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Atmospheric Chemistry and Physics Discussions

Rapid meridional transport of tropical airmasses to the Arctic during the major stratospheric warming in January 2003

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Abstract

We present observations of unusually high values of ozone and N_2O in the middle stratosphere that were observed by the airborne submillimeter radiometer ASUR in the Arctic. The observations took place in the meteorological situation of a major stratospheric warming that occurred in mid-January 2003 and was dominated by a wave 2 event. On 23 January 2003 the observed N_2O and O_3 mixing ratios around 69° N in the middle stratosphere reached maximum values of ~190 ppb and ~10 ppm, respectively. The similarities of these N_2O profiles in a potential temperature range between 800 and 1200 K with N_2O observations around 20° N on 1 March 2003 by the same instrument suggest that the observed Arctic airmasses were transported from the tropics by isentropic transport. Using a linearized ozone chemistry model along idealized trajectories at different altitudes transport times between about 3 and 7 days are estimated from the difference between the Arctic and tropical O_3 mixing ratios observed in this potential temperature range. PV distributions suggest that these airmasses did not stay confined in the Arctic region which makes it unlikely that this dynamical situation lead to the formation of dynamically caused pockets of low ozone.

1. Introduction

Stratospheric warmings are a common feature in the Arctic stratosphere (e.g. Andrews et al., 1987), and have also been found in the Antarctic stratosphere, recently in connection with a split of the Antarctic ozone hole in Southern Hemisphere winter 2002 (e.g. Sinnhuber et al., 2003). Manney et al. (1994) described the evolution of the Arctic vortex during two stratospheric warmings in 1993 in which wave 1 was dominant, leading to a displacement of the vortex from the pole. It was shown that low-latitude air was drawn into high latitudes. Further work showed that these events could lead to the formation of low ozone pockets in the middle stratosphere (Manney et al., 1995) which could be explained by confinement of airmasses within the anticyclone at high latitudes and subsequent destruction of ozone towards the photochemical equilibrium (Morris et al., 1997).

In the following we report measurements of unusually high mixing ratios of N_2O and ozone in the Arctic middle stratosphere by the airborne submillimeter radiometer ASUR during a major stratospheric warming in January 2003 that was dominated by wave 2 and lead to a split of the polar vortex. The measurements are compared with measurements in the tropics by the same instrument, to determine the origin of these airmasses. A simple ozone chemistry model will be used along idealized trajectories to estimate a timescale for this transport to the Arctic. Eventually the development of the meteorological situation is studied with a focus on the formation of low ozone pockets.

2. The ASUR instrument

Measurements of N_2O and ozone were performed by the Airborne SUbmillimeter Radiometer ASUR (von König et al., 2000). ASUR is a passive heterodyne radiometer. It uses a liquid helium cooled SIS (superconductor-insulator-superconductor) detector (Mees et al., 1995) and operates in single sideband mode, covering a frequency range from 604.3 to 662.3 GHz in which continuous tuning is possible. For spectral analysis of the signals, an acousto-optical spectrometer (AOS) with a band width of 1.5 GHz and a resolution of 1.5 MHz is used (Rosolen et al., 1994). The ASUR instrument is designed to operate on board an aircraft flying near the tropopause to avoid signal absorption due to tropospheric water vapor.

The pressure broadening of the detected emission lines allows the retrieval of vertical profiles of volume mixing ratio (VMR) of the measured species in an altitude range of about 15 to 50 km. To achieve a sufficient signal-to-noise ratio, the individually measured spectra are integrated over a time span of about 100 s in the case of ozone, and about 150 s in the case of N_2O. These time spans include calibration measurements and correspond to horizontal distances of about 20 and 30 km at typical aircraft speeds. The retrieval is based on the optimal estimation method (Rodgers, 1976, 1990)

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and was described in more detail in Bremer et al. (2002).

