Answer to Referee # 3

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March 15, 2012

Dear Referee, thank you for carefully reading our paper and for your helpful and constructive comments and suggestions. They will help to improve the article. Reviewer comments are in bold face, replies in italic.

Specific issues: 1) ECWMF operational analysis are used for backward trajectories. Trajectories in the middle atmosphere driven by analysis data suffer from strong dispersion both horizontally and vertically (Schoeberl et al. JGR 2003). Here, it was critical whether the vertical wind was derived kinematically or diatabically. Recent ECMWF analysis have improved this over-dispersive behavior, visible in the "age of air" (Monge-Sanz et al. GRL 2007). Again, an important role comes to the matter of vertical winds, which produce more realistic ages when calculated diabatically. The authors should discuss this problem in light of their data usage.
In the study of Monge-Sanz et al. GRL 2007 trajectories calculated using the ECMWF operational wind fields produce a quite realistic BD-circulation.
We shortly discussed the topic of diabatic versus kinematic trajectories with Alan Geer from ECMWF. In his opinion the choice might well depend on the application and the location in the atmosphere. He proposes that the uncertainty involved in this choice could be quantified by computing both types of trajectories and comparing the effects on our specific application. However, as we mainly use the ECMWF trajectories in order to get information about mixing and the presence of the polar vortex over Sodankylä we believe that such a study is beyond the scope of this paper.
We now state more clearly that there are large uncertainties in the trajectory computations.

2) The reliability and uncertainty of the model data has to be discussed in more detail, both for ECMWF with its poorly resolved mesosphere but also for WACCM-SD with its nudging terms. In this matter, it might be of interest to examine Nezlin et al. (Tellus 2009) who point out that scales smaller than total horizontal wavenumber 10 are not well represented in the mesosphere even from a perfect data assimilation system.
We added the following section 3.3. In addition we added the text printed in the answer to comment 3 to section 4:
3.3 Mesospheric wind in the two models
Lower mesospheric winds are poorly observed and therefore models with assimilated data are probably our best way of determining 4 dimensional wind fields at

these altitudes. The two models used in this study, ECMWF and SD-WACCM, assimilate data or use assimilated data, respectively, in the lower and middle stratosphere and are unconstrained in the upper levels. Therefore, the inaccuracy of their wind fields increases with altitude in the mesosphere. However, [2] show that in WACCM error growth is limited when the lower atmosphere is continually reinitialized, as it effectively is in the SD-WACCM. In addition WACCM includes a physically based gravity wave source parameterization which realistically simulates zonal mean winds [5]. Still, the mesospheric winds of ECMWF and SD-WACCM suffer under large uncertainties and need to be handled with care. A comparison between the zonal mean zonal winds from the two models is given in the middle and lower panels of Fig. 1. The plots illustrate that below 0.1 hPa there is a good qualitative agreement between the two data sets while there are major differences even in the wind directions above that level. At altitudes above 0.1 hPa the zonal mean winds of SD-WACCM are regarded as more reliable than those of ECMWF since the upper model boundary of WACCM (approximately 150 km) is higher than the one of ECMWF (approximately 80 km). Therefore, WACCM outputs are used to illustrate zonal mean winds at these altitudes. ECMWF data and Lagrangian backward trajectories are only presented up to 0.1 hPa.

3) The uncertainties of horizontal winds in the mesosphere from ECMWF and WACCM-SD cast serious doubt on the concept of trajectories in the mesosphere, since only the large-scale will be appropriate for exact trajectories. The role of uncertainties in the ECMWF and WACCM-SD data should be discussed and included in the trajectory calculations. Due to the general uncertainties in the advecting winds, it might be considered to show directly the winds, e.g. the vertical residual wind.

We now also use vertical residual wind in Sect. 6.2.3 where we estimate descent rates (compare answer to minor issue 23)).

Concerning the uncertainty of the trajectories we now mention in the text that we believe that models with assimilated data are probably our best way of determining 4 dimensional wind fields in the mesosphere, but also mention the large uncertainty associated with these winds (compare answer to specific comment 2)). In addition we added the following text to Sect. 4:

In general the TEM trajectories are regarded as more reliable than the Lagrangian trajectories especially in the mesosphere. The reason is that zonal mean winds are used for the calculation of the TEM trajectories while for the calculation of the Lagrangian trajectories 4 dimensional wind fields are needed. [4] point out that scales smaller than total horizontal wavenumber 10 are not well represented in the mesosphere even by a perfect data assimilation system. As the Lagrangian trajectories are calculated on scales much smaller than wavenumber 10 this introduces a large uncertainty.

