The authors thank the reviewers for their thorough, detailed, and insightful reviews. We have used all these recommendations to improve the clarity of this paper. In the following we insert our replies directly into the review.

Review #1:

Review: General Comments
von Clarmann et al. 2019 present results from an inverse method which uses observed (MIPAS) zonal-mean tracer fields to calculate residual circulation fields which are resolved in altitude, latitude, and time. This work expands on the work of von Clarmann and Grabowski 2016 (hereafter CG16) by providing time-resolved circulation fields, and continues the line of investigation of a number of other studies which have sought to constrain the strength of the residual circulation. However, the present work seeks to provide a substantial expansion in this direction by quantifying the circulation strength in terms of two-dimensional, time-resolved velocities. Only one previous work, to my knowledge, has quantified velocities at all - that being Fu, Hu, and Yang 2007 GRL - but this was only for a single profile of upwelling, while other work has provided some sense of two-dimensional motion but without velocities, such as the work of Stiller et al. 2012.
The results show several inconsistencies with current theory. For example: The mesopheric overturning circulation is considerably higher (at least 10 km, which seems very unexpected) when southward-bound as opposed to northward-bound; the tropical pipe shows quite a bit of meridional movement rather than isolated upwelling. If reliable, such results would be of substantial and immediate interest for a large section of the middle atmospheric research community.

Reply: The authors thank the reviewer for the appreciation of our results.

Action: None to this point.

Review: However, there are considerable issues with the

validity of the results, and I do not think the work should be published until they are addressed. I outline them in the following three points:
1. The inverse model robustness (specifically in terms of sensitivity to input fields) has not been explored. My impression from reading CG16 is that the inverse method requires multiple tracers but that the limit on the minimum number of tracers needed is rather soft (i.e. it is not strictly necessary to have X or more tracers). I suppose that it is possible to use a subset of the nine tracers applied, and thereby estimate the robustness of the method with respect to input data. In my opinion, having even a simple estimate is necessary. Having read this paper, I am left without an idea of how the results depend on the input tracer fields. Even if the method is mathematically sound, there may be biases in the results which extend from errors in tracer measurement or the calculation of chemical sources and sinks, and until this possibility is addressed the results remain in a somewhat skeptical position. In particular, I would propose something like a jackknife test, calculating the fields with only eight tracers, excluding one tracer for each calculation, each tracer in turn, and seeing how strongly the velocity fields vary. It may not need to be a recalculation of the entire approx. decade-long climatology, but I think a test like this (or something more advanced) in multiple seasons is necessary to establish the validity of the method.

Reply: We have meanwhile submitted a validation paper of the ANCISTRUS (Analysis of the circulation of the stratosphere using spectroscopic measurements) method available (enclosed). It includes an assessment of the relevance of sinks versus transport of patterns, the jackknife tests, model recovery tests, and an assessment of the adequacy of the regularization strength chosen. In a nutshell, the results are: below 30 km ANCISTRUS is quite accurate in a quantitative sense. Above, due to the regularization of the inversion along with less measurement information, peak velocities are underestimated. All structures and patterns, however, are nicely reproduced, and no artifical patterns are generated. Since none of the conclusions of the paper under review are fully quantitative but are related to structures and patterns, we are confident that the validity of our method for the purpose of our paper has now been sufficiently established, and it can safely be excluded that the patterns detected are mere artefacts.

Action: The draft of the validation paper is enclosed to the resubmission. In the climatology paper we make reference to the results of the validation paper.

Review: 2. The inverse model accuracy has not been quantified well. In CG16, an accuracy test was performed where dynamical quantities were prescribed in simple distributions, which showed that the method had some inaccuracy in the center of the domain and much more inaccuracy on the borders.

Reply: The inaccuracies at the borders were caused by the fact that the test fields, which were chosen in an ad hoc manner, did not satisfy the continuity equation. A method that allows only solutions which do satisfy the continuity equation will never be able to reproduce such fields. That is to say, the problem was the test fields, not the method. More adequate tests are included in the validation paper mentioned above.

Action: See above.

Review: I think a test with dynamical and chemical fields that are more similar to observations (i.e. less homogenous and, simply-said, messy) is necessary to ascertain the uncertainty of the results. I would suggest using CCM model data to produced inversted circulation fields and compare them with the actual, directly-calculated model fields. To be clear, the results of such a test could not be used to pin a quantity directly onto the method's results (since, for example, the inverse method includes some effects of mixing, although knowing how the "effective" velocities could differ from the actual velocities would be valuable). However, this would provide some level of confidence in the

results where, at the moment, the only indication extends from an example which simply does not resemble the observed atmosphere. As a final note on this, it would be best if the test could also examine the difference between CCM and inverted velocities, and not the residual between tracer distributions (as was done in CG16). The velocities are what matter, after all. As an example of possible data, the ESCIMO (Joeckel et al. 2016 GMD) simulations have a variety of chemical species included (all the chemicals used in this study are in the model output) and calculations of the residual circulation strength have also been performed. I am not involved in that work, but I would guess that the members of that project would be interested in sharing the data.

