The authors would like to take the opportunity to thank the reviewers for their comments and for taking the time to offer them. We believe the manuscript has been improved with the helpful input.

Response to Reviewer 1

5

The study significantly contributes to the derivation of the descent rate in the polar middle atmosphere. The authors find that previous studies underestimated the descent rate by a factor of 3 or more. Their data analysis is careful and the good agreement of the SD WACCM CO VMR time series with the observations are good reasons to

10 believe their new finding of a fast descent rate. Thus, the study is appropriate for a publication in ACP and I only suggest some minor corrections.

1) I was not aware that the model descent rate differs so much from the observed descent rate. Straub et al. (2012) found a small descent rate of 325 m/day for the

- SD WACCM simulation. Please can you argue why SD WACCM is now faster in your simulation? The value quoted by Straub et al. (2012) is for an average of the SD-WACCM w* over the altitude range of 0.6 hPa to 0.06 hPa (approx. 52 – 68 km), and over the time from 5 February to 5 March. This is to match the averaging from the ground-based instrument. The averaging information for the instrument is now included in the edited Table 1 of the new manuscript.
- Straub et al. (2012) also show the time-averaged profile of WACCM-SD w* with values ranging from 150 – 700/800 m/day. The daily values of w* and another trajectory analysis reach 1200 m/s at 0.06 hPa.

Tabe 1 has been edited to include information about the altitude ranges over which the descent rates were calculated and a whether averaging was used. Section 1 also now contains the following

25 information:

"The altitude range over which the rates were determined, and whether averaging was performed, is also shown in Table 1. It is important to note that an average over altitude can mask the higher descent rates that are found in the mesosphere. For example, Straub et al. (2012) show a descent rate of -325 m/day from averaged modelled wind profiles, between 0.6 hPa (~52 km) and 0.06 hPa

30 (~68 km), whereas the individual wind profiles often show descent rates larger than -1000 m/day at 0.06 hPa."

2) p.1 line 28 and at other places. I would not use "concentration" since you only work
 with the volume mixing ratios (VMR). I would introduce VMR in the beginning and then
 you can always write CO VMR instead of CO concentration.
 This has been done.

3) p.3 line 8 it is unclear for me what you mean with a "quiet winter"

This has been changed to say "a winter with a relatively stable vortex"

4) p.4 line 18 discuss instead of discusses

This has been fixed.

5

25

5) p.7 line 17 "negative" means poleward? I guess the sign depends on the hemisphere and you mean the northern hemisphere?

The lines have been edited to clarify that the "negative" refers to the CO tendency, and the direction of v* is towards the winter pole. "This is expected, considering the direction of $\overline{v*}$, toward the winter pole, and the low-to-high gradient of CO from lower to higher latitudes in the winter hemisphere"

6) p.7 line 28 Is it Hoffman or Hoffmann like in the Bibliography?

It should be Hoffmann. This has been fixed.

7) p.10 line 6 what do you mean with "fall short"?This has been edited to *"are smaller than"*

8) Conclusions : I am missing a statement that trace gas monitoring by ground-based microwave radiometers in the polar region remains invaluable , e.g., for tuning of the

20 SD WACCM model parameters. Otherwise the paper may give the impression that the observations are useless for derivation of the descent rate.

A line has been added to the end of the conclusion: "Continuous ground-based and satellite measurements of trace gases remain an essential tool in understanding the short- and long-term evolution of the middle atmosphere, as well as for the validation and parameterisation of atmospheric models."

9) Figure 1 The grey background should be changed by a white background since the contrast is not so good.

The figure has been edited to have a white background. The panels were edited and made larger to 30 make the data more readable. The layout has been changed to landscape.

10) You may mention somewhere the connection between the polar descent rate and the Brewer-Dobson circulation.

Section 3.2 has been edited and now contains the statements: "The magnitude of the TEM wind is

³⁵ larger for the higher altitudes, as is also shown in Smith et al. (2011), and the air parcels that arrive above 66 km altitude originate in the summer hemisphere. The parcels that arrive below this, which could be considered as part of the Brewer Dobson circulation (Brewer, 1949), originate at latitudes closer to the equator."

Response to Reviewer 2

The authors use results from the WACCM model together with observations of CO from two sensors to investigate how well descent rates can be derived from a chemically

- 5 (nearly) inert tracer with a strong vertical gradient in the altitude range 45-85 km (i.e., the mesosphere). It is found that considering corrections due to horizontal advection, turbulence, and chemical loss can imply differences in the descent rates derived from CO of more than 1 km/day particularly around strong sudden stratospheric warmings. Credibility is provided by a comparison of the modelled CO to the two observation
- 10 data sets which generally show a good agreement. Considering that descent rates derived from these methods mostly lie in the range of 100-300 m/day, this is quite a large margin of error. Inert tracers are widely used to derive descent rates in the polar winter middle atmosphere – not only in the mesosphere to estimate the input of thermospheric tracers, but also in the stratosphere to derive chemical ozone loss rates
- 15 and the paper provides an important caveat for these methods. I found the paper very clearly structured and well written, and recommend publication in ACP with a few minor changes.

Page 10, line 12: what does it mean if "w* corrected" derived from modeled CO using

- 20 corrections from the model itself does not provide the model w*? If equation 1 is a correct description of all terms affecting CO in the model, then "w* corrected" should provide w* in a self-consistent way. I would say that this means that the terms in Equation 1 do not reflect what the model does to CO. I would expect that in the model, the resolved eddy term (Xedd) is not treated separately but as part of the advection
- 25 scheme; in which case it is counted double if subtracted for derivation of "w* corrected". Does this make sense?

The terms in equation 1 do represent the changes in CO VMR, but in the Transformed Eulerian Mean (TEM) representation of the atmosphere. It is correct to say that what the model "does" in simulating the atmosphere is not the same as following the TEM equations. Equation 1 is a highly derived

- 30 equation (Andrews et al., 1987), the terms of which are calculated using the output from SD-WACCM. The TEM offers a way to represent the atmosphere as an interaction of a mean flow with disturbances, i.e., eddies and waves, imposed upon it, and it contains a description of a mean meridional flow in the atmosphere. The interaction is generally a two-way process and the disturbances feed back into the mean flow through non-linear effects.
- 35 So the calculation of w*, using the TEM formalism and using CO VMRs, will have some differences due to the way that each is calculated. The calculation of w*_corrected is also somewhat crude (as mentioned in the paper and now expanded upon in the new manuscript), as it combines tendencies in the TEM formalism with values derived using CO VMRs in the atmosphere. These points are now emphasized in Section 4 and it is made clearer that the goal of w*_corrected is to get a qualitative

estimate of the errors that may be incurred by assuming pure vertical advection when using tracers to calculate w*.

"The resulting rate is called w_{co} corrected. This could be considered a crude approach, combining daily averaged CO output with CO tendencies calculated using the TEM formalism, but the aim here is

to provide an estimate of the errors that may be incurred by neglecting influences on CO other than vertical advection. In any case, the results involving w_{CO} corrected are discussed in a qualitative manner, instead of for quantitative error analysis."

The discussion in Section 6 offers some other reasons for the discrepancy: mainly parameterization of gravity waves in the model, which play a role in the strength of w* and also in the parameterised eddy flux divergence (Xkzz), and the time resolution of the model output. Meraner and Schmidt (2016) found differences in calculated w* when using 6-hourly average model output compared to daily average output.

- 15 As I understand the term, the middle atmosphere comprised the stratosphere and mesosphere. As you really focus on the mesosphere here (the altitude range from 45-85 km) you might want to change the title of your paper to "polar mesospheric descent". The term was chosen because altitude of the stratopause can be around 55 km, which would mean that a 10 km layer of the analysis is within the stratosphere.
- 20 Because the analysis does not cover the whole of the middle atmosphere, the first line of the abstract has been edited to express the altitude range. Combined with the title, the reader will now immediately know the area under investigation: *"We investigate the reliability of using trace gas measurements from remote sensing instruments to infer polar atmospheric descent rates during winter in the 46 – 86 km altitude range."*
- 25

The altitude range is explicitly mentioned in the conclusions now also.

Page 1, lines 16-17: "The relative importance of vertical advection is lessened : : :" that means that other processes become more important, could you add a sentence which?

30 (Turbulence, horizontal advection,: ...?)

The sentence has been edited to read:

"The relative importance of vertical advection is lessened during periods directly before and after a sudden stratospheric warming, mainly due to an increase in eddy transport"

35 Page 1, lines 25 and following: dynamical tracers have also been used (quite extensively) to derive stratospheric descent rates: to distinguish chemical ozone loss from dynamical processes.

The following statement and references have been added to Section 1: *"This technique has often been used in combination with ozone measurements to separate chemical and dynamical influences when*

determining ozone depletion (e.g. Proffit et al., 1990, 1993; Müller et al., 1996, 2003; Salawitch et al., 2002; Rösevall et al., 2007)."

Page 2, line 2-3: you could also reference Funke et al, 2014a, b; and Funke et al.,

5 **2017.**

These references have been added to the main text and to the references section.

Page 2, line 16: ... "and photochemical destruction in the upper mesosphere" limits the altitudes at which it can be used to the stratosphere and lowermost mesosphere.

10 We would prefer not to provide such a definition because the referenced paper (Lee et al., 2011) does not make such a definite statement.

Lee et al. (2011) states: "However, it is not as good a tracer as CO for diagnosing vertical motions throughout the middle atmosphere due to the relative complexity of photochemical sources and sinks in the stratosphere."

15

Page 4, section 2.2, line 6: can you also state the approximate altitude range of MLS (in km)?

The sentence in question now reads: "These CO profiles cover a pressure range of 215 - 0.0046 hPa (approximately 11 - 86 km) ..."

20

Page 4, section 2.3, line 28: What exactly does daily output mean – once per day at a specific global time (a global snapshot with varying solar zenith angle) or at a specific local time (a global snapshot with nearly fixed solar zenith angle), or output of daily averages? For a dynamical tracer this probably does not make a big difference apart

25 from some impact of the tidal phase in the upper mesosphere.

The model output Is daily averages. This sentence has been edited to read: "Model output of daily averages from 2008 to 2014 are used for this study."

Page 5, lines 1-2, discussion of Figure 1: Figure 1 is too small – in my A4 one page

30 per page printout each panel is about 1 cm high, making it very hard to distinguish the lines. You could more than double the vertical range of the panels without filling the page. Please do.

The panels have been enlarged, and superfluous date labels have been removed to give more space for the panels. The figure has also been changed to landscape layout so that the panels can be made

35 larger. The background was also changed to a light colour at the request of Reviewer #1.

Page 5, line 7: ": ... but a systematic change in the results ... isn't found ..." despite the very cramped figure (see my previous comment) I do see a systematic difference between MLS and WACCM in early and late winter, i.e., in the buildup and decrease

of the winter maximum: the winter maximum starts earlier and lasts longer in WACCM than in MLS, at least above 66 km.

That particular sentence regards the difference of using bilinear interpolation of the model data, or not.

- 5 However, your point about the systematic difference between the model and data remains valid. The following lines have been added to the section to make the point: "A systematic difference is evident between MLS and SD-WACCM during the times of year when CO VMRs are rapidly increasing or decreasing, with SD-WACCM showing larger values of CO. The difference is most pronounced at higher altitudes and is predominantly during August/September and April/May."
- 10

Page 6, line 2-3: "The Prandtl number is 2 for the model runs in this work" I am not quite clear what this means. My understanding is that the Prandtl number describes a physical property of a gas or liquid, namely the relation between momentum diffusivity and thermal diffusivity; as such it should be an exact quantity. The Prandtl number

of gases is usually given as lower than 1; for air, values around 0.7-0.8 are given. Does this change around the mesopause (where molecular diffusion becomes more important) compared to the lower atmosphere, or is this really used as a scalable fudge factor in WACCM? – I am aware that this is a feature of WACCM which has been implemented for a good reason; I'm not suggesting that this is changed. I am just

20 curious what it means.

The Prandtl number (Pr) as used in GW parameterizations describes the ratio of momentum flux to heat flux, and is properly thought of as a "turbulent Prandtl number"; in particular, it is not a property of a gas or liquid, but of the process whereby gravity waves dissipate when they "break".

For breaking gravity waves, we really do not know what Pr should be, so to some extent it has been
used as an adjustable parameter in GW parameterizations. This is the way Pr is used in WACCM and, in fact, in all models that parameterize GW breaking and attempt to derive turbulent mixing due to such breaking.

Section 3.1 in the edited manuscript now clarifies this with the following sentences: "The value of K_{zz} calculated with SD-WACCM depends, among other things, upon the Prandtl number (or more properly,

30 the "turbulent Prandtl number"), which describes the ratio of momentum flux to heat flux. The Prandtl number is a property of the process whereby gravity waves dissipate when they "break" (see e.g., Fritts and Dunkerton, 1985, for a more details). The Prandtl number is 2 for the model runs in this work (see Sect. 6) and is used in SD-WACCM to parameterise gravity wave breaking (Garcia et al., 2007)."

35 Page 6, line 5: The terms of Eq. 1 are "renamed" here. "Rewritten" suggests that you adapted the terms mathematically.

This has been changed.

Page 6, lines 18 and following: I found it quite intriguing that air parcels ending above 66 km actually have their origin in the summer hemisphere. Maybe you can add a

mention of this here.

Section 3.2 has been edited and now contains the following information: "The magnitude of the TEM wind is larger for the higher altitudes, as also shown in Smith et al. (2011), and the air parcels that arrive above 66 km altitude originate in the summer hemisphere. The parcels that arrive below this,

5 which could be considered as part of the Brewer Dobson circulation (Brewer, 1949), originate at latitudes closer to the equator."

Page 8, line 17 and following, discussion of Figure 4: again, I was intrigued to see that differences between wco and wco corrected sometimes are larger than 1 km / day: two

10 to ten times larger than (most) estimates of descent rates based on tracers as given in Table 1. That really is a big discrepancy.