However, the authors believe that additional information about mixing processes can be gained from the Lagrangian trajectories despite their large uncertainties.

4) page 32817, it should be discussed that the operational ECMWF system was updated on the 26 January 2010. http://ecmwf.int /products/data/operational_system/evolution/evolution_2010.html. This update could have a severe impact on the before-after interpretation

of the middle atmospheric flow based on ECMWF. In connection with this, the reviewer would like to see a comparison of the zonal wind from WACCM-SD with ECMWF which could be added to Fig. 2. This would confirm that both data sources support the same transport interpretation. Alternatively to the operational ECMWF data, the authors could use ERA-interim reanalysis data (Dee et al. QJRMS 2011).
Thanks for pointing out that there has been an upgrade to the ECMWF operational system. We now use the new version T1279 also for the time before the upgrade in order to avoid discontinuities. A comparison of the ECMWF and WACCM-SD zonal winds can now be found in Fig. 2 in the paper (here Fig. 1). We decided against using ERA-interim because its upper limit is at 0.1 hPa. Even if the wind fields in the upper mesosphere suffer under large uncertainties we believe that we can gain additional information about mixing from backward trajectories started at 0.1 hPa.

Minor issues:
1) page 32813, please provide a reference for Aura/MLS.
Done

2) page 32813, define abbreviation VMR here as well. For the reader's comfort, it should be repeated here after the definition in the abstract.
Done.

3) page 32813, line 24, consider "usually at least 25 oC in a week or less)".
Done.

4) page 32813, line 28, "or" seems unfitting. Please reformulate.
We changed this sentence to:
Dissipation of planetary waves decelerates the polar night jet and induces a poleward residual circulation, which produces adiabatic heating due to downward flow in the high latitude stratosphere and adiabatic cooling due to upward flow in the high latitude mesosphere. The forcing by planetary waves can be strong enough to reverse the polar night jet.

5) page 32814, line 11, consider "the disappearance of the high-latitudinal transport barrier"
Changed.

6) Consider removing abbreviation definitions for EOF and TTL, since they are hardly used.
Done.

7) page 32813, line 11, typo "Solomon"
Changed.

8) page 32817, line 8, the reference to "Monge-Sanz et al. 2007" seems not appropriate here, as it just uses the data to examine the

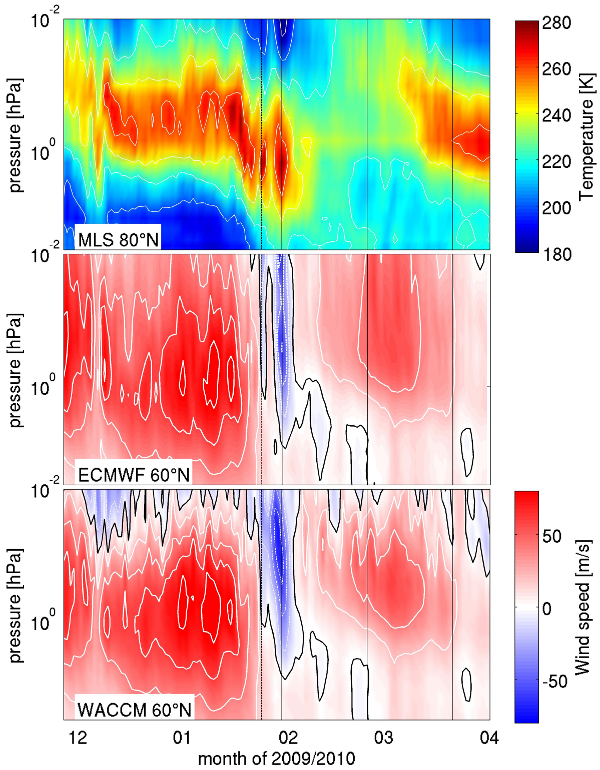

Figure 1: MLS zonal mean temperature at 80° N and ECMWF zonal mean zonal wind at 60° N.
Top panel: Red relatively higher values and blue relatively lower values. Middle panel: Red eastward winds and blue westward winds from ECMWF. Bottom panel: Red eastward winds and blue westward winds from SD-WACCM. The vertical lines indicate the following dates (from the left): 24 January (wind reversal mesosphere), 30 January (maximum temperature at 60° N and 10 hPa), 24 February (end of the time of enhanced meridional mixing) and 21 March (equinox).

age of air. It could be used in line 17. Instead a reference for the ECMWF data assimilation system should be used.

