

Abstract

Sudden stratospheric warmings (SSW) are large-scale transient events, which have a profound effect on the Northern Hemisphere stratospheric circulation in winter. During the SSW events the temperature in stratosphere increases by several tens of Kelvins and zonal winds decelerate or reverse in direction. Changes in temperature and dynamics significantly affect the chemical composition of the middle atmosphere.

In this paper, the response of the middle-atmosphere trace gases during several sudden stratospheric warmings in 2003–2008 is investigated using measurements from the GOMOS (Global Ozone Monitoring by Occultation of Stars) instrument on board the Envisat satellite. We have analyzed spatial and temporal changes of NO_2 and NO_3 in the stratosphere, and of ozone in the whole middle atmosphere. To facilitate our analyses, we have used the temperature profiles data from the MLS (Microwave Limb Sounder) instrument on board the Aura satellite, as well as simulations by the FinROSE chemistry-transport model and the Sodankylä Ion and Neutral Chemistry model (SIC). NO_3 observations in the polar winter stratosphere during SSWs are reported for the first time.

Changes in chemical composition are found not to be restricted to the stratosphere, but to extend to mesosphere and lower thermosphere. They often exhibit a complicated structure, because the distribution of trace gases is affected by changes in both chemistry and dynamics. The tertiary ozone maximum in the mesosphere often disappears with the onset of SSW, probably because of strong mixing processes. The strong horizontal mixing with outside-vortex air is well observed also in NO_2 data, especially in cases of enhanced NO_2 inside the polar vortex before SSW. Almost in all of the considered events, ozone near the secondary maximum decreases with onset of SSW. In both experimental data and FinROSE modelling, ozone changes are positively correlated with temperature changes in the lower stratosphere in the dynamically controlled region below ~ 35 km, and they are negatively correlated with temperature in the upper stratosphere (altitudes 35–50 km), where chemical processes play a significant role.

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Large enhancements of stratospheric NO₃, which strongly correlate with temperature enhancements, are observed for all SSWs, as expected by the current understanding of temperature-dependence of NO₃ concentrations and simulations with the CTM.

1 Introduction

Sudden Stratospheric Warmings (SSWs) are large scale perturbing events in the winter polar regions that affect the structure and circulation of the middle atmosphere. SSWs are caused by dissipation of planetary waves in the upper stratosphere, which are generated in the troposphere (Holton, 2004; Matsuno, 1971). This explains, in particular, the fact that sudden stratospheric warmings are rare in the Southern Hemisphere, which is affected much less by planetary waves than the Northern Hemisphere. During a SSW, the zonal mean temperature in polar stratosphere increases by several tens of Kelvins in few days. This warming is accompanied with a weakening of zonal winds and disturbance of the polar vortex. In the case of major sudden stratospheric warming, the zonal mean wind is reversed and the polar vortex can break down completely.

It is known since the work of Matsuno (1971) that SSWs are accompanied with a cooling in the mesosphere. This was explained in his paper as a result of the mean flow and planetary wave interaction based on mass balance. Holton (1983) pointed out that the changes in the mean wind profile alter the conditions for the gravity wave propagation and result in reduced gravity wave momentum flux in the mesosphere, which leads to mesospheric cooling via reducing wave-induced diabatic descent (Garcia and Boville, 1994). SSWs can also have a significant effect on tropospheric weather patterns (Baldwin and Dunkerton, 2001; Liu et al., 2009).

The dynamical changes related to SSWs are accompanied by remarkable changes in the chemical composition of the middle atmosphere, as shown by modelling studies (e.g., Sonnemann et al., 2006). The changes in the chemical composition attract increasing attention during the last decade because of several reasons. First, observations of trace gases and temperature in the middle atmosphere have become available

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

with several new satellite instruments having good global coverage of polar regions in winter. Second, these observations provide a dataset for testing chemistry-climate models. The response of the middle atmosphere to SSWs is still difficult to simulate (Salmi et al., 2011; Siskind et al., 2010). Third, it has been discovered recently that some of the sudden stratospheric warmings (as observed in 2004 and then again in 2006 and 2009) results in unusual subsequent features: dramatic cooling at ~50 km, then the reformation of stratopause near 80 km, following by the enhanced downward transport from the mesosphere and thermosphere into the polar vortex area. The strong descent of NO_x species is of further interest because it can cause ozone depletion through catalytic chemical reaction cycles. Observational evidences of enhanced downward transport of trace species have been reported in several papers (Damiani et al., 2010; Funke et al., 2005; Hauchecorne et al., 2007; Manney et al., 2005, 2008; Randall et al., 2006, 2009; Smith et al., 2009; Sofieva et al., 2009).

The short-term changes in the chemical composition of the middle atmosphere in response to SSWs have been less reported: the experimental studies include observations of OH, ozone and temperature by Microwave Limb Sounder (MLS) in 2005–2009 at altitudes 50–90 km (Damiani et al., 2010), and MLS observations of CO, N₂O and H₂O during SSW in 2009 (Manney et al., 2009).

The response of the middle atmosphere composition to sudden stratospheric warming is difficult to estimate, because the distribution of trace gases is affected by changes in both chemistry (the rates of chemical reactions depend on temperature) and dynamics (changes in wind velocity and mixing). Simulations with the LIMA model (Sonnenmann et al., 2006) have predicted an increase in secondary and tertiary ozone maxima after the occurred temperature minimum in the mesosphere, while the observations (Damiani et al., 2010) have shown more complicated ozone changes.

This paper is dedicated to short-term changes in the middle-atmospheric ozone, NO₂ and NO₃ distributions caused by sudden stratospheric warmings, as seen by the GOMOS (Global Ozone Monitoring by Occultations of Stars) instrument on board the Envisat satellite. We consider Northern Hemisphere (NH) SSWs in four winters: 2002–

2003, 2003–2004, 2005–2006 and 2007–2008. This analysis presents an extension of the previous studies listed above towards a larger altitude range (for ozone, it is 15–100 km), more species (in particular, NO₃, which has a unique global representation by GOMOS), and a larger number of SSW events (in particular, SSWs in January 2003 and December 2003–January 2004 have not been considered in details in the previous studies). To facilitate analyses, we use also temperature data from MLS (Microwave Limb Sounder) instrument on board the Aura satellite when available, as well as simulations with chemistry-transport models (CTM).

The paper is organized as follows. Brief description of used data and models is presented in Sect. 2. Results and discussion are presented in Sect. 3; they are followed by summary (Sect. 4).

2 Data and models

2.1 GOMOS measurements of trace gases

GOMOS (Bertaux et al., 2010; Kyrölä et al., 2010b) is the first operational stellar occultation instrument, which measures the stellar spectrum continuously as a star sets behind the Earth limb. Vertical profiles of ozone, NO₂, NO₃, and aerosol extinction are retrieved from the UV-Visible spectrometer measurements. Since aerosol extinction spectrum is not known a priori, a second-degree polynomial model is used for the description of the aerosol extinction. Due to non-orthogonality of cross-sections of Rayleigh scattering by air with the considered polynomial model of aerosol extinction, the air density is not retrieved from UV-VIS measurements by GOMOS. It is taken from ECMWF analysis data corresponding to occultation locations. The GOMOS data processing relies on the two-step inversion and a minimal use of a priori information, as described in detail in (Kyrölä et al., 1993, 2010b). The vertical resolution (including the smoothing properties of the inversion) of GOMOS ozone profiles is 2 km below 30 km and 3 km above 40 km, and it is ~4 km for other species. The vertical resolution of the

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



retrieved profiles is the same for all occultations, independent of angles between the orbital plane and the direction to the star, thanks to the “target-resolution” regularization (Kyrölä et al., 2010b; Sofieva et al., 2004; Tamminen et al., 2004). While ozone can be retrieved up to ~ 100 km altitude, other species are usually detectable in the upper troposphere and in the stratosphere. Accuracy of the GOMOS retrievals depends on stellar magnitude and spectral class. For this study, we have selected dark-limb occultations (solar zenith angle $\geq 107^\circ$ at the tangent point, and $\geq 90^\circ$ at the satellite) of hot (effective temperature ≥ 6000 K) and sufficiently bright (visual magnitude < 2) stars. The precision of individual ozone profiles is 0.5–2 % in the stratosphere and 1–5 % in the mesosphere and lower thermosphere (MLT), 5–20 % for NO_2 , and 10–30 % for NO_3 (for more details, see (Tamminen et al., 2010). The GOMOS night-time data have been extensively compared with collocated ground-based, in situ and satellite data. Review of validation results is presented in (Bertaux et al., 2010; Kyrölä et al., 2010a) (see also references therein).

