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Unusually strong nitric oxide descent in the Arctic middle atmosphere in early 2013 as observed by Odin/SMR

K. Pérot, J. Urban, and D. P. Murtagh

Chalmers University of Technology, Department of Earth and Space Sciences,
Gothenburg, Sweden

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Correspondence to: K. Pérot (kristell.perot@chalmers.se)

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Abstract

The middle atmosphere has been affected by an exceptionally strong midwinter stratospheric sudden warming (SSW) during the Arctic winter 2012/2013. These unusual meteorological conditions led to a breakdown of the polar vortex, followed by the reformation of a strong upper stratospheric vortex associated with particularly efficient descent of air. Measurements by the Sub-Millimetre Radiometer (SMR), on board the Odin satellite, show that very large amounts of nitric oxide (NO), produced by Energetic Particle Precipitation (EPP) in the mesosphere/lower thermosphere (MLT), could thus enter the polar stratosphere in early 2013. The mechanism referring to the downward transport of EPP generated-NO_x during winter is generally called the EPP indirect effect. SMR observed up to 20 times more NO in the upper stratosphere than the average NO measured at the same latitude, pressure and time during three previous winters where no mixing between mesospheric and stratospheric air was noticeable. This event turned out to be an unprecedentedly strong case of this effect. Our study is based on a comparison with the Arctic winter 2008/2009, when a similar situation was observed and which was so far considered as a record-breaking winter for this kind of events. This outstanding situation is the result of the combination between a relatively high geomagnetic activity and an unusually high dynamical activity, which makes this case a prime example to study the EPP impacts on the atmospheric composition.

1 Introduction

Energetic Particle Precipitation (EPP) refers to the process by which energetic protons and electrons affect the Earth's middle atmosphere. It leads, amongst other things, to the production of odd nitrogen in the mesosphere and lower thermosphere (MLT). This family of chemical species, involved in catalytic ozone (O₃) destruction, plays an important role in atmospheric chemistry (Solomon et al., 1982). Energetic electrons trapped into the magnetospheric field lines can reach the atmosphere during geomag-

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netic perturbations and generate large amounts of nitric oxide (NO) in the polar regions. In winter polar night conditions, the NO_x ($\text{NO} + \text{NO}_2$) produced by EPP have a lifetime long enough to be transported down to the stratosphere by the meridional circulation. This mechanism has already been described by a number of authors (e.g., Siskind et al., 2000; Funke et al., 2005; Randall et al., 1998, 2009). It is generally called the EPP indirect effect (EPP IE).

This mechanism is controlled both by space weather and middle atmosphere dynamics. It indeed depends on the EPP- NO_x production level, which can be inferred from the Ap index. Irregular changes in Earth's magnetic field are caused by the interaction between the solar wind with the magnetosphere. The Ap index was designed to describe this phenomenon, linked to solar variability. It is a measure of geomagnetic activity over the globe. EPP represents therefore an important solar-terrestrial coupling mechanism. But the indirect effect also depends on transport. This second factor plays an important role, especially in the Northern Hemisphere (NH) where dynamical variability is higher than in the south (Randall et al., 2007). Exceptional dynamical conditions can lead to surprisingly strong EPP IE. Such a situation has been observed several times during the last decade. Using Odin/Sub-Millimetre Radiometer (SMR) data over the period 2001–2009, Orsolini et al. (2010) presented evidence for an anomalously strong descent of mesospheric air into the upper stratosphere in the Arctic region in three winters over the 8 analyzed years. The 2008/2009 NH polar winter in particular was characterized by an unusually strong and persistent midwinter stratospheric sudden warming (SSW) (Labitzke et al., 2009; Manney et al., 2009). SSW is a phenomenon that takes its name from a rapid temperature increase of several tens of Kelvin over a few days at high latitude. It is triggered by planetary scale wave motions propagating upward from the troposphere. They break when reaching the stratosphere, releasing their energy and disturbing the polar vortex. It is important to highlight that only midwinter warmings are considered in this study. For that kind of events, a coherent stratospheric polar vortex is reestablished, contrary to final warmings that cause the definitive breakdown of the vortex at the end of the winter. The 2009 SSW event was characterized by a full

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breakdown of the vortex, followed by the reformation of a strong upper stratospheric vortex associated with very efficient descent of air. Randall et al. (2009) showed that very large amounts of NO_x could thus enter the stratosphere despite a level of geomagnetic activity well below average, which clearly demonstrates the importance of dynamical modulations of EPP IE.