During winter and spring 2003 the ASUR instrument was deployed on board of the German research aircraft FALCON. In the framework of the European polar stratospheric cloud and lee wave experiment (EUPLEX) nine research flights were undertaken in the Arctic between 14 January and 12 February 2003. During the Sciamachy validation and utilization experiment (SCIA-VALUE) measurements in the tropics were performed between 19 February and 3 March 2003, followed again by measurements in the Arctic between 10 and 19 March 2003. ASUR was looking to the starboard side of the aircraft with a constant elevation angle of 12°.

3. Observations

3.1. Meteorological Situation

The vortex situation in the Arctic winter 2002/2003 was characterized by very low temperatures and a very strong vortex already in late November 2002. The low temperatures persisted until the end of December when a minor warming in the upper stratosphere occurred. In the lower stratosphere, however, the temperature distribution was hardly disturbed and the vortex remained strong and stable (EORCU, 2003).

This situation changed around mid-January 2003 when a major stratospheric warming took place in the Arctic. The criteria for a major warming, a positive temperature gradient between 60° N and the pole together with a reversal of the mean zonal winds at 60° N at a pressure level of 10 hPa from westerly to easterly were fulfilled on 18 January 2003 (EORCU, 2003). Figure 1 shows maps of the modified potential vorticity (MPV) (Lait, 1994) at the potential temperature levels of 475 K (~19 km) and 950 K (~33 km) on three selected days where measurement flights were performed. It can be clearly seen that the warming was accompanied by strong planetary wave 2 activity that led to a split of the vortex on 19 January 2003. The vortex was strongly sheared with altitude. At 950 K the airmasses above Kiruna had higher PV than the airmasses close to Spitsbergen. On 23 January 2003 the two vortex parts had re-merged on both potential temperature levels. At 950 K airmasses with high PV had moved northwards and air with very low MPV values (<5 PVU) had moved to the North Atlantic region. On 26 January 2003 the vortex had split again on the 950 K level and airmasses with an MPV around 10–15 PVU had moved further northwards over Spitsbergen and across the pole.

3.2. Arctic observations

The FALCON with the ASUR instrument undertook flights from Kiruna to Spitsbergen and back to Kiruna on 19, 23, and 26 January 2003. The flight tracks are shown in the maps in Fig. 1.

Figure 2 shows a latitudinal cross section of the ASUR N_2O measurements on 23 January 2003 during the flight leg from Spitsbergen to Kiruna. The latitudinal variation up to about 20 km altitude is small, the N_2O mixing ratios are typical for Arctic vortex profiles after significant descent of the airmasses. Between 76° N and 73° N a strong increase of N_2O with decreasing latitude starts to occur, and N_2O values of almost 200 ppb are reached at altitudes between 25 and 30 km around 69° N. This behavior is qualitatively correlated with a decrease in the MPV of the airmasses at these altitudes, which decreases from about 50 PVU to about 15 PVU during this flight leg.

Figure 2 also shows the latitudinal cross section of the ASUR O_3 measurements during the same flight leg. Peak mixing ratios between 5 and 6 ppm at around 80° N increase with decreasing latitude to values above 10 ppm around 68° N.

A similar information is shown in Fig. 2 for the flight on 26 January 2003. Again are high N_2O mixing ratios in the middle stratosphere qualitatively correlated with low values of MPV, though the N_2O mixing ratios reach only ~140 ppb in the maximum. Airmasses with N_2O mixing ratios around 80 ppb had moved to the region around 80° N. The ozone observed in the middle stratosphere is more homogeneous compared to the flight from 23 January 2003, with maximum mixing ratios around 8–9 ppm.

The profile with the maximum peak value in N_2O on the flight from 23 January 2003 is shown in detail in the left part of Fig. 3 on a potential temperature scale. The lowermost part of the profile is determined by a decrease in N_2O, as it can be expected in the Arctic stratosphere at these altitudes. For comparison an averaged profile of measurements inside the vortex at a potential temperature of 475 K from the flight on 19 January 2003 is also shown. Up to a potential temperature level of about 500 K (~20 km) the profiles are basically identical. Above this level the N_2O mixing ratio in the profile from 23 January 2003 starts to rise, peaking at about 750 K (~28 km) with a mixing ratio of 193 ppb. Above this peak the mixing ratio decreases again.