The differences between w^{*} and w^{*}_corrected can be quite large, but it is hard to compare them quantitatively to the values listed in Table 1. There are two points here:

- 15 The first point is that the differences between w* and w*_corrected were used to provide more of a qualitative estimation of the errors that can be incurred by neglecting processes other than vertical advection. This is mainly due to the crudeness of combining information derived in two different ways: changes in daily averaged CO from the model/instrument, and TEM tendencies. Section 4 of the edited manuscript now clarifies this point:
- ²⁰ "The resulting rate is called w_{CO} corrected. This could be considered a crude approach, combining daily averaged CO output with CO tendencies calculated using the TEM formalism, but the aim here is to provide an estimate of the errors that may be incurred by neglecting influences on CO other than vertical advection. In any case, the results involving w_{CO} corrected are discussed in a qualitative manner, instead of for quantitative error analysis."
- 25

The second point is that the values in Table 1 come from a variety of analyses, some of which are averages in space, time, or both. Averages in altitude generally provide lower values for w* than those that are seen at altitudes above about 70 km.

Straub et al. (2012), for example, quote a value of w^* of ~ 325 m/day, from instrument, model, and

30 trajectory analysis. The value is an average over Feb/March and also over an altitude range of 0.6 hPa - .06 hPa (approx. 52 – 68 km). The modelled and trajectory analysis w* profiles, from which the averages are made, often show values of ~1200 m/s at 0.06 hPa.

Table 1 has been edited to state where averaging has been performed, and also the altitude ranges

that were used in the studies. A point is now made in Section 1 about noting the effect different averaging techniques.

"The altitude range over which the rates were determined, and whether averaging was performed, is also shown in Table 1. It is important to note that an average over altitude can mask the higher descent rates that are found in the mesosphere. For example, Straub et al. (2012) show a descent rate of -325 m/day from averaged modelled wind profiles, between 0.6 hPa (~52 km) and 0.06 hPa (~68 km), whereas the individual wind profiles often show descent rates larger than -1000 m/day at 0.06 hPa. ."

Page 10, lines 7-12: here you compare w* from the model (Figure 8) with values derived from tracer observations (Figure 4) – it would certainly be easier to follow your argument here if a) the panels in Figure 4 were larger, and b) more importantly, the scale of the colour bars was the same in Figure 4 and 8. It is difficult to appreciate

10 that the values of "w* corrected" provided by tracer observations in 60-90 (Figure 4) is really smaller than the values provided from model wind fields in Figure 8, as the scale in Figure 8 actually covers a smaller range (-1 to 1 km/day compared to -2 to 2 km/day in Figure 4).

Figure 8 from the current manuscript has been edited to have the same colour limits as Figure 4. The

15 scenarios from Figure 4 (spot, zonal mean, and polar mean) have been split into separate figures and the panels made larger so that the plots are clearer.

Page 10, line 18: see my comment above – what does a Prandtl number of 2-4 mean?

This is addressed above in response to the referenced comment.

⁵

Response to Reviewer 3

The authors use WACCM to show the tendencies in CO for the winters of 2008/2009 and 2010/2011. As the authors show, using WACCM, vertical advection is not the only

- ⁵ important contributor to these tendencies. These model results are generally reasonably discussed, although I do have some concerns about the presentations in some of the figures (as detailed below). But my much more serious concern is that the authors fail to make appropriate use of their measurements.
- Before comparing descent rates in the models and measurements, and before addressing the six major processes that govern this overall tendency in the model, the authors should first show a comparison of the overall CO tendencies in measurements and models. Admittedly, the model analysis could continue without such a comparison (as the authors state on page 3), but if the CO tendencies in measurements and models
- are not similar then why are the measurements included here at all? Such a good comparison of WACCM with the measurement components used in this study would be invaluable in helping to judge the ability of the model to accurately address the issue of descent. However, currently the only figure that shows measured CO is Figure 1, and this is both almost impossible to read and does nothing to help the reader to judge
- 20 **the quality of the data as it relates to this study (I would suggest to remove this figure).** The aim of the paper is to use the individual tendencies of CO in the atmosphere to ascertain whether vertical advection can be considered dominant to such an extent that the atmospheric descent rates can be calculated by observing tracer motion. This cannot be achieved with only measurements, as there is not enough information to separate the contributions to the observed VMRs. A model that
- 25 simulates accurately the observed evolution of atmospheric CO VMRs is used to separate the contributions, or tendencies.

The comparison of atmospheric CO measured by instruments and modelled with SD-WACCM is vital to determining whether the model accurately represents the CO VMRs that are observed in the atmosphere. Figure 1 has been enlarged, changed to landscape layout, and edited to make the data

- 30 clearer. Table 2 lists the quantitative results of the comparison and shows the level of agreement between the model and the instruments, which is quite high for daily averages. An in-depth comparison of KIMRA, MLS, and SD-WACCM has been made by Hoffmann et al. (2012a), and the comparison is made in the current manuscript because there have been updates to the model and the datasets. Section 1 now includes this information:
- 35 "The values are similar to those found for earlier versions of the model and data (Hoffmann et al., 2012a), with differences mainly due to updates to the modelled CO (Garcia et al., 2014) and the data products (Livesey et al., 2015; Ryan et al., 2017)."

Section 4 has been edited to include the calculations that were made with the modelled CO, instead of the measured CO. We agree that this is more consistent and avoids the differences between the model and the instruments (Table 2). The results led to the same conclusions because of the level of agreement between the modelled and measured CO, as stated in the original manuscript.

5 Section 1 has been edited to clarify the above points:

"The aim of this study is to assess the limits of the above assumption when using tracer measurements from remote sounders to derive rates of vertical motion in the middle atmosphere. Measurements alone do not provide enough information to enable separation of the contributions to changes in tracer VMRs, and so an atmospheric model must be employed. The specified dynamics version of the Whole

- 10 Atmosphere Community Climate Model (SD-WACCM) is used to determine the relative contributions to changes in CO VMRs during polar winter. The results are combined with daily average modelled CO to estimate the error associated with descent rates calculated assuming pure vertical advection of the tracer. Three commonly used representations of the data are assessed: a local area above a specific location (Kiruna, 67.8° N, 20.4° E, in this case), a zonal mean at a certain latitude (80° N is used as an
- 15 example), and a polar mean (60° 90° N). The winters of 2008/2009 and 2010/2011 are used in the study as an example of a winter with a strong SSW and a winter with a relatively stable vortex, respectively. The rate calculations were also performed using CO measurements from the Kiruna Microwave Radiometer (KIMRA) and the Microwave Limb Sounder (MLS) (not shown), and the results lead to the same conclusion. This was expected due to the level of agreement found in a comparison of

20 the modelled and measured CO (Sect. 2.4)."

Table 1 – Please put a "+" in front of any rising vertical motions to assure the reader that the "-" has not just accidentally been left out. This has been done.

25

Figure 3 – The main point of this figure seems to be that "CO VMRs cannot be attributed solely to vertical advection." To make that point the authors need to put all of the contour plots on the same scale. As is, I'm not even convinced that "Tendencies due to resolved eddy diffusion (>`I´S´ N>`I´SŠ.`I´S´ S>`I´SS´) are the most variable", since I can't compare Xedd

- 30 plots with the advection plots. If as a result of using consistent scales some plots are left blank, then it's certainly fine to reduce the number of panels and mention the negligible effect of certain terms in the text. And, as mentioned above, there should, in addition to the current 6 panels, be a panel showing "total CO tendency" from both measurement and model.
- ³⁵ This sentence was supposed to refer to the fact that Xedd varies the most between positive and negative values. It has been edited in the new manuscript to correct this: *"Tendencies due to resolved eddy diffusion (Xedd) show the most variation between positive and negative values, ..."*

Figure 3 has been separated, by the locations (i.e., 67N, 80N, and polar average), into three figures so that the panels can be made larger and more easily read.

In originally making the figures, it was decided not to use the same colour range for each tendency because too much of the information is lost from the plots. Because of the varying values of the

- 5 tendencies (within a winter and from year to year), there are times, for example, when all tendencies show relatively low values. With the same colour bar for each panel, the information about relative influence is then lost. There are too many instances of this nature to choose a single colour range that includes the relevant information. Instead, it was decided to use both labelled contours and colour bars. While it is admittedly not easy to quickly determine the relative magnitudes of the tendencies
- 10 from a glance, relevant information is not omitted from the figure. The separation of the Figure 3 into three, makes it easier for the reader to attain this information for each scenario in the edited manuscript.

Section 3.3 now emphasises that there are different colour bars and added contours: *"Note that the tendencies are plotted with individual colour scales to retain relevant information when*

15 there are low magnitudes, and labelled contours are added."

The chemistry and the two advection terms in Figure 3 generally seem to peak at 80km. Is there a physical reason for this (if so please explain) or is this related to changes in the model that occur near this level? In the text there is a comment about

a chemical sink layer near this altitude. Secondly, please more explicitly explain the normalization applied to Figure 5.

The peak around 80 km in the chemical tendency is due to a layer of nighttime OH at this altitude, which acts as a chemical sink for CO. This is stated at the following points of the original manuscript: Abstract. Page 1, line 16:

25 "It was also found that CO chemistry cannot be ignored in the mesosphere due to the night-time layer of OH at approximately 80 km altitude." Section 3.3. Page 7, line 3-8:

Section 3.3. Page 7, line 3-8: "Changes in CO due to chemistry (*chem*) are smo

"Changes in CO due to chemistry (chem) are small below approximately 70 km, but all cases show a sustained sink for CO during the winter in a layer at around 80 km altitude. The layer coincides with the

30 location of a night- time layer of hydroxyl (OH) around 82 km altitude (Brinksma et al., 1998, Pickett et al., 2006, Damiani et al., 2010). OH is known as the dominant chemical sink for middle-atmospheric CO (Solomon et al, 1985)."

Conclusion: Page 11, line 9-12:

"The results also show a chemical sink for CO, present throughout polar night, due to the layer of nighttime OH at approximately 80 km."

The higher values of the advection tendencies around 70 to 80 km are mainly due to two points: the first is larger magnitudes of the TEM circulation compared to lower altitudes before there is a turnaround in the direction of the circulation at higher altitudes. The circulation changes from

poleward and downward to *poleward and upward*. The turnaround point is at approximately 95 km in WACCM.

The second reason is that the vertical gradient of CO, which is proportional to the TEM vertical advection, generally increases with altitude.

5 The following information is included in the edited manuscript:

"The advection tendencies show maximum values around 70 – 80 km for two main reasons. The first is the larger magnitude of the TEM circulation, compared to lower altitudes, before there is a turnaround in the direction of the circulation at higher altitudes, at which point the circulation changes from poleward and downward to poleward and upward (e.g., Lieberman et al., 2000; Smith et al., 2011). The

10 turnaround point is at approximately 95 km in WACCM (Smith et al., 2011). The second is the generally increasing vertical gradient of CO with altitude (see Eq. 1)."

The description of the normalisation has been clarified and now reads:

"For a given tendency, the daily values are separated by calendar month and averaged, to give a monthly mean tendency. The daily sums of the absolute values of all tendencies are also separated by month and averaged, to give a monthly mean total absolute tendency. The monthly mean tendencies are then normalised by the monthly mean total absolute tendency, and will be referred to here as relative strengths. Using absolute values for normalisation retains the sign of the individual tendencies and avoids a large spread in the results when there is a small denominator (i.e., when the tendencies are the specified to the tendencies and avoids a large spread in the results when there is a small denominator (i.e., when the tendencies and avoids a large spread in the results when there is a small denominator (i.e., when the tendencies and avoids a large spread in the results when there is a small denominator (i.e., when the tendencies are the specified to the specif

20 cancel each other and their sum is near zero)."

In the conclusion, and elsewhere, the authors declare that using tracer isolines is "invalid". Yet, if I understand Figures 5 and 6 correctly, there are several months and altitude ranges (e.g. near the winter solstice in the lower mesosphere) where w* does seem to be

25 the dominant term. A more nuanced conclusion would therefore seem to be in order.

Section 5 has been edited to provide more quantitative information that qualifies the statement in the first sentence of the paragraph, and elsewhere. The variation in the relative strength is discussed and the changes in tendencies with time from earlier is also emphasised:

- ³⁰ "There are no months where the relative strength of other processes can be considered negligible compared to the relative strength of $adv_w *$. The closest approximations of this situation are at 50 km altitude in October and at 46 km altitude in November, when other processes contributes 13.7 % and 9.6 % of $adv_w *$, respectively. These percentages then vary significantly with altitude. For October, the value increases to 18.6 % at 46 km, 22.5 % at 60 km, and is 61.13 % at 80 km. For
- November, the value increases to 34.4 % at 54 km, and is 70.8 % at 80 km. The results for the south polar average, in Fig. 6, are qualitatively similar to those for the north. The relative strength of adv_w * shows a maximum of ~0.8. Both hemispheres show a peak in chem at 80 km for most of winter (see Sect. 3.3). The relative strength of Xedd is not as prominent at the south as the north, likely due to the higher stability of the southern polar vortex. The points at which the

relative strength of other processes is smallest compared to $adv_w * are at 56$ km in April (8.3 %) and at 46 km in May (6.8 %). For April, the value increases to 22.5 % at 46 km and 21.5 % at 66 km, and is 56.9 % at 80 km. In May, the value increases to 16 % at 54 km, and is 69.1 % at 80 km. For the 10 days directly before and after SSWs, in Fig. 7, the relative strength of $adv_w *$ is less than

- 5 0.5 at all altitudes. Xedd is strong below 60 km, such that the relative strength of other processes has a larger magnitude than that of $adv_w * at$ many altitudes. The relative strength of $adv_w *$ shows a more oscillatory structure with altitude, and there is a local minimum at about 70 km in the data for 10 days after SSWs. There is also a positive peak in the relative strength of Xk_{zz} after SSWs at this altitude.
- 10 Aside from considering what value would classify as negligible, the significant variation in strength of other processes compared to adv_w *, over altitude, adds complexity to the method of following a tracer over an altitude range to determine the descent rate. One must also consider that while this section discusses monthly averaged data, tracers are often followed for several days to determine the changes in altitude over that time, and that the magnitudes of each tendency can vary significantly
- 15 over this time scale (see Figures 3, 4, and 5)."