The spatio-temporal coverage of the selected GOMOS observations related to the sudden stratospheric warmings in the four recent winters is shown in Fig. 1. It is characterized by a very good coverage of northern high latitudes with occultations of very bright stars, which provide a very good precision. The number of occultations for the last two winters is smaller than that available earlier due to the instrumental problems of GOMOS. Latitudes north of 80° N can not be observed after mid-January with sufficiently bright stars. All the considered occultations are in the polar night conditions, except a few days after the 1 February 2008 (see the lines in Fig. 1 indicating the latitude of the polar night terminator).

2.2 MLS measurements of temperature

MLS observes thermal microwave limb emission by the atmosphere in five spectral bands from 115 GHz to 2.5 THz (Waters et al., 2006). MLS scans the atmosphere from ground to ~ 90 km every 24.7 s, or 240 times per orbit. Scan rate is synchronized to the Aura Orbit, which means that scans are made at the same latitudes each orbit (Fig. 2).

**Middle atmosphere
composition during
sudden stratospheric
warmings**

V. F. Sofieva et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

used for ozone and water vapour, and trends for long-lived gases. In the stratosphere FinROSE produces distributions of 40 species and families taking into account both chemistry and dynamics. However, only the long-lived constituents are transported. The model includes about 120 homogeneous reactions and 30 photodissociation processes. Chemical kinetic data, reaction rate coefficients and absorption cross-sections are based on the Jet Propulsion Laboratory compilation by (Sander et al., 2006), including updates from the available supplements. The model photodissociation rates are calculated using a radiative transfer model PHODIS Kylling et al., 1997). In addition, 30 heterogeneous reactions on/in liquid binary aerosols and type Ia, Ib and II polar stratospheric clouds (PSC) are included. The sedimentation of PSC particles, leading to dehydration and denitrification, is also accounted for.

In this study, we used FinROSE model data corresponding to 10:00 p.m., in order to coincide with GOMOS measurements. This means that we get one 3-D field per day and the field is a composite of model results at 10:00 p.m. local time during that day.

2.4 SIC model

The Sodankylä Ion and Neutral Chemistry (SIC) model is a one-dimensional tool for studies of middle atmospheric chemistry. SIC was originally developed for interpretation of ionospheric observations (Turunen et al., 1996). The altitude range of the model is 20–150 km, with 1-km resolution. In addition to several hundred ionic reactions, the current version includes neutral reaction schemes of O_x , NO_x , and HO_x , as well as a few other minor constituents (see (Verronen, 2006; Verronen et al., 2005) for a detailed description of SIC). The main external input is solar radiation spectrum, provided by the SOLAR2000 model (Tobiska et al., 2000), which is used to calculate the photoionization and dissociation rates. The model includes a vertical transport scheme, i.e. eddy and molecular diffusion (Banks and Kockarts, 1973), (Chabrilat et al., 2002), which affects the vertical distribution of the long-lived species in the mesosphere and lower thermosphere (MLT). In recent years, the model has been used mainly to study the effects of energetic particle precipitation, e.g. solar proton events, in the polar regions

and the subsequent interaction between neutral and ionized species (Rodger et al., 2008; Seppälä et al., 2008; Verronen et al., 2008).

In our current paper, SIC was used to study a period of 62 days from 19 December 2005 to 18 February 2006 at two latitudes, 72° N and 77° N. First, the model was initialized to NH winter conditions. Second, periods of 62 days were run using daily average MLS temperature profiles in the reaction rate calculations. Third, a control model run was made, similar to the MLS temperature run except that the 1st day MLS temperature was fixed for the whole duration of the modelling. Because SIC is a 1-D model, it cannot reproduce horizontal transport processes. Also, it cannot be used to study the changes in constituents caused by dynamical changes. Instead, it can provide information on the chemical changes in minor species composition, which are related to the sudden changes in temperature. Therefore, contrasting the SIC results with the changes from observations and the FinROSE 3-D CTM allows us, to some extent, separate the chemical and dynamical effects of the SSW, and discuss their relative importance.

3 Results and discussion

In our analysis, we considered four winters when sudden stratospheric warmings have occurred. We have used the WMO definition of sudden stratospheric warmings: 10 hPa zonal mean winds and temperature gradient reversal poleward of 60° N for more than 5 days (minor SSW) accompanied with zonal mean winds reversal in case of major SSW. In all figures shown in our paper, the onset of a minor SSW (dashed black lines) is the first day of temperature gradient reversal, and the onset of a major SSW (solid black lines) is the first day of zonal wind reversal. In 2008, there were altogether four SSWs (Wang and Alexander, 2009), but only two of them are covered by GOMOS data.

Figure 3 shows the evolution of temperature and trace gases at 70°–90° N during the four winters. For trace gases, GOMOS observations are used. Temperature is taken

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



from ECMWF analysis (January 2002 and December 2003–January 2004) and MLS (2006 and 2008) data.

For the sudden stratospheric warming of 2006, we run two models: FinROSE CTM (the data at 22:00, the approximate time of GOMOS observations, are shown in Fig. 4 for altitudes 20–65 km) and 1-D chemistry model SIC, which was forced by MLS temperature observation (the evolution of trace gases is shown in Fig. 5). In absence of dynamical mixing in SIC, the concentrations of trace gases (especially NO_2 and NO_3) depend strongly on latitude, therefore the weighted mean of the simulated data at 72°N and 77°N (with the weights corresponding to the proportion of GOMOS measurements at these latitudes) is presented in Fig. 5. In the following, we discuss the changes in trace gases associated with sudden stratospheric warmings.

3.1 Changes in the stratosphere

The distribution of trace gases in the high-latitude winter stratosphere is largely affected by the presence of the polar vortex. The polar night jet acts as a transport barrier between polar and mid-latitude air. Under polar night conditions (absence of solar light), stratospheric O_x species have a long photochemical lifetime, and they are believed to be primarily influenced by transport processes (Brasseur and Solomon, 2005, Fig. 5.11). The ozone loss reaction $\text{O}_3 + \text{O} \rightarrow 2\text{O}_2$ is more effective at higher temperatures (the ozone production is low in the polar night conditions).

Halogen compounds play an important role in the stratospheric chemical processes that lead to ozone depletion in both Arctic and Antarctic polar regions. The inert reservoir species are converted into active species by heterogeneous reactions, which occur on the surface of polar stratospheric clouds (PSC) formed in the lower stratosphere if temperatures are below 195 K. ClO_x and BrO_x compounds destroy ozone in catalytic reaction cycles, which are effective in the presence of solar light (Brasseur and Solomon, 2005).

Stratospheric ozone is also influenced by reactions with nitrogen oxides. These are mainly relevant above 30 km and in sunlight conditions. The ozone depletion in the

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



upper stratosphere was clearly observed when amount of NO_2 was increased due to solar proton events (SPE) (Seppälä et al., 2004) or strong downward transport of NO_2 from the MLT (Hauchecorne et al., 2007; Randall et al., 2006; Seppälä et al., 2007).