We now use the documentation on the following website as reference: http://www.ecmwf.int/research/ifsdocs/CY36r1/index.html. Monge-Sanz et al. 2007 is now used where you suggest.

9) page 32817, a new paper is available on the Brewer-Dobson in ERA-interim (Seviour et al. QJRMS 2011).

Thank you for pointing this out, we did not know that paper. However, as we are using the operational data set for the present study we believe it would not *be appropriate to cite this paper.*

10) page 32818, line 11. What is meant by 1% of the meteorological fields? Is only every 100th grid-point used? Please specify.
We added the following sentence to the text:
The nudging alters the model predictions by effectively combining 0.99 x the model predicted field with 0.01 x the value from the assimilation model, i.e., T = 0.99 x T(WACCM) + 0.01 x T(GEOS-5).

11) page 32819, line 8. Same is true for WACCM-SD trajectories, since it is not a free model run, but nudged in the troposphere-stratosphere.
True. This is now mentioned like that in the text.

12) page 32819, line 17, how many profiles are typically used in order to derive the air parcel's water vapor.
It is one or two profiles. This is now mentioned in the text.

13) page 32820, line 1. WACCM has more reliable physical description of the mesosphere. Whether the data of the nudged WACCM-SD is more reliable remains to be shown. If WACCM-SD are more reliable in the mesosphere, why not use the data for the backward trajectories?
It would certainly be interesting to also calculate the Lagrangian trajectories using WACCM data. However, we believe that the mixing processes we want to illustrate are well represented in the ECMWF trajectories. A comparison between WACCM and ECMWF trajectories would be beyond the scope of this paper as our main goal is to explain the evolution in our ground-based water vapor data.

15) page 32822, line 27, only qualitative agreement. Can this agreement be quantified?
It is very difficult to quantify this agreement because the increase in water vapor is due to combined effects of upwelling and horizontal transport of H_2O. We changed this sentence to:
The upwelling seen in the WACCM output is in qualitative agreement with the conclusions drawn from the zonal mean water vapor distribution observed by Aura/MLS.

16) page 32823, line 10, please provide the measurement uncertainty.
Done.

17) Fig. 7. Why is the agreement not so good at 1hPa, while it looks better for the trajectories in Fig. 8?
We assume this is due to the fact that Figure 7 displays a zonal mean value. Before the SSW the mesosphere was dryer within the polar vortex than outside of it. At the same time the vortex was shifted towards Europe which means for the zonal mean value vortex profiles are averaged together with extra vortex profiles. The stratosphere and mesosphere above Sodankylä was within the polar

vortex before the SSW.

18) page 32824, line 7-8, In my opinion the comparison of the Lagranto/ECMWF trajectories is not conclusive to state a validation. The problem is that the water distribution is very smooth, in fact for 0.3 and 0.1 hPa it is pretty uniform inside or outside the polar vortex (Fig. 4). So, the exact latitude origin cannot be stated from the water vapor VMR and no conclusive validation can be given on basis of the results. The only information seems to be whether the water vapor comes from within or outside of the polar vortex. This puts relatively low requirement on the precision of the trajectories. This problem should be discussed. Also, the trajectories in Fig. 9 should be understood in this light, i. e. forced by the "reliable" large-scale component while "small-scale" variations could cause large changes to the actual "true" origin of the parcels.
You are right and therefor we changed this sentence to:
Mesospheric air within the polar vortex is dryer than outside of it. Therefore, the good agreement in the water vapor data sets indicates that the Lagranto/ECMWF mesospheric trajectories are precise enough to distinguish whether the air comes from within or from outside of the polar region.

19) Fig.1 seems unnecessary, given that Fig. 4a yields a good representation of the mean distribution.
This might be true. However, we would like to keep it as it is referenced in the introduction.

20) Fig.3 and text: Please give the exact date of the 2009 warming.
Done.

21) page 32826, line 16, typo "indicates"
Changed.