The referred to statement in Section 6 has been edited to emphasise that the conclusion is indicated by the results, from all sections, using SD-WACCM.

20 Section 6:

"The results of the previous sections, using SD-WACCM, are clear on one indication, that the assumption of observed changes in CO VMRs being solely due to vertical advection is not a valid one."

The referenced sentence in the conclusion has been edited to emphasise that this conclusion is

²⁵ indicated by the results from all sections. Statements of the main results have been added/edited in the conclusion as follows:

- "The results show that dynamical processes other than vertical advection cause non-negligible changes in CO VMRs during winter, and particularly directly before and after sudden stratospheric warmings when eddy transport can become dominant."

30 - "Significant changes in CO tendencies from SD-WACCM occur on the order of days. The results also show a chemical sink for CO, present throughout polar night, due to the layer of night-time OH at approximately 80 km."

- "Rates of atmospheric motion were calculated when assuming only vertical advection, and corrected rates were calculated by including tendency information for all processes. The differences between the

35 two results are of the same order as the calculated rates, and the rates are prone to showing opposite directions for the mean vertical wind."

- "The "true" rate of atmospheric descent appears to be masked by sinks of CO, and by transport processes that oppose the tendency due to vertical advection"

- "Monthly mean relative tendencies for CO show that the summed magnitude of processes other than vertical advection can constitute a large fraction of the changes in CO VMR. For a given month, the summed magnitude of the other processes, relative to vertical advection, changes by several tens of percent over the altitude range under investigation."

5 - "The results suggest that there are no months during polar winter when vertical mean advection dominates the budget of CO to such an extent that vertical mean velocity can be accurately derived within the altitude range."

Response to Reviewer 4

First review of Ryan et al. entitled "Assessing the ability to derive rates of polar middle-atmospheric descent using trace gas measurements from remote sensors" for publication in ACP. The authors use

- 5 the SD-WACCM model to argue that processes other than vertical advection of CO are important in the calculation of polar winter descent rates in the upper stratosphere and mesosphere. The paper is well written and the results will be of interest to the scientific community. I recommend publication after the following revisions.
- 10

-General comments— I echo here a comment made by another reviewer that the authors need to first show consistency between the CO measurements and the evolution of CO in SD-WACCM. If the CO tendencies between the obs and the model do not agree then it's not appropriate to use the obs to calculate we corrected

15 to use the obs to calculate w-corrected.

Section 4 has been edited to include the calculations that were made with the modelled CO, instead of the measured CO. We agree that this is more consistent and avoids the differences between the model and the instruments (Table 2). The results led to the same conclusions because of the level of agreement between he modelled and measured CO, as stated in the original and edited manuscript.

20

Overall, both in the abstract (maybe even the title), throughout the paper, and in the conclusions, the authors need to emphasize that these results are based on SDWACCM. Report quantitative error estimates to vertical motions derived from tracers instead of using provocative language like "found to be invalid".

25 The referenced sentence, from the conclusion, has been edited to emphasise SD-WACCM and to clarify that the conclusion is indicated from the results:

"An assessment using SD-WACCM indicates that a commonly used approximation of the vertical mean velocity of the atmosphere, $\overline{w*}$, using tracer (CO in this case) isolines is not valid, and an alternative interpretation of the rates derived from trace gas measurements is suggested: an effective rate of vertical transport for the given trace gas."

30 vertical transport for the given trace gas."

The second line of the abstract states that SD-WACCM is what is used to assess the assumption of dominant vertical advection:

"Using output from the Specified Dynamics Whole Atmosphere Community Climate Model (SD-

35 WACCM) between 2008 and 2014, tendencies of carbon monoxide (CO) volume mixing ratios (VMRs) are used to assess a common assumption of dominant vertical advection of tracers during polar winter." The edit to use the SD-WACCM CO profiles instead of the measurements for calculating descent rates is now also mentioned in the abstract:

"SD-WACCM CO profiles are combined with the CO tendencies to estimate errors involved in calculating the mean descent of the atmosphere from remote sensing measurements."

5

The calculation of w^{*} corrected is somewhat crude (as mentioned in the paper and now expanded upon in the new manuscript), as it combines tendencies in the TEM formalism with values derived using CO VMRs in the atmosphere. These points are now emphasized in Section 4 and it is made clearer that the goal of w^{*} corrected is to get a qualitative estimate of the errors that may be incurred by assuming pure vertical advection when using tracers to calculate w*:

- 10 "The resulting rate is called w_{co} corrected. This could be considered a crude approach, combining daily averaged CO output with CO tendencies calculated using the TEM formalism, but the aim here is to provide an estimate of the errors that may be incurred by neglecting influences on CO other than vertical advection. In any case, the results involving w_{co} corrected are discussed in a qualitative
- manner, instead of for quantitative error analysis." 15

The conclusion contains the qualitative information from Section 4 about the estimated errors that are found using w CO corrected:

"The differences between the two results are of the same order as the calculated rates, and the rates are prone to showing opposite directions for the mean vertical wind. The corrected rates more closely 20 match the TEM vertical wind velocity from SD-WACCM, but both results using CO show smaller magnitudes relative to the TEM vertical wind, in agreement with the work of Hoffmann (2012b). The "true" rate of atmospheric descent appears to be masked by sinks of CO, and by transport processes that oppose the tendency due to vertical advection."

25

A more quantitative analysis of the relative influence of tendencies is now included in Section 5 offering a clearer picture of the results as they relate to an approximation of pure vertical advection when deriving descent rates. The reader is also reminded of the daily tendencies showing significant variation on time scales of a week:

- "There are no months where the relative strength of other processes can be considered negligible 30 compared to the relative strength of $adv_w *$. The closest approximations of this situation are at 50 km altitude in October and at 46 km altitude in November, when other processes contributes 13.7 % and 9.6 % of adv w *, respectively. These percentages then vary significantly with altitude. For October, the value increases to 18.6 % at 46 km, 22.5 % at 60 km, and is 61.13 % at 80 km. For
- November, the value increases to 34.4 % at 54 km, and is 70.8 % at 80 km. 35 The results for the south polar average, in Fig. 6, are qualitatively similar to those for the north. The relative strength of adv w * shows a maximum of ~0.8. Both hemispheres show a peak in chem at 80 km for most of winter (see Sect. 3.3). The relative strength of Xedd is not as prominent at the south as the north, likely due to the higher stability of the southern polar vortex. The points at which the

relative strength of other processes is smallest compared to $adv_w * are at 56$ km in April (8.3 %) and at 46 km in May (6.8 %). For April, the value increases to 22.5 % at 46 km and 21.5 % at 66 km, and is 56.9 % at 80 km. In May, the value increases to 16 % at 54 km, and is 69.1 % at 80 km. For the 10 days directly before and after SSWs, in Fig. 7, the relative strength of $adv_w *$ is less than

- 5 0.5 at all altitudes. Xedd is strong below 60 km, such that the relative strength of other processes has a larger magnitude than that of $adv_w * at$ many altitudes. The relative strength of $adv_w *$ shows a more oscillatory structure with altitude, and there is a local minimum at about 70 km in the data for 10 days after SSWs. There is also a positive peak in the relative strength of Xk_{zz} after SSWs at this altitude.
- 10 Aside from considering what value would classify as negligible, the significant variation in strength of other processes compared to $adv_w *$, over altitude, adds complexity to the method of following a tracer over an altitude range to determine the descent rate. One must also consider that while this section discusses monthly averaged data, tracers are often followed for several days to determine the changes in altitude over that time, and that the magnitudes of each tendency can vary significantly
- 15 over this time scale (see Figures 3, 4, and 5)."

Figures 1, 3, and 4 are too small, bordering on illegible. In many cases all of the figure panels shown are neither introduced nor discussed. Please reduce the content of each of these figures to simply support the key point being made in the text.

20 Figure 1 has been enlarged, changed to landscape layout, and edited to make the data clearer.

Figure 3 and 4 have been separated into three figures, according to the different scenarios assessed: above Kiruna, 80N zonal mean, and north polar average). The panels have also now been made larger.

- For Figure 1: Section 2.4 indicates that Table 2 shows the correlation and regression coefficient for each of the panels in Figure 1. The caption for Figure 1 states that there are four altitudes shown (one for each panel), and indicates that more information can be found in Section 2.4 and in Table 2: *Figure 1: Comparisons of daily CO VMRs from KIMRA, MLS, and SD-WACCM above Kiruna for 2008 through 2014. Values are displayed at 46, 56, 66, 76, and 86 km altitude. Correlation and regression coefficients for the datasets are given in Table 2. See Sect. 2.4 for datasits "*
- 30 coefficients for the datasets are given in Table 2. See Sect. 2.4 for details."

For Figure 3: The caption incorrectly stated that the tendencies shown in the panels are described in Section 2.4. This should have said Section 3.1 and has been fixed:

Figure 3: 11-day running mean tendencies of CO (in ppmv/day), calculated using daily averaged SDWACCM output. Tendencies shown are for 67° N for the winters of 2008/2009 and 2010/2011. See section 3.1 for a description of the tendencies which are represented in the TEM continuity equation."
Section 3.3 discusses each of the tendencies that are plotted in Figure 3. Each panel is not sequentially discussed, but rather the relevant points, as well as similarities and differences between the scenarios.

For Figure 4 (original manuscript): w_CO_corrected and the difference between that and w_CO were not mentioned in the caption. This has now been fixed:

"Figure 6: Rates of vertical motion, in km/day, calculated by tracking CO VMRs over time. w_{CO} is calculated using SD-WACCM CO profiles. w_{CO} corrected is calculated using a combination of SD-

- 5 WACCM CO profiles and TEM tendencies (see Sect. 4 for details). The difference between the two rates of descent is also shown. The results plotted are for above Kiruna for the winters of 2008/2009 and 2010/2011. Contour lines are spaced by 0.2 km/day. Areas with tightly packed contours (black areas) occur when there are very low CO VMRs and the calculation method is unreliable. White areas are where a CO VMR could not be tracked within the shown altitude range. The start date of the SSW on
- 10 January 28th, 2009, is shown with a vertical green dashed line."

Figures 3, 4, and 8: swap the color bar to be blue for negative values and red for positives. Whenever possible, hold fixed the color bar range so that comparisons between winters and between tendency terms can be made.

15 As the swapping of colour placement is a subjective matter, we will keep the current colour choice.

In originally making the figures, it was decided not to use the same colour range for each tendency because too much of the information is lost from the plots. Because of the varying values of the tendencies (within a winter and from year to year), there are times, for example, when all tendencies

- 20 show relatively low values. With the same colour bar for each panel, the information about relative influence is then lost. There are too many instances of this nature to choose a single colour range that includes the relevant information. Instead, it was decided to use both labelled contours and colour bars. While it is admittedly not easy to quickly determine the relative magnitudes of the tendencies from a glance, relevant information is not omitted from the figure. The separation of the Figure 3 and
- 25 Figure 4 into three, makes it easier for the reader to attain this information for each scenario in the edited manuscript.

-Line-by-line comments-

30 Abstract Line 16 - "the relative importance of vertical advection

is lessened: : : " - by how much? Give %

The sentence has been edited to read

"The relative importance of vertical advection is lessened, and exceeded by other processes, during periods directly before and after a sudden stratospheric warming, mainly due to an increase in eddy

35 transport."

The magnitudes of the processes are variable and to come up with a percentage would require choosing a single reference point with which to compare. The point being made here is that vertical advection cannot be considered as dominant, which is indicated by the fact that other processes become more important.

1 Introduction Page 2, lines 25-35: ": : :defining the edges of the polar vortex is not straightforward." – cite Harvey et al. (2009) and Harvey et al. (2015)

These references have been included in the edited manuscript.

5

2.1 KIMRA, Page 3, line 29: does "average precision" mean daily average?

Average precision refers to the fact that the precision varies somewhat from profile to profile. The sentence has been edited to say this and to give the approximate time resolution of a measurement:

¹⁰ "The average precision (values can vary from one profile to another) of wintertime KIMRA CO VMRs range from 0.06 ppm at 46 km altitude to 2.7 ppm at 86 km. The average time resolution of a CO measurement is around 2 hours. KIMRA CO data presented in this work have been averaged to give daily profiles."

15 **2.2. MLS, Page 4 line 7 - Does "highest pressure level" refer to the pressure level at the highest altitude?**

The sentence has been edited to clarify that is it is the pressure level at the highest altitude: "... and have a maximum (largest) precision of 11 ppm at the highest (in altitude) pressure level."

20 Line 8 - Does "averaged to produce daily profiles" in some spatial region?

Yes, the information was originally in Section 2.4 but has been moved to Section 2.2: "MLS data presented here are within $\pm 2^{\circ}$ latitude and $\pm 10^{\circ}$ longitude of Kiruna, and have been averaged to produce daily profiles."

25

30

2.3 SD-WACCM – Given the fallibility in MERRA winds (mentioned in the intro) in the upper stratosphere and their inability to properly model the elevated stratopause in February of 2009, what (if any) impact does this have on SD-WACCM and the conclusions?

Insofar as the actual winds are not well known in the upper stratosphere, then SD-WACCM may not reproduce the precise evolution of a given elevated stratopause event. However, WACCM can, and

- does, produce realistic elevated stratopause events (de la Torre at al., JGR, 2012; Chendran et al., JGAR, 2013), which is what counts as regards evaluating the effects of such variability on the behavior of CO.
- ³⁵ The model can simulate accurately the statistical properties of elevated stratopause events, even if it does not simulate precisely the weather. The imprecise simulation of a specific elevated stratopause event does not materially change any of the conclusions of the paper.