The ozone measurement closest to the N_2O profile from 23 January 2003 was located at 68.6° N. It is shown in the right part of Fig. 3, together with an average of measurements inside the vortex at a potential temperature of 475 K on 19 January 2003. Around 450 K the ozone profile from 23 January 2003 is identical with the average from 19 January 2003. Above this altitude the profile from 23 January 2003 exceeds the profile from 19 January 2003 and reaches its maximum of about 10.5 ppm around 900 K.

3.3. Comparison with tropical measurements

To study the origin of these unusual N_2O mixing ratios in the Arctic, the profile has been compared with measurements obtained during flights of the second phase of the SCIA-VALUE campaign, which took place between mid-February and mid-March 2003. During this campaign latitudinal cross sections ranging from about 80° N in the Arctic to about 5° S in the tropics were flown. A profile which is very similar to the upper part of the Arctic profile from 23 January 2003 was found on a flight on 1 March 2003 from Douala, Cameroon to Tozeur, Tunisia, at 17.5° N. Figure 3 shows this profile in comparison with the Arctic profile. The agreement between 800 K (~29 km) and 1200 K (~39 km) is striking, considering that these two measurements were separated by more than 50° in latitude.

The very good agreement between the N_2O measurement in the tropics and the Arctic measurement on 23 January 2003 above 800 K suggests that the origin of these airmasses was in the tropics, and that they were transported to the Arctic by isentropic transport. It is noted that due to the altitude resolution of the ASUR measurement tropical airmasses down to an altitude around 25 km (∼650 K) would be required to result in a peak structure as observed, assuming that the retrieved ASUR profile in the tropics reflects the shape of the true tropical profile sufficiently well. However, it is possible that the shape of the profile below about 800 K could also be caused by contributions of airmasses transported from regions in mid-latitudes.

To study the variation in ozone the profile next to the tropical measurement of N_2O was considered. It was located at 20° N and is shown in Fig. 3. Above 550 K the profile from 23 January 2003 is very similar to the tropical ozone profile measured on 1 March 2003. Above about 900 K the two profiles start do deviate from each other, and at 1200 K the tropical profile exceeds the Arctic profile by about 1 ppm. As the lifetime of ozone is in the order of days around 40 km and about a month at 30 km altitude (e.g. Brasseur and Solomon, 1986), the similarity of the Arctic and tropical O_3 profiles leads to the conclusion, that the isentropic transport must have occurred rather rapidly to preserve most of the ozone between 30 and 40 km.

4. Model calculations

4.1. Modeling of the ozone change

To study the consistency between the N_2O and O_3 measurements on 23 January 2003 with respect to the hypothesis of rapid isentropic transport a simple model of linearized ozone chemistry (LINOZ) (McLinden et al., 2000) is used together with a simple transport on idealized trajectories.

Some care has to be taken concerning the start and end profiles of ozone, as the ozone measurements shown in Fig. 3 were not exactly co-located with the N_2O measurements, and significant ozone gradients between different measurements exist. In the tropics ozone measurements are available at latitudes 20° N and 15° N which will be considered as a lower and upper limit, respectively. Additionally a calculation is performed with an initial profile obtained from an interpolation between these two ozone measurements. In the Arctic the ozone measurement closest to the N_2O measurement in Fig. 3 is located 0.6° to the South and will be considered as an upper limit. The closest ozone measurement to the North is significantly farther away, so an interpolation to a location 0.6° North of the N_2O measurement seems to be a reasonable estimate for a lower ozone limit.

Model calculations were performed to simulate transport along idealized trajectories from 20° N to 70° N with a vertical spacing of 2 km. Transport times of 3, 5, 7, and 10 days were assumed, respectively. Figure 4 shows the results of the model calculations using the different initial profiles. The expected ozone mixing ratios around the N_2O measurement from 23 January 2003 are displayed as shaded areas in light gray. The resulting profiles were convolved to the altitude resolution of the ASUR ozone measurements by using the appropriate averaging kernel functions (Bremer et al., 2002).