22) page 32826, line 19 and 23, next page line 1, please give also height in km for comparison with Fig. 6.
Done.

23) Section 6.2.3, for the interpretation of the descent, it seems more natural to examine directly the vertical residual velocity as a function of time and height. Please provide also a value of the descent rate for this method.
This has been done along with other changes to this section. The text is now as follows:
The vertical motion from the TEM wind fields is given by either the residual vertical wind w^* or the vertical displacement along the TEM trajectories. The information content of w^* and the along trajectory altitude change is slightly different; w^* indicates vertical displacement at a fixed latitude while the TEM trajectories follow the latitude change of the bulk motion of air masses. The vertical motion along the backward trajectories is calculated by taking the difference between the along trajectory altitudes on day 0 and day -3.

Assessment of errors in the atmospheric circulation of the WACCM model is subject to current research. Validation of the polar descent rate with direct measurements of the atmospheric wind field is difficult as wind measurements suffer under large uncertainties in the order of 0.1 to 1 m/s (9 to 90 km/d) as shown in [?]. For that reason no errors are provided for the descent rates determined from WACCM data.
The descent rates from the TEM winds are displayed in Fig. 2 together with the value determined from MIAWARA-C's measurements. The left panel displays daily values at three different altitudes (0.6, 0.2 and 0.06 hPa) within the range covered by the 5.2 ppmv water vapor isopleth. The mean descent rate determined from water vapor, shown as blue horizontal line, is an altitude average and therefore shown on all three pressure levels.
The right panel shows the profiles of the temporal mean of descent rates with standard deviation, w^* in green and along trajectory altitude change in red, for the time period in which the water vapor data has been considered for the linear fit (5 February to 5 March). The plot shows that the values of the two profiles are comparable. The descent rates from the TEM wind fields increase from approximately 80 m/d at 0.6 hPa to approximately 700 m/d at 0.06 hPa. The linear fit to the 5.2 ppmv isopleth provides a mean descent rate for the covered altitude range which is shown as blue dot in right panel of Fig. 2. In order to make the descent rates determined from the TEM wind fields comparable to those from water vapor the mean value is taken over the same altitude range. This results in 335 m/d for the along trajectory altitude change (red dot) and in 325 m/d for w^* being in good agreement with the 350±40 m/d found from MIAWARA-C's measurements.
The lower mesospheric descent rates determined are slightly smaller than the values of 500 to 700 m/d [1] and [6] found after the 2009 SSW. In addition, the upper stratospheric descent rates in 2010 are slightly smaller than those of [3] who determined values of 150 m/d after the SSW 2004. The smaller descent rates after the 2010 compared to the two other years could indicate that the vortex recovery was weaker after the 2010 SSW than after the 2004 and 2009 SSW's.

24) please provide errors for your estimates of descent rates.
Done. We describe how we estimate the errors in the text:
From the water vapor observations the descent rate is found by a least squares linear fit to the 5.2 ppmv water vapor isopleth. Assuming a relative uncertainty of 10% and 1.2% for MIAWARA-C and MLS zonal mean H2O VMR respectively, we get an uncertainty of the isopleth altitude of 2.5 km for MIAWARA-C and 0.2 km for MLS. The determined descent rates and uncertainties are 350±40 m/d for MIAWARA-C at Sodankylä and 360±5 m/d for MLS zonal mean (valid for interval 5 February to 5 March 2010 and pressure range 0.06 to 0.6 hPa). The results of the polynomial fits together with the original data are displayed in Fig. 6. The values found are an average over altitude and time. Therefore the attribution of the descent rates to a certain altitude is imprecise.

25) Fig. 5, Is the increase in vertical displacement linear in time? It might be useful to plot the displacement per day.
We now display daily altitude changes instead of total altitude changes. The plots indicate, that the vertical displacement is indeed linear in time during the three days the trajectories are calculated for.