In the comparison of CO from instruments and models, as in the manuscript, imprecise simulation of a specific elevated stratopause event may cause differences in the measured and modelled CO profiles. Looking at January 2009 in Figure 1 (enlarged version in the edited manuscript), SD-WACCM captures the quick decrease and subsequent increase in CO VMRs seen by both KIMRA and MLS at the time of the SSW. The differences seen between the CO profiles on a daily timescale are reflected in the regression coefficients and correlations listed in Table 2.

5

2.4 CO VMR comparison, Page 5 Figure 1 is inadequate. Please compare the model and measured CO in a comprehensive way that convincingly demonstrates that CO tendencies are in agreement.

As the comment overlaps somewhat with the first general comment, there is some repetition in the answer.

Section 4 has been edited to include the calculations that were made with the modelled CO, instead of the measured CO. We agree that this is more consistent and avoids the differences between the model and the instruments (Table 2). The results led to the same conclusions because of the level of

agreement between the modelled and measured CO, as stated in the original manuscript.

The aim of the paper is to use the individual tendencies of CO in the atmosphere to ascertain whether vertical advection can be considered dominant to such an extent that the atmospheric descent rates can be calculated by observing tracer motion. This cannot be achieved with only measurements, as

20 there is not enough information to separate the contributions to the observed VMRs. A model that simulates accurately the observed evolution of atmospheric CO VMRs is used to separate the contributions, or tendencies.

The comparison of atmospheric CO measured by instruments and modelled with SD-WACCM is vital to determining whether the model accurately represents the CO VMRs that are observed in the

- 25 atmosphere. Figure 1 has been enlarged, changed to landscape layout, and edited to make the data clearer. Table 2 lists the quantitative results of the comparison and shows the level of agreement between the model and the instruments, which is quite high for daily averages. A more in-depth comparison of KIMRA, MLS, and SD-WACCM has been made by Hoffmann et al. (2012), and the comparison is made in the current manuscript because there have been updates to the model and the
- datasets. Section 1 now includes this information:
 "The values are similar to those found for earlier versions of the model and data (Hoffmann et al., 2012a), with differences mainly due to updates to the modelled CO (Garcia et al., 2014) and the data products (Livesey et al., 2015; Ryan et al., 2017)."
- 35 Section 1 has been edited to clarify the above points:

"The aim of this study is to assess the limits of the above assumption when using tracer measurements from remote sounders to derive rates of vertical motion in the middle atmosphere. Measurements alone do not provide enough information to enable separation of the contributions to changes in tracer VMRs, and so an atmospheric model must be employed. The specified dynamics version of the Whole Atmosphere Community Climate Model (SD-WACCM) is used to determine the relative contributions to changes in CO VMRs during polar winter. The results are combined with daily average modelled CO to estimate the error associated with descent rates calculated assuming pure vertical advection of the tracer. Three commonly used representations of the data are assessed: a local area above a specific

- 5 location (Kiruna, 67.8° N, 20.4° E, in this case), a zonal mean at a certain latitude (80° N is used as an example), and a polar mean (60° 90° N). The winters of 2008/2009 and 2010/2011 are used in the study as an example of a winter with a strong SSW and a winter with a relatively stable vortex, respectively. The rate calculations were also performed using CO measurements from the Kiruna Microwave Radiometer (KIMRA) and the Microwave Limb Sounder (MLS) (not shown), and the results
- 10 lead to the same conclusion. This was expected due to the level of agreement found in a comparison of the modelled and measured CO (Sect. 2.4)."

Figure 2 – increase panel size and symbol size. Reword last line of the caption to be

15 **"Parcel positions on Jan 28th (start of the 2009 SSW) is indicated by black asterisks."** The panels and symbols have been made larger and the sentence has been edited to above.

3.3 Tendencies of CO during Arctic winter Page 6, line 28 – ": : :in depth analysis is not made as it is not the focus of the study." – Then can the results be summarized

20 in fewer than 36 panels?

Thorough analyses of the tendencies trace gases have been made as the sole focus of a paper (e.g., Monier and Weare, ACP, 2011). Such an analysis is not warranted in the current manuscript, but the tendencies are an essential part in understanding the processes that effect CO.

- 25 The figure has now been separated into three, according to the different scenarios. The different scenarios are used to reflect the predominant ways that the tracer data are used: a point measurement (from a ground-based instrument), a zonal mean at a specific latitude (most often from satellite data and sometimes from ground-based), and a north polar average or vortex average (from satellite data). The two winters are used as examples of a winter with a SSW and one without.
- 30 With the figures separate, the reader can now clearly see the tendencies for both winters of a scenario, and focus on one scenario if they so choose.

Page 6, line 31 – ": : :decrease in CO VMRs" add "in the upper mesosphere" – Does this mean air is ascending there?

35 The sentence has been edited to contain the addition. While the vertical advection term refers to changes in CO due to ascent and descent of air, the molecular diffusion and eddy diffusion terms are diffusive in nature. The effect of molecular diffusion on a trace gas can be regarded as the sum of two contributions: diffusion, which is proportional to the second derivative of the mixing ratio, and a vertical drift velocity, which is related to differences in the molecular mass of the trace gas compared to the molecular mass of the background atmosphere. The mass of CO is close to that of the background atmosphere and so CO has a small drift velocity.

The effect of eddy diffusion also depends on the gradient of the mixing ratio as well as the diffusion 5 coefficient. The process is a related to the turbulent diffusion associated with gravity wave breaking.

Page 7, first paragraph –

Mention different color scales. Give relative magnitudes wrt w*, i.e., chem is 10% of w*. Can we interpret negatives = ascent/poleward and positives = descent/equatorward (or

10 is it not that simple)?

The different colour scales are now mentioned, and there have been additions to the quantitative description of each tendency, and information added about what the sign of the advection tendencies indicates about the direction of air motion:

- "Figure 3 plots the wintertime tendencies of CO (RHS of Eq. (2)) for 2008/2009 and 2010/2011. The
 zonal mean tendencies are shown for the three scenarios of 67° N, 80° N, and a north polar average (60° 90° N), and are plotted as an 11-day running mean. Note that the tendencies are plotted with individual colour scales to retain relevant information when there are low magnitudes, and labelled contours are added. In the context of a point measurement at Kiruna, a full rotation of the vortex is on the order of 10 days (assuming a zonal wind speed of 20 m/s at 67° N). Relevant comments on the
- ²⁰ results are provided here but an in-depth analysis is not made as it is not the focus of the study. Molecular diffusion (Xmol) generally causes negligible changes in CO, compared to other process, below approximately 83 km, and shows little variation between different scenarios and winters. Above that, the magnitudes increase quickly, with tendencies < -0.1 ppm/day in the altitude range shown here. Unresolved eddy transport (Xk_{zz}) is also negligible below approximately 75 km, but can show
- 25 tendencies < -0.2 ppm/day above that altitude for short times (order of a week). Significant variation is seen for the different winters. Both processes tend to cause a decrease in CO VMRs throughout the winter in the upper mesosphere, agreeing with results of Smith et al. (2011). For comparison, vertical advection ($adv_w *$) at these altitudes shows positive tendencies ranging from < 0.2 to > 1.6 ppm/day. Changes in CO due to chemistry (chem) are small below approximately 70 km, but each scenario and
- 30 year shows a sustained sink for CO during the winter in a layer at around 80 km altitude. The layer coincides with the location of a night-time layer of hydroxyl (OH) around 82 km altitude (Brinksma et al., 1998, Pickett et al., 2006, Damiani et al., 2010). OH is known as the dominant chemical sink for middle-atmospheric CO (Solomon et al, 1985). chem tendencies are stronger at 80° N compared to 67° N, with magnitudes reaching more than 0.3 ppm/day in November and December 2010, ranging
- from approximately 10 % to 50 % of adv_w * over that time. The results suggest that CO chemistry cannot be ignored in the mesosphere during winter. Tendencies due to resolved eddy diffusion (Xedd) show the most variation between positive and negative values, mainly at 67° N because of proximity to the edge of the polar vortex. The north polar average shows that Xedd generally reduces CO VMRs during the winter and, above ~ 70 km, has magnitudes greater than 25 % of adv_w * for time scales of

a week. The largest tendency in CO is from $adv_w *$, and causes an almost constant increase in CO VMRs throughout the winter, before reversing when the TEM vertical wind changes direction in Spring (visible in all $adv_w *$ plots). The increase is due to the downward motion of air and the positive gradient of CO VMR with altitude. The tendency is stronger at 80° N compared to 67° N due to a

- 5 stronger vertical component of the residual circulation at the higher latitude (Smith et al., 2011, and see Figure 2). A signature of the major SSW in 2009 can be seen in the adv_w * tendency for that year, with a decrease and eventual change to a negative tendency. A negative tendency generally indicates ascent of air at this time. For some time directly afterwards, the tendency has a stronger positive magnitude than before. This agrees with observations of stronger vertical motion above the pole after
- a SSW (see references in Table 1). There is also a brief change to a negative $adv_w * at 80$ N, around 80 km altitude, in early January 2011. This coincides with a relatively strong positive value for Xedd at the same time and location, indicating strong wave activity. The CO tendency from horizontal advection $(adv_v *)$ is negative almost everywhere. This is expected, considering the direction of $\overline{v} *$, toward the winter pole, and the low-to-high gradient of CO from lower to higher latitudes in the winter
- 15 hemisphere. The magnitude of the tendency decreases in spring in each scenario and year. but a change of sign is not obvious by the end of April. The advection tendencies show maximum values around 70 80 km for two main reasons. The first is the larger magnitude of the TEM circulation, compared to lower altitudes, before there is a turnaround in the direction of the circulation at higher altitudes, at which point the circulation changes from poleward and downward to poleward and
- 20 upward (e.g., Lieberman et al., 2000; Smith et al., 2011). The turnaround point is at approximately 95 km in WACCM (Smith et al., 2011). The second is the generally increasing vertical gradient of CO with altitude (see Eq. 1). At 67° N, the magnitudes of adv_v * are roughly half that of adv_w *, and at 80° N they are roughly one fifth. Considering this observation alone, changes in CO VMRs cannot be attributed solely to vertical advection."
- 25

Page 7, first paragraph, line 7 – ": : :because of proximity to the

edge of the polar vortex." – No, both are well inside the vortex core.

The polar vortex is not a fixed structure in space; it moves and can be distorted. Kiruna has been shown to be inside, outside, or in the edge of the polar vortex on many occasions (e.g.

30 Kopp et al., JGR, 2003; Ryan et al., AMT, 2016, Ryan et al., ESSD, 2017). The same has been shown for Eureka, which is at 80N (e.g., Bird et al., JGR, 1997; Batchelor et al., AMT, 2010).

One can expect Kiruna to experience more variability with respect to the edge of the polar vortex, due to planetary scale waves, for instance, because of its location in latitude.

35 Some of the references in Section 1 of the current manuscript, like from Manney et al., describe the movements and distortions/splitting of the north polar vortex.

Page 7, line 14

- "There is also a brief change to a positive" - do you mean negative?

Yes. Thank you. This has been fixed.

Page 7, lines

19-20 – This is very useful. Please do this for all tendency terms.

5 Quantitative information has been added for each tendency term, with the other additions to Section 3.3.

4 Rates of vertical motion with KIMRA and MLS Page 7, lines 30-31 - "::: the concentration is adjusted using the tendencies of the continuity equation:::" add "from

10 WACCM". This section will gain credibility after showing that the model and observed tendencies are in agreement.

As the comment overlaps somewhat with an earlier comment regarding Section 2.4, there is some repetition in the response.

15 Section 4 has been edited to include the calculations that were made with the modelled CO, instead of the measured CO. We agree that this is more consistent and avoids the differences between the model and the instruments (Table 2). The results led to the same conclusions because of the level of agreement between the modelled and measured CO, as stated in the original manuscript.

Page 8, lines 17-20 – please reword. Are derived descent rates stronger because they need to counteract the opposing terms? The lines have been reworded, and an additional sentence added for clarity: *"... the values of w_{CO} are generally of a smaller magnitude than w_{CO} corrected during winter, meaning the calculated rates of descent are stronger if one accounts for CO tendencies other than*

25 vertical advection. This makes sense because, as seen in Figure 3, the other transport terms of the continuity equation (and the chemical loss term) tend to oppose the vertical advection term. In other words, the results indicate that the "true" rate of atmospheric descent is masked by sinks of CO, and by transport processes that oppose the tendency due to vertical advection."

30 Page 8,

line 23 - ":: around the time of SSW is decreased: :: " could use an arrow in the figure to highlight this location.

A vertical dashed line has been added to mark the date. The caption has been edited to reflect this.

Figure 4 – can any of this information be shown using a scatter plot with w* along one axis and w*-corrected along another? The points could be colored by altitude. It is currently very difficult to look at the panels and understand the comparisons quantitatively. How often would you get points with opposite signs? Is it more likely to get different directions up high or down low? As was stated earlier in relation to a previous comment, because the method combines daily averaged CO profiles and TEM tendencies, the aim of the calculations is to provide a qualitative error estimate. This is now emphasised in the text:

- "The resulting rate is called w_{CO} corrected. This could be considered a crude approach, combining daily averaged CO output with CO tendencies calculated using the TEM formalism, but the aim here is to provide an estimate of the errors that may be incurred by neglecting influences on CO other than vertical advection. In any case, the results involving w_{CO} corrected are discussed in a qualitative manner, instead of for quantitative error analysis."
- 10 The text, which describes the results of Section 4, now explicitly states that three main qualitative points are made about the results.

"There are three main qualitative points, common to each scenario and year, that are evident from the results.

