Adv. Geosci., 13, 37–43, 2008
www.adv-geosci.net/13/37/2008/

Advances in Geosciences

An estimate of the impact of transient luminous events on the atmospheric temperature

E. Arnone[1,*], **P. Berg**[2], **N. F. Arnold**[1], **B. Christiansen**[2], **and P. Thejll**[2]

[1]Physics and Astronomy, University of Leicester, Leicester, UK
[2]Danish Meteorological Institute, Copenhagen, Denmark
[*]now at: Department of Physical and Inorganic Chemistry, University of Bologna, Bologna, Italy

Received: 6 December 2006 – Revised: 20 March 2008 – Accepted: 2 September 2008 – Published: 22 September 2008

Abstract. We present an order of magnitude estimate of the impact of sprites and other transient luminous events (TLEs) on the atmospheric temperature via ozone changes. To address the effects of expected TLE-ozone changes of at most a few percent, we first study the linearity of the radiatively driven response of a stratosphere-mesosphere model and of a general circulation model (GCM) to a range of uniform climatological ozone perturbations. The study is limited to Northern Hemisphere winter conditions, when planetary wave activity is high and the non linear stratosphere-troposphere coupling can be strong. Throughout most of the middle atmosphere of both models, the radiatively driven temperature response to uniform 5% to 20% ozone perturbations shows a close-to linear relationship with the magnitude of the perturbation. A mid-latitude stratopause ozone perturbation is then imposed as an idealised experiment that mimics local temperature gradients introduced by the latitudinal dependence of TLEs. An unrealistically high 20% magnitude is adopted for the regional ozone perturbation to obtain statistical significance in the model response. The local linearity of the radiatively driven response is used to infer a first order estimate of TLE-induced temperature changes of the order of 0.015 K under typical conditions, and less than a peak temperature change of 0.3 K at 60–70 km height in coincidence of extraordinarily active TLE-producing thunderstorms before horizontal mixing quickly occurs. In the latter case, dedicated mesoscale modelling is needed to study the relevance of regional non linear processes which are expected to impact these radiatively driven responses.

1 Introduction

A number of natural phenomena affect the distribution of middle atmosphere ozone, which in turn induces a degree of variability in the atmosphere and climate. The seasonal cycle causes changes up to 30% in total ozone at high latitude. Gradual variations produced by the solar cycle UV changes, or oscillations such as the quasi-biennial oscillation and El Niño can induce changes of a few percent in stratospheric ozone. Anthropogenic chlorofluorocarbons lead to ozone depletion in the lower stratosphere and to the so called ozone hole in the Southern Polar spring. Besides cyclic changes, impulsive processes such as large solar proton events lead to sporadic large ozone reductions in the polar regions (see Wayne, 2000, for a review of stratospheric ozone perturbations). Recently, growing attention has been paid to the possible chemical impact of transient luminous events (TLEs), electrical discharges which occur in the middle atmosphere in coincidence of intense tropospheric thunderstorms (see e.g. Neubert et al., 2003, 2008).

Enell et al. (2008) used an ion-chemistry model to estimate the chemical impact of sprites and found them to induce negligible global changes, but local changes of up to 500% on atmospheric NO_x over extremely intense thunderstorms. Their typical case led to a few tens of percent change in NO_x, in agreement with the calculations by Sentman et al. (2008). The corresponding changes in ozone were found to be globally negligible, and possibly at most a few percent over extraordinarily active sprite-producing thunderstorms. These estimates are compatible with a possible local sprite signature found in remotely sensed middle atmosphere NO_2 by Arnone et al. (2008), and by the lack of a corresponding global signal (Arnone et al., 2008; Rodger et al., 2008).

Even though these ozone changes are globally negligible, the interest in studying the radiative and dynamical response of the middle atmosphere to small localised ozone perturbations arises from the evidence of non linear wave-driven

---

Correspondence to: E. Arnone
(arnone@fci.unibo.it)

mechanisms that can amplify the atmospheric response and couple the middle atmosphere to the troposphere (Haynes, 1991; Baldwin and Dunkerton, 1999; Christiansen, 2001). Moreover, the major contribution to the observed lower stratosphere cooling over the last decades is due to reductions of ozone (WMO, 2006) which is thus the driver of such a dynamically disturbed atmospheric region.