The behaviour of nitrogen compounds in polar regions in winter is the result of complex chemical and physical processes. In the polar night, NO is converted into NO_2 and further into NO_3 by reactions with ozone. NO_3 then combines with NO_2 to form N_2O_5 , which provides an important reservoir for nitrogen compounds in the polar winter. N_2O_5 can be rapidly converted into nitric acid by the heterogeneous reaction on the surface of sulphate aerosol particles and and/or on the surface of PSCs (the “denitrification” of the lower polar winter stratosphere (Brasseur and Solomon, 2005). For example, the abundance of NO_x is very low inside the Antarctic vortex during winter and spring. Denitrification processes are observed also in the Arctic. For example, Tetard et al. (2009) have observed low NO_2 and O_3 abundances in the interior of polar vortex in January 2008 before SSW. Denitrification increases ozone depletion, since the lack of NO_x reduces the conversion of reactive chlorine and bromine species into inactive reservoir species.

In undisturbed conditions (i.e., without SSW), ozone mixing ratio is lower inside the polar vortex than at mid-latitudes in the whole stratosphere (e.g., Kyrölä et al., 2006). Compared to mid-latitudes, night-time NO_2 abundances is usually lower inside the polar vortex in the lower stratosphere (see the discussion on denitrification above), but they can be either lower or significantly higher (in case of SPE or strong downward transport from upper altitudes) in the upper stratosphere (e.g. Hauchecorne et al., 2005, GOMOS global maps at <http://fmilimb.fmi.fi/gomosdatapool.html>)

3.1.1 Response of stratospheric ozone near the main maximum to SSWs

Since catalytic ozone loss reactions are inactive in the polar night conditions, the response of ozone mixing ratio to SSW is expected to be influenced by two opposite tendencies: (i) a decrease due to the temperature dependence of ozone loss reaction and (ii) an increase due to mixing with mid-latitude air.

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Middle atmosphere
composition during
sudden stratospheric
warmings**

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Nearly for all considered sudden stratospheric warmings, GOMOS observes a local increase in ozone close to the main stratospheric maximum (Fig. 3). The only exceptions are the major SSW on 5 January 2004 and the minor SSW on 9 January 2006. These ozone enhancements indicate the prevailed dynamic origin of these changes.

The effect of the strong horizontal mixing is revealed also in synchronous NO₂ decrease associated with SSWs. This is seen especially clear in SSW on 19 December 2003, which is characterized by high NO₂ values before the SSW due to a strong SPE November 2003 (Seppälä et al., 2004). With the onset of this SSW, an ozone enhancement is accompanied with a sharp NO₂ decrease as a result of horizontal mixing.

For SSWs in 2006, the changes in ozone simulated by FinROSE over the whole considered period are in rather good agreement with GOMOS observations (Fig. 4). However, some differences can be found: for example, GOMOS observes a local increase of ozone associated with SSW on 3 January 2006, while FinROSEs ozone is first decreased and then increased. These peculiar differences are caused probably by the model dynamics (for example, the temperature distributions are slightly different in ECMWF and MLS data) and mixing (see also below).

3.1.2 Response of NO₂ to SSWs

In polar night conditions, NO₂ has a long lifetime, and can be considered therefore as a dynamical tracer. The influence of dynamics (mixing with outside-vortex air) during a SSW may induce a clear enhancement/reduction, if the amount of outside-vortex NO₂ is significantly higher/lower than inside.

For NO₂, no clear changes associated with onsets of SSW are observed in GOMOS data. Probably, the only exception is minor SSW on 19 December 2003, when a clear decrease in NO₂ mixing ratio is observed (this is discussed above). In addition, NO₂ decreases are observed also in December 2002 (1st SSW) and in January 2006 (1st SSW).

For SSWs in January 2006, FinROSE predict NO₂ enhancements at altitudes 45–50 km, which are well correlated with temperature enhancements at these altitudes

(Fig. 4). The similar (but smaller because of smaller values of mixing ratio) changes are observed also in SIC at altitudes 40–50 km (Fig. 5). However, such behaviour is not detected in GOMOS data. In Sect. 3.1.4, we consider quantitative aspects of NO₂ response to temperature changes in the whole altitude range 25–50 km and discuss possible reasons for difference between model predictions and observations.

3.1.3 Response of NO₃ to SSWs

In all GOMOS observations, stratospheric NO₃ shows strong enhancements at altitudes 30–45 km during all SSWs. This is expected because of strong temperature dependence of the reaction NO₂ + O₃ → NO₃ (Hauchecorne et al., 2005). For the January 2006 SSWs, FinROSE model shows changes in NO₃ that are very similar to GOMOS observations. Note that ECMWF temperature, which is used in FinROSE simulations, is different from that observed by MLS during this SSW. Therefore, local enhancements in FinROSE NO₃ time series are at slightly higher altitudes and slightly shifted in time with respect to the GOMOS NO₃ enhancements (and they correspond to the structure of ECMWF temperature enhancements). For the same event, SIC predicts enhancements in NO₃, which are similar to that observed by GOMOS both in magnitude and in altitude location (Fig. 5). However, the SIC NO₃ enhancements persist significantly longer than in both GOMOS observations and FinROSE simulations (see enhancement after SSW on 9 January 2006). This indicates that NO₃ enhancements associated with SSWs are mostly due to changes in temperature affecting the chemistry, although the higher NO₃ values in SIC after 15 January compared to that in GOMOS suggest that dynamical dilution has also an effect.

3.1.4 Correlation analysis

To quantify the importance of chemical and dynamical effects in the response of trace gases to sudden stratospheric warmings, we computed correlation coefficients between temperature and trace gases using zonally averaged data at latitudes 70°–90° N

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Middle atmosphere
composition during
sudden stratospheric
warmings**

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



from 1 to 25 January 2006, the period of sudden stratospheric warmings. Only short-term changes in the chemical composition associated with SSW events are reflected in this correlation analysis (opposite/complementary to the correlation analysis performed by Damiani et al. (2010) using long time series). Figure 6 shows the correlation coefficient in the altitude range of 20–50 km computed using GOMOS trace gases and MLS temperature observations (left panels), and FinROSE (center panels) and SIC (forced by MLS temperature, right panels) simulations.

As seen in Fig. 6, ozone is correlated with temperature in the dynamically controlled region below ~ 35 km, and anti-correlated with temperature at altitudes 35–50 km, where chemical processes dominate. This is observed clearly in both GOMOS and FinROSE data. The SIC model predicts anti-correlation at most altitudes, and a (positive) correlation below 35 km is not even expected, because the absence of dynamics in this model. Note that a similar transition between dynamically and chemically controlled altitude regions has been also observed in longer time series' at mid-latitudes and in tropics (e.g., Hauchecorne et al., 2010; Kyrölä et al., 2010a).

As expected and clearly seen in data, NO_3 is positively correlated with temperature in the whole altitude range of 25–50 km. The correlation is very high (~ 0.9) in SIC simulations (chemistry only), but it is slightly lower when dynamics is taken into account (FinROSE and GOMOS). In GOMOS data, NO_3 -temperature correlation coefficient has a local minimum at ~ 35 km, the altitude of transition from dynamically to chemically controlled altitude regions. A much shallower minimum is also observed in the FinROSE data.

GOMOS NO_2 is practically not correlated with MLS temperature data from the considered period. However, a strong correlation between temperature and NO_2 is predicted by FinROSE in the altitude range 25–45 km, with some decrease below 35 km and above 40 km. The similar positive correlation between NO_2 and temperature was observed also for January 2008 (not shown). In SIC data, a positive significant correlation is observed in January 2005 above 30 km, while the correlation becomes negative below 30 km. These features can be explained by the chemical considerations as

**Middle atmosphere
composition during
sudden stratospheric
warmings**

V. F. Sofieva et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

follows. In the chemically controlled upper stratosphere, ozone is anti-correlated with temperature. At the same time, ozone is anti-correlated with NO_2 through the catalytic ozone loss reaction. These two negative correlations result in positive correlation between NO_2 and temperature above ~ 35 km. Below 35 km another process seems to dominate: NO_2 is positively correlated with temperature through the denitrification of the polar vortex mechanism. The observations indicate favourable conditions for PSC formation before the SSW (e.g., Tetard et al., 2009) and well seen correlation between NO_2 and temperature in the lower stratosphere. FinROSE also shows the presence of PSC before the SSW. In FinROSE, the correlation between temperature and NO_2 is always positive because of the above reasons. In SIC, the temperature- NO_2 correlation is positive above ~ 35 km, and becomes negative below ~ 30 km with the change in temperature-ozone correlation, because SIC does not include the heterogeneous chemistry. The disagreement of GOMOS correlations with that provided by the CTM is probably because the horizontal mixing is under-represented in FinROSE. This assumption is confirmed by considering another SSW in December 2003, when there was a large amount of NO_2 in the stratosphere. The realistic amount of NO_2 after the Halloween SPE was simulated with FinROSE (see Funke et al., 2011 for details). Although these pre-SSW NO_2 values are comparable to observations, the sharp decrease in NO_2 with the onset of SSW on 19 December 2003 is not reproduced by FinROSE (not shown here).