First, the values of w_{CO} are generally of a smaller magnitude than w_{CO} corrected during winter,

- 15 meaning the calculated rates of descent are stronger if one accounts for CO tendencies other than vertical advection. This makes sense because, as seen in Figure 3, the other transport terms of the continuity equation (and the chemical loss term) tend to oppose the vertical advection term. In other words, the results indicate that the "true" rate of atmospheric descent is masked by sinks of CO, and by transport processes that oppose the tendency due to vertical advection. Second, the differences
- ²⁰ between the two rates are often of the same order as w_{CO} . Third, the signs of w_{CO} and w_{CO} corrected are often opposite, meaning the calculated direction of air motion is prone to change when accounting for CO tendencies other than vertical advection. In each example for 2008/2009, the magnitude of the positive (upward) motion around the time of SSW is decreased for w_{CO} corrected compared to w_{CO} . After the SSW, and into March, the strongest descent values are seen around 70 – 80 km in
- w_{co} corrected, compared to values of ascent seen in w_{co} at the same location."

The panels are now larger because of the separation of the figure into the three scenarios., so the reader can better observe the times/altitudes when the two rates have different signs, which is indicated by them having different colours.

30

Figure 5, 6, and Page 9 – refer to 60-90 as the "polar cap" – not the pole.

"North pole" or "south pole" are not used in the edited manuscript. "... polar average" is used.

6 Discussion, Page 10 line 2 - ": : :not a valid one." Add "according to SD-WACCM" line

35 The line now reads:

"As the results here using SD-WACCM indicate that the commonly used approximation of $\overline{w*}$ with w_{χ} (using tracer observations) is not valid, we suggest an alternative interpretation of w_{χ} : as an effective rate of vertical transport for the trace gas χ ."

30 – Reword ": : : are representative for the complete mesospheric air: : :"

The line now reads:

"... but with an assumption that the overall dynamic effects on CO are representative for mesospheric air, and so w_{CO} is representative of w_{χ} for all tracers."

5

7 Conclusion, Page 11, line 17 – ": : :no months during polar winter when vertical mean advection dominates the budget of CO to such an extent that vertical mean velocity can be accurately derived." – This statement is too strong. Instead, give error estimates as a function of altitude and time over the winter.

10 The referenced sentence in the conclusion has been edited to emphasise that this conclusion is indicated by the results from all sections. Statements of the main results have been added/edited in the conclusion as follows:

- "The results show that dynamical processes other than vertical advection cause non-negligible changes in CO VMRs during winter, and particularly directly before and after sudden stratospheric

15 warmings."

- "Significant changes in CO tendencies from SD-WACCM occur on the order of days. The results also show a chemical sink for CO, present throughout polar night, due to the layer of night-time OH at approximately 80 km."

- "Rates of atmospheric motion were calculated when assuming only vertical advection, and corrected

20 rates were calculated by including tendency information for all processes. The differences between the two results are of the same order as the calculated rates, and the rates are prone to showing opposite directions for the mean vertical wind."

- "The "true" rate of atmospheric descent appears to be masked by sinks of CO, and by transport processes that oppose the tendency due to vertical advection"

25 - "Monthly mean relative tendencies for CO show that the summed magnitude of processes other than vertical advection can constitute a large fraction of the changes in CO VMR. For a given month, the magnitude of the other processes, relative to vertical advection, changes by several tens of percent over the altitude range under investigation."

- "The results suggest that there are no months during polar winter when vertical mean advection

30 dominates the budget of CO to such an extent that vertical mean velocity can be accurately derived within the altitude range."

Section 5 now contains a quantitative description of the results and a discussion of the results that indicate the conclusion with respect to the monthly data, and also reference the significant changes in tendencies on time scales of several days that is seen in the earlier section:

35 tendencies on time scales of several days that is seen in the earlier section: "There are no months where the relative strength of other processes can be considered negligible compared to the relative strength of adv_w *. The closest approximations of this situation are at 50 km altitude in October and at 46 km altitude in November, when other processes contributes 13.7 % and 9.6 % of that of adv_w *, respectively. These percentages then vary significantly with altitude. For October, the value increases to 18.6 % at 46 km, 22.5 % at 60 km, and is 61.13 % at 80 km. For November, the value increases to 34.4 % at 54 km, and is 70.8 % at 80 km. The results for the south polar average, in Fig. 6, are qualitatively similar to those for the north. The relative strength of $adv_w *$ shows a maximum of ~0.8. Both hemispheres show a peak in chem at

- 5 80 km for most of winter (see Sect. 3.3). The relative strength of Xedd is not as prominent at the south as the north, likely due to the higher stability of the southern polar vortex. The points at which the relative strength of other processes is smallest compared to $adv_w *$ are at 56 km in April (8.3 %) and at 46 km in May (6.8 %). For April, the value increases to 22.5 % at 46 km and 21.5 % at 66 km, and is 56.9 % at 80 km. In May, the value increases to 16 % at 54 km, and is 69.1 % at 80 km. For the 10 days
- 10 directly before and after SSWs, in Fig. 7, the relative strength of adv_w * is less than 0.5 at all altitudes. Xedd is strong below 60 km, such that the relative strength of other processes has a larger magnitude than that of adv_w * at many altitudes. The relative strength of adv_w * shows a more oscillatory structure with altitude, and there is a local minimum at about 70 km in the data for 10 days after SSWs. There is also a positive peak in the relative strength of Xk_{zz} after SSWs at this altitude.
- 15 Aside from considering what value would classify as negligible, the significant variation in strength of other processes compared to $adv_w *$ over altitude adds complexity to the method of following a tracer over an altitude range to determine the descent rate. One must also consider that while this section discusses monthly averaged data, tracers are often followed for several days to determine the changes in altitude over that time, and that the magnitudes of each tendency can vary significantly
- 20 over this time scale (see Figures 3, 4, and 5.)"

Assessing the ability to derive rates of polar middle-atmospheric descent using trace gas measurements from remote sensors

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Abstract. We investigate the reliability of using trace gas measurements from remote sensing instruments to infer polar atmospheric descent rates during winter within 46 - 86 km altitude. Using output from the Specified Dynamics Whole Atmosphere Community Climate Model (SD-WACCM) between 2008 and 2014, tendencies of carbon monoxide (CO)

- 15 volume mixing ratios (VMRs)eoneentrations are used to assess a common assumption of dominant vertical advection of tracers during polar winter. The results show that dynamical processes other than vertical advection are not negligible, meaning that the transport rates derived from trace gas measurements do not represent the mean descent of the atmosphere. The relative importance of vertical advection is lessened, and exceeded by other processes, during periods directly before and after a sudden stratospheric warming, mainly due to an increase in eddy transport. It was also found that CO chemistry
- 20 cannot be ignored in the mesosphere due to the night-time layer of OH at approximately 80 km altitude. CO <u>VMReoneentration profiles</u>data from the Kiruna Microwave Radiometer and the Microwave Limb Sounder <u>wereare compared to SD-WACCM output</u>, and show good agreement on daily and seasonal timescales. SD-WACCM CO profiles are <u>combinedused in combination</u> with the modelled CO tendencies to estimate errors involved in calculating the mean descent of the atmosphere from remote sensing measurements. The results indicate errors on the same scale as the calculated descent
- 25 rates, and <u>that the method is prone to aoften_a misinterpretation of the direction of air motion. The "true" rate of atmospheric descent is seen to be masked by processes, other than vertical advection, that affect CO. We suggest an alternative definition of the rate calculated using remote sensing measurements: not as the mean descent of the atmosphere, but as an effective rate of vertical transport for the trace gas under observation.</u>

1 Introduction

30 The rate of the descent of air above the poles during winter has been an area of interest for some time because it influences the transport of trace gases from the thermosphere to the middle atmosphere (mesosphere and stratosphere) (e.g., Plumb et al., 2002; Engel et al., 2006; Smith et al., 2011; Manney et al., 2009). This vertical branch of the meridional circulation can transport gases with high thermospheric volume mixing ratios (VMRs)eoncentrations, and change the composition of the middle-atmosphere (e.g., Solomon et al., 1982; Allen et al., 2000; Hauchecorne et al., 2007; Smith et al., 2011; Garcia et al., 2014; Manney et al., 2009, 2015; Funke et al., 2014a, 2014b, 2017). The downward transport of nitrogen oxide (NO), produced around 110 km through energetic particle precipitation (EPP) events (e.g. Barth and Bailey, 2004; Randall et al.,

- 5 2005, 2007, 2015), garners particular attention because NO_x (NO + NO₂) catalytically destroys ozone in the stratosphere. Periods of strong atmospheric descent are known to coincide with the timing of sudden stratospheric warmings (SSWs) (e.g. Manney et al., 2003, 2009; Jackman et al., 2009, Siskind et al., 2010, Holt et al., 2013). Elevated <u>concentrationVMR</u>s of carbon monoxide (CO) and NO_x have been observed to linger in the middle atmosphere when there is an exceptionally strong polar vortex after a strong SSW, helping to confine descending air at the pole (Randall et al., 2006). Randall et al. (2009) suggest that, in these cases, <u>concentrationVMR</u>s of EPP-produced NO_x are controlled more by mesosphere and lower
- thermosphere (MLT) descent rates than by the structure of the vortex. Siskind et al. (2016) found that due to downward transport of methane (CH₄) in years with strong, uninterrupted mesospheric descent, summertime upper stratospheric chlorine monoxide (ClO) is about 50 % greater than in years with strong horizontal transport.

A direct measurement of the mean vertical motion of air in the middle-atmosphere is currently not possible because of the

- 15 small velocities, and so an analysis of changes in measured tracer (relatively long-lived trace gas) concentration<u>VMR</u>s offers a means to indirectly observe the vertical motion. <u>This technique has often been used in combination with ozone</u> <u>measurements in the stratosphere to separate chemical and dynamical influences when determining ozone depletion (e.g.</u> <u>Proffit et al., 1990, 1993; Müller et al., 1996, 2003; Salawitch et al., 2002; Rösevall et al., 2007).</u> Another indirect determination can be made using the diabatic circulation approach (e.g., Dunkerton, 1978; Solomon et al., 1986; Medvedev
- 20 and Fomichev, 1994) but this method is not discussed further here. The chemical lifetime of CO during polar night and the strong vertical gradient in its concentration VMR make it a good tracer (Solomon et al., 1985; Allen et al., 1999; Lee et al., 2011). Water vapour (H₂O) is used to infer vertical motion (e.g., Straub et al., 2012) but a varying vertical gradient limits the altitudes at which it can be used_-(Lee et al., 2011). Nassar et al. (2005) used nitrous oxide (N₂O), CH₄, and H₂O to infer rates of vertical motion in the upper stratosphere and lower mesosphere, and Bailey et al. (2014) used a combination of NO.
- H₂O, and CH₄ to derive profiles of vertical motion in the middle atmosphere. A partial list of studies that have used tracers to calculate rates of vertical motion is given in Table 1, similar to Hoffmann (2012b) for studies using CO. The tracers used and the determined rates are also listed, along with the terminology used to describe the motion. The descent rates range from 100 m/day to -1200 m/day and show much variability, which can be expected as the studies wereare performed for different years and/or different times of the year, and at different locations (with the minus sign indicating descent rather than ascent).
- 30 The altitude range over which the rates were determined, and whether averaging was performed, is also shown in Table 1. It is important to note that an average over altitude can mask the higher descent rates that are found in the mesosphere. For example, Straub et al. (2012) show a descent rate of -325 m/day from averaged modelled wind profiles, between 0.6 hPa (~52 km) and 0.06 hPa (~68 km), whereas the individual wind profiles often show descent rates larger than -1000 m/day at 0.06 hPa.

A general assumption made in the derivations of the rates is that the observed change in a tracer <u>concentrationVMR</u> over time is caused by vertical advection. The assumption draws from the fact that the polar vortex edge acts as a barrier to lower latitude air and hinders horizontal mixing of air masses between the inside and outside of the vortex (Schoeberl et al., 1992, Manney et al., 1994), but limited mixing still occurs and defining the edges of the polar vortex is not straightforward

- 5 (Manney et al., 1994, 1997; Harvey et al., 2009, 2015). During the formation/breakdown of the polar vortex at the beginning/end of winter, the transport barrier is weaker and the location of the vortex edge becomes much less well-defined (Manney et al., 1997), making it more difficult to identify inner-vortex air masses. This is also true for SSW events where the vortex is weakened, or breaks down and reforms, allowing increased mixing (Manney et al., 2009, 2015). When the vortex is well established, the edge definitions that rely on wind fields (such as scaled potential vorticity (e.g., Manney et al.,
- 10 1994, 2007, 2011; Jin et al.,2006)) become less reliable in the mesosphere where wind observations are uncommon and reanalysis winds are known to be fallible (Manney et al., 2008a, b; Rienecker et al., 2011). The aim of this study is to assess the limits of the above assumption when using tracer measurements from remote sounders to derive rates of vertical motion in the middle atmosphere. Measurements alone do not provide enough information to

enable separation of the contributions to changes in tracer VMRs, and so an atmospheric model must be employed. The

- 15 specified dynamics version of the Whole Atmosphere Community Climate Model (SD-WACCM) is used to determine the relative contributions to changes in CO concentration<u>VMR</u>s during polar winter. The results are combined with <u>daily average modelled</u>measurements of CO from the Kiruna Microwave Radiometer (KIMRA) and the Microwave Limb Sounder (MLS)-to estimate the error associated with descent rates calculated assuming pure vertical advection of the tracer. Three commonly used representations of the data_-are assessed: a local area above a specific location (Kiruna, 67.8° N, 20.4° E, in
- 20 this case), a zonal mean at a certain latitude (80° N is used as an example), and a polar mean (60° 90° N). The winters of 2008/2009 and 2010/2011 are used in the study as an example of a winter with a strong SSW and <u>a winter relatively quiet</u> winterwith a relatively stable vortex, respectively. This study could be performed using model output in place of the measured CO concentrations, but ground based and satellite measurements are presented because the aim of the study is to evaluate a methodology that relies solely on data from instruments. The rate calculations were also performed using only
- 25 model-output<u>CO</u> measurements from the Kiruna Microwave Radiometer (KIMRA) and the Microwave Limb Sounder (MLS)-(not shown), and the results lead to the same conclusion. This was expected due to the level of agreement found in a comparison between of the modelled and measured CO (Sect. 2.4).