In this paper, we describe the temperature and zonal wind response of two atmospheric models to an imposed 20% regional mid-latitude stratopause perturbation that mimics the distribution of observed TLEs. We use a stratosphere-mesosphere model and an atmospheric general circulation model (GCM) as described in Sect. 2. The description of the ozone reduction experiments is given in Sect. 3. The linearity of the local radiatively driven response is studied with a series of uniform ozone perturbations and used to infer the impact of TLEs on the basis of the regional experiment. In Sect. 4, we discuss the results of these experiments. Conclusions are given in Sect. 5.

2 The models

The experiments are performed with a radiative-dynamic stratosphere-mesosphere model with a high resolution in the middle atmosphere, and with an atmospheric GCM that covers the troposphere-lower stratosphere region and extends at a lower resolution into the low mesosphere.

The first model is the Stratosphere-Mesosphere Model (SMM), originally derived from the UK Met Office (Austin and Butchart, 1992). A number of previous investigations have shown the validity of this model in studying the radiative and dynamical behaviour of the middle atmosphere (O'Neill and Pope, 1988; Austin et al., 1992; Arnold and Robinson, 2000; Gray et al., 2003). The SMM has 32 vertical levels equally spaced in log-pressure 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. The model is forced at the lower boundary by 300 hPa geopotential heights. We use a set of NCEP/NCAR reanalysis geopotential heights that were filtered, keeping only the mean and the first three planetary waves to guarantee model stability on long term experiments from 1962 to 1984 (see details in Berg et al., 2007). The radiation scheme accounts for carbon dioxide, ozone and water vapour in the longwave range, and for diatomic oxygen and ozone in the shortwave range over six spectral bands (Strobel, 1978; Shine, 1987). Climatological distributions of these trace gases from the seventies are used in order to be consistent with the lower boundary forcing and to be in pre-ozone hole conditions. Even though the SMM is a simple model compared to state-of-the-art GCMs, the adopted version forced with NCEP geopotential heights showed a close reproduction of the observed (NCEP/ERA40) planetary wave activity and interannual variability, which most current GCMs struggle to reproduce.

The atmospheric GCM used is cycle 14 of the ARPEGE model from Météo France (Déqué et al., 1994; Christiansen et al., 1997). It has 41 vertical levels, with a high resolution in the low to middle stratosphere, about 1–2 km, but only few levels in the high stratosphere to low mesosphere. The horizontal resolution is the same as for the SMM, i.e. 5×5 degrees. The sea-surface temperatures and sea-ice are in a prescribed climatological state. The radiation scheme (Morcrette, 1991) calculates longwave cooling over six bands and shortwave heating over 2 bands (UV/visible and near-infrared). Constants for a linear parameterization of the ozone mixing ratio are calculated using photochemical sources and sinks in a 2-D stratospheric model with pre-ozone hole conditions. The climatology of the ozone is similar to that used in the SMM, and drifts from the climatology due to the perturbations in this study are small. Model temperatures above 0.7 hPa are relaxed to a climatological state.

3 The experiments

The experiments were performed by reducing the climatological ozone fed to the radiation schemes, with no (or low for ARPEGE) feedback on the ozone distribution itself. This approach limits the degrees of freedom of the system and allows a clearer interpretation of the dynamical response.

Firstly, uniform ozone reductions by 5%, 10% and 20% were applied to both models to investigate the linearity of the model response at different magnitudes of the perturbation. For clarity we label these experiments respectively SMM_U5, SMM_U10 and SMM_U20 for the SMM, and ARP_U5, ARP_U10 and ARP_U20 for ARPEGE. On the SMM we used 20 model year runs with full seasonal cycle and NCEP lower boundary forcing from 1965 to 1984 (1962–1964 were used as a spin up and discarded). We limited the study to boreal winter conditions when the northern polar region is strongly affected by dynamical activity, and the troposphere-stratosphere coupling can be strong. ARPEGE was used in perpetual January mode to produce the equivalent of 20-year model runs to be consistent with previous studies and limit computing time (e.g. Christiansen et al., 1997). The differences of ARPEGE in perpetual January mode compared to the January mean state of the full seasonal cycle mode were investigated for temperature and zonal winds and were found to be less than one percent throughout the stratosphere.