The correlation between species is more complicated, because it includes implicitly temperature dependence. In particular, significant and nearly constant O_3 and NO_3 anti-correlation predicted by SIC can be explained by a strong positive temperature- NO_3 correlation and a negative temperature-ozone correlation. For the same reason, ozone- NO_3 correlation coefficient is positive (and significant) below 30–35 km and negative above 35 km in GOMOS and FinROSE data.

Figure 7 summarizes the experimental correlations between temperature and trace gases by considering all the SSW periods in years 2003, 2004 and 2006. The 2008 SSW is incompletely covered by the GOMOS data and excluded therefore from this

analysis. Only statistically significant correlations are shown. They are: strong positive correlation between temperature and NO_3 , and the significant temperature – ozone correlation changing from positive in the dynamically controlled region below 30–35 km to negative in the chemically controlled region. Ozone- NO_3 correlation exhibit a similar sign change due to the two abovementioned correlations. The negative NO_2 -ozone correlation above 40 km reflects probably their relationship through the catalytic ozone loss reaction.

3.2 Secondary ozone maximum

According to the GOMOS observations, a clear decrease in secondary ozone maximum is observed practically for all considered SSWs. The only exceptions are major SSW on 21 January 2006 and minor SSW on 23 January 2008, when no evident changes in thermospheric ozone are observed. Simulations with SIC and FinROSE models are not available at these altitudes: for FinROSE due to ECMWF data do not extend that high, and for SIC due to large uncertainty of MLS data. The lower-thermospheric ozone is expected to be anti-correlated with temperature and depends on amount of atomic oxygen (production) and hydrogen (destruction) (Smith et al., 2009). On short time-scales, atomic oxygen and temperature are positively correlated, and downward motion increases both. The simulations by (Sonnemann et al., 2006) predict increase in the secondary ozone associated with MLT cooling during SSW, while GOMOS data show rather different behaviour. Three of the considered sudden stratospheric warmings: 21 January 2006, 23 January 2008 and 2 February 2008 were observed also with SABER/TIMED instrument; the temperature and ozone changes at these altitudes are reported in (Smith et al., 2009). The SABER observations of changes in the secondary ozone maximum are in very good agreement with GOMOS observations: no visible changes for 21 January 2006 and 23 January 2008 events, and a pronounced decrease on 2 February 2008. For the SSW on 21 January 2006, such behaviour can be explained qualitatively by temperature variations observed by

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

SABER (Fig. 2 in Smith et al., 2009): the MLT cooling has started earlier than pronounced warming in the stratosphere, and local changes in the secondary ozone maximum are anti-correlated with local temperature variations at ~ 95 km. For SSWs in 2008, such explanation cannot be accepted: anti-correlation of ozone and temperature fluctuations is not observed. Based on analysis of SABER temperature, atomic oxygen and ozone in 2002–2009, Smith et al. (2009) have pointed out that there is a discrepancy in the current ozone-temperature relationship above ~ 90 km (which might be due to incomplete understanding of mesopause ozone or/and due to inconsistent observations). At this stage, GOMOS measurements cannot contribute to resolving this problem, due to the lack of simultaneous observations of O, H, and temperature.

A reduced amount of atomic oxygen due to reduced/stopped downward motion with the onset of a SSW might contribute to the observed secondary ozone reduction. This kind of strong reduction in atomic oxygen was observed in a self-generated SSW by the TIME-GSM/CCM3 model (Liu and Roble, 2002). Another reason might be a complicated structure of temperature variations due to geomagnetic activity, thus temperature changes can be affected by both SSW and Joule heating. In addition, the mesospheric cooling might not extend that high, thus a warming might already start at ~ 95 km, as shown in (Funke et al., 2010).

3.3 Tertiary ozone maximum

The tertiary ozone maximum (TOM) is typically observed in the high-latitude winter mesosphere at altitudes ~ 72 km with maximum close to the polar night terminator. It is caused by low concentrations of odd-hydrogen, which result in the subsequent decrease in odd-oxygen losses. Due to a long photochemical lifetime of ozone in the polar night below ~ 80 km, TOM can serve as a passive tracer in absence of strong energetic particle precipitation, as shown in (Sofieva et al., 2009) and (Smith et al., 2009).

Analogously to the secondary ozone maximum, tertiary ozone maximum decreases with the onset of SSW, in some cases, even radically. Such behaviour was observed nearly in all the considered SSWs, except for 21 January 2006 and 23 January 2008 events.

If we consider the response of mesospheric ozone to temperature only, then it is expected to be increased due to a cooling in the mesosphere. This slight increase in TOM can be seen in simulations with 1-D SIC chemical model shown in Fig. 5. At lower latitudes, where there is more sunlight, and in the real atmosphere (taking into account the horizontal mixing), a temperature-induced chemical increase of ozone is expected to be larger. The opposite behaviour of TOM (a reduction instead of an increase) is often observed in GOMOS data. TOM is sensitive to the amount of HO_x species, but, according to (Damiani et al., 2010), OH concentrations do not change much at ~72 km with the onsets of sudden stratospheric warmings. These are the changes in dynamics accompanied by SSWs that can reduce the tertiary ozone: (i) via horizontal mixing with mid-latitude air or/and (ii) due to the change of the zonal wind from westerly to easterly, which reduces night-time for air parcels and thus the night-time ozone concentration (Doppler-Sonnemann effect, (Sonnemann et al., 2006). The strong horizontal mixing occurs also in the mesosphere (Fig. 2 in Seppälä et al., 2007, SSW on 19 December 2003). We believe that these dynamic processes and changes in temperature explain the response of TOM to the onset of SSWs. It is worth also to note that the GOMOS observations of tertiary ozone maximum are in good agreement with SABER (Smith et al., 2009) and MLS (Damiani et al., 2010) data for commonly observed SSWs.

4 Summary

In this study, we have analyzed GOMOS observations of ozone, NO₂ and NO₃ during sudden stratospheric warmings in four winters 2002–2003, 2003–2004, 2005–2006 and 2007–2008. As far as we know, the NO₃ observations in the stratosphere during SSWs have not been reported before. MLS temperature measurements and

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



simulations with the FinROSE CTM and 1-D ion-chemistry model SIC have been used for analysis and interpretation of changes in the middle atmosphere chemical composition associated with the SSWs. Overall, due to influence of changes in both dynamics and chemical reaction rates, the changes in the trace gases distributions are rather complicated. Our observations and findings can be summarized as follows.

1. Changes in the chemical composition are found not to be restricted to the stratosphere, but they extend to the mesosphere and the lower thermosphere, as expected.
2. Large enhancements of stratospheric NO_3 , which strongly correlate with temperature enhancements, are observed for all SSWs, as expected by the current understanding of the temperature-dependence of NO_3 concentrations and simulations with the CTM.
3. In both experimental data and FinROSE modelling, ozone changes are positively correlated with temperature changes in the lower stratosphere, i.e., in the dynamically controlled region below ~ 35 km, and they are negatively correlated with temperature in the upper stratosphere (altitudes 35–50 km), where chemical processes are significant.
4. Despite the cooling in the mesosphere and thus expected increase of ozone, the tertiary ozone maximum in the mesosphere often disappears with the onset of SSWs. This can be explained by strong mixing processes.
5. According to GOMOS observations, ozone near the secondary maximum decreases with onset of SSWs almost for all the considered events.
6. The experimental response of NO_2 to sudden stratospheric warming exhibits a complicated structure. It seems to be a consequence of strong mixing with outside-vortex air. In particular, if the amount of NO_2 inside polar vortex is much higher than outside, a sharp decrease of NO_2 with onset of SSWs is observed.