Section 2 outlines the instruments and the model used in this study as well as their datasets. <u>A</u>. A brief comparison of the three CO datasets is also provided to assess how well the model represents observations of the atmosphere. Section 3

30 investigates the trajectories of air parcels arriving in the Arctic during winter, and the evolution of the<u>mean</u> tendencies of CO concentration<u>VMR</u>s in the Arctic middle atmosphere due to each component of the continuity equation. Section 4 shows the rates of vertical motion calculated using CO measurements and the above assumption, and estimates how these rates change when accounting for all parts of the continuity equation. Section 5 uses CO concentration<u>VMR</u> tendencies from 2008 to 2014 to assess their relative importance during different months. Section 6 contains a discussion of the results and the

limitations of the study, and suggests a different interpretation of the rates derived from tracer measurements. Section 7 provides concluding remarks.

2 Instruments, model, and data

2.1 KIMRA

5 KIMRA is a ground-based microwave remote sensor located at the Swedish Institute for Space Physics, Kiruna, Sweden (67.8° N, 20.4° E). The instrument is a passive remote sensor and radiances from atmospheric CO are measured at a frequency 230.54 GHz. Specific details on the instrument can be found in Raffalski et al. (2002) and Hoffmann et al. (2011). The current CO dataset from KIMRA covers Arctic winters from 2008 to 2015 with gaps corresponding to instrument non-operation and summer periods when CO concentrationVMRs in the middle atmosphere are too low to be accurately measured. The average altitude range of the data is 46 – 86 km and the vertical resolution is 15 – 18.5 km, depending on the altitude. Details on the measurement technique and CO inversion scheme are given in Ryan et al. (2017). The average precision (values can vary from one profile to another) of wintertime KIMRA CO volume mixing ratios (VMRs) range from 0.06 ppm at 46 km altitude to 2.7 ppm at 86 km. The average time resolution of a CO measurement is around 2 hours. KIMRA CO data presented in this work haves been averaged to give daily profiles.

15 2.2 MLS

MLS is a microwave remote sensor aboard the Aura satellite, launched in July 2004, and is part of NASA's Earth Observing System. Atmospheric CO is retrieved from radiance measurement made in two bands of the 240 GHz radiometer. A description of the MLS instrument can be found in Waters et al. (2006) and details on the retrieval can be found in Pumphrey et al. (2007) and Livesey et al. (2008). The data used here <u>areis</u> version 4.2 (Schwarz et al., 2015), which is described in Livesey et al. (2015). These CO profiles cover a pressure range of 215 – 0.0046 hPa (<u>approximately 11 – 86 km</u>) and have a maximum (largest) precision of 11 ppm at the highest (in altitude) pressure level. For the data used here, the vertical resolution is between 3.8 and 6.2 km, and the horizontal resolution is between 200 and 250 km. MLS data presented here <u>MLS dataare within ± 2° latitude and ± 10° longitude of Kiruna, andre used here</u> haves been averaged to produce daily profiles.

25 2.3 SD-WACCM

The Community Earth System Model version 1 (CESM1), Whole Atmosphere Community Climate Model (WACCM), is a coupled chemistry climate model from the Earth's surface to the lower thermosphere (Marsh et al., 2013 and references therein). WACCM is a superset of the Community Atmosphere Model, version 4 (CAM4), and includes all of the physical parameterizations of CAM4 (Neale et al., 2013) and a finite volume dynamical core (Lin, 2004) for the tracer advection. The

30 simulation of WACCM4 used in this study is run with specified dynamics (SD) fields, using meteorological analyses from

the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2011). The chemical component is based on version 3 of the Model for Ozone and Related Chemical Tracers (Kinnison et al, 2007). Garcia et al. (2014) discusses an update to the absorption cross section for O_2 , which increased modelled CO mixing ratios in the MLT, bringing them closer to observations

- 5 them closer to observations.
 - SD-WACCM constrains the atmosphere towards observations below 50 km through nudging with data from the abovementioned analysed meteorological fields. Above 60 km the atmosphere is fully interactive and between 50 and 60 km the nudging linearly decreases to zero. Details on the nudging of the temperature and wind fields in the model can be found in Lamarque et al. (2012) and references therein. The model also tends towards observations at altitudes above 60 km because
- 10 the zonal-mean mesospheric winds and temperatures at higher altitudes have been shown to be strongly constrained by the stratosphere (Liu et al., 2010; McLandress, 2013), but precise agreement cannot be expected. For the model runs used in this work, the pressure grid consists of 88 layers from the ground to the thermosphere (~133 km). The altitude resolution of the grid increases from ~0.1 km near the surface to ~3.5 km in thermosphere. The horizontal resolution is 1.9° x 2.5° in latitude and longitude. Model output of daily averages Daily model output from 2008 to 2014
- 15 areis used for this study.

20

2.4 CO VMR comparison

Because CO information from three sources is being used in this study, a brief comparison is called for. Figure 1 plots the CO VMRs from KIMRA, MLS, and SD-WACCM above Kiruna for 2008 through 2014. The aim of a comparison is to see whether the datasets capture the same variability in middle-atmospheric CO. The VMRs are plotted at five altitudes between 46 and 86 km. This is the average altitude range of KIMRA CO data and reaches the upper altitude limit of MLS CO data.

- The MLS and SD-WACCM concentration <u>VMR</u>s are also plotted after the profiles have been smoothed with the KIMRA averaging kernels (Rodgers and Connor, 2003). This method allows a meaningful comparison of datasets that have significantly different vertical resolutions. <u>MLS data within $\pm 2^{\circ}$ latitude and $\pm 10^{\circ}$ longitude of Kiruna are used here.</u> A more comprehensive comparison of <u>the current</u> KIMRA and MLS <u>data</u> is given in Ryan et al. (2017). SD-WACCM data is
- 25 here bilinearly interpolated to the location of Kiruna, but a significant change in the results isn't found when simply using the model coordinate grid point closest to Kiruna. The three CO datasets show agreement on seasonal and daily time scales. Agreement between the model and instruments on such time scales highlights the power of SD-WACCM as a tool for investigating trends as well as temporally short events in the atmosphere. <u>A systematic difference is evident between MLS</u> and SD-WACCM during the times of year when CO VMRs are rapidly increasing or decreasing, with SD-WACCM showing
- 30 larger values of CO. The difference is most pronounced at higher altitudes and is predominantly during August/September and April/May. Table 2 lists the correlation and regression coefficients calculated for each data pairing. Regression coefficients are calculated accounting for errors in the abscissa and ordinate variables (York et al., 2004), with a 15 % error assumed for SD-WACCM CO VMRs. Correlations between KIMRA and smoothed MLS, and KIMRA and smoothed SD-

WACCM, are ≥ 0.86 at all altitudes, and MLS and SD-WACCM correlations are ≥ 0.88 . MLS and SD-WACCM were compared at other polar locations (not shown here) and display similar agreement. The values are similar to those found for earlier versions of the model and data (Hoffmann et al., 2012a), with differences mainly due to updates to the modelled CO (Garcia et al., 2014) and the data products (Livesey et al., 2015; Ryan et al., 2017).

5 3 Contributions to the CO continuity equation

3.1 The TEM continuity equation

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The mass transport of the residual mean meridional circulation is well represented by the Transformed Eulerian Mean (TEM) formulation (Andrews and McIntyre, 1976), and is covered in detail in Andrews et al. (1987). The TEM circulation in the solstice seasons is dominated by flow from the summer to the winter pole, accompanied by downward and upward transport above the winter and summer poles, respectively. The TEM zonal-mean tracer continuity equation has been described in various works (e.g., Garcia and Solomon, 1983; Andrews et al., 1987; Brasseur and Solomon, 2005; Monier and Weare, 2005; Smith et al., 2011):

$$\frac{\partial \overline{\chi}}{\partial t} = -\overline{w} * \frac{\partial \overline{\chi}}{\partial z} - \overline{v} * \frac{\partial \overline{\chi}}{\partial y} + \overline{S} + \overline{X_{mol}} + \frac{1}{\rho_0} \nabla \cdot M + \frac{1}{\rho_0} \frac{\partial}{\partial z} \left(\rho_0 K_{zz} \frac{\partial \chi}{\partial z} \right), \tag{1}$$

where *χ* is the CO VMR, *w* is the vertical component of the residual mean meridional circulation, and *v* is the horizontal
component. *S* is the zonal-mean net chemical production of CO and *X*_{mol} is the zonal-mean molecular diffusion of CO. *v* · *M* is the divergence of the resolved eddy flux vector and describes the eddy transport of CO, with *ρ*₀ as the basic density. *K*_{zz} is the diffusion coefficient due to unresolved small-scale gravity wave breaking, and the last component of Eq. (1) represents the transport of CO due to parameterised eddy flux divergence (from gravity waves). The right-hand-side (RHS) terms of Eq. (1) are calculated using daily averaged output from SD-WACCM and details on the exact equations can be found in
Andrews et al. (1987). The value of *K*_{zz} calculated with SD-WACCM depends, among other things, upon the Prandtl number (or more properly, the "turbulent Prandtl number"), which describes the ratio of momentum flux to heat flux. The

- Prandtl number is a property of the process whereby gravity waves dissipate when they "break" (see e.g., Fritts and Dunkerton, 1985, for more details). The Prandtl number is 2 for the model runs in this work (see Sect.tion 6) and is used in SD-WACCM to parameterise gravity wave breaking (Garcia et al., 2007). Finite differences in Eq. (1) are calculated as
- 25 centred differences except at the boundaries of grids, where forward and backward differences are used. The terms of Eq. (1) are renamedwritten here as:

$$\frac{\partial \overline{\chi}}{\partial t} = adv_w * + adv_v * + chem + Xmol + Xedd + Xk_{zz},$$
(2)

to simply express the tendencies of CO in the continuity equation. The change in zonal-mean CO VMR with time is a sum of the contributions from (following the RHS of Eq. (2)): vertical advection, horizontal advection, net chemical production, molecular diffusion, eddy transport, and unresolved eddy transport, which, for present purposes, is due to gravity waves.

3.2 Trajectories during Arctic winter

5

As a first step to examine the assumption of purely vertical tracer advection, the back-trajectories of air parcels during two Arctic winters are plotted in Figure 2. The parcels arrive at 5 altitudes between 46 and 86 km and at two locations, 67° N and 80° N. They are advected, from these locations, backwards in time over 60 days, in 4 hour steps, using $\overline{w*}$ and $\overline{v*}$ from SD-WACCM. The starting date for the trajectory calculations (arrival date of the air parcels) is February 28th, for 2009 and 2011.

- The winter of 2009 had a major SSW (during which the 10 hPa zonal circulation becomes easterly at 60° N) beginning on the 24th January, and 2011 had a relatively stable vortex throughout the winter. The results in Figure 2 are consistent with similar calculations in Smith et al. (2011) and Straub et al. (2012), for the general shape of the trajectory and in that the parcels do not originate above approximately 100 km. The parcels at 80° N arrive from higher altitudes due to a stronger
- 10 vertical component of the circulation compared to 67° N. <u>Conversely, the horizontal component of the circulation is stronger</u> at 67° N and the parcels arriving there originate from lower latitudes compared to those arriving at 80° N. <u>The magnitude of</u> the TEM wind is larger for the higher altitudes, as is also shown in Smith et al. (2011), and the air parcels that arrive above 66 km altitude originate in the summer hemisphere. The parcels that arrive below this altitude, which could be considered as part of the Brewer Dobson circulation (Brewer, 1949), originate at latitudes closer to the equator. <u>Conversely, the horizontal</u>
- 15 component of the circulation is stronger at 67° N and the parcels arriving there originate from lower latitudes compared to those arriving at 80° N. A clear reversal of the trajectory around the time of the SSW can be seen for the air parcel arriving at 66 km altitude, 80° N, because of temporary changes in the direction of $\overline{w*}$ and $\overline{v*}$. These changes cause the air parcel to reverse direction before starting to descend again. It is evident from Figure 2 that the circulations at the pole have varying degrees of vertical and horizontal components.

