, these are very weak imposed ozone changes, corresponding to about 0.4% reduction of total ozone column.

In order to improve the simulation of the sporadic occurrence of SPEs, the same perturbation was applied impulsively every 4 days and led to much larger changes in the dynamically driven winter Arctic (Figure 2 – bottom panels). Even though these changes are not statistically significant (because of the large natural variability), they show a large sudden warming signature (increase in temperature and decrease in wind).

Triggering of sudden warmings

Figures 3 and 4 show the temperature timeseries for the two perturbed experiments described (red) compared to the control experiment (black). The impulsive experiment was found to be more efficient in altering the onset of SSWs compared to the constant in time experiment (green shades indicate winters showing larger differences).

In the impulsive experiment, in 4 out of 19 model years the yearly mean temperature was warmer than that of the constant experiment by at least 1 K, and 8 years showed the temperature standard deviation larger than that of the constant experiment by at least 0.5 K. Quite surprisingly, these changes were caused by an impulsive perturbation which is equivalent to a constant ozone column reduction by only 0.1%.

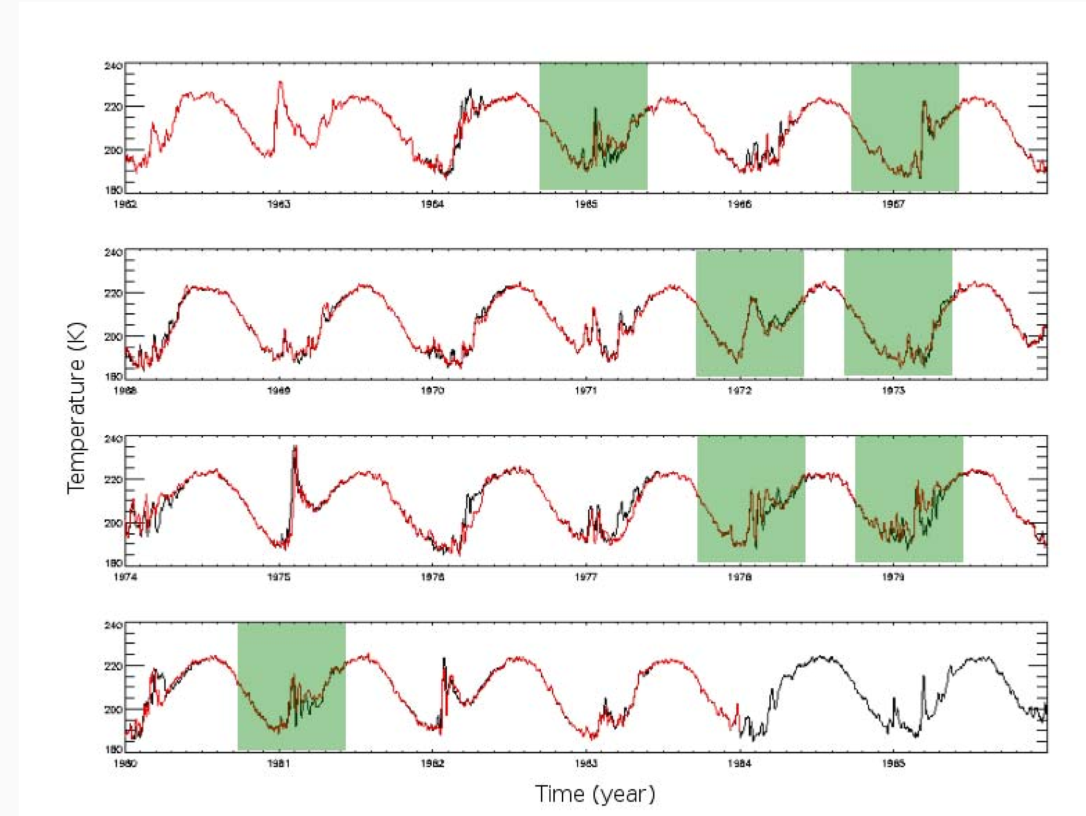

Figure 3: Timeseries of the Arctic temperature at 56 hPa for the 10% polar stratopause constant in time perturbation experiment (red) and for the control experiment (black).