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The presented GOMOS observations constitute datasets that are useful for testing 3-D chemistry-transport models, which still exhibit deviations from observations.

Acknowledgements. The authors thank ESA and the GOMOS team for the GOMOS data. This work has been supported by the Academy of Finland projects (MIDAT, SPOC, THERMES) and the ESA Dragon-2 project.

References

Baldwin, M. P. and Dunkerton, T. J.: Stratospheric harbingers of anomalous weather regimes, *Nature*, 294, 581–584, doi:10.1126/science.1063315, 2001.

Banks, P. M. and Kockarts, G.: *Aeronomy*, Academic Press, 1973.

10 Bertaux, J. L., Kyrölä, E., Fussen, D., Hauchecorne, A., Dalaudier, F., Sofieva, V., Tamminen, J., Vanhellemont, F., Fanton d'Andon, O., Barrot, G., Mangin, A., Blanot, L., Lebrun, J. C., Pérot, K., Fehr, T., Saavedra, L., Leppelmeier, G. W., and Fraisse, R.: Global ozone monitoring by occultation of stars: an overview of GOMOS measurements on ENVISAT, *Atmos. Chem. Phys.*, 10, 12091–12148, doi:10.5194/acp-10-12091-2010, 2010.

15 Brasseur, G. P. and Solomon, S.: *Aeronomy of the Middle Atmosphere*, 3rd ed., Springer, Dordrecht, 2005.

Chabrilat, S., Kockarts, G., Fonteyn, D., and Brasseur, G.: Impact of molecular diffusion on the CO₂ distribution and the temperature in the mesosphere, *Geophys. Res. Lett.*, 29, 1–4, 2002.

20 Damiani, A., Storini, M., Santee, M. L., and Wang, S.: Variability of the nighttime OH layer and mesospheric ozone at high latitudes during northern winter: influence of meteorology, *Atmos. Chem. Phys.*, 10, 10291–10303, doi:10.5194/acp-10-10291-2010, 2010.

Damski, J., Thölix, L., Backman, L., Kaurola, J., Taalas, P., Austin, J., Butchart, N., and Kulmala, M.: A chemistry-transport model simulation of middle atmospheric ozone from 1980 to 2019 using coupled chemistry GCM winds and temperatures, *Atmos. Chem. Phys.*, 7, 2165–2181, doi:10.5194/acp-7-2165-2007, 2007.

25 Funke, B., López-Puertas, M., Bermejo-Pantaleón, D., Garcia-Comas, M., Stiller, G. P., von Clarmann, T., Kiefer, M., and Linden, A.: Evidence for dynamical coupling from the lower atmosphere to the thermosphere during a major stratospheric warming, *Geophys. Res. Lett.*, 37(13), L13803, doi:10.1029/2010GL043619, 2010.

23336

ACPD

11, 23317–23348, 2011

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Middle atmosphere
composition during
sudden stratospheric
warmings**

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Funke, B., Baumgaertner, A., Calisto, M., Egorova, T., Jackman, C. H., Kieser, J., Krivolutsky, A., López-Puertas, M., Marsh, D. R., Reddmann, T., Rozanov, E., Salmi, S.-M., Sinnhuber, M., Stiller, G. P., Verronen, P. T., Versick, S., von Clarmann, T., Vyushkova, T. Y., Wieters, N., and Wissing, J. M.: Composition changes after the “Halloween” solar proton event: the High-Energy Particle Precipitation in the Atmosphere (HEPPA) model versus MIPAS data intercomparison study, *Atmos. Chem. Phys. Discuss.*, 11, 9407–9514, doi:10.5194/acpd-11-9407-2011, 2011.

Funke, B., López-Puertas, M., Gil-Lopez, S., von Clarmann, T., G. P., Stiller, Fischer, H., and Kellmann, S.: Downward transport of upper atmospheric NO_x into the polar stratosphere and lower mesosphere during the Antarctic 2003 and Arctic 2002/2003 winters, *J. Geophys. Res.*, 110(D24), D24308, doi:10.1029/2005JD006463, 2005.

Garcia, R. R. and Boville, B. A.: “Downward Control” of the mean meridional circulation and temperature distribution of the polar winter stratosphere, *J. Atmos. Sci.*, 51, 2238–2245, 1994.

Hauchecorne, A., Bertaux, J.-L., Dalaudier, F., Cot, C., Lebrun, J. C., Bekki, S., Marchand, M., Kyrölä, E., Tamminen, J., Sofieva, V. F., Fussen, D., Vanhellemont, F., D’Andon, O. F., Barrot, G., Mangin, A., Theodore, B., Guirlet, M., Snoeij, P., Koopman, R., de Miguel, L. S., Fraisse, R., and Renard, J. B.: First simultaneous global measurements of nighttime stratospheric NO_2 and NO_3 observed by Global Ozone Monitoring by Occultation of Stars (GOMOS)/Envisat in 2003, *J. Geophys. Res.*, 110(D18), doi:10.1029/2004JD005711, 2005.

Hauchecorne, A., Bertaux, J.-L., Dalaudier, F., Russell, J. M., Mlynczak, M. G., Kyrölä, E., and Fussen, D.: Large increase of NO_2 in the north polar mesosphere in January–February 2004: Evidence of a dynamical origin from GOMOS/ENVISAT and SABER/TIMED data, *Geophys. Res. Lett.*, 34, 3810, doi:10.1029/2006GL027628, 2007.

Hauchecorne, A., Bertaux, J. L., Dalaudier, F., Keckhut, P., Lemennais, P., Bekki, S., Marchand, M., Lebrun, J. C., Kyrölä, E., Tamminen, J., Sofieva, V., Fussen, D., Vanhellemont, F., Fanton d’Andon, O., Barrot, G., Blanot, L., Fehr, T., and Saavedra de Miguel, L.: Response of tropical stratospheric O_3 , NO_2 and NO_3 to the equatorial Quasi-Biennial Oscillation and to temperature as seen from GOMOS/ENVISAT, *Atmos. Chem. Phys.*, 10, 8873–8879, doi:10.5194/acp-10-8873-2010, 2010.

Holton, J. R.: The influence of gravity wave breaking on the general circulation of the middle atmosphere, *J. Atmos. Sci.*, 40, 2497–2507, 1983.

Holton, J. R.: An Introduction to Dynamic Meteorology, 4th edn., Elsevier Academic Press,

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2004.

Kylling, A., Albold, A., and Seckmeyer, G.: Transmittance of a cloud is wavelength-dependent in the UV-range: Physical interpretation, *Geophys. Res. Lett.*, 24(4), 397–400, doi:10.1029/97GL00111, 1997.

5 Kyrölä, E., Sihvola, E., Kotivuori, Y., Tikka, M., Tuomi, T., and Haario, H.: Inverse Theory for Occultation Measurements, 1: Spectral Inversion, *J. Geophys. Res.*, 98, 7367–738, 1993.

Kyrölä, E., Tamminen, J., Leppelmeier, G. W., Sofieva, V. F., Hassinen, S., Seppälä, A., Veronen, P. T., Bertaux, J.-L., Hauchecorne, A., Dalaudier, F., Fussen, D., Vanhellemont, F., D'Andon, O., Fanton, Barrot, G., Mangin, A., Theodore, B., Guirlet, M., Koopman, R., de Miguel, Saavedra, L. Snoeij, P. Fehr, T. Meijer, Y., and Fraisse, R: Nighttime ozone profiles in the stratosphere and mesosphere by the Global Ozone Monitoring by Occultation of Stars on Envisat, *J. Geophys. Res.*, 111(D24), doi:10.1029/2006JD007193, 2006.