The regional experiment was then performed perturbing the climatological ozone of both models with a 20% perturbation localised in the mid-latitude upper stratosphere. The perturbation was applied imposing a double Gaussian latitudinal profile centred at 45° S and 45° N, and extending over a few grid points latitude (standard deviation equals to 4 model grid points or 20 degrees latitude), and further imposing a Gaussian vertical profile centred at 1.0 hPa (with a standard deviation equal to 5 model levels or about 10 km,

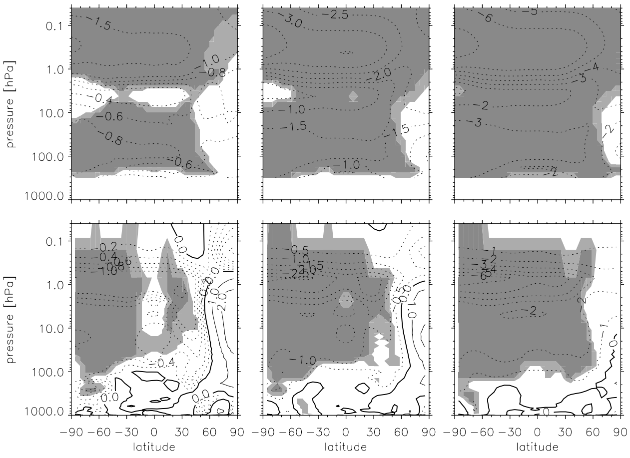

Fig. 1. Zonal mean difference in temperature (K) between perturbed experiments and control experiments for the SMM (top panels) and the ARPGE GCM (bottom panels). A uniform ozone reduction was applied with magnitudes 5%, 10% and 20% (left to right). Statistically significant changes at 99% level are shaded in grey (95% light grey).

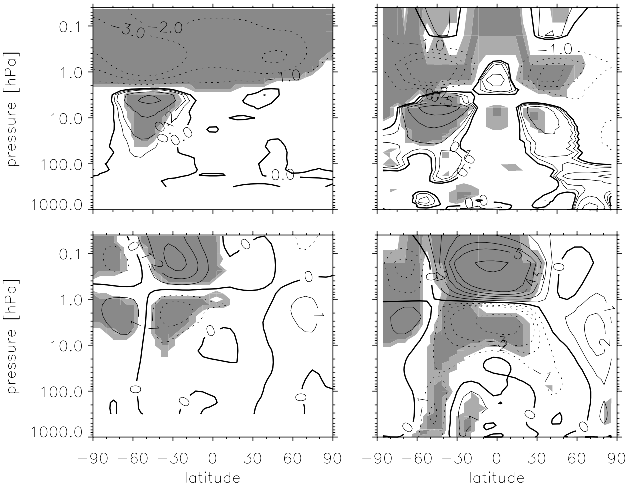

Fig. 2. Zonal mean difference between the regional (mid latitude 1hPa region) 20% ozone perturbations and the control experiments for the SMM (left) and for the ARPGE GCM (right). The responses in temperature (K – top) and zonal winds (m/s – bottom) are shown. Statistically significant changes at 99% level are shaded in grey (95% light grey).

thus away from the model upper boundary). We label these experiments SMM_MM20 and ARP_MM20. Since TLEs are sub-grid phenomena and cannot be directly modelled, the applied perturbation mimics their overall impact above active mid-latitude regions where TLEs are most observed (see e.g. Lyons, 2006): efficient zonal transport leads to the adopted zonally homogeneous distribution over timescales of a few days.

The perturbation experiments were compared to the corresponding unperturbed control experiment. A Student's t-test of the mean was applied to the perturbed and control runs to investigate the significance of the model responses to the perturbations. We refer to a difference as significant when it is above the 99% significance level.