Reply: A validation with realistic test fields has been performed and included in the validation paper mentioned above. Comparisons to models are interesting in their own right, and this is on our agenda for the future. We think, however, that validation does not necessarily have to rely on model data.

Action: See above.

Review: 3. The inverse model result uncertainty has not been quantified. This is a rather small point, and not as important as the previous two. In CG16, quantifications of uncertainties of wind and diffusion coefficient fields were shown (in Figure 5) for fields computed using MIPAS data. Those uncertainties seem rather small, but it seems imprudent to exclude an estimation of uncertainties when a method for estimating them is possible. I suggest including a description or depiction of those uncertainties, if the method still applies for the present work.

Reply: The method is still applicable and we have the data available, but we consider this as largely redundant in this context. We present the standard deviations of the monthly averages, and this quantity includes both the uncertainty of the inversion and the year-to-year atmospheric variability. Thus, the standard deviations characterize how well the climatology of a month can represent any particular month of the sample. The CG16 estimates of the random uncertainty represent the mapping of the measurement errors on the inferred velocity fields only, but not the representativeness problems due to natural variability. But since both types of uncertainties are independent from each other and add up quadratically, small standard deviations indicate that also the measurement-error-based uncertainties must be small. The standard deviations are even a more reliable estimate of the upper bound of the precision because they do not depend on any assumption on the measurement uncertainty.

Action: We have added to the manuscript: "(To diagnose this effect, the standard deviations of the circulation vectors, which are a measure of their variability, are also shown in Figs 5–8.) This variability is caused by the natural variability of the circulation over the years and its random uncertainty. The latter is the random uncertainty of the MIPAS measurements propagated onto the circulation vectors.

Review: In my view, the first two points are necessary before these results should be published. Without a clear indication of the model validity, the novel results shown in this work seem as likely to be artifacts of the inverse method (or the calculation of chemical balances) as they are to correspond to reality.

Reply: The validation is reported in a separate paper, see above. There it is shown that the method does not create artificial patterns.

Action: As stated above, the draft of the validation paper is enclosed to the resubmission, and in the revised version of the paper under review we make reference to it..

Review: Furthermore, I find that the figures in the manuscript are difficult to interpret, and should be changed before publication. I have made more specific comments on this topic below. In general, the figures provide a qualitative idea of the circulation, in that I can examine the figures and know where the circulation is the strongest and which way

it is headed at any one time and know how that strongest location changes with time. That does provide a general characterization of the circulation, but knowing how the circulation strength changes with time in each location is of equal value to knowing where the circulation is strongest. The changing color scales in the first 12 panels makes that assessment difficult.

Reply: While we think that a qualitative empirical representation at this detail level is still unprecedented, we do agree that the figures should be improved.

Action: Circulation patterns are now represented on a common color scale. Beyond this, the original data will be made publically available via KITOpen, with a document identification number, thus fully quotable, allowing each user to plot them in their preferred representation.

Review: The figures showing standard devations need to be explained clearly, because they are so unusual, but do not seem to be properly explained anywhere. I think the figures should be remade showing contours or heatmaps, or some combination of both methods, so that readers can assess the strength of the vertical and meridional velocities and the variability of them. Maybe including stream lines would maintain the ease in understanding the flow direction. I understand that this likely means a doubling of the number of figures (assuming there is not a clever way to combine the meridional and vertical information), but I think that it is warranted for the clarity of interpretation.

Reply: We have decided to follow the suggestion to represent the variabilities in a different way.

Action: Separate plots for variabilities in v and w are now provided.

Review: Furthermore, I have the following two points which I think warrant explanation, but are not addressed in the text: Why do boundaries seem to be included in results,

when they were problematic following CG16? Are they somehow excluded?

Reply: No, boundaries are not excluded. These problems in CG16 were not a problem of our transport and inversion schemes but they were due to the simplified velocity fields used there which were not consistent with the continuity equation. E.g., if I have a poleward flow but no backward flow it does not come as a surprise that funny things happen near the pole. In CG16 such simple velocity fields were used because they allowed much simpler tests whether the transport scheme does what it is supposed to do, e.g. if a feature is transported with the right velocity etc. Applied to real data this type of problem does not exist because the true concentration fields are well described by the continuity equation, and the Earth's air is not forced to accumulate at the pole because of unrealistic velocity fields, or to do other funny things.

Action: None specific to this point. We have, however, summarized the results of the validation paper and discuss which kind of conclusions are supported by the data.

Review: How were the sources and sinks of each species calculated?

Reply: The general description of sources and sinks was already described in Section 2.1.2 of the original paper. Some missing information has been included, particularly the assumptions on the abundancies of involved species.

Action: For details, see below under comment on line 78.

Review: To conclude, I would like to stress that results from this method should be published in the future if the reliability of the method can be addressed. They would be of very substantial interest, and therefore I wholeheartedly recommend resubmission.

Reply: A validation paper is ready has been submitted. It confirms that the conclusions in the paper under review are robust.