10 Kyrölä, E., Tamminen, J., Sofieva, V., Bertaux, J. L., Hauchecorne, A., Dalaudier, F., Fussen, D., Vanhellemont, F., Fanton d'Andon, O., Barrot, G., Guirlet, M., Fehr, T., and Saavedra de Miguel, L.: GOMOS O₃, NO₂, and NO₃ observations in 2002-2008, *Atmos. Chem. Phys.*, 10, 7723–7738, doi:10.5194/acp-10-7723-2010, 2010a.

15 Kyrölä, E., Tamminen, J., Sofieva, V., Bertaux, J. L., Hauchecorne, A., Dalaudier, F., Fussen, D., Vanhellemont, F., Fanton d'Andon, O., Barrot, G., Guirlet, M., Mangin, A., Blanot, L., Fehr, T., Saavedra de Miguel, L., and Fraisse, R.: Retrieval of atmospheric parameters from GOMOS data, *Atmos. Chem. Phys.*, 10, 11881–11903, doi:10.5194/acp-10-11881-2010, 2010b.

20 Liu, H.-L. and Roble, R. G.: A study of a self-generated stratospheric sudden warming and its mesospheric-lower thermospheric impacts using the coupled TIME-GCM/CCM3, *J. Geophys. Res.*, 107(D23), 4695, doi:10.1029/2001JD001533, 2002.

25 Liu, Y., Liu, C. X., Wang, H. P., Tie, X. X., Gao, S. T., Kinnison, D., and Brasseur, G.: Atmospheric tracers during the 2003-2004 stratospheric warming event and impact of ozone intrusions in the troposphere, *Atmos. Chem. Phys.*, 9, 2157–2170, doi:10.5194/acp-9-2157-2009, 2009.

Livesey, N. J. and Snyder, W. V.: EOS MLS Retrieval Processes Algorithm Theoretical Basis, Pasadena, California, 2004.

30 Manney, G. L., Krüger, K., Sabutis, J. L., Sena, S. A., and Pawson, S.: The remarkable 2003–2004 winter and other recent warm winters in the Arctic stratosphere since the late 1990s, *J. Geophys. Res.*, 110(D9), D04107, doi:10.1029/2004JD005367, 2005.

Manney, G. L., Krüger, K., Pawson, S., Minschwaner, K., Schwartz, M. J., Daffer, W. H., Livesey,

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



N. J., Mlynczak, M. G., Remsberg, E. E. Russell III, J. M. Waters, J. W.: The evolution of the stratopause during the 2006 major warming: Satellite data and assimilated meteorological analyses, *J. Geophys. Res.*, 113(D11), D11115, doi:10.1029/2007JD009097, 2008.

Manney, G. L., Schwartz, M. J., Kruger, K., Santee, M. L., Pawson, S., Lee, J. N., Daffer, W. H., Fuller, R. A., and Livesey, N. J.: Aura Microwave Limb Sounder observations of dynamics and transport during the record-breaking 2009 Arctic stratospheric major warming, *Geophys. Res. Lett.*, 36(12), L12815, doi:10.1029/2009GL038586., 2009

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

Randall, C. E., Harvey, V. L., Singleton, C. S., Bernath, P. F., Boone, C. D., and Kozyra, J. U.: Enhanced NO_x in 2006 linked to upper stratospheric Arctic vortex, *Geophys. Res. Lett.*, 33, L18811, doi:10.1029/2006GL027160, 2006.

Randall, C. E., Harvey, V. L., Siskind, D. E., France, J., Bernath, P. F., Boone, C. D., and Walker, K. A.: NO_x descent in the Arctic middle atmosphere in early 2009, *Geophys. Res. Lett.*, 36(18), L18811, doi:10.1029/2009GL039706, 2009.

Rodger, C. J., Verronen, P. T., Clilverd, M. A., Seppälä, A., and Turunen, E.: Atmospheric impact of the Carrington event solar protons, *J. Geophys. Res.*, 113(D23), D23302, doi:10.1029/2008JD010702, 2008.

Salmi, S.-M., Verronen, P. T., Thölix, L., Kyrölä, E., Backman, L., Karpechko, A. Yu., and Seppälä, A.: Mesosphere-to-stratosphere descent of odd nitrogen in February/March 2009 after sudden stratospheric warming, *Atmos. Chem. Phys.*, 11, 4645–4655, doi:10.5194/acp-11-4645-2011, 2011.

Sander, S. P., Golden, D. M., Kurylo, M. J., Moortgat, G. K., Wine, P. H., Ravishankara, A. R., Kolb, C. E., Molina, M. J., Finlayson-Pitts, B. J., Huie, R. E., and Orkin, V. L.: Chemical kinetics and photochemical data for use in Atmospheric Studies Evaluation Number 15, JPL, Pasadena, USA, 2006.

Schwartz, M. J.: Validation of the Aura Microwave Limb Sounder temperature and geopotential height measurements, *J. Geophys. Res.*, 113(D15S11), doi:10.1029/2007JD008783., 2008

Seppälä, A., Verronen, P. T., Clilverd, M. A., Randall, C. E., Tamminen, J., Sofieva, V. F., Backman, L., and Kyrölä, E.: Arctic and Antarctic polar winter NO_x and energetic particle precipitation in 2002–2006, *Geophys. Res. Lett.*, 34, L12810, doi:10.1029/2007GL029733, 2007.

Seppälä, A., Clilverd, M. A., Rodger, C. J., Verronen, P. T., and Turunen, E.: The effects of hard-spectra solar proton events on the middle atmosphere, *J. Geophys. Res.*, 113(A11),

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

A11311, doi:10.1029/2008JA013517, 2008.

Seppälä, A., Verronen, P. T., Kyrölä E., Hassinen, S., Backman, L., Hauchecorne, A., Bertaux, J.-L., and Fussen, D.: Solar Proton Events of October–November 2003: Ozone depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat, *Geophys. Res. Lett.*, 31(19), L19107, doi:10.1029/2004GL021042, 2004.

Siskind, D. E., Eckermann, S. D., McCormack, J. P., Coy, L., Hoppel, K. W., and Baker, N. L.: Case studies of the mesospheric response to recent minor, major, and extended stratospheric warmings, *J. Geophys. Res.*, 115, D00N03, doi:10.1029/2010JD014114, 2010.

Smith, A. K., Lopez-Puertas, M., Garcia-Comas, M., and Tukiainen, S.: SABER observations of mesospheric ozone during NH late winter 2002–2009, *Geophys. Res. Lett.*, 36(23), L23804, doi:10.1029/2009GL040942, 2009.

Sofieva, V. F., Kyrölä, E., Verronen, P. T., Seppälä, A., Tamminen, J., Marsh, D. R., Smith, A. K., Bertaux, J.-L., Hauchecorne, A., Dalaudier, F., Fussen, D., Vanhellemont, F., Fanton d'Andon, O., Barrot, G., Guirlet, M., Fehr, T., and Saavedra, L.: Spatio-temporal observations of the tertiary ozone maximum, *Atmos. Chem. Phys.*, 9, 4439–4445, doi:10.5194/acp-9-4439-2009, 2009.

Sofieva, V. F., Tamminen, J., Haario, H., Kyrölä, E., and Lehtinen, M.: Ozone profile smoothness as a priori information in the inversion from limb measurements, *Ann. Geophys.*, 22, 10, 3411–3420, 2004

Sonnemann, G. R., Grygalashvily, M., and Berger, U.: Impact of a stratospheric warming event in January 2001 on the minor constituents in the MLT region calculated on the basis of a new 3-D-model LIMA of the dynamics and chemistry of the middle atmosphere, *J. Atmos. Sol.-Terr. Phys.*, 68, 2012–2025, 2006.

Tamminen, J., Kyrölä, E., and Sofieva, V. F.: Does prior information improve measurements?, in: *Occultations for Probing Atmosphere and Climate – Science from the OPAC-1 Workshop*, edited by: Kirchengast, G., Foelsche, U. and Steiner, A. K., pp. 87–98, Springer Verlag, 2004.