It will be shown in this paper that the 2012/2013 polar winter has also been affected by an exceptionally strong midwinter SSW. Unusually large amounts of EPP-generated NO have been transported downward into the Arctic stratosphere and lower mesosphere in early 2013. The purpose of this work is to describe this event, based on the analysis of Odin/SMR observations, and to present a basic comparison with the case of 2009 which was so far considered as a record-breaking winter for this kind of events (Labitzke et al., 2009; Manney et al., 2009; Randall et al., 2009). The concentration of nitric oxide is an important quantity to monitor since this species is involved in O_3 depletion, which plays a crucial role in atmospheric chemistry. The results presented here can contribute to a better understanding of its variability. They will be described in Sect. 2 and discussed in Sect. 3.

2 Results

2.1 The sub-millimetre radiometer

Odin is a small Swedish-led research satellite, in cooperation with the Canadian, French and Finnish space agencies, launched in 2001 (Murtagh et al., 2002). It was initially dedicated to aeronomy and astronomy, but is entirely dedicated to aeronomy since April 2007. It is also an European Space Agency (ESA) third party mission since the same year.

The Sub-Millimetre Radiometer is one of the instruments aboard Odin. It is a limb emission sounder measuring globally a variety of trace gases as well as temperature in the whole middle atmosphere. The work presented in this paper is based on the

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measurements performed by this instrument. Water vapour (H_2O) is retrieved from a strong thermal emission line at 557 GHz, providing information from ~ 40 to ~ 100 km with an altitude resolution of about 3 km. Temperature data are derived simultaneously from the same band in the ~ 40 – 90 km altitude range. Retrieval and error analysis for these measurements are described in detail by Lossow et al. (2007). SMR also observes NO thermal emission lines in a band centered near 551.7 GHz. The vertical resolution for this species is ~ 7 km in the upper stratosphere and in the mesosphere. NO data are available from 2003 on the basis of one measurement day per month. As noted above, the instrument is entirely dedicated to the Earth observation since 2007. NO measurements could therefore been performed much more frequently after this date, on an irregular basis of four observation days in a 16 day cycle (approximately 8 days month⁻¹). More details about these measurements are given by Sheese et al. (2013). For our study, only the observations made after 2007, with a good temporal sampling, have been used.

2.2 Middle atmospheric dynamical activity

Figure 1 represents the state of the middle atmosphere during the Arctic winter 2012/2013, from November to May, in the vertical range 2–0.003 hPa (approximately 40–90 km, which is the altitude range in which temperature data are available). Odin/SMR measurements are plotted in the two first panels. Figure 1a shows the evolution of zonal mean temperatures poleward of 70° . A clear increase of the temperature appears in the upper stratosphere, around 1 hPa, in early January. This stratospheric warming is associated with a mesospheric cooling, clearly visible around 0.03 hPa. The black diamonds indicate the maximum of the temperature profile in the vertical range considered. They represent the stratopause, which clearly descends immediately after the warming event, but reforms at a particularly high altitude (around 80 km) in the following weeks. The white dots, overlaid for comparison, show the evolution of the stratopause height during the winter 2008/2009, as inferred from temperature measurements from SMR. As explained in Sect. 1, both winters were characterized by a particularly strong

SSW event. This plot shows that the behaviour of the temperature structure was very similar in both cases. Such elevated stratopause (ES) events are most of the time observed during winter when the middle atmospheric zonal wind structure is disturbed by a SSW (Chandran et al., 2013).