20 3.3 Tendencies of CO during Arctic winter

Figure 3, 4, and 5 plots the wintertime tendencies of CO (RHS of Eq. (2)) for 2008/2009 and 2010/2011, for the three scenarios of 67° N, 80° N, and a north polar average ($60^\circ - 90^\circ$ N), respectively. The zonal mean tendencies are shown for 67° N, 80° N, and a north pole average ($60^\circ - 90^\circ$ N), and are plotted as an 11-day running mean. Note that the tendencies are plotted with individual colour scales to retain relevant information when there are low magnitudes, and labelled contours are

- 25 <u>added.</u> In the context of a point measurement at Kiruna, a full rotation of the vortex is on the order of 10 days (assuming a zonal wind speed of 20 m/s at 67° N). Relevant comments on the results are provided here but an in-depth analysis is not made as it is not the focus of the study. Molecular diffusion (*Xmol*) generally causes negligible changes in CO, compared to other process, below approximately 83 km, and shows little variation between different scenarios and winters. Above that, the magnitudes increase quickly, with tendencies < -0.1 ppm/day– in the altitude range shown here. Unresolved eddy
- 30 transport (Xk_{zz}) is also negligible below approximately 75 km, but can show tendencies < -0.2 ppm/day above that altitude for short times (order of a week). Significant variation is seen for the different winters. Both processes tend to cause a decrease in CO VMRs throughout the winter in the upper mesosphere, agreeing with results of Smith et al. (2011). For

comparison, vertical advection $(adv_w *)$ at these altitudes shows positive tendencies ranging from < 0.2 to > 1.6 ppm/day. Changes in CO due to chemistry (*chem*) are small below approximately 70 km, but <u>eachall scenario and yearcases</u> shows a sustained sink for CO during the winter in a layer at around 80 km altitude. The layer coincides with the location of a nighttime layer of hydroxyl (OH) around 82 km altitude (Brinksma et al., 1998, Pickett et al., 2006, Damiani et al., 2010). OH is

- 5 known as the dominant chemical sink for middle-atmospheric CO (Solomon et al, 1985). *chem* tendencies are stronger at 80° N compared tothan 67° N, with magnitudes reaching more than 0.3 ppm/day in November and December 2010, ranging from approximately 10% to 50% of adv_w * over that time.² The results suggest that CO chemistry cannot be ignored in the mesosphere during winter. Tendencies due to resolved eddy diffusion (*Xedd*) show the most variation between positive and negative values are the most variable, and more somainly at 67° N than 80° N because of proximity to the edge of the
- 10 polar vortex. The north polar average shows that Xedd generally reduces CO concentrationVMRs during the winter and, above ~ 70 km, has magnitudes greater than 25 % of adv_w * for time scales of a week. The largest tendency in CO is from vertical advection (adv_w *), and causes an almost constant increase in CO VMRs throughout the winter, before reversing when the TEM vertical wind changes direction in Spring (visible in all adv_w * plots). The increase is due to the downward motion of air and the positive gradient of CO VMR with altitude. The tendency is stronger at 80° N compared to 67° N due
- to a stronger vertical component of the residual circulation at the higher latitude (Smith et al., 2011), and see Figure 2). A signature of the major SSW in 2009 can be seen in the adv_w * tendency for that year, with a decrease and eventual change to a negative tendency. A negative tendency generally indicates ascent of air at this time. For some time directly afterwards, the tendency has a stronger positive magnitude than before. This agrees with observations of stronger vertical motion above the pole after a SSW (see references in Table 1). There is also a brief change to a negativepositive adv_w * at 80 N, around
- 20 80 km altitude, in early January 2011. This coincides with a relatively strong positive value for *Xedd* at the same time and location, indicating strong wave activity. The <u>CO</u> tendency from horizontal advection $(adv_v *)$ is negative almost everywhere. This is expected, considering the direction of $\overline{v *}$, <u>during wintertoward the winter pole</u>, and the low-to-high gradient of CO from lower to higher latitudes in the winter hemisphere. The magnitude of the tendency decreases in spring in each scenario and year. but a change of sign is not obvious by the end of April. The advection tendencies show maximum
- 25 values around 70 80 km for two main reasons. The first is the larger magnitude of the TEM circulation, compared to lower altitudes, before there is a turnaround in the direction of the circulation at higher altitudes, at which point the circulation changes from poleward and downward to poleward and upward (e.g., Lieberman et al., 2000; Smith et al., 2011). The turnaround point is at approximately 95 km in WACCM (Smith et al., 2011). The second is the generally increasing vertical gradient of CO with altitude (see Eq. 1). -At 67° N, the magnitudes of $adv_v *$ are roughly half that of $adv_w *$, and at 80° N
- 30 they are roughly one fifth. Considering this observation alone, changes in CO VMRs cannot be attributed solely to vertical advection.

4 Rates of vertical motion with <u>SD-WACCM COKIMRA and MLS</u>

In this section, the rates of vertical motion are calculated, using CO data from KIMRA and MLSCO profiles from daily averaged SD-WACCM output, by two methods. The first method assumes that observed changes in CO VMRs are due to vertical advection alone. This is a commonly used method (see Table 1) and involves tracking the altitude of a chosen concentration VMR of CO over time and then performing a linear regression on the data of altitude (z) vs. time (t). The rate 5 for a given date is calculated here by performing a regression on the CO data within ± 5 days of the date. This gives an 11day running mean of the rate of vertical motion. The calculation can be done for multiple concentration VMRs, to retrieve a vertical profile of the rates of vertical motion, as in Bailey et al. (2014). The term used here to denote the rate of vertical motion calculated using CO concentration VMR is w_{CO} , following Hoffmann (2012b). The second method used here includes 10 information on changes in CO VMRs due to all terms of the continuity equation in Sect. 2. Before tracking a CO concentration VMR from one time step to the next, the concentration VMR is adjusted using the tendencies of the continuity equation, except for $adv_w *$, for the corresponding time frame. This accounts for changes in CO concentration VMR from other processes as one tracks its movement due to vertical advection. The resulting rate is called w_{CO} corrected. This could be considered a crude approach, combining daily averaged CO output with CO tendencies calculated using the TEM 15 formalismeombining instrument data and model output, but the aim here is to provide an estimate of the errors that may be

- incurred by neglecting influences on CO other than vertical advection. In any case, the results involving w_{co} corrected are discussed in a qualitative manner, instead of for quantitative error analysis. To illustrate the difference between w_{co} and w_{co} corrected, example algebraic expressions for the rates between a time step *n* and *n*+1 are given: Eq. (3), (4), and (5). In practice, w_{co} and w_{co} corrected were calculated by performing a linear regression on the 11-day altitude vs. time data,
- 20 including errors in the estimated altitude of the measured CO concentration<u>VMRs</u>. Equation (3), (4), and (5) refer to scalar (values at a given altitude/latitude/longitude) VMRs and tendencies, in contrast to Eq. (1) and (2), which refer to three-dimensional variables.

$$w_{CO}(z,t) = \frac{z_{n+1} - z_n}{t_{n+1} - t_n} \Big|_{\overline{\chi}}$$
(3)

$$w_{co}\ corrected(z,t) = \frac{z(\bar{\chi}_{n+1}) - z(\bar{\chi}_n)}{t_{n+1} - t_n} \tag{4}$$

25 where,

$$\bar{\chi}_{n+1} = \bar{\chi}_n + \left(\frac{1}{2}\sum_{i=n}^{n+1} [adv_v + chem + Xmol + Xedd + Xk_{zz}]\right)(t_{n+1} - t_n)$$
(5)

The results for winters 2008/2009 and 2010/2011 are <u>shownplotted in Fig 4</u>. For each winter, w_{co} and w_{co} corrected are calculated as: a local value above Kiruna-using KIMRA data, a zonal mean at 80° N-using MLS data, and a polar mean (60° – 90° N), and plotted in Figure 6, 7, and 8, respectively using MLS data. The methods above were found to be unreliable

30 when there are very low CO VMRs, and gave unrealistic rates of motion. This was more likely to occur at lower altitudes where CO VMRs are relatively low. Sometimes a CO concentration VMR could not be followed within the specified altitude

range (no extrapolation was used) and so there are a few locations with no rate information. The differences between the two rates, w_{co} corrected – w_{co} , are also shown in <u>each figureFig. 4</u>.

There are three main qualitative points, common to each scenario and year, that are evident from the results.

- First, tThe values of w_{co} are generally of a smaller magnitude than w_{co} corrected during winter, meaning t, he
 calculatedmeaning that the derived rates of descent are stronger if onewhen accountsing for CO tendencies other than vertical advection. This makes sense because, as seen in Figures 3-5, the other transport terms of the continuity equation (and the chemical loss term) tend to oppose the vertical advection term. In other words, tThe results indicate that the "true" rate of atmospheric descent is masked by sinks of CO, and by transport processes that oppose the tendency due to vertical advection. Second, tThe differences between the two rates are often of the same order as w_{co}. Third, tThe signs of w_{co} and
- 10 w_{co} corrected are often opposite, meaning the calculated direction of air motion is prone to change when accounting for CO tendencies other than vertical advection. In each example for 2008/2009, the magnitude of the positive (upward) motion around the time of SSW is decreased for w_{co} corrected compared to w_{co} . After the SSW, and into March, the strongest descent values are seen around 70 – 80 km in w_{co} corrected, compared to values of ascent seen in w_{co} at the same location. The results indicate that the "true" rate of atmospheric descent is masked by sinks of CO, and by transport

15 processes that oppose the tendency due to vertical advection.

5 Relative strengths of CO tendencies, by month

To give an idea of the relative influence each tendency has on middle-atmospheric CO concentration<u>VMR</u>s each month, daily CO tendencies from 2008 to 2014 are used to provide relative values of their monthly mean. For a given tendency, the daily values are separated by calendar month and averaged, to give a monthly mean tendency. <u>TThe same is done for the</u>

- 20 absolute sum of he daily sums of the absolute values of all_all_tendencies_tendene_are also separated by month and averagedies, to give a monthly mean total absolute-tendencysum. The monthly mean tendencies are then normalised by the monthly mean total absolute-sum_tendency, and will be referred to here as relative strengths. Using_an absolute valuessum for normalisation retains the sign of the individual tendencies and avoids a large spread in the results when there is a small denominator (i.e., when the tendencies cancel each other and their sum is near zero). The relative strength of the sum of all
- 25 tendencies, excluding adv_w *, is also included as a variable. This variable will be referred to here as "other processes" and can be directly compared to the relative strength of adv_w *, to judge the influence of vertical advection compared to all other processes. The results are shown for the north polar averagee ($60^\circ - 90^\circ$ N) in Fig. <u>95</u>, and the south polar averagee ($60^\circ - 90^\circ$ S) in Fig. <u>106</u>. For the north-pole, tendencies corresponding to 10 days directly before and after a SSW (starting on January 22nd, 24th, and 26th, 2008, 2009, 2010, respectively, and February 6th, 2013) are excluded from the calculation, as
- 30 well as the <u>SSW</u> start-date. Ten days was chosen to remove effects directly before and after a SSW, but signatures of the events remain in the data. The information from before and after an SSW is used to separately calculate the relative strengths for these times and is shown in Fig. <u>11</u>7.

For the north polare average in Fig. <u>95</u>, <u>t</u>The relative strength of *other processes* is everywhere negative from October to March and the relative strength of $adv_w *$ is positive. Both $adv_w *$ and *other processes* show a change of sign in April. The relative strength of $adv_w *$ reaches a maximum value of 0.8 at lower altitudes in October and November, and decreases with altitude to approximately 0.5 at 86 km for these months. The relative strength of *other processes* shows an

- 5 opposite trend: negative values strengthening with altitude to approximately -0.4. At the lower limit of the altitude range in January, *adv_w* * shows a lower relative strength than *other processes* due to a strong *Xedd* influence. This is likely the "left-over" influence of the SSWs in the data. By March, the relative strength of *chem* is prominent below 65 km, and the magnitude of *adv_w* * is matched by *other processes*. By April, the residual mean circulation has reversed direction and *adv_w* * has changed sign at most altitudes. The negative value of *chem* is then dominant at lower altitudes, and there is a stronger positive tendency above ~80 km (from photolysis of carbon dioxide (CO₂)).
- -There are no months where the relative strength of *other processes* can be considered negligible compared to the relative strength of $adv_w *$. The closest approximations of this situation are at 50 km altitude in October and at 46 km altitude in November, when *other processes* contributes 13.7 % and 9.6 % of $adv_w *$, respectively. These percentages then vary significantly with altitude. For October, the value increases to 18.6 % at 46 km, 22.5 % at 60 km, and is 61.13 % at 80 km.
- 15 For November, the value increases to 34.4 % at 54 km, and is 70.8 % at 80 km. The results for the south polar averagee, in Fig. 106, are qualitatively similar to those for the north-pole. The relative strength of adv_w * shows a maximum of ~0.8. Both hemispheres show a peak in *chem* at 80 km for most of winter (see Sect. 3.3). The relative strength of Xedd is not as prominent at the south pole-as the north, likely due to the higher stability of the southern polar vortex. The points at which the relative strength of other processes is smallest compared to adv_w * are at
- 20 <u>56 km in April (8.3 %) and at 46 km in May (6.8 %). For April, the value increases to 22.5 % at 46 km and 21.5 % at 66 km, and is 56.9 % at 80 km. In May, the value increases to 16 % at 54 km, and is 69.1 % at 80 km.</u>

-For the 10 days directly before and after SSWs, in Fig. <u>117</u>, the relative strength of $adv_w *$ is less than 0.5 at all altitudes. *Xedd* is strong below 60 km, such that the relative strength of *other processes* has a larger magnitude than that of $adv_w *$ at many altitudes. The relative strength of $adv_w *$ shows a more oscillatory structure with altitude, and there is a local

25 minimum at about 70 km in the data for 10 days after SSWs. There is also a positive peak in the relative strength of Xk_{zz} after SSWs at this altitude.

Aside from considering what value would classify as negligible, the significant variation in strength of *other processes* compared to $adv_w *$, over altitude, adds complexity to the method of following a tracer over an altitude range to determine the descent rate. One must also consider that while this section discusses monthly averaged data, tracers are often followed

30 for several days to determine the changes in altitude over that time, and that the magnitudes of each tendency can vary significantly over this time scale (see Fig. 3, 4, and 5).