Tamminen, J., Kyrölä, E., Sofieva, V. F., Laine, M., Bertaux, J.-L., Hauchecorne, A., Dalaudier, F., Fussen, D., Vanhellemont, F., Fanton-d'Andon, O., Barrot, G., Mangin, A., Guirlet, M., Blanot, L., Fehr, T., Saavedra de Miguel, L., and Fraisse, R.: GOMOS data characterisation and error estimation, *Atmos. Chem. Phys.*, 10, 9505–9519, doi:10.5194/acp-10-9505-2010, 2010.

Tétard, C., Fussen, D., Bingen, C., Capouillez, N., Dekemper, E., Loodts, N., Mateshvili, N.,

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Vanhellemont, F., Kyrölä, E., Tamminen, J., Sofieva, V., Hauchecorne, A., Dalaudier, F., Bertaux, J.-L., Fanton d'Andon, O., Barrot, G., Guirlet, M., Fehr, T., and Saavedra, L.: Simultaneous measurements of OCIO, NO₂ and O₃ in the Arctic polar vortex by the GOMOS instrument, *Atmos. Chem. Phys.*, 9, 7857–7866, doi:10.5194/acp-9-7857-2009, 2009.

5 Tobiska, W. K., Woods, T., Eparvier, F., Viereck R., Floyd, L. D. B., Rottman, G., and White, O. R.: The SOLAR2000 empirical solar irradiance model and forecast tool, *J. Atmos. Terr. Phys.*, 62, 1233–1250, 2000.

Turunen, E., Matveinen, H., Tolvanen, J., and Ranta, H.: D-region ion chemistry model, in *STEP Handbook of Ionospheric Models*, edited by R. W. Schunk, pp. 1–25, SCOSTEP Secretariat, Boulder, Colorado, USA, 1996.

10 Verronen, P. T. : Ionosphere-Atmosphere Interaction During Solar Proton Events, Finnish Meteorological Institute, Helsinki, Finland, 2006.

Verronen, P. T., Seppälä, A., Clilverd, M. A., Rodger, C. J., Kyrölä, E., Enell, C.-F., Ulich, T., and Turunen, E.: Diurnal variation of ozone depletion during the October-November 2003 solar proton events, *J. Geophys. Res.*, 110, A09S32, doi:10.1029/2004JA010932, 2005.

15 Verronen, P. T., Funke, B., Lopez-Puertas, M., Stiller, G. P., von Clarmann, T., Glatthor, N., Enell, C.-F., Turunen, E., and Tamminen, J.: About the increase of HNO₃ in the stratopause region during the Halloween 2003 solar proton event, *Geophys. Res. Lett.*, 35(20), L20809, doi:10.1029/2008GL035312, 2008.

20 Wang, L. and Alexander, M. J.: Gravity wave activity during stratospheric sudden warmings in the 2007-2008 Northern Hemisphere winter, *J. Geophys. Res.*, 114(D18), D18108, doi:10.1029/2009JD011867, 2009.

25 Waters, J. W. Froidevaux, L. Harwood, R. S., Jarnot, R. F., Pickett, H. M., Read, W. G., Siegel, P. H., Cofield, R. E., Filipiak, M. J., Flower, D. A., Holden, J. R., Lau, G. K. K., Livesey, N. J., Manney, G. L., Pumphrey, H. C., Santee, M. L., Wu, D. L., Cuddy, D. T., Lay, R. R., Loo, M. S., Perun, V. S., Schwartz, M. J., Stek, P. C., Thurstans, R. P., Boyles, M. A., Chandra, K. M., Chavez, M. C., Chen, G. S., Chudasama, B. V., Dodge, R., Fuller, R. A., Girard, M. A., Jiang, J. H., Jiang, Y. B., Knosp, B. W., LaBelle, R. C., Lam, J. C., Lee, K. A., Miller, D., Oswald, J. E., Patel, N. C., Pukala, D. M., Quintero, O., Scaff, D. M., Van Snyder, W., Tope, M. C., Wagner, P. A., and Walch, M. J.: The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite, *IEEE T. Geosci. Remote*, 44(5), 1075–1092, doi:10.1109/TGRS.2006.873771, 2006.

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

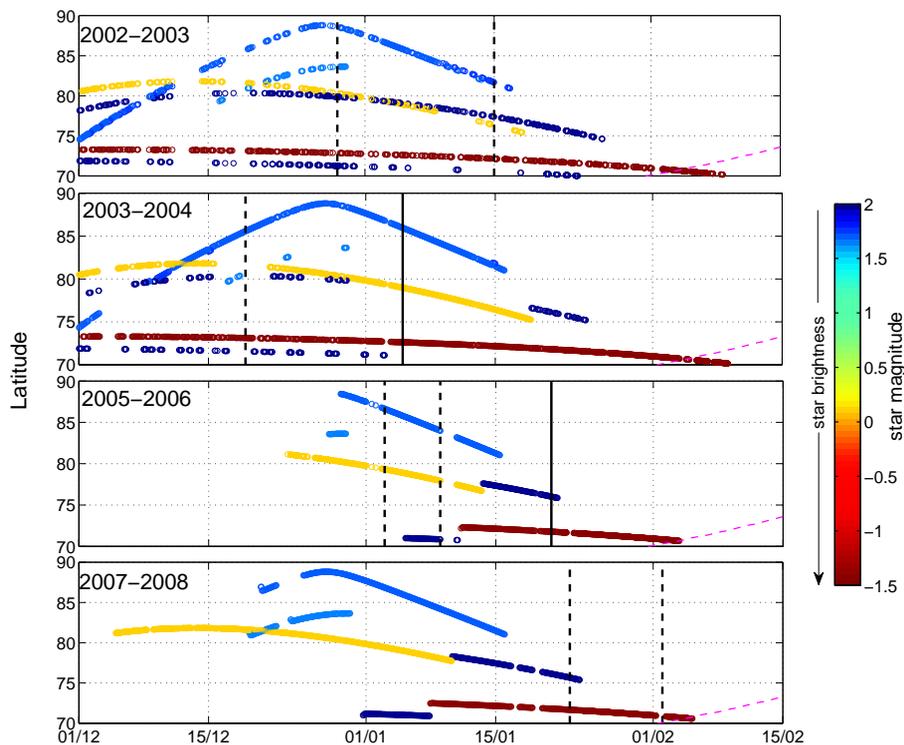


Fig. 1. GOMOS data availability in the latitudinal band 70° – 90° N in four winters. Colour indicates the visual magnitude of the occulted stars: the smaller the visual magnitude the brighter the star. Black dashed and solid lines indicate onsets of minor and major SSW, respectively. Pink dashed lines indicate the latitude of the polar night terminator.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Middle atmosphere
composition during
sudden stratospheric
warmings**

V. F. Sofieva et al.

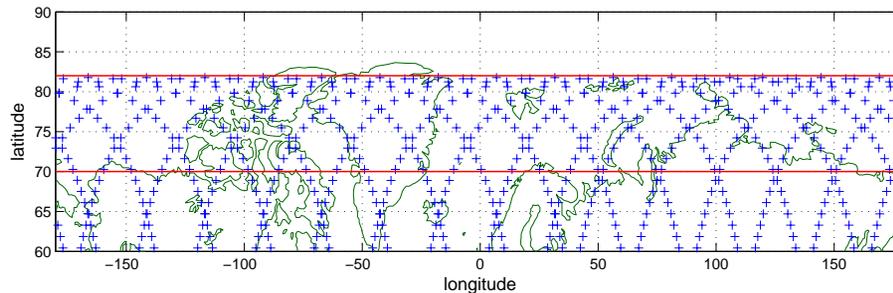


Fig. 2. Locations of the MLS profiles for January 21 2006; red lines indicate the zonal band used in this study.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