The bottom panel of Fig. 1 shows how the typical wintertime circulation has been disrupted in early 2009 (thin grey line) and in early 2013 (thick purple line). For this plot, wind fields from the European Centre for Medium-range Weather Forecast (ECMWF) operational analyses have been used as ancillary meteorological data. According to the World Meteorological Organization (WMO), a major midwinter warming occurs when the zonal mean zonal winds at 60° N and 10 hPa become easterly during winter (between November and March) (Andrews et al., 1985). In addition to the reversal of the winds, the WMO definition requires that the 10 hPa zonal mean temperature gradient between 60° and 90° N is positive. The first day on which the zonal wind reverses is defined as the central date of the SSW event. As shown in Fig. 1c, this occurred on the 23 January 2009 and on the 6 January 2013. The temperature gradients also reversed poleward of 60° (not shown here). The criteria for a major midwinter warming have therefore been fulfilled for these two winters. The zonal wind stayed easterly for about ten days and then reversed again. The easterlies were clearly stronger in 2013 than in 2009. In both cases, the vortex fully recovered in late February, but, in 2009, contrary to what happened in 2013, the wind speed didn't reach values comparably high as before the warming.

Figure 1b represents the vertical-time section of zonal mean H₂O volume mixing ratios (vmr) measured by SMR between November 2012 and May 2013. Water vapour is a very good tracer for the dynamical processes in the middle atmosphere (e.g., Orsolini et al., 2010). Here for example, looking at the 3 ppmv and 5 ppmv contours allows a good visualization of the evolution of air masses throughout the winter. In November and December, at a given pressure level, mixing ratios slightly drop in time as a result of early winter descent of air due to the meridional mesospheric circulation (more pronounced on the 3 ppmv contour). This evolution is interrupted by a brief increase of

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however, it is very clearly visible. In January, only a few days after the central date of the stratospheric warming event, a clear distortion of the polar vortex appears, and it has also been split into two smaller vortices. This feature is much more pronounced in the lower stratosphere where the vortex is more confined and extends over a smaller area. That is the level where the classification of SSW events is generally established. Here we have chosen to stay focused in the altitude range under consideration in this paper (~ 40 – 90 km). We only point out that the polar maps of N_2O vmr, measured by SMR at a level of about 20 km (not shown), show very clearly a breakdown of the vortex into two vortices of similar size, associated with the shift in wind direction in early January. The 2013 SSW can then be classified as a vortex split event, like the one of 2009. Figure 2 shows that the vortex recovers in early February, simultaneously with the formation of the elevated stratopause (see Fig. 1a). Some weeks later, the vortex becomes significantly stronger than before the warming event, and it finally disappears at the beginning of the spring (30 March 2013).

2.3 Energetic particle precipitation indirect effect

Figure 3a and b show the evolution of zonally-averaged NO mixing ratio in the Arctic region during the 2008/2009 and 2012/2013 winters. As previously explained, both of these winters were characterized by a particularly efficient descent of air due to the reformation of the polar vortex after a major midwinter warming event. SMR observations of NO illustrate the dynamical modulations of the EPP indirect effect during these two particular winters. The white dash-dotted lines indicate the central date of the warming events. A slight depletion of NO in the upper stratosphere and mesosphere is visible in January, immediately after this date. This is due to the upward transport of H_2O -rich, NO-poor air, as seen in Fig. 1, and it also might be a signature of poleward mixing. This observation fits with the modelling study by Tweedy et al. (2013), which shows a hint of such a decrease. In both 2009 and 2013, very large amounts of NO descended quickly into the upper stratosphere. There were at least 40 ppbv, around 0.4 hPa (~ 55 km), 2 months after the central date of the SSW event, in both years. As seen in Fig. 2, the