In this context we would like to mention that during the recent meeting of the EGU's publication committee (Utrecht, NL, 1 Oct 2019), which is responsible for the EGU journals including ACP, the following guideline was agreed: In the case of novel methods or results based on novel methods the authors should be given the benefit of doubt, and the risk should be taken that it may be necessary to revise these results later. After the preparation of our validation paper we think that we actually do not need to invoke this board decision, but we think that it applies *a fortiori* **when a validation is available.**

Action: A validation paper is now available, see above.

Review: Specific Comments
Line 14: Neither Brewer nor Dobson suggest upper and lower branches to the BDC, nor the mesospheric overturning circulation. I think it would be best to cite somebody here who talks about that. Maybe Butchart's 2014 review paper would be good, to provide a general reference.

Reply: Agreed.

Action: The related paragraph has been rewritten and the Butchart (Rev. Geophys. 52(2), doi10.1002/2013RG000448, 157-184, 2014) reference has been included.

Review: Line 20: The new sentence in this line seems to dismiss the value of having a single estimate of the upwelling mass flux / intensity. Perhaps it's just the use of the words "merely" and "far" (more/too). I'm not sure if anyone has ever suggested that a single quantity could sufficiently characterize the circulation, but certainly the upwelling mass flux has provided a lot of value as a broad estimate of the circulation. I suggest simplifying the sentence - "These studies suggest that the ... is too complicated and detailed to be fully characterized by a scalar intensity." - or something similar.

Reply: agreed to remove the words which make the sentence sound dismissive.

Action: These words have been deleted.

Review: Line 56: I don't understand what is meant by point b. Stiller et al. also uses MIPAS data. What does the present method do differently? Since the chemistry of SF_6 is not considered, any chemistry that is actually happening would create biases in those regions where it occurs (but I am no expert on this, and cannot say if those regions are included here). As a secondary point, there is no over-aging involved in this method because ages are not calculated. What would you expect in the case of your inversion method, if you had this bias? I would assume the result would be a faster lower-strat to upper-middle atmosphere circulation.

Reply: The main SF_6 depletion happens in the mesosphere. Thus in the following we refer only to air parcels travelling through the mesosphere and back to the stratosphere. The method by Stiller et al., as well as earlier studies using this approach, are sensitive to the destruction of SF_6 along the entire trajectory of an air parcel from the stratospheric entry point, through the stratosphere and mesosphere and back into the stratosphere, because the age is calculated by comparison of actual SF_6 stratospheric mixing ratios and past SF_6 mixing ratios at the entry-point. Our method is different in that we use SF_6 mixing ratios measured at the upper boundary as a reference for gradient calculations in the uppermost model layer. Thus, any calculation of differences used for the calculation of the gradients (needed to solve the transport equation) is based on SF_6 mixing ratios which are, if coming from the mesosphere, already depleted in SF_6. Thus, mesospheric SF_6 destruction cannot lead to artefacts in the gradients. The only SF_6 loss that we possibly miss is SF_6 destruction within the **stratosphere** from one month to the other, which is a minor inaccuracy compared to the problem of mesospheric SF_6 depletion in age-of-air applications. In short: The reference SF_6 used by Stiller is the (past) tropospheric SF_6 while

our reference SF_6 is the depleted SF_6 in airmasses intruding from the mesosphere.
Beyond this, one result of our validation paper is that SF_6 contributes relatively little information. Therefore, inaccuracies due to the neglect of SF_6 sinks inside our analysis domain are not very relevant in quantitative terms.

Action: A clarifying sentence has been added.

Review: Line 78: Where did the data for OH, $O^1(D)$, and Cl come from? As I understand it, those JPL publications only contain reaction rate and cross-section information. Did you obtain that data from somewhere else (does MIPAS have those species?) or did you model those in some other way?

Reply: We estimate OH using the parametrization by Minschwaner et al. (Atmos. Chem. Phys. 11(3), 955-962, doi10.5194/acp-11-955-2011, 2011). $O^1(D)$ is estimated using the equilibrium equation 5.38 in Brasseur & Solomon (2005, Springer), applied to MIPAS ozone; Cl is estimated by interpolating a climatological noon profile (Brasseur & Solomon, 2005, Fig 5.50) to the actual atmospheric state. Inaccuracies in the latter are considered to be less important because the atomic Cl sink is of much less relevance than the other sinks.

Action: This missing information has been included in Section 2.1.2.

Review: Line 86: How necessary is the stabilization of the inversion, that mixing coefficients were assumed to be zero? Can you compute mixing coefficients for even a single pair of months, or perhaps for a pair of boreal summer and a pair of boreal winter months? Otherwise, it's difficult to say how the effective velocities compare to advective velocities.

Reply: We think that the effective velocities represent the essence of the Brewer-Dobson circulation in the sense that they conflate all the effects (advection, correlation effects, mixing) that bring, in a

2D world, a trace gas from here to there. From comparison with zonal mean advective velocities we can learn about the relative contribution of the non-advective terms.
Technically speaking, all monthly results are inferred independently. That is to say, the instability does not come from