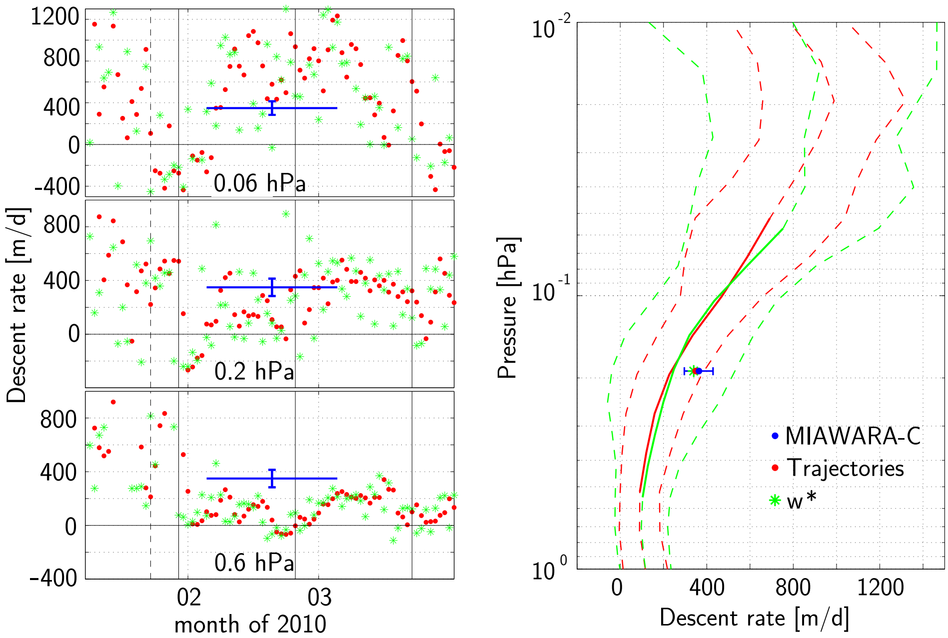

Figure 2: Descent (or during the SSW ascent) rates at 67° N and over Sodankylä determined from TEM trajectories (red), w* (green) and MIAWARA-C water vapor measurements (blue horizontal lines in the left panel and blue dot in the right panel).
Left panel: Daily vertical motion at the indicated altitude levels; positive values indicate descent, negative values ascent. The vertical lines indicate the following dates (from the left): 24 January (wind reversal mesosphere), 30 January (maximum temperature at 60° N and 10 hPa), 24 February (end of the time of enhanced meridional mixing) and 21 March (equinox).
Right panel: Mean value and standard deviation of daily descent rates between 5 February and 5 March. The solid part of the red and green curve indicates the altitude range covered by the 5.2 water vapor isopleth. The green asterisk, red and blue dots are the mean descent rates in that range found from TEM vertical wind and trajectories and determined from MIAWARA-C's measurements, respectively.

26) Fig. 6, Please use also discrete color steps in the color bar.
Done.

27) Fig. 8 (left), colors are difficult to separate. Consider a clear marker for 60 degrees in order to separate the arctic and mid latitudinal air.
Done.

28) Fig. 9, pressure notation in figure and caption are not in sync.
They are now.

References

[1] J. N. Lee, D. L. Wu, G. L. Manney, M. J. Schwartz, A. Lambert, N. J. Livesey, K. R. Minschwander, H. C. Pumphrey, and W. G. Read. Aura microwave limb sounder observations of the polar middle atmosphere: Dynamics and transport of co and h2o. *Journal Of Geophysical Research*, 116(D05110):D05110, 2011.

[2] H.-L. Liu, F. Sassi, and R. R. Garcia. Error growth in a whole atmosphere climate model. *Journal of the Atmospheric Sciences*, 66:173–186, 2008.

[3] R. Nassar, P. F. Bernath, C. D. Boone, G. L. Manney, S. D. McLeod, C. P. Rinsland, R. Skelton, and K. A. Walker. Ace-fts measurements across the edge of the winter 2004 arctic vortex. *Geophysical Research Letters*, 32(L15S05):L15S05, 2005.

[4] Y. Nezlin, Y. J. Rochon, and S. Polavarapu. Impact of tropospheric and stratospheric data assimilation on mesospheric prediction. *Tellus Series A*, 61(1):154–159, 2009.

[5] J. H. Richter, F. Sassi, and R. R. Garcia. Toward a physically based gravity wave source parameterization in a general circulation model. *Journal of Atmospheric Sciences*, 67:136–156, 2010.

[6] S.-M. Salmi, P. T. Verronen, L. Thölix, E. Kyrölä, L. Backman, A. Y. Karpechko, and A. Seppälä. Mesosphere-to-stratosphere descent of odd nitrogen in february–march 2009 after sudden stratospheric warming. *Atmospheric Chemistry and Physics*, 11:4645–4655, 2011.