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vortex is not always located above the pole. It can be shifted away, especially during the warming event. Consequently, even if measurements represented in Fig. 3 have mainly been done inside the vortex, there can also be a slight influence of some mixing with the air from outside the vortex. Using equivalent latitude as a coordinate can decrease the effect of this mixing. In this case, the air masses we are looking at would be more likely located inside the vortex, at least below 3000 K (~ 0.5 hPa, ~ 60 km) (Harvey et al., 2009). The same plots have therefore been made with NO measurements performed in the $[70\text{--}90]^\circ$ N equivalent latitude range (not shown). Equivalent latitude is calculated from ECMWF PV fields, which are available only up to 0.4 hPa (~ 55 km). As a result, only the bottom part of the descent event can be observed. As expected, the descent pattern was slightly more pronounced and more continuous. But, in the limited altitude range available, we found that the overall pattern was very similar. That is a confirmation that Fig. 3 gives a good representation of the phenomenon.

Figure 4 represents the relative NO enhancements for the Arctic winters 2008/2009 and 2012/2013. The goal is to compare the EPP indirect effect for these two years. All measurements done after 2007, when the temporal sampling of the instrument was much better, have been considered in this study. Nitric oxide measurements from Odin/SMR have been analyzed for each of these six winter seasons. In 2007/2008 and 2010/2011, no significant dynamical event disturbed the middle atmosphere in the middle of the winter. The EPP-induced NO stayed in the MLT, and EPP IE was therefore very low. A SSW event occurred in late January 2010. However no particular NO downward transport has been observed and the EPP IE was very low that year as well. This can be explained by the fact that this warming event was dynamically very weak. No mixing between mesospheric and stratospheric air masses was noticeable in the SMR data set. In addition, the geomagnetic activity was particularly low. The average Ap index from 1 October 2009 to 1 March 2010 was 3.1 only, and never exceeded 14 (data from ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/). As a result, very little NO was produced in the MLT. The winter 2009/2010 can therefore be considered as dynamically quiet with respect to NO. As for the winter 2011/2012,

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a quite uncommon situation was observed. This winter has been affected by a minor stratospheric warming in January and by a solar proton event (SPE) approximately at the same time. A series of coronal mass ejections generated intense particle fluxes of high energy, which could penetrate deep into the Earth's atmosphere in the polar regions and dramatically alter the middle atmospheric composition (von Clarmann et al., 2013). This mechanism is generally called the EPP direct effect. In January 2012, this effect was superimposed on the subsidence of mesospheric NO-rich air caused by the SSW event, making the EPP IE more challenging to observe. That is the reason why we decided not to include this winter in our study.

The NO mixing ratios measured during the three winters 2007/2008, 2009/2010 and 2010/2011 have been averaged in order to get an estimate of the background levels during quiet conditions. These averaged values are represented in Fig. 3c, and will be considered as a reference for the standard NO winter distribution in the Arctic region. A slight increase in NO mixing ratios is noticeable in this figure in the stratosphere from March to May. This seasonal variation is due to NO_x partitioning. During winter and until March, SMR measures only during nighttime in the latitude range considered here. However, after March, the data set used in this study corresponds to a combination of measurements performed in dark and sunlit conditions. As explained by Funke et al. (2011), stratospheric NO₂ is converted into NO in the presence of sun light, hence the slight increase observed in NO vmr.

The ratio of nitric oxide measured by SMR in 2008/2009 and 2012/2013 to this reference background has been calculated and plotted in Fig. 4. A tongue of increased NO vmr for both winters is clearly visible. There could possibly be an influence of the seasonal variation, but this one would be very small, as the seasonal signal is negligible compared to the EPP IE (as seen in Fig. 3). The red diamonds represent the height of the stratopause as seen by Odin/SMR. It appears that the onset of the enhancements coincides exactly with the formation of the elevated stratopause, which is due to an interplay between gravity wave and planetary wave forcing, as explained by Limpasuvan et al. (2012). In both years, at least three times more NO than average is observed

between ~ 70 and 85 km immediately after the ES event. The high NO tongue stays just below the stratopause, following its evolution in altitude and time for at least two months.

