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Interactive comment on "Rapid meridional transport of tropical airmasses to the Arctic during the major stratospheric warming in January 2003" *by* A. Kleinböhl et al.

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We would like to thank the reviewer for his comments on our manuscript. The main criticism of the review is based on the fact that transport times from the tropics to the Arctic were estimated using a linearized ozone chemistry along idealized trajectories. Although we had thought that this would be an elegant way to support our interpretation of the observations without having to rely on trajectory calculations, we followed the reviewer's suggestions and included trajectory calculations at different potential temperature levels to further constrain the origin of the observed airmasses and the transport times. We considered this as particularly important as these calculations were requested by both reviewers. We found that the trajectory calculations generally support the origin of the airmasses that was estimated from the measurements in the potential temperature range around 800-1000 K. For the revision of the manuscript we change our argumentation in section 4 such that it is now mainly based on the trajectory calculations, and uses the chemical studies only to show the consistency with the airmass origins and estimated transport times.

In the following we respond to the individual points of the reviewer's report and explain changes to our manuscript to address these points.

$>>$ ... wave breaking event.

Fig. 1 was originally designed to give the reader an overview on the meteorological situation, in which the three Arctic flights had been carried out, of which measurements were presented later on in the paper. However, we agree that it could be interesting for the reader to get a better impression of the development of the situation. Hence we add a new set of maps to narrow the gap between the maps of 19 and 23 Jan. 2003. We chose the meteorological situation on 22 Jan. 2003 as this is most suitable to illustrate how the low PV airmasses moved into the Arctic.

$>>$ ... could be understood more fully.

As outlined in the introducing paragraph we consider this as the main point of the reviewer's critics. We follow this suggestion and calculated trajectories based on meteorological analyses. We calculated backward trajectories with the trajectory model ftraj provided by the Goddard Space Flight Center (GSFC) using meteorological analyses by the GSFC Data Assimilation Office. We chose the potential temperature levels 450, 600, 800, 1000, and 1200 K for the calculations. The trajectories were started on these levels along the line of sight of the Arctic ozone measurement shown in Fig. 3 (approx. 68.6 deg N, 20.3 deg E). For comparison trajectories were also calculated from locations 0.5 deg north and south as well as 1.5 deg east and west of the field of view of the measurement.

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The trajectory calculations show that the airmasses at 450 K potential temperature originated in the vortex region, as expected from the observed N2O volume mixing ratios. It is further shown that the different initialized airparcels stay in close proximity to each other. At 600 K the trajectory shows that the airmasses had been moving around the Arctic in proximity of the vortex and were located over Asia around 50-60 deg latitude five days before the measurement. We note that the trajectories of the different airparcels initialized close to the measurement at this potential temperature level had started to diverge after five days of backward calculation.

The trajectories at 800 and 1000 K show that the airmasses at these altitudes indeed originated in the tropics at about 20 deg latitude. The 1000 K trajectory had reached this latitude after calculating three days backward, for the 800 K trajectory it was 4-5 days. Divergence of the different airparcel initializations exists after 4-5 days but is small in latitudinal direction. The trajectory at 1200 K in contrast suggests that the airmasses had circled once around the pole in the five day period and were located in close proximity to each other between 40 and 50 deg latitude.

We note that for comparison calculations were also performed using a different meteorological data set (UKMO). While agreeing in the latitudes of origin of the airmasses, differences between the actual trajectory paths and in the divergence were observed, revealing some uncertainty in the calculation of the actual airmass trajectory in this complicated meteorological situation.

We partially rewrite section 4 to accommodate the new findings based on the trajectory calculations. We add a new figure in which the trajectory calculations are presented, and a new subsection (4.1) in which they are discussed. We modify the section "Modeling of the ozone change". We remove the calculations based on idealized trajectories with a transport time of 7 and 10 days, which seem less realistic considering the calculated trajectories. We include ozone simulations along the calculated trajectories instead. We modify the error discussion section accordingly.

$>>$ ... must be made coherent.