Using the lowest initial profile best agreement with the Arctic profile is achieved with the trajectory calculation that transports the airmasses from the tropics to the Arctic in only 3 days. The other transport times yield ozone mixing ratios that are too low at potential temperatures above 850 K. With the intermediate start profile best agreement is achieved with a transport time of 5 days, slightly longer than the result with the lowest initial profile. The modeled profile agrees well with the Arctic observation in the range from 750 K up to 1200 K. Reasonable agreement is also achieved with the lower transport time of 3 days around 900 K and with the higher transport time of 7 days around 800 K. However, at higher potential temperature levels these times tend to give worse estimates of the ozone mixing ratios. The start profile in the upper limit yields too high ozone mixing ratios with 3 days of transport. The modeled profiles with transport times of 5 and 7 days however are in reasonable agreement with the Arctic measurement above 850 K.

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4.2. Error discussion

As the initial profiles were derived from ASUR ozone measurements the true initial profiles might deviate from the measured profile shape due to the altitude resolution of the measurement. Sensitivity studies using the climatological ozone mixing ratios of the LINOZ model suggest that the deviations due to altitude resolution should be less than 0.6 ppm below 40 km.

The run shown in Fig. 4 was performed with climatological temperatures and ozone columns taken from the LINOZ model. To test the sensitivity on the ozone column, a run has been performed where the ozone column was calculated from the initial profile, and successively from the modeled profile after each time step. The modeled deviations were less than 0.1 ppm below 30 km and less than 0.25 ppm below 40 km, which does not change the results significantly.

To test the sensitivity on the temperature profiles runs with climatological temperatures from the LINOZ model increased by 5 K and decreased by 10 K were performed. These values were chosen as they reflect the maximum deviations of the climatological profiles from synoptic temperature profiles from analyses by the Data Assimilation Office (DAO) at the ASUR measurement locations in the tropics and in the Arctic, respectively. The run with increased temperature did not show significant deviations, only with the highest initial ozone profile the results showed a better fit to a transport time of 5 days. In the run with decreased temperatures the profile shape was less well reproduced. The result using the highest start profile was in reasonable agreement with a transport time of 10 days.

A final consideration in terms of sensitivity is the accuracy of the ASUR measurements, which is estimated to be 15%. As most of the ozone comparisons with other measurements indicate that ASUR ozone measurements are rather on the high side (Bremer et al., 2002), a test run with ASUR ozone decreased by 15% was performed. Similar to the run with decreased temperatures the observed profile shape was less well reproduced by the model. Using the highest initial ozone profile the model results with 7 to 10 days of transport time were in reasonable agreement with the measurements.

4.3. Development of the meteorological situation

To study the development of the situation, maps of modified PV up to 4 February 2003 are considered. The morphology of the situation is of particular interest concerning the formation of low ozone pockets, which can be caused by confinement of airmasses in anticyclones at high latitudes and subsequent ozone destruction towards the photochemical equilibrium.

Already in the map of MPV at 950 K from 26 January 2003 (Fig. 1) it can be seen in that the feature of low PV airmasses moving into the North Atlantic was moving southwards and only a filament was moving northwards over the pole. This leads to a rather homogeneous ozone distribution in the middle stratosphere along the flight track, as observed by ASUR in Fig. 2.

Figure 5 shows that by 29 January the area with low PV has moved further south again and on 1 February no airmasses with PV lower than 15 PVU are found over Scandinavia north of 60° N. Similarly, the anticyclone over Alaska and Eastern Siberia, well developed around 19 and 23 January, gets disturbed and moves eastwards and southwards around 1 February, such that only little air with PV lower than 15 PVU is found north of 60° N by 4 February 2003.

It can be concluded that the confinement of airmasses at polar latitudes which is necessary for the formation of low ozone pockets was not realized after the stratospheric warming in mid-January 2003, likely related to the planetary wave activity present, and the resulting movement of airmasses between Arctic and mid-latitude regions.

5. Conclusions

During the wave 2 dominated major stratospheric warming in January 2003 in the Arctic unusually high mixing ratios of ozone and N_2O were observed by ASUR in the middle stratosphere (~25–40 km). The maximum N_2O mixing ratios observed during a flight between 68° and 80° N on 23 January 2003 in the Arctic were nearly identical to mixing ratios measured around 20° N on 1 March 2003 above about 800 K potential temperature. The observed ozone values corresponding to these N_2O measurements in the Arctic were very similar to their tropical counterparts between 600 and 900 K, and started to decrease slowly above. In the lower stratosphere (~20 km) the values of N_2O and ozone remained typical for Arctic conditions.

From the very good agreement between the N_2O mixing ratios observed in the Arctic and the tropics between 800 and 1200 K (~29–39 km) it can be concluded that the airmasses must have been transported from the tropics to the Arctic by rapid isentropic transport. To reproduce the observed structure in N_2O transport from lower latitudes had to occur on isentropic levels down to about 650 K (~25 km).

Model studies using a linearized ozone chemistry along a set of idealized trajectories at different altitudes from 20° N to 70° N and initialized with ASUR ozone measurements around 20° N reveal best agreement with the measured ozone in the Arctic when a time between 3 and 7 days is assumed for the transport along this distance. Only at the extreme boundaries of the estimated uncertainties transport times of ~10 days cannot be excluded.

PV maps do not suggest that this wave 2 process lead to the formation of low ozone pockets, in contrast to earlier work by Manney et al. (1995) which dealt with wave 1 dominated stratospheric warmings, as the airmasses were not confined long enough at polar latitudes to allow the development of low ozone pockets.

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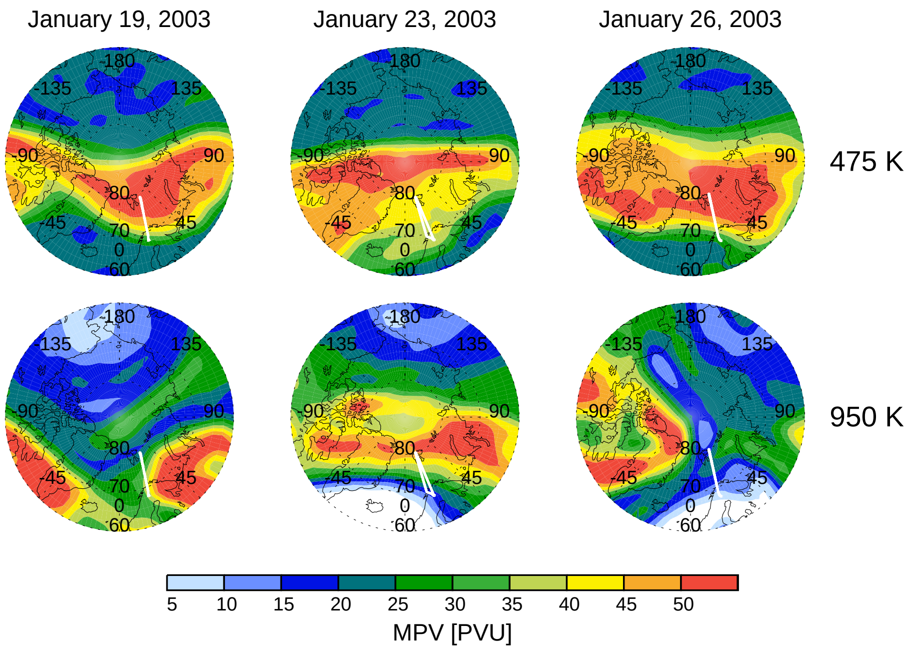

Fig. 1. Maps of modified potential vorticity at a potential temperature of 475 K (~19 km, top) and 950 K (~33 km, bottom) on 19 January (left), on 23 January (middle), and on 26 January 2003 (right) derived from analyses by the European Centre for Medium range Weather Forcast (ECMWF). The reference level for the modified PV is 475 K. The thick white lines indicate the flight paths of the Falcon aircraft.

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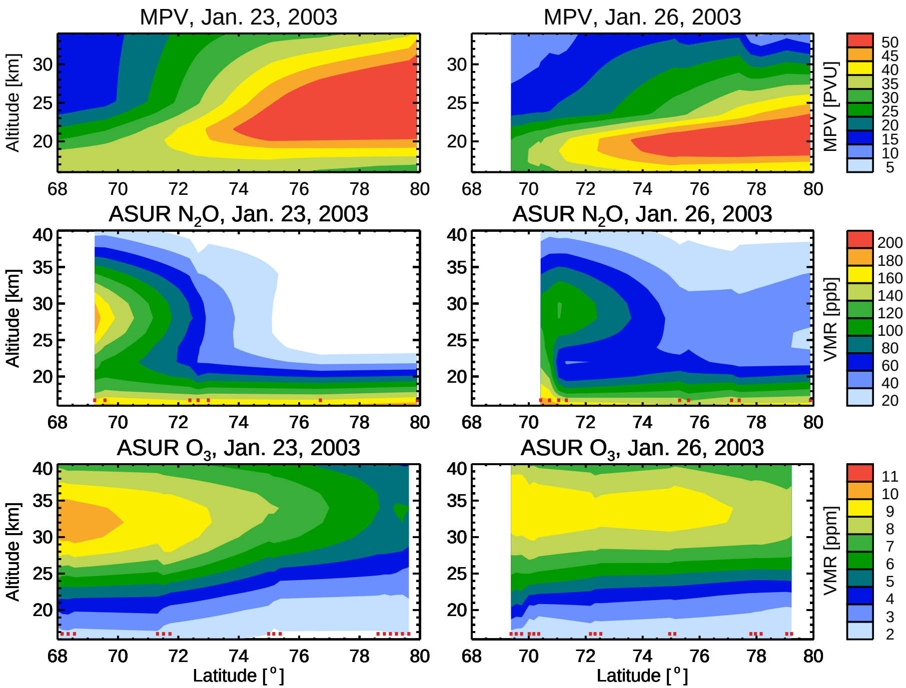

Fig. 2. Left: Modified PV from ECMWF analyses along the line of sight of the ASUR instrument (top), ASUR measurements of N_2O (middle), and ASUR ozone measurements (bottom) during the flight on 23 January 2003 on the flight leg from Spitsbergen to Kiruna. Right: ECMWF MPV, ASUR N_2O, and ASUR ozone during the flight on 26 January 2003. The small red tick marks on the bottom of the measurement contour plots indicate the position of the individual measurements.

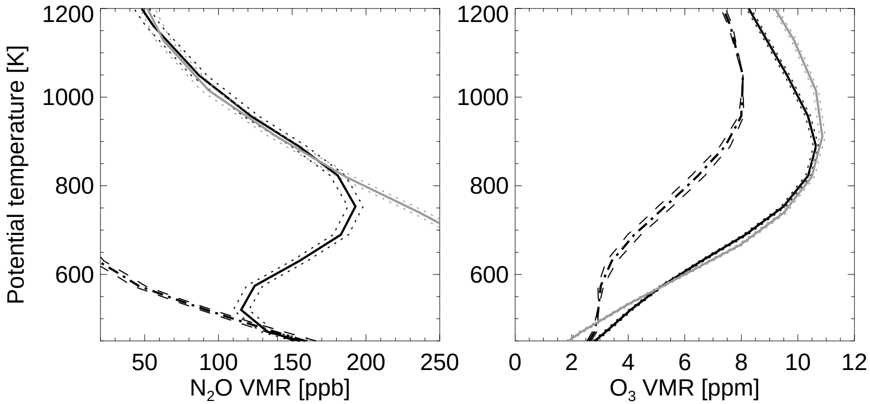

Fig. 3. Black dash-dotted lines: ASUR N_2O profile (left) and O_3 profile (right) of averaged ASUR measurements on 19 January 2003 inside the vortex using a vortex edge at 475 K. The dashed lines represent the standard deviation. Black solid lines: ASUR N_2O measurement at 69.2° N, 20.2° E (left) and ASUR O_3 measurement at 68.6° N, 20° E (right) on 23 January 2003. The dotted lines represent the statistical error derived from the measurement noise. Gray lines: ASUR N_2O measurement at 17.5° N, 8.1° E (left) and ASUR O_3 measurement at 20° N, 8.8° E (right) on 1 March 2003. The dotted lines represent the statistical error derived from the measurement noise.