3 Summary and discussion

5 The major warming event that occurred in January 2009 was unusually strong and persistent in time, as shown by Manney et al. (2009). We have seen in the previous section that the 2013 SSW was even stronger, with a very efficient downward motion that extends particularly low in altitude. As it appears in SMR measurements (Fig. 3), the downward transport of NO can be strongly amplified during the Arctic winters affected by such an event. NO formed in the MLT by the impact of energetic particles has indeed been transported down to the mesosphere and upper stratosphere in very large amounts during the months following these two SSW events. Figure 4 shows that the 2013 SSW led to significantly larger NO enhancements than the 2009 warming event. Up to 20 times more NO than average was observed in the upper stratosphere, whereas this ratio did not exceed a value of ~ 9 in 2009. If we consider all of the values greater than 3, the mean excess NO is 4.9 in 2013, while it is only 4.0 in 2009. Moreover, the tongue of EPP-NO extends much lower in altitude (below ~ 40 km vs. ~ 50 km in 2009). It is also significantly more extended in time (93 days after the central date of the warming event vs. 79 days in 2009). This last SSW has therefore a higher potential to affect the stratospheric composition.

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25 The effects of EPP on the atmosphere are not only governed by the dynamics, but also by the solar activity. The winter 2012/2013 was close to the solar maximum of the solar cycle 24, whereas the winter 2008/2009 corresponded to the solar minimum. The average Ap index from 1 October 2012 to 1 March 2013 was quite high: 6.6 with a maximum of 47, while it was just 4.8 and never exceeded 34 for the same period four years earlier (data from ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/). The geomagnetic activity was therefore relatively high during this

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latest winter. That allowed more magnetospheric electrons to precipitate into the polar MLT, which increased ionisation and led to a higher NO production level (as we can see on the top part of Fig. 3). The outstanding EPP IE observed in early 2013 was therefore the result of the combination between a high geomagnetic activity and an exceptionally high dynamical activity. All the elements were gathered for an unprecedented strong EPP indirect effect, which makes this event a very good example of how the solar activity can influence the Earth atmosphere.

There are only a few examples of EPP IE on record. Randall et al. (2009) present the cases of the years 2004, 2006 and 2009, from the measurements by the Atmospheric Chemistry Experiment (ACE). Exceptionally large amount of NO_x were observed in early 2004, but these results were inconclusive because of the unavailability of ACE data during the first half of the winter, and also because there was a possible influence of the strong solar storms that occurred in late 2003 (see Funke et al. (2011) for more details about this event). EPP-NO_x enhancements were larger in 2009 than in 2006 according to Randall et al. (2009) (see Randall et al. (2006) for more details about the case of 2006). SMR measurements presented in our paper confirm therefore that the NO descent observed during the Arctic winter 2012/2013 corresponds to the strongest EPP indirect effect available on record.

The indirect effect of energetic particle precipitation is still poorly understood, and its representation in current atmospheric models is challenging (Funke, 2011). Addressing the case of the winter 2012/2013 is a good opportunity for the scientific community to get more information about this mechanism. Further studies are needed to find out if this unusually strong event affected the ozone layer, and had an impact on climate through stratospheric chemical and dynamical processes.

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2013 Arctic NO in
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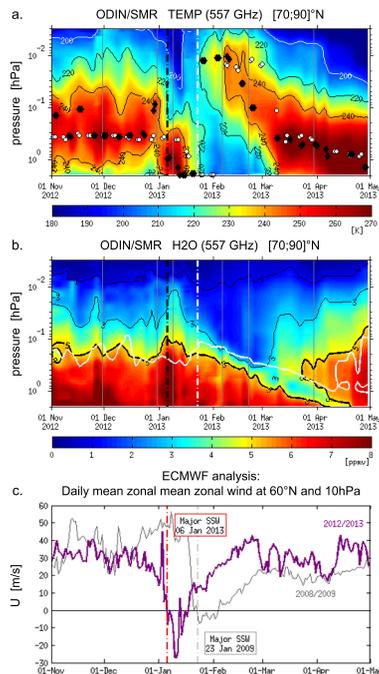