In most of the paper's figures and statements potential temperature is used as an altitude coordinate. The use of hPa as an altitude coordinate on page 7124 originated in the reference that was cited for this statement. We give an approximate potential temperature to give the reader better idea how this fits in the context. Fig. 2 gives the altitude in km as this is the altitude coordinate the ASUR trace gas retrieval works with (altitude steps of 2 km spacing). As the main goal of this figure is to present the trace gas measurements along the flight path we keep km as the main altitude coordinate but give approx. potential temperature levels on the right hand side of the individual plots to give the reader a better overview. Furthermore we would like to point out that the approx. altitude in km has been given in brackets wherever a potential temperature is given in the text to help the reader with this.

$>>$ ... on a normal printout.

The maps in figs. 1 and 5 are designed to give the reader an impression of the meteorological situation in which the measurements were performed, and of its development. Our intention was not to provide maps detailed enough read exact MPV values at certain coordinates. Furthermore for the measurements on 23 and 26 Jan. we have provided interpolations of the MPV on the line of sight of the instrument, which serve this purpose much better than a map could do. We have further enlarged the figures, however we think that half of an A4 page should be enough per figure, especially as reviewer 2 did not seem to have a problem with the size of these figures.

$>>$ Page 7127, line 1: Why isentropic transport? Isentropic transport is an idealization that does not occur in reality. Strictly, it is certain that this transport (like any other in the atmosphere) was NOT isentropic.

The main indication that lead us to the assumption of isentropic transport is the very good agreement between the Arctic N2O profile measured on 23 Jan. 2003 and the tropical N2O profile. We note that this agreement is that good only when plotted versus

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the potential temperature of the individual measurements, the agreement is less good when plotted simply over altitude. We are aware of the fact that isentropic transport is an idealization that does not strictly occur in the real atmosphere. However, the timescales we are dealing with are only a few days, and the net cooling rate in the middle stratosphere at mid-latitudes is in the order of 1 K/d in winter (e. g. Andrews et al., 1987). These considerations lead us to the conclusion that a large deviation from isentropic transport is not to be expected. We change the formulation in the paper and add a few sentences to make this clear.

$>>$ In section 2, the (approximate?) horizontal and vertical resolution of the measurements should be indicated.

The horizontal resolution along track is given in the paper. The vertical resolution of the measurements is 6-8 km in the lower stratosphere, increasing to 12-15 km in the middle and upper stratosphere (Bremer et al., 2002). A note concerning this has been included in the paper. The horizontal resolution cross track is determined by the vertical resolution and the elevation angle of 12 deg.

$>>$ On page 7124, line 22, MPV is introduced without an explanation. The concept of MPV should be briefly explained.

A brief explanation of the concept of MPV is included in the revised version.

$>>$ Page 7128, lines 4-6: north, south, north should not start with capital letters.

Ok.

$>>$ Page 7130, lines 20-23: What do you mean with that the air masses must be confined at polar latitudes in order to form low ozone pockets? Do you expect that the high ozone pockets would eventually end up as low-ozone (i.e., lower than normally inside the vortex) pockets? Could you explain the underlying chemistry?

In their paper from 1995 Manney et al. described the observation of low ozone pockets at pressure levels between 5 and 15 hPa. These observations took place several days

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after stratospheric warmings related to wave 1 events, during which tongues of high ozone had been drawn up from lower latitudes into the developing anticyclone. The low ozone pockets were located inside the anticyclone and revealed ozone mixing ratios comparable to inner vortex values. Morris et al. (1998) showed that the underlying mechanism of these low ozone pockets was the confinement of the airmasses at high latitudes long enough, such that ozone loss towards the photochemical equilibrium could occur. We discuss our observations with respect to this background. Considering the displacement of the anticyclone southward (Fig. 6) we come to the conclusion that the airmasses were not confined at high altitudes and hence this meteorological situation was not likely to cause low ozone pockets. We add a few explaining sentences to the introductory section to give a more detailed overview on this background.

Andrews et al., Middle atmospheric dynamics, Academic Press, 1987.

Bremer et al., J. Geophys. Res., 107, 10.1029/2001JD000546, 2002.

Manney et al., J. Geophys. Res., 100, 13939-13950, 1995.

Morris et al., J. Geophys. Res., 103, 3599-3610, 1998.

Interactive comment on Atmos. Chem. Phys. Discuss., 4, 7121, 2004.