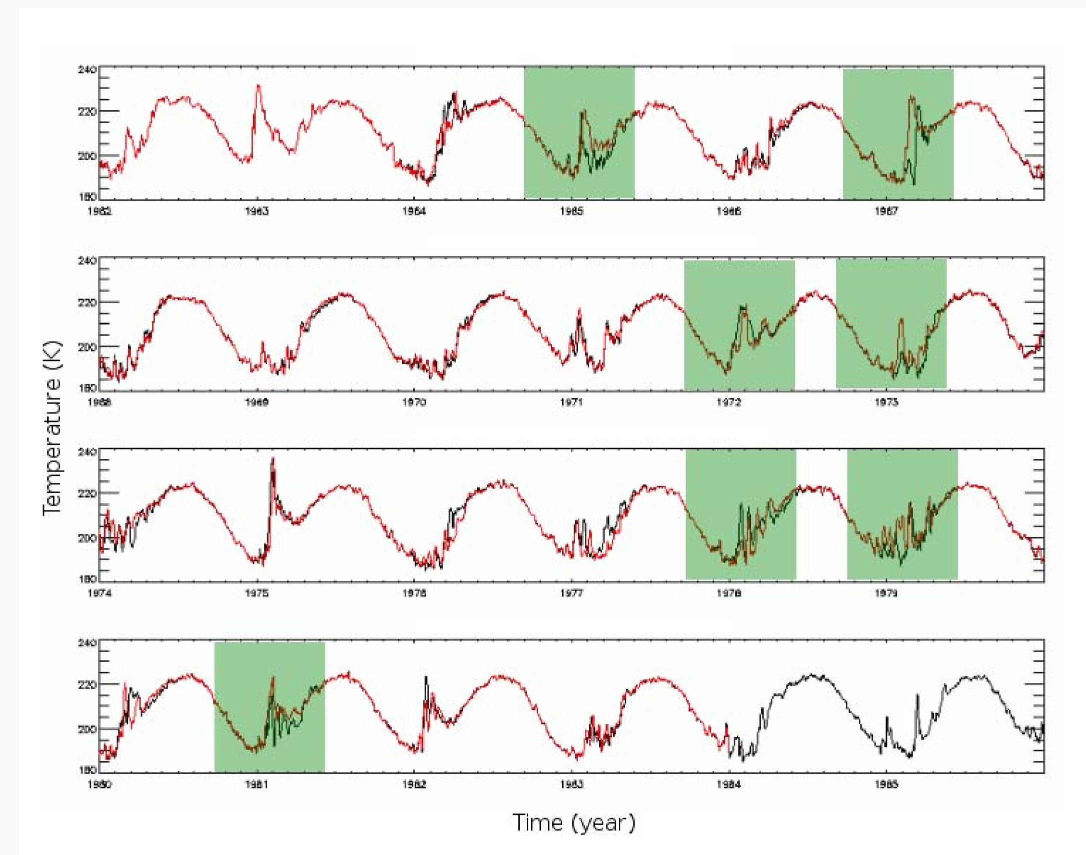

Figure 4: As Figure 3 but for the impulsive perturbation applied every 4 days.

Summary and Future Work

The impulsive ozone perturbation experiment we performed showed that during winters that have not a definite strong or weak vortex mode, even very small ozone perturbations can significantly alter the onset of SSWs. On the contrary, large SSWs during weak vortex winters seem not to be altered by small perturbations. This suggests that the occurrence of a SPE at a particularly unstable time may trigger large temperature changes in the Arctic stratosphere, then affecting the yearly temperature mean. Further work will be dedicated to the reproduction of these experiments on AGCMs, together with an attempt to estimate the relevance of TLE perturbations.

References

[1] C. H. Jackman and R. D. McPeters. The effect of solar proton events on ozone and other constituents. In Judit M. Pap and Peter Fox, editors, *Solar Variability and Its Effects on Climate*, page 305. A.G.U., 2004.

[2] E. Arnone, A. Kero, B. M. Dinelli, C.-F. Enell, N. F. Arnold, E. Papandrea, C. J. Rodger, M. Carlotti, M. Ridolfi, and E. Turunen. Seeking sprite-induced signatures in remotely sensed middle atmosphere NO_2. *Geophys. Res. Lett.*, 35:5807–+, 2008.

[3] J. Austin and N. Butchart. A three-dimensional modeling study of the influence of planetary wave dynamics on polar ozone photochemistry. *J. Geophys. Res.*, 97:10165, June 1992.

[4] L. J. Gray, S. Sparrow, M. Juckes, A. O'Neill, and D. G. Andrews. Flow regimes in the winter stratosphere of the northern hemisphere. *Quarterly Journal of the Royal Meteorological Society*, 129:925–945, January 2003.