6 Discussion

The results of the previous sections, using SD-WACCM, are clear on one <u>indicationpoint</u>, that the assumption of observed changes in CO <u>concentrationVMR</u>s being solely due to vertical advection is not a valid one. What is not obvious, is what the rates inferred from the behaviour of tracer isolines (w_{γ} , under the nomenclature used here) represent. When making

- 5 observations on timescales of weeks, the TEM offers a suitable representation of the governing dynamics. The vertical velocities calculated by observing CO, however, fall short of are smaller than the magnitudes of the TEM vertical wind, $\overline{w*}$, found with SD-WACCM. Figure <u>-128</u> shows the polar average (60° 90° N) $\overline{w*}$ for the winters of 2008/2009 and 2010/2011, calculated using daily averaged SD-WACCM output data. Comparing this to the values of w_{co} and w_{co} corrected in Figure <u>84</u>, it is clear that the rates derived from CO values are generally of lower magnitude than $\overline{w*}$.
- 10 This agrees with the results of Hoffmann (2012b). w_{co} corrected more closely matches the sign and general pattern of w̄ *, but does not reach the semi-persistent descent rates of -1.2 km/day between 60 and 70 km, or the magnitude of the enhanced rate of descent (≤ -1.6 km/day) after the SSW in 2009. Similar results are observed when using KIMRA and MLS-SD-WACCM CO profiles to derive vertical velocity, instead of KIMRA and MLS dataSD-WACCM output (not shown here). Some of the difference may be attributed to the time resolution, or assumed parameters, of the SD-WACCM output used in
- 15 this work. Meraner and Schmidt (2016) showed that the tendency of NO due to $\overline{w*}$ can be quite different (by > 1 ppm/day at 90 km) when calculated using 6-hourly <u>averaged</u> output or daily <u>averaged</u> output from HAMMONIA (Hamburg Model of the Neutral and Ionized Atmosphere)). Meraner et al. (2016) showed that NO_x transport in the mesosphere is highly sensitive to the strength of the gravity wave source. The amplitudes of gravity waves influence the altitude at which the waves break and deposit their momentum, which in turn affects the vertical profile of $\overline{w*}$. Garcia et al. (2014) found that using a Prandtl
- 20 number of 4 for WACCM (see Sect. 3.1), instead of 2 (as used here), gave better agreement with polar CO profiles from satellite instruments (the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) on SCISAT-1, and the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on Envisat). The opposite was found for tropical and mid-latitude CO profiles, and Garcia et al. (2014) consider that deficiencies in the modelling of diffusive eddy transport may be due to problems in producing the correct latitudinal profile of K_{zz}, which cannot be addressed by simply

25 adjusting the Prandtl number.

As the results here <u>using SD-WACCM</u> indicate that the commonly used approximation of $\overline{w*}$ with w_{χ} (from measurement data onlyusing tracer observations) is not valid, we suggest an alternative interpretation of w_{χ} : as an effective rate of vertical transport for the trace gas χ . The interpretation still concerns the descent of a tracer through the middle atmosphere, but allows for a chemical sink, or for processes other than vertical advection to influence the descent rate, e.g., horizontal

30 advection or an increase in unresolved eddy transport after a SSW. Hoffmann (2012b) put forward a similar interpretation for w_{CO} , but with an assumption that the overall dynamic effects on CO are representative for the complete mesospheric air, and so w_{CO} is representative of w_{χ} for all tracers. The results here do not confirm that assumption, as it would require tracers to have the same horizontal and vertical concentrationVMR gradients (see Sect. 2.5 and references therein). The consistent negative chemical tendency of CO, seen here in a layer around approximately 80 km, also indicates the need to account for the behaviour of chemical sinks, even during polar night.

7. Conclusion

The aim of this work was to assess how well polar atmospheric descent rates can be derived from remote sensing measurements of atmospheric trace gases. Tendencies of middle atmospheric CO were calculated using output from SD-WACCM for the years 2008 to 2014, within 46 – 86 km altitude, and used to evaluate the relative influence of processes involved in the TEM CO continuity equation. The results show that dynamical processes other than vertical advection cause non-negligible changes in CO concentrationVMRs during winter, and particularly directly before and after sudden stratospheric warmings when eddy transport can become dominant. Significant changes in CO tendencies from SD-WACCM occur on the order of days. The results also show a chemical sink for CO, present throughout polar night, due to the layer of night-time OH at approximately 80 km. CO data from the ground-based radiometer, KIMRA, and satellite-borne

- radiometer, MLS, Modelled CO profiles were used in combination with the tendency data to provide a qualitative estimate of the errors that can be incurred involved when in assuming pure vertical advection of CO. Rates of atmospheric motion were calculated when assuming only vertical advection, and corrected rates were calculated by including tendency information for
- 15 all processes. The differences between the two results are of the same order as the calculated rates, and the rates <u>are prone</u> <u>tooften</u> showing opposite directions for the mean vertical wind._-The corrected rates more closely match the TEM vertical wind velocity from SD-WACCM, but both results using CO show smaller magnitudes relative to the TEM vertical wind, in agreement with <u>the work of Hofmann (2012b)previous work</u>. The "true" rate of atmospheric descent appears to be masked by sinks of CO, and by transport processes that oppose the tendency due to vertical advection. Monthly mean relative
- 20 tendencies for CO show that the summed magnitude of processes other than vertical advection can constitute a large fraction of the changes in CO VMR. For a given month, the summed magnitude of the other processes, relative to vertical advection, changes by several tens of percent over the altitude range under investigation. -The results here suggest that there are no show that there are no months during polar winter when vertical mean advection dominates the budget of CO to such an extent that vertical mean velocity can be accurately derived within the altitude range.
- 25 <u>An assessment using SD-WACCM indicates that aA</u> commonly used approximation of the vertical mean velocity of the atmosphere, $\overline{w*}$, using tracer (CO in this case) isolines is <u>not</u>found to be invalid, and an alternative interpretation of the rates derived from trace gas measurements is suggested: an effective rate of vertical transport for the given trace gas. Such an interpretation still concerns the descent of trace gases from the mesosphere and thermosphere, but allows for chemical sinks, and changes in <u>concentrationVMR</u> from dynamical processes other than vertical advection. Due to possible differences in
- 30 the behaviour of chemical sinks and <u>concentrationVMR</u> gradients, it is not clear whether the rate of vertical transport for one tracer is representative of the rate for another. Continuous ground-based and satellite measurements of trace gases remain an

essential tool in understanding the short- and long-term evolution of the middle atmosphere, as well as for the validation and parameterisation of atmospheric models.

Author contributions

Mathias Palm and Christoph G. Hoffmann outlined the project. Niall J. Ryan designed the method. Douglas E. Kinnison
performed the SD-WACCM runs and provided the output. Rolando R. Garcia provided scripts to calculate TEM variables from WACCM output. Uwe Raffalski maintains and operates KIMRA, and provided the instrument spectra. Niall J. Ryan performed the study with valuable insight and interpretation of results provided by Douglas E. Kinnison and Rolando R. Garcia. Justus Notholt oversaw project development. Niall J. Ryan prepared the paper with contributions from eoauthorsco-authors.

10 Competing interests

The authors declare that they have no conflict of interest.

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reference	tracer	location	instrument	rate of vertical motion [m/day]	approximate altitude(s)	time of year	terminology
Allen at al. (2000)	CO	Antarctica	satellite	-250 at 60° S330 at 80° S	30 - 50 km average	April/May average, 1992	atmospheric descent
Forkman et al. (2005)	CO	NH mid-latitudes	ground-based	+250 to +450	60 - 95 km	Spring, 2002	mesospheric circulation
Forkman et al. (2005)	CO	NH mid-latitudes	ground-based	0 to -300	60 - 95 km	Autumn, 2002	mesospheric circulation
Nassar et al. (2005)	CH_4 , H_2O	Arctic	satellite	-150	upper straosphere	Feb/Mar, 2004	atmospheric descent
Nassar et al. (2005)	CH_4 , H_2O	Arctic	satellite	-175	lower mesosphere	Oct 2003 to Feb 2004 average	atmospheric descent
Hauchercorne et al. (2007)	NO ₂	Arctic	satellite	from -600 in Jan, to -200 in Mar	45 - 70 km	20 Jan to 10 Mar, 2004	descent of NO2 layer
Funke et al. (2009)	CO	Arctic	satellite	-350 to 400	50 - 70 km	Sep/Oct, 2003	polar descent
Funke et al. (2009)	CO	Arctic	satellite	-200 to -300	40 - 70 km	Nov/Dec, 2003	polar descent
Funke et al. (2009)	CO	Arctic	satellite	-1200	mesosphere	after SSW, 2004	polar descent
Di Bagio et al. (2010)	CO	Arctic	ground-based	-200 to -300	descent from 58 - 62 km	after SSW, 2009	descent of air
Di Bagio et al. (2010), from Orsolini et al. (2010)	H ₂ O	Arctic	ground-based	-200 to -300	descent from 59 and 62 km	after SSW, 2009	descent of air
Straub et al. (2012)	H ₂ O	Arctic	ground-based	-350	52 - 68 km average	5 Feb to 5 Mar average, 2010	polar descent
Straub et al. (2012)	H ₂ O	Arctic	satellite	-360	52 - 68 km average	Jan/Feb/Mar average, 2010	polar descent
Bailey et al. (2014)	NO, $H_2 O$, CH_4	Arctic	satellite	up to -1000	40 - 90 km	after SSW, 2013	atmospheric descent

Table 1: A partial list of studies that used atmospheric tracers to derive rates of vertical air motion in the atmosphere.

	KIMRA-MLS	KIMRA-MLSsmooth	KIMRA-WACCM	KIMRA-WACCMsmooth	MLS-WACCM	MLSsmooth-WACCMsmooth
86km	0.87, 0.95 ± 0.03	0.93, 1.26 ± 0.05	0.81, 1.05 ± 0.01	0.86, 1.25 ± 0.01	0.90, 1.00 ± 0.02	0.89, 0.93 ± 0.05
76km	0.90, 1.46 ± 0.03	0.94, 1.27 ± 0.03	0.89, 1.18 ± 0.01	0.89, 1.26 ± 0.01	0.91, 0.78 ± 0.01	0.87, 0.78 ± 0.02
66km	0.90, 1.27 ± 0.02	0.95, 1.36 ± 0.03	0.85, 1.20 ± 0.01	0.90, 1.26 ± 0.01	0.90, 0.83 ± 0.01	0.85, 0.72 ± 0.01
56km	0.91, 1.01 ± 0.02	0.95, 1.20 ± 0.02	0.88, 0.95 ± 0.01	0.90, 01.00 ± 0.01	0.89, 0.86 ± 0.01	0.86, 0.70 ± 0.01
46km	0.88, 0.38±0.01	0.91, 1.23 ± 0.04	0.89, 0.30 ± 0.01	0.90, 0.95 ± 0.02	0.88, 0.86 ± 0.01	0.83, 0.63 ± 0.01

Table 2: "correlation coefficient, regression coefficient ± error" for comparisons of daily CO VMRs from KIMRA, MLS, and SD-WACCM above Kiruna for 2008 through 2014. The abscissa variable is the first-named of each instrument pairing. A regression

5 coefficient > 1 (< 1) indicates a larger (smaller) range in the abscissa variable. Figure 1 shows the time-series' of each CO VMR dataset. See Sect. 2.4 for details.



Figure 1: Comparisons of daily CO VMRs from KIMRA, MLS, and SD-WACCM above Kiruna for 2008 through 2014. Values are displayed at 46, 56, 66, 76, and 86 km <u>altitude</u>. Correlation and regression coefficients for the datasets are given in Table 2. See Sect. 2.4 for details.



Figure 2: Trajectories of air parcels advected backwards 60 days in time from February 28th, 2009 and 2011, by the TEM circulation<u>using SD-WACCM</u>. Trajectories are calculated for air parcels arriving at 67° N and 80° N, at 46, 56, 66, 76, and 86 km altitude and locations are plotted at midnight each day. <u>Parcel positions on The start date of the 2009 SSW on January</u> 28th January 2009 (start date of an SSW) areis indicated with black asterixstars. See Sect. 3 for more details.



Figure 3: <u>11-day running mean t</u>Tendencies of CO (in ppmv/day) for 67° N for the winters of 2008/2009 and 2010/2011, calculated using daily averaged SD-WACCM output. Tendencies shown are for 67.8° N for the winters of 2008/2009 and 2010/2011. –See section 3.12.4 for a description of the tendencies which are represented in the TEM continuity equation.



Figure 4: The same as Fig. 3, but for 80° N.



Figure 5: The same as Fig. 3, but for the north polar average (60° – 90° N).



Figure 6: Rates of vertical motion, w_{co} , in km/day, calculated by trackingusing CO VMRs over time. w_{co} data is calculated using daily averaged SD-WACCM CO profiles. w_{co} corrected is calculated using a combination of SD-WACCM CO profiles and TEM tendencies (see Sect. 4 for details). The difference between the two rates of descent is also shown. The results plotted are for

5 TEM tendencies (see Sect. 4 for details)_L. The difference between the two rates of descent is also shown. The results plotted are for above Kiruna for the winters of 2008/2009 and 2010/2011.rom SD-WACCM (see Sect. 4). Contour lines are spaced by 0.2 km/day. Areas with tightly packed contours (black areas) occur when there are very low CO VMRs and the calculation method is unreliable. White areas are where a CO VMR could not be tracked within the shown altitude range. The start date of the SSW on January 28th 2009, is shown with a vertical green dashed line.

80° N zonal mean



Figure 7: The same as Fig. 6, but for a zonal mean at 80° N.



Figure 8: The same as Fig. 6, but for the north polar average $(60^{\circ} - 90^{\circ} \text{ N})$.



Figure <u>95</u>: <u>North polar average (60° – 90° N) m</u>Monthly mean CO tendencies (<u>see Eq. (2)</u>) over the north pole (60° – 90° N) around winter time, calculated using SD-WACCM <u>outputdata</u> from January 2008 to April 2014. Model output corresponding to 10 days directly before and after a SSW, as well as the start-date, are excluded. The values are expressed relative to the to the monthly means of the <u>sum of the absolute values of absolute sum of</u> all tendencies, and are referred to as relative strengths (<u>see Sect. 5</u>). A strength of the sum of the tendencies, excluding $adv_w *$, is also plotted.



Figure <u>106</u>: Same plots as for Fig. <u>95</u>, but for the south $\text{pol}_{\underline{\text{ar averagee}}}$ (60° - 90° S), around the time of southern hemisphere winter, and with no exclusion of model output for SSWs.



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Figure <u>117</u>: Same-<u>plots</u> as-<u>for</u> Fig. <u>95</u> (60 – 90 N), but for the 10 days directly before and after SSWs within Jan 2008 to April 2014. See Sect. 5 for details.



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