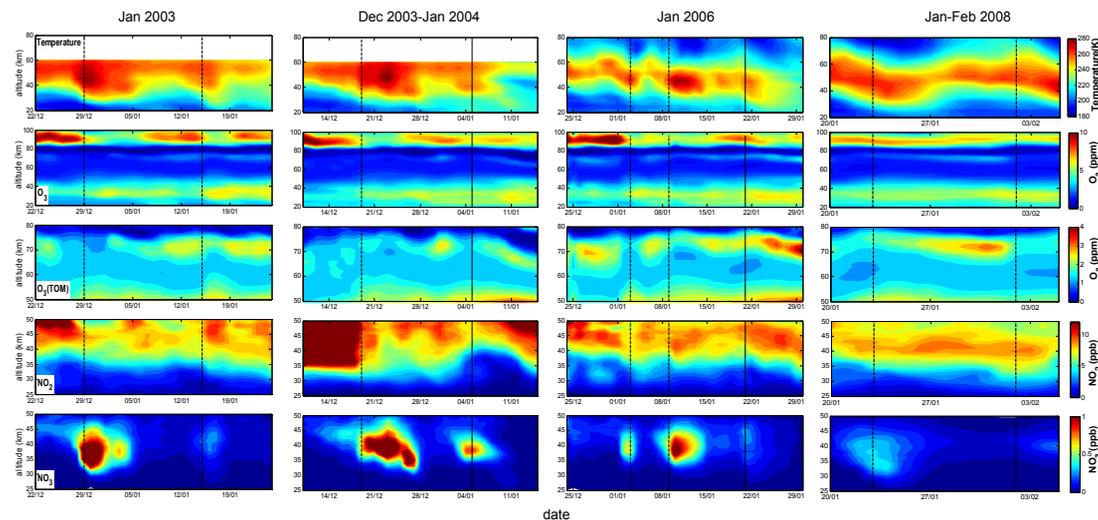


Fig. 3. Data at 70°–90° N during four winters; 1st row: temperature from ECMWF (years 2002–2004) and MLS data (years 2006 and 2008); GOMOS observations of ozone (2nd row) with the zoom on tertiary ozone maximum (TOM) (3rd row), NO₂ (4th row) and NO₃ (5th row). Vertical black dashed and solid lines indicate the onsets of minor and major SSW, respectively.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Middle atmosphere
composition during
sudden stratospheric
warmings

V. F. Sofieva et al.

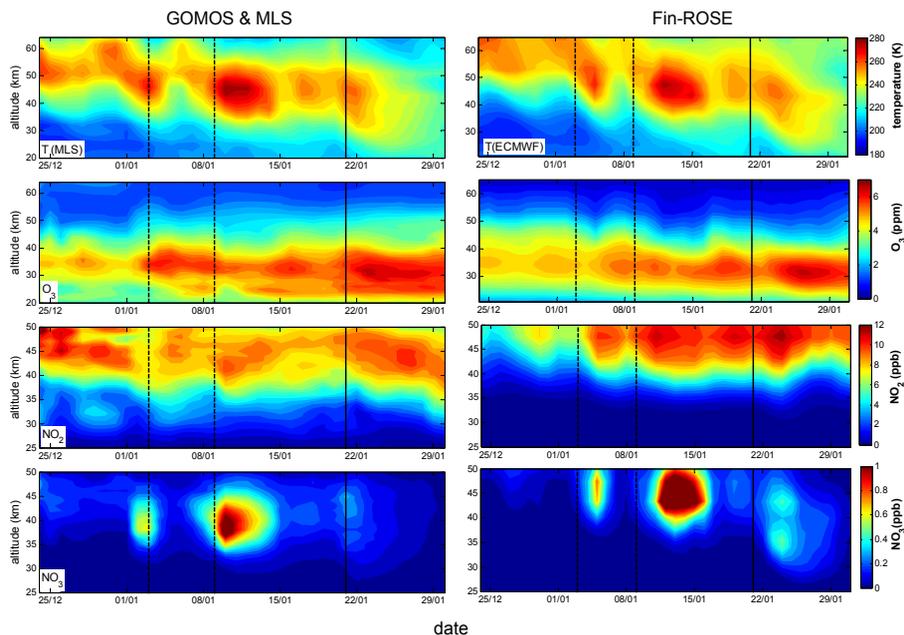


Fig. 4. Changes in the middle atmosphere during January 2006 SSW as observed by GOMOS-MLS (left), and as simulated with FinROSE (right). The results present zonally averaged data in the latitudinal band 70°–90° N.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

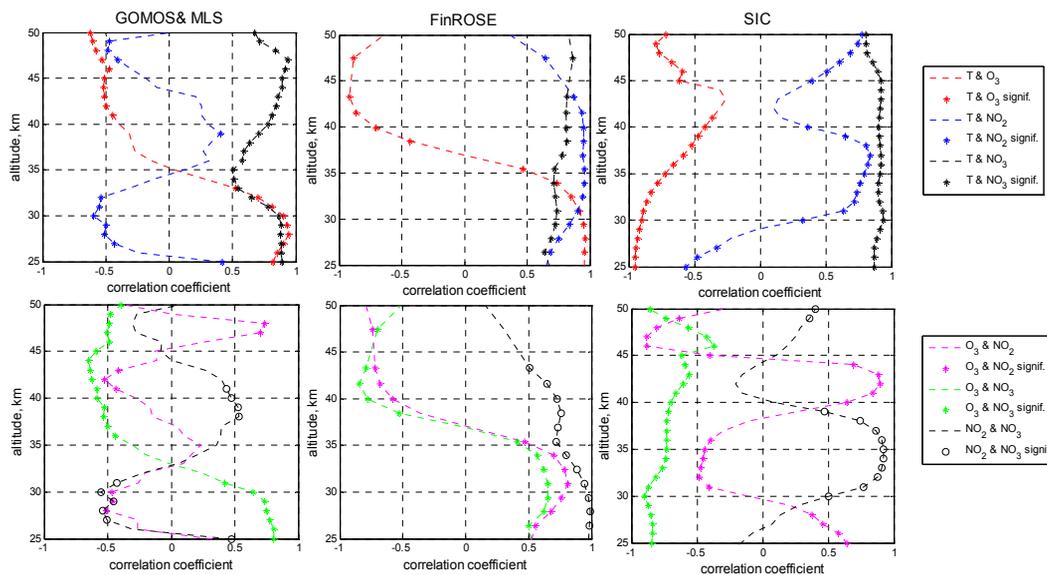


Fig. 6. Correlation coefficients between temperature and trace gases using zonally averaged data from 1–25 January 2006 at latitudes 70–90° N; left GOMOS trace gases and MLS temperature, center: FinROSE simulations, right: SIC simulations. Markers (stars and circles) indicate values with statistically significant correlation (i.e., values with probability of zero correlation smaller than 5 %).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Middle atmosphere composition during sudden stratospheric warmings

V. F. Sofieva et al.

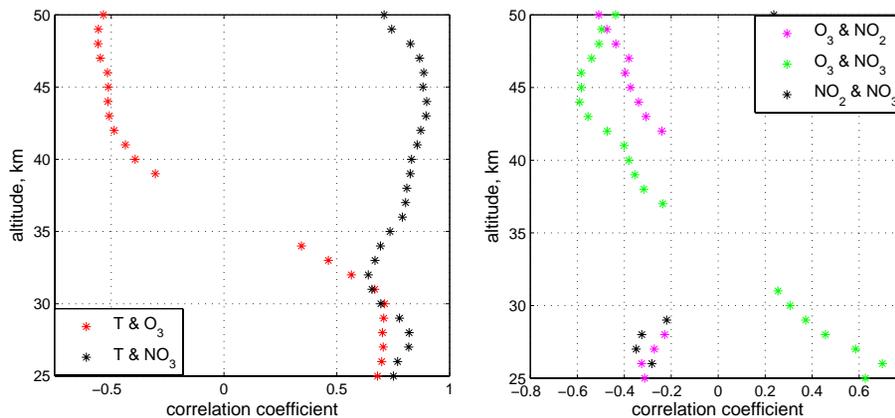


Fig. 7. Statistically significant correlations between temperature (MLS and ECMWF) and trace gases (GOMOS) for SSW in years 2003, 2004, and 2006.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion