Observations of 2010 and 2011 winter-spring anomalies of stratospheric ozone and NO_2 over Moscow region

A.N. Gruzdev[1], E.P. Kropotkina[2], S.V. Solomonov[2], and A. Elokhov[1]

[1]A.M. Obukhov Institute of Atmospheric Physics, Moscow, Russia
[2]P.N. Lebedev Physical Institute, Moscow, Russia

Measurements of the stratospheric contents of O_3 and NO_2 in the Moscow region are used to analyse the anomalies of these species related to the sudden stratospheric warming and associated deformation of the stratospheric circumpolar vortex in early February 2010, and the latitudinal displacement of the stratospheric vortex towards the European sector in late March 2011 before the final spring warming. In the former case, an increase in the O_3 and NO_2 contents up to 85% and by two times, respectively, was observed. In the latter case, the O_3 content decreased by a quarter and the NO_2 content dropped by two times compared to periods preceding the beginning of the anomalies.

1. Introduction

The dynamic and chemical processes in the extratropical stratosphere in the winter–spring period are related to the spatial-time evolution of the circumpolar stratospheric vortex to a considerable degree (Schoeberl *et al.* 1992). A strong steady vortex causes dynamic isolation of the Arctic stratosphere, leads to enhanced cooling of the stratosphere, and restrains the accumulation of ozone in the internal area of the vortex. If the cooling is rather strong and followed by the formation of polar stratospheric clouds and stratospheric denitrification as in 2011, there can be additional depletion of stratospheric ozone (Manney *et al.* 2011).

During a winter a sudden stratospheric warming (SSW) can develop in the Arctic stratosphere, which affects the thermal regime, the structure and the circulation of the middle atmosphere [Schoeberl 1978, Charlton and Polvani 2007]. Major SSW lead to considerable redistribution of stratospheric species like ozone.

This work demonstrates the results of simultaneous observations of vertical distributions of O_3 and NO_2 over the Moscow region during the SSW in 2010 and the Arctic ozone hole in 2011. Denitrification of the Arctic stratosphere at the end of the winter of 2011 were established, for example, by Manney *et al.* (2011) and Adams *et al.* (2012). Effects of the 2011 Arctic ozone hole on stratospheric NO_2 in the middle latitudes were studied by Gruzdev and Elokhov (2013) and Ageyeva *et al.* (2014, 2015).

2. Data used

Measurements of the vertical distribution and column NO_2 content are carried out during morning and evening twilight at Zvenigorod Scientific Station located in a rural area 50 km west to Moscow (Gruzdev and Elokhov 2011). The station is a part of the Network for the Detection of Atmospheric Composition Change (NDACC). Measurements are done with a zenith-viewing spectrometer in the 435-450 nm wavelength range. Retrieving of NO_2 vertical profiles allows eliminating effects of near-surface pollution NO_2. The column NO_2 contents are calculated by integrating profiles above the boundary layer.

The vertical distribution of O_3 in the stratosphere over Moscow is determined by ground-based measurements of the thermal emission of O_3 at 2.1 mm wavelength using an original high-sensitive spectrometer (Solomonov *et al.* 2011). The total error of O_3 profile retrieval usually does not exceed 5–7% in 20–50 km layer and increases gradually at higher and lower levels. The field of view of the spectrometer is approximately oriented the region of the stratosphere above Zvenigorod station.

In this work we also use the data on the temperature, wind velocity, and potential vorticity of the British Atmospheric Data Center, the data of ERA-Interim reanalysis from the European Center for Medium-Range Weather Forecasts, and the results of total ozone measurements by the OMI instrument onboard the EOS-Aura satellite obtained from the Giovanni online data system developed and maintained by the NASA GES DISC.

3. Results

Figures 1a and 1b shows the O_3 mixing ratios on the isobaric surfaces 10 and 20 hPa and the deviation of the column NO_2 content from the NO_2 annual cycle in the periods of 2010 and 2011 under analysis. The annual cycle of NO_2 was removed due to its high amplitude to visualize the anomalies.

3.1. Effect of the 2010 sudden stratospheric warming

At the end of January and the beginning of February 2010, the sharp increase occurred in the O_3 and NO_2 contents (Fig. 1a) caused by the SSW and associated meridional advection of low-latitude stratospheric air (Fig. 2a-b). As a result of the warming, the temperature in the polar stratosphere quickly increased, its meridional gradient changed sign, and the zonal wind weakened and changed its direction (Fig. 3a). These were accompanied by the increase in the amplitude of the planetary wave with zonal wave number 1 (Fig. 3b).

The ozone and NO_2 concentration maxima were reached on February 3–5 (Figs. 1a, 4a-b). The increase in the concentrations was observed in the entire stratospheric layer, but it was not equal at different heights (Fig. 4d). Temperature in 15-30 km layer over Moscow increased; the increase in the neighbourhood of 25 km altitude was about 40℃ per eight days (Fig. 4c). It is in the neighbourhood of this altitude there was the largest increase by 85% in the O_3 concentration while the NO_2 concentration tripled (Fig. 4d). The total ozone content increased by a quarter and the column NO_2 content doubled relative to January values.

3.2. Effect of the 2011 Arctic ozone hole

Figure 1b shows a significant decrease in the ozone and NO_2 contents in the end of March 2011. These anomalies were caused by the shift of the polar stratospheric vortex toward the European sector (Fig. 2c-d). As a result, the polar air with a significant deficit of ozone and NO_x observed that year in the Arctic stratosphere arrived to the mid-latitudes. The O_3 concentration in the 20–5 hPa layer decreased by a quarter at the anomaly peak, and the column NO_2 content decreased to half amount.

Figure 5a–c shows O_3, NO_2 and temperature profiles on the date of the O_3 and NO_2 anomalies (March 29) compared to the profiles for the date that immediately preceded the beginning of the decrease in the species contents. The decrease in the O_3 and NO_2 concentrations occurred mainly in the stratosphere below 40 km, and the relative decreases at the lower levels were larger than at the upper levels. The most significant NO_2 decrease – more that half – occurred in the neghbourhood of 20-km altitude where maximal decrease in temperature also took place.

3.3. Comparison of 2010 and 2011 negative anomalies

Figure 1a shows that negative anomalies in the O_3 and NO_2 contents were also observed in the end of March 2010 despite the winter SSW. After the SSW, one of the two fragments of the split polar stratospheric vortex was localized in the second half of February over Canadian Arctic. Then it drifted by the middle of March westward to the European part of Russian Arctic. The O_3 and NO_2 negative anomalies in March 2010 were caused by the subsequent southward shift of the southern periphery of this vortex fragment. It is important to emphasize that the anomalies were caused by one of the two fragments which during the winter was predominantly in the polar latitudes.

4. Conclusions

On the whole, significant anomalies of stratospheric ozone and NO_2 over Moscow in a winter-spring period are related to the spatial-temporal evolution of the stratospheric circumpolar vortex. We found a strong negative correlation of the stratospheric contents of the species with the potential vorticity at the 850 K potential temperature level (~10 hPa) and a strong positive correlation with geopotential at different stratospheric levels in March-April 2011. Stratospheric O_3 and NO_2 in 2011 were also strongly correlated with each other, but the correlation was weaker in the winter-spring period of 2010.

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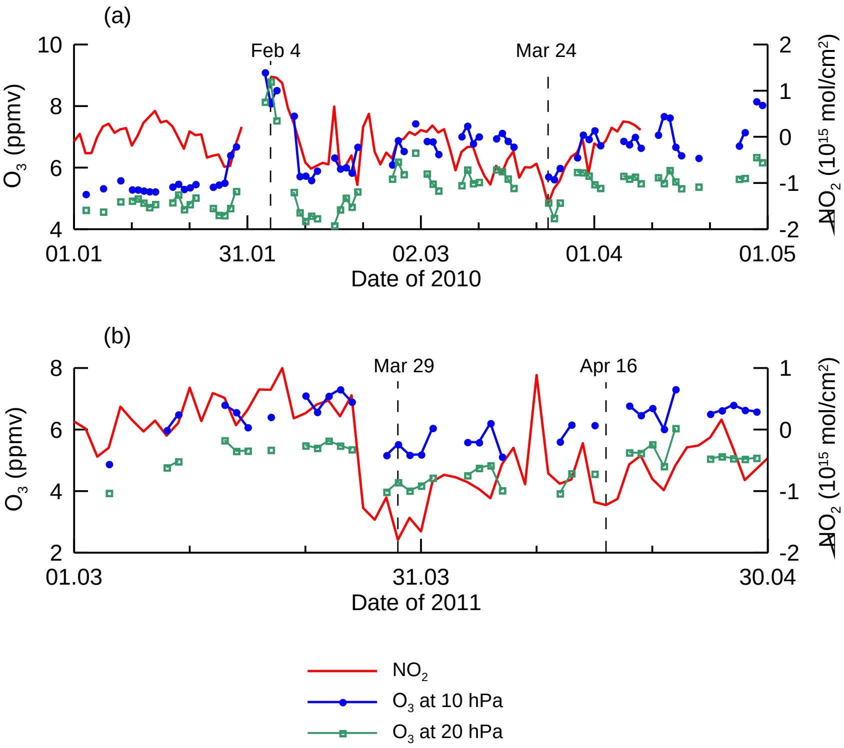

Fig. 1. Ozone mixing ratio on isobaric surfaces 10 hPa (blue) and 20 hPa (green) and deviation of column NO_2 from the annual cycle (red) in (a) January–March 2010 and March–April 2011. Vertical dashed lines correspond to the dates of O_3 and NO_2 anomalies.

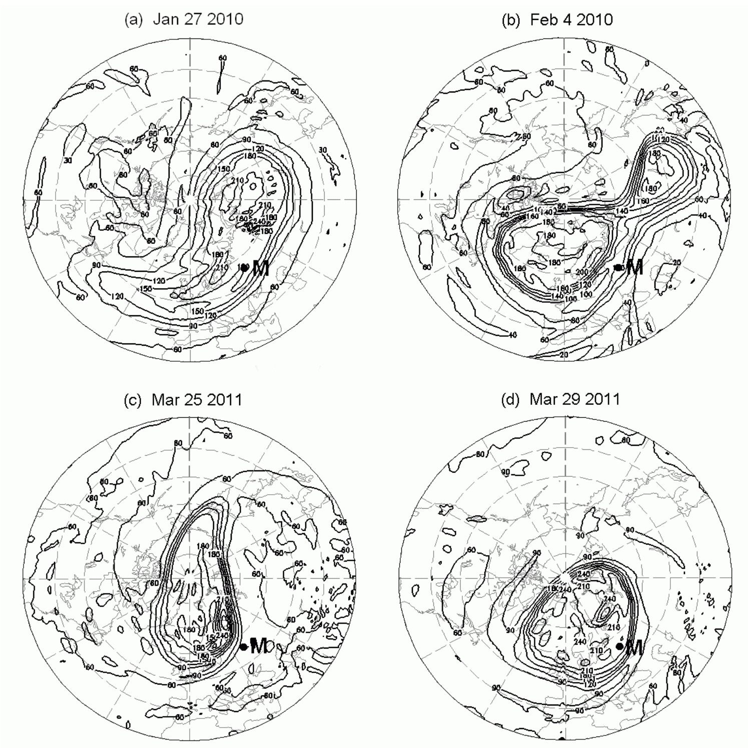

Fig. 2. Distributions of potential vorticity on potential temperature surface 660 K on (a) January 27 and (b) February 4 2010, and on (c) March 25 and (d) March 29 2011. The spot signed M corresponds to Moscow pos

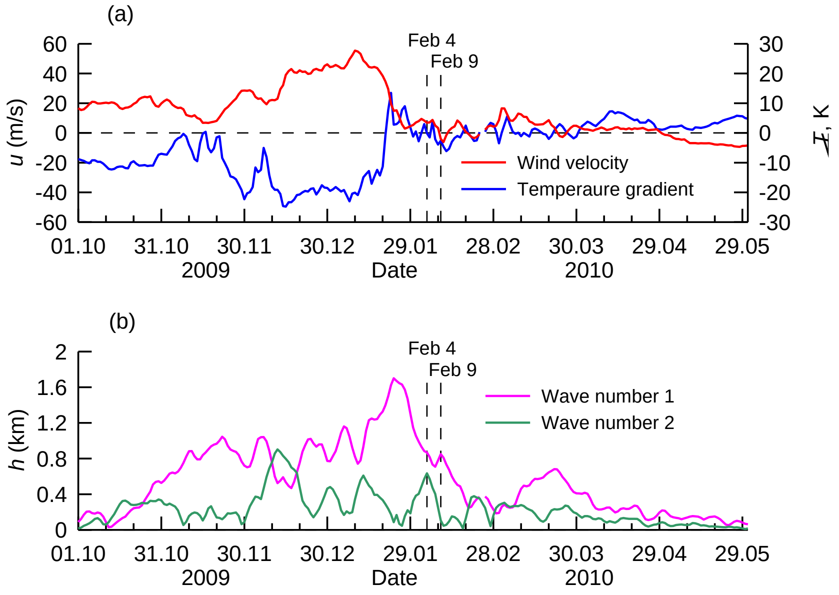

Fig. 3. (a) Zonal mean zonal wind velocity *u* (red) and difference of zonal mean temperatures ΔT on isobaric surface 10 hPa between 85ºN and 60ºN (blue) and (b) zonal harmonic amplitudes *h* of geopotential height of the 10 hPa level – planetary waves with zonal wave numbers 1 (purple) and 2 (green) – in October 2009 through May 2010. Vertical dashed lines correspond to the date of the O_3 and NO_2 positive anomalies (Feb 4) and the date of the zonal wind reversal (Feb 9).

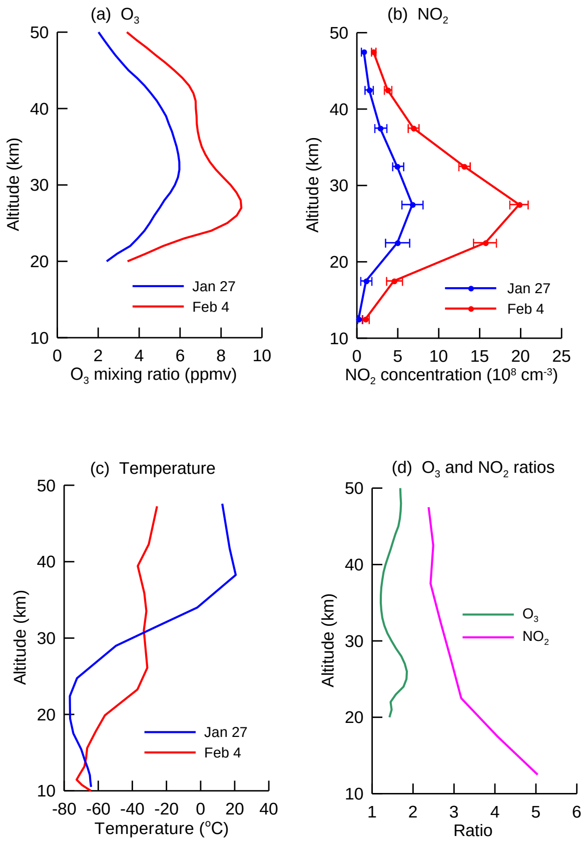

Fig. 4. (a–c) Vertical profiles of (a) O_3, (b) NO_2 and (c) temperature on January 27 (blue) and February 4 (red) 2010. (d) Ratio of the O_3 (green) and NO_2 (purple) concentrations on the date of the stratospheric warming on February 4 to the concentrations on January 27. Horizontal bars on plot (b) are random errors of NO_2 profiles retrieval.

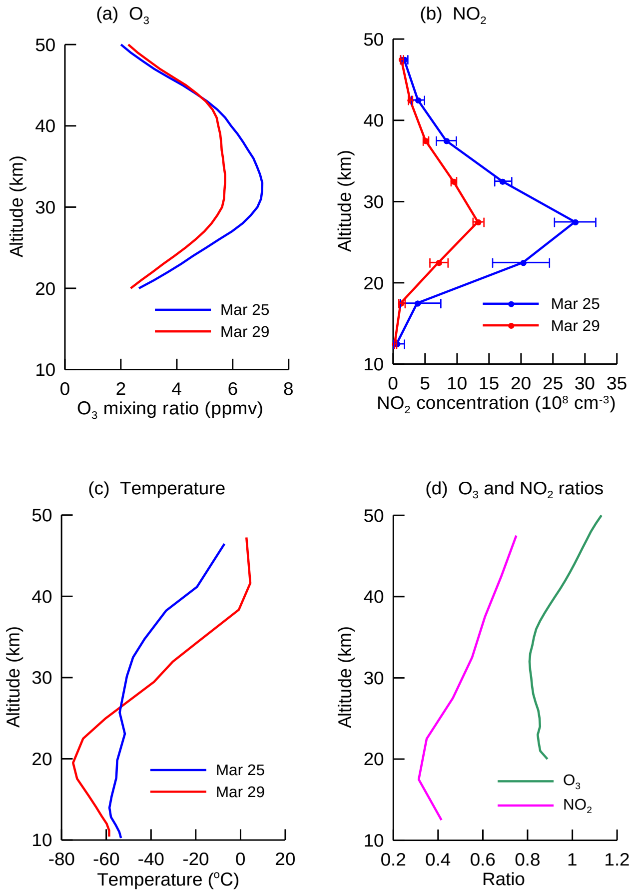

Fig. 5. (a–c) Vertical profiles of (a) O_3, (b) NO_2 and (c) temperature on March 25 (blue) and March 29 (red) 2011. (d) Ratio of the O_3 (green) and NO_2 (purple) concentrations on the date of the negative anomaly on March 29 to the concentrations on March 25. Horizontal bars on plot (b) are random errors of NO_2 profiles retrieval.