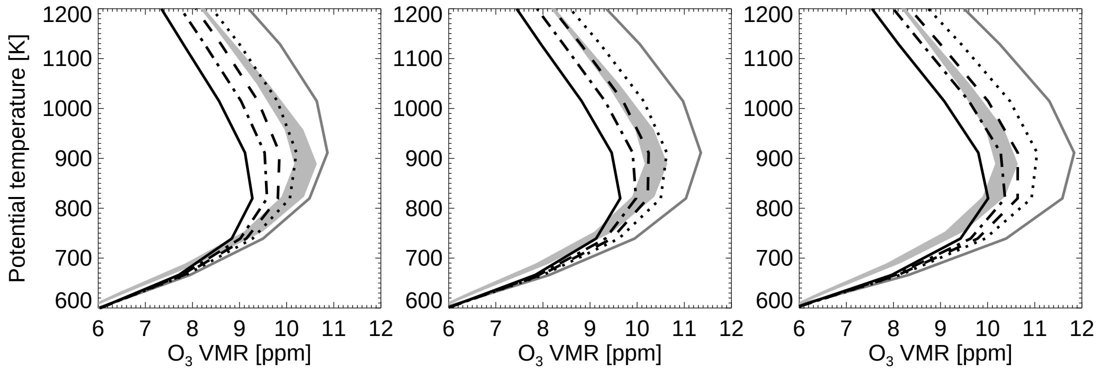

Fig. 4. Model calculation of ozone mixing ratios after transportation on idealized trajectories from 20° N to 70° N with a vertical spacing of 2 km and different initial profiles (dark gray lines). Left: ozone profile measured at 20° N; right: ozone profile measured at 15° N; middle: ozone profile interpolated to 17.5° N. The black lines indicate the modeled profile, convolved to ASUR's altitude resolution, assuming a transport time of 3 days (dotted), 5 days (dashed), 7 days (dash-dotted), and 10 days (solid) from 20° N to 70° N. The light gray shaded area indicates the expected ozone derived from the measurements on 23 January 2003.

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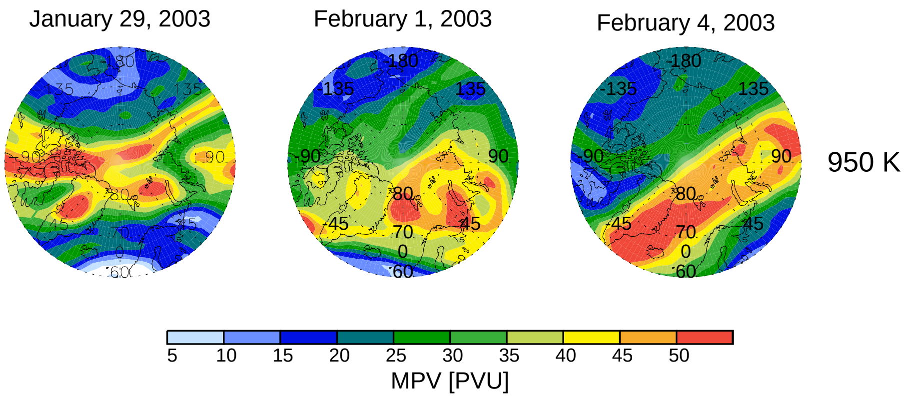

Fig. 5. Maps of modified PV for 29 January, and 1, 4 February 2003 at a potential temperature level of 950 K from ECMWF analyses. The reference level for the modified PV is 475 K.