4 Results and discussion

The experiments and main results are summarized in Table 1. The results for the 5, 10 and 20% uniform ozone reduction experiments are shown in Fig. 1. The figure shows the zonal mean temperature difference between perturbed runs and the control run. Figure 2 shows the temperature and zonal wind response of the two models to the regional perturbation experiment. All results shown are for Northern Hemisphere winter (SMM) and perpetual January (ARPEGE), with the 99% level of statistical significance shaded in grey (95% in light grey).

The changes applied to the ozone field cause a change of the short-wave UV absorption and of the long-wave emission/absorption, which affect the heating rates. Following earlier studies of ozone perturbations (e.g. Fels et al., 1980), we discuss the results in terms of "radiative" and "dynamical" responses of the atmosphere, under the assumption that the atmospheric shortwave heating and longwave cooling (whose sum is the net radiative heating) are equilibrated by dynamical heating and cooling according to the first law of thermodynamics. In fact, internal energy changes can be neglected on the time scales we study, and phase transitions of water are absent in the relatively dry stratosphere (Christiansen et al., 1997). "Radiative" refers thus to atmospheric adjustments that do not involve any dynamical heating or cooling; "dynamical" implies dynamical changes needed to balance a change in the net heating rates. The radiative responses of this study are equilibrium responses after temperature adjustment: in the case of longwave cooling these do not directly relate to the instantaneous radiative forcing.

4.1 The temperature response of the stratosphere-mesosphere model to the uniform perturbations

As shown in Fig. 1 (top panel), most of the middle atmosphere temperatures respond to the ozone perturbations in a linear way, mainly through radiative changes. This is evident in the SMM where most regions with direct sunlight (thus where TLE ozone perturbations occur, assuming a persistence from night-time to day-time) show significant changes resembling the patterns of the UV heating rates (not shown). The peak temperature response of -1.8 K (SMM_U5), -3.9 K (SMM_U10) and -8.1 K (SMM_U20) at 1.0 to 0.2 hPa show a close-to linear dependence on the magnitude of the perturbation. Interestingly, even a 5% ozone perturbation causes temperature changes that are significant

Table 1. Ozone reduction experiments performed on the SMM and the ARPEGE GCM. The name of the experiment (columns from the left), the percentage of ozone reduction, the peak temperature change, an indication of the qualitative response of the winter North Pole and of the troposphere are shown. See text for details.

Experiment	Ozone perturbation	Peak temperature change (K)	Significant changes in the North Pole	Significant changes in the troposphere
SMM_U5	Uniform 5%	−1.8	above 0.1 hPa	–
SMM_U10	Uniform 10%	−3.9	above 1.0 hPa	–
SMM_U20	Uniform 20%	−8.1	above 2.0 hPa and at 200 hPa	–
SMM_MM20	1 hPa Mid-latitude 20%	−3.9	above 0.3 hPa	–
ARP_U5	Uniform 5%	−1.7	none	none
ARP_U10	Uniform 10%	−3.2	none	50° S/40° S
ARP_U20	Uniform 20%	−6.8	none	70° S/60° S
ARP_MM20	1 hPa Mid–latitude 20%	−4.8	none	70° S/Equator and NP in winds

in a large part of the middle atmosphere with the exception of the dynamically driven winter pole and of a layer at 3.0 hPa. Ozone perturbations of only a few percent can thus lead to significant changes when applied to radiatively driven regions of the atmosphere, with roughly 0.4 K peak temperature decrease per percentage of ozone change at 0.3 hPa. The low significance of the changes at 3.0 hPa arises due to the competition of the cooling induced by locally reduced ozone and to the increased UV flux due to the reduced ozone in the upper layers (see regional experiment in Sect. 4.3). The region of strong cooling that appears at 100 hPa is likely due to the lack of tropospheric feedback – however detailed investigation of this issue is subject for a separate study.