Fig. 1. (a) Upper stratosphere/mesosphere pressure-time section of SMR zonal mean temperature in the 70–90° latitude band during the Arctic winter 2012/2013. Black diamonds indicate the zonal average stratopause height and the black dash-dotted line indicates the central date of the warming. For comparison, overlaid white dots and white dash-dotted line correspond to the same parameters for the 2009 event. The thin vertical grey lines indicate the six selected days for which a polar map has been plotted in Fig. 2. (b) Same as (a) but for SMR zonal mean H₂O volume mixing ratio. The thick black contour is associated with volume mixing ratio values of 5 ppmv. The same contour measured in 2008/2009 (solid white line) is overlaid for comparison. (c) Daily mean zonal mean zonal wind at 60°N and 10 hPa from ECMWF analyses during the Arctic winters 2008/2009 (thin grey line) and 2012/2013 (thick purple line). The dash-dotted lines indicate the central dates of these warmings.



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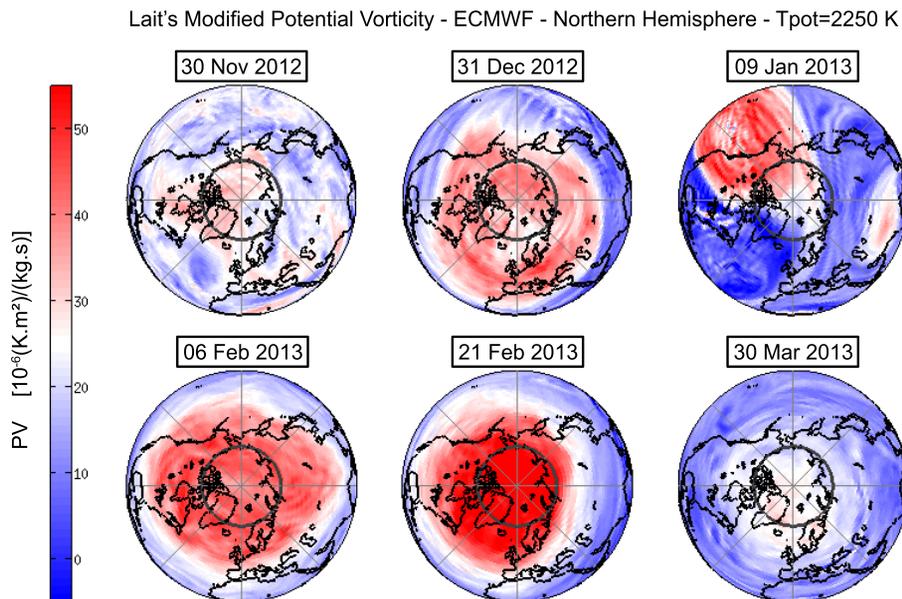


Fig. 2. Polar maps of potential vorticity from ECMWF analyses in the upper stratosphere (2250 K level of potential temperature) for six selected days (which have been represented by thin vertical grey lines in Fig. 1a and b). These maps allow us to visualise the evolution of the vortex shape during the Arctic winter 2012/2013. The whole Northern Hemisphere is represented, with 0° E at bottom. The thick grey circle corresponds to a latitude of 70° N, which delimits the area considered in this study.

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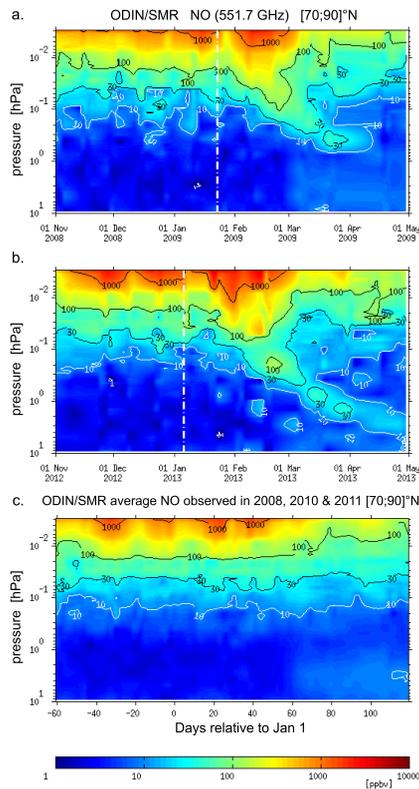