The winter pole shows an increasingly stronger response (Fig. 1, left to right) which becomes significant over a larger altitude range with increasing magnitude of the perturbation. In the SMM_U20 experiment, the only low-significant region is the winter Hemisphere north of 70° N, between 200 and 3 hPa. This region is affected by sudden stratospheric warmings and thus has very high variability which can bury any small change induced by perturbations (Kodera, 1995). There is a convincing similarity in the patterns in the temperature response of the northern polar stratosphere to perturbations of different magnitudes: this suggests that the changes induced by uniform perturbations of different magnitude are driven by the same dynamical mechanism, however they can be too weak to be significant in an experiment of this limited length.

4.2 The temperature response of the general circulation model to the uniform perturbations

The behaviour shown by the ARPEGE GCM (Fig. 1, bottom panels) is similar to that of the SMM. The temperature response of −1.7 K (ARP_U5), −3.2 K (ARP_U10) and −6.8 K (ARP_U20) scales close-to linearly with the magnitude of the ozone perturbation.

There are some important differences compared to the SMM results. First of all, the relaxation to prescribed temperatures above 0.7 hPa prevents the lower mesosphere temperature response from decreasing as much as in the SMM. The temperature response of the two models is similar just below 1 hPa where the relaxation has no direct effect. Secondly, ARPEGE shows a much lower significance in the winter hemisphere, suggesting a weaker dynamical response. Indeed, none of the 5% to 20% ozone perturbations cause significant changes in the region north of 60° N. The lower vertical resolution might dampen the dynamical response to the perturbation (e.g. Polvani and Kushner, 2002). Moreover, inspection of the divergence of the Eliassen Palm (EP)-flux in ARPEGE suggests that the planetary wave forcing is weaker in ARPEGE compared to the SMM and to observations. An investigation on shorter length experiments shows that the extent of the significant region depends on the length of the experiment, i.e. on the number of independent data points in the t test, but that the two models maintain their main differences (not shown). The extent of the significant region is affected by the reduced number of years of the experiment in a similar fashion as it is affected by the reduced magnitude of the perturbation in the range 20% to 5% (see Fig. 1 right to left).

Surprisingly, the low-significant response in the winter pole shows patterns which are consistent in the different perturbation runs. There is an increased capability of the perturbation to reduces the positive temperature response (+2.4 K at 5%, Fig. 1 bottom-left) to a negative response (about −1 K) in the 20% ozone reduction experiment (Fig. 1 bottom-right). The SMM shows a similar behaviour in the winter pole during the first few years of the experiment: the positive change dominates the winter pole and disappears after a few years (not shown). Indeed comparison to NCEP/ECMWF temperature reanalysis data shows that the SMM reproduces the observed interannual variability well, while in ARPEGE the variability is much lower (not shown). Moreover, inspection of the divergence of the EP-flux and of the mass stream function shows that the SMM models the wave activity well (see Berg et al., 2007) while in ARPEGE this is weaker by a factor five (not shown). Therefore, it is not surprising that a weaker wave activity in ARPEGE leads to a weaker non-local response in the winter pole, which should be taken into account while discussing the non linear components of the response to the regional experiment (see Sect. 4.3). Below 100 hPa the two models show a large difference between their peak temperatures: this is the largest temperature difference between the two models and is likely to be induced by the absence of tropospheric feedback in the SMM.

The ARPEGE GCM shows signs of significant temperature changes down into the troposphere, between 70° S and 40° S. A tongue of negative change at 60° S next to a weak positive change at 40° S is consistent in all experiments ARP_U5, ARP_U10 and ARP_U20. Interestingly, in a 50% ozone reduction experiment (not shown) this tongue of tropospheric temperature changes vanishes leading to completely different patterns of temperature changes, mostly non significant. Zonal wind changes follow a similar behaviour, with larger changes in the uniform 20% ozone reduction experiment than in the 50% one. This suggests a non-linearity in the non-local response of the troposphere where the stronger 50% perturbation leads to a weaker response compared to the 20% perturbation.

4.3 The regional mid-latitude upper-stratosphere perturbation

The uniform perturbation experiments described in the previous sections show that the temperature response scales close to linearly with the magnitude of the ozone perturbation in sunlit conditions while it behaves non linearly in the winter pole and in the troposphere. Here we study the response of the two models to the regional mid latitude upper stratosphere perturbation described in Sect. 3 and investigate whether limiting the latitudinal and height extent of the perturbation can induce a different local and tropospheric response.

This idealised experiment is suggested by the TLE impact on ozone discussed by Enell et al. (2008). TLEs are caused by thunderstorm activity and their occurrence is typically seasonally limited to a latitude band in the summer hemisphere: the most common observations occur over the midlatitudes where TLE-triggering mesoscale convective systems more easily develop (Lyons, 2006). Here we impose a perturbation both in the summer hemispheres (where the stronger TLE activity is expected) but also in the winter hemisphere so to understand the impact of the weaker TLE activity in the winter Northern Hemisphere mid latitudes. The sub-model grid extent of these phenomena lead us, to a first order approximation, to consider their global impact in a collective manner, which is zonally homogeneous on time scales longer than a few days.

The results of the regional experiment performed with the SMM (SMM_MM20) and the ARPEGE GCM (ARP_MM20) are shown in Fig. 2. The local temperature response, i.e. within the region perturbed, is fairly similar in the two models as shown by the peak temperature reduction of about 3 K centred at 1 hPa (50 km height) at 45° S and 45° N. The increase in temperature below the perturbed region is induced by a higher UV flux now reaching deeper into the atmosphere. The ARPEGE response is almost symmetrical in the two hemispheres while the SMM response lack the heating below the perturbed region in the Northern Hemisphere. As in the case of the winter pole in uniform perturbations, the SMM non-local response is stronger than in ARPEGE, leading the former to have a temperature change in the upper stratosphere which spreads across the whole latitude range. On the contrary, ARPEGE shows a much more localised response in the upper stratosphere.

The change in the zonal winds is very similar in the Southern Hemisphere upper stratosphere of the two models but resemble the difference in the temperature response in the Northern Hemisphere: the SMM response shows almost no changes in the polar night jet (PNJ) while ARPEGE shows a PNJ response which is almost symmetrical to the summer Hemisphere jet response. In the lower stratosphere, the SMM shows no response while ARPEGE has been affected down to the troposphere: the lack of an interactive troposphere inhibits any response in the stratosphere-troposphere coupling in the SMM.

In the troposphere, the regions of significant changes that appear in both temperature and winds are different and/or larger than in the uniform experiments (winds for the ARP_U20 are not shown). Interestingly, the significant positive response in the tropospheric winds at 60°–30° S in the regional ARP_MM20 (shown in Fig. 2) is opposite in sign to the significant negative response in the uniform ARP_U20 experiment. The localisation of the perturbation at mid latitudes and in the upper stratosphere has introduced temperature gradient changes which are larger than in the uniform perturbation, thus leading to larger zonal wind changes and larger non-local responses. This experiment shows that the changes in temperature and winds in the troposphere in the regional experiment have no relation with those in the uniform perturbation experiment.

A linear scaling of the peak temperature change of 3 K obtained in this 20% ozone reduction experiment to account for the maximum (insignificant) 0.1% ozone change of the typical TLE scenario by Enell et al. (2008), leads to an impact of TLEs on atmospheric temperature at 60–70 km of at most an average 0.015 K. On the other hand, adopting Enell et al. (2008) maximum case scenario of possibly a local few percent change above extraordinary active sprite producing thunderstorms, the extrapolated temperature change would be at most a localised 0.3 K over a 200 km×50 km region at sunrise. Likely, any such a radiative change would last at most for a few hours before photochemistry and mixing vanished the ozone change, thus with a negligible impact on the atmospheric temperature. Clearly, dedicated meoscale modelling is needed to study these localised scenarios and account for non linear local processes which are neglected in the adopted global models.

5 Summary and conclusions

This study has investigated the radiative-dynamical response of the middle and low atmosphere to a mid-latitude stratopause regional ozone perturbation that resemble the possible atmospheric impact of TLEs. The perturbation experiments were performed on a middle atmosphere model SMM and the atmospheric GCM ARPEGE, together with a study of the linearity of the response on the magnitude of the perturbation.

The response of the models to uniform 5% to 20% ozone reductions shows a close-to linear dependence on the magnitude of the perturbation in the sunlit regions. The SMM shows a larger spread of the area of significant response, which extends to most of the middle atmosphere already at 5% magnitude. Furthermore, the SMM shows significant responses in the winter north pole for experiments above 10% magnitude, whereas in ARPEGE the significant region does not extend north of 60° N. This implies a weaker reactivity of ARPEGE to dynamically driven changes compared to the SMM. The tropospheric response was investigated in ARPEGE. The results show tropospheric changes at 60° S which are consistent for the 5 to 20% ozone reduction experiments (and significant for the 20%).

The mid-latitude stratopause perturbation experiment mimicked the latitudinal dependence of the possible ozone impact of transient luminous events. The 20% magnitude led to statistically significant changes which were extrapolated down to the scenarios of Enell et al. (2008) adopting the linear dependence of the radiatively driven response found in the uniform experiments. The local response of the two models to this regional perturbation was fairly similar, leading to a maximum temperature change of 0.3 K at 60–70 km over extraordinary active TLE-producing thunderstorms and of the order of at most 0.015 K at 60–70 km height in typical TLE scenarios. Given the size of the perturbed region, the maximum case scenario needs to be investigated with dedicated mesoscale modelling.

A scaling of the tropospheric response to this regional perturbation leads to insignificant changes. Interestingly, at the 20% magnitude, a regional perturbation can lead to tropospheric changes which are different (if not larger) compared to uniform perturbation experiments.

Acknowledgements. E. Arnone and P. Berg acknowledge funding through the European Community's Human Potential Programme under contract HPRN-CT-2002-00216, Coupling of Atmospheric Layers, during 2003–2006. E. Arnone acknowledges funding through the European Community's Human Potential Programme Marie Curie under contract MERG-CT-2007-209157. P. Berg acknowledges funding from the Copenhagen Global Change Initiative (COGCI). E. Arnone thanks C.-F. Enell for very useful suggestions. The authors wish to thank unknown referees for their comments which led to substantial improvement of this article.

Edited by: N. Crosby and M. Rycroft
Reviewed by: J. Austin and another anonymous referee

References

Arnold, N. F. and Robinson, T. R.: Amplification of the influence of solar flux variations on the winter stratosphere by planetary waves, Space Sci. Rev., 94, 279–286, 2000.

Arnone, E., Kero, A., Dinelli, B. M., Enell, C.-F., Arnold, N. F., Papandrea, E., Rodger, C. J., Carlotti, M., Ridolfi, M., and E. Turunen: Seeking sprite-induced signatures in remotely sensed middle atmosphere NO2, Geophys. Res. Lett., 35, L05807, doi:10.1029/2007GL031791, 2008.

Austin, J. and Butchart, N.: A three-dimensional modeling study of the influence of planetary wave dynamics on polar ozone photochemistry, J. Geophys. Res., 97(D9), 10 165–10 186, 1992.

Austin, J., Butchart, N., and Shine, K. P.: Possibility of an Arctic ozone hole in a doubled-CO_2 climate, Nature, 360, 221–225, 1992.

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

Berg, P., Christiansen, B., Thejll, P., and Arnold, N. F.: The dynamical response of the middle atmosphere to the tropospheric solar signal, J. Geophys. Res., 112(D20), D20122, doi:10.1029/2006JD008237, 2007.

Christiansen, B.: Downward propagation of zonal mean zonal wind anomalies from the stratosphere to the troposphere: Model and reanalysis, J. Geophys. Res., 106(D21), 27 307–27 322, 2001.

Christiansen, B., Guldberg, A., Hansen, A. W., and Riishøjgaard, L. P.: On the response of a three–dimensional general circulation model to imposed changes in the ozone distribution, J. Geophys. Res., 102(D11), 13 051–13 077, 1997.

Déqué M., Dreveton, C., Braun A., and Cariolle, D.: The ARPEGE/IFS atmosphere model: a contribution to the French community climate modelling, Clim. Dynam., 10, 249–266, 1994.