Fig. 3. Upper stratosphere/mesosphere pressure-time sections of SMR zonal mean NO mixing ratio in the NH high latitudes (poleward of 70° N), from 1 November to 1 May, for the Arctic winter seasons 2008/2009 **(a)** and 2012/2013 **(b)**. The white dash-dotted lines indicate the central date of the warmings. Panel **(c)** represents the average NO measured during winters 2007/2008, 2009/2010 and 2010/2011, when no downward transport of NO was noticeable in the SMR data set.

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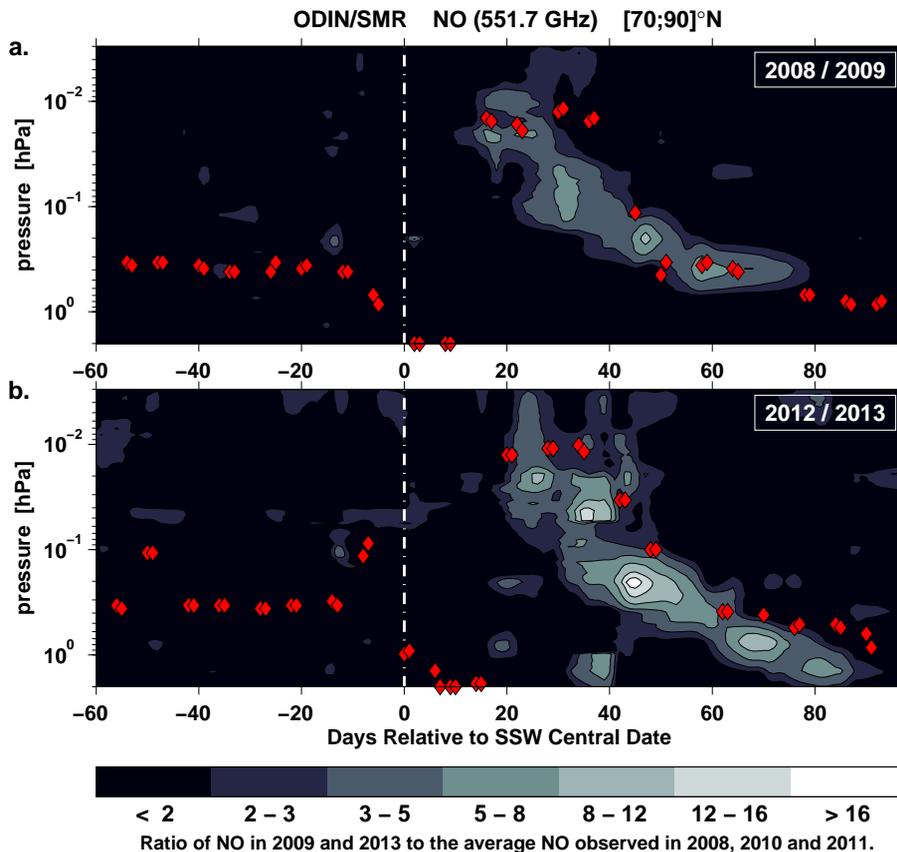


Fig. 4. Relative NO enhancements: ratio of nitric oxide in 2008/2009 and 2012/2013 to the average NO measured at the corresponding latitude, pressure and time in 2007/2008, 2009/2010 and 2010/2011. Time is expressed in days relative to the central date of each SSW event (white dash-dotted lines) to make the comparison easier. Red diamonds indicate the height of the stratopause as inferred from SMR temperature measurements.