Enell, C.-F., Arnone, E., Adachi, T., Chanrion, O., Verronen, P. T., Seppälä, A., Neubert, T., Ulich, T., Turunen, E., Takahashi, Y., and Hsu, R.-R.: Parameterisation of the chemical effect of sprites in the middle atmosphere, Ann. Geophys., 26, 13–27, 2008, http://www.ann-geophys.net/26/13/2008/.

Fels, S. B., Mahlman, J. D., Schwarzkopf, M. D., and Sinclair, R. W.: Stratospheric sensitivity to perturbations in ozone and carbon dioxide: Radiative and dynamical response, J. Atmos. Sci., 37, 2265–2297, 1980.

Gray, L. J., Sparrow, S., Juckes, M., O'Neill, A., and Andrews, D. G.: Flow regimes in the winter stratosphere of the northern hemisphere, Q. J. Roy. Meteor. Soc., 129, 925–945, 2003.

Haynes, P. H., Marks, C. J., McIntyre, M. E., Shepherd, T. G., and Shine, K. P.: On the "downward control" of extratropical diabatic circulations by eddy–induced mean zonal forces, J. Atmos. Sci., 48, 651–678, 1991.

Kodera, K.: On the origin and nature of the interannual variability of the winter stratospheric circulation in the northern hemisphere, J. Geophys. Res., 100(D7), 14 077–14 087, 1995.

Lyons, W. A.: The meteorology of transient luminous events – an introduction and overview, in: Sprites, Elves and Intense Lightning Discharges, edited by: Füllekrug, M., Mareev, E. A., and Rycroft, M. J., Vol. 225 of NATO Science Series II, Mathematics, physics and chemistry, Springer Verlag, ISBN 1-4020-4628-6, 19–56, 2006.

Morcrette, J.–J.: Radiation and cloud radiative properties in the European Centre for Medium–Range Weather Forecasts forecasting system, J. Geophys. Res., 96, 9121–9132, 1991.

Neubert, T.: On Sprites and Their Exotic Kin, Science, 300, 747–749, 2003.

Neubert, T., Rycroft, M., Farges, T., Blanc, E., Chanrion, O., Arnone, E., Odzimek, A., Arnold, N. F., Enell, C.-F., Turunen, E., Bösinger, T., Mika, Á., Haldoupis, C., Steiner, R., van der Velde, O., Soula, S., Berg, P., Boberg, F., Thejll, P., Christiansen, B., Ignaccolo, M., Füllekrug, M., Verronen, P. T., Montanya, J., and Crosby, N.: Recent results from studies of electric discharges in the mesosphere, Surv. Geophys., doi:10.1007/s10712-008-9043-1, accepted, 2008.

O'Neill, A. and Pope, V. D.: Simulations of linear and non–linear disturbances in the stratosphere, Q. J. Roy. Meteor. Soc., 114, 1063–1110, 1988.

Polvani, L. M. and Kushner, P. J.: Tropospheric response to stratospheric perturbations in a relatively simple general circulation model, Geophys. Res. Let., 29, 7, 18–1, 2002.

Rodger, C. J., Seppälä, A., and Clilverd, M. A.: Significance of transient luminous events to neutral chemistry: Experimental measurements, Geophys. Res. Lett., 35, 7803, doi:10.1029/2008GL033221, 2008.

Sentman, D. D., Stenbaek-Nielsen, H. C., McHarg, M. G., and Morrill, J. S.: Plasma chemistry of sprite streamers, J. Geophys. Res., 113(D11), D11112, doi:10.1029/2007JD008941, 2008.

Shine, K. P.: The middle atmosphere in the absence of dynamical heat fluxes. Q. J. Roy. Meteor. Soc., 113, 603–633, 1987.

Strobel, D. F.: Parameterization of the atmospheric heating rate from 15 to 120 km due to O2 and ozone absorption of solar radiation, J. Geophys. Res., 83, 6225–6230, 1978.

Wayne, R. P.: Chemistry of Atmospheres, 3rd Ed., Oxford University Press, Oxford, UK, 2000.

World Meteorological Organization (WMO): The 2006 scientific assessment of ozone depletion, ozone.unep.org/Assessment_Panels/SAP/Scientific_Assessment_2006/index.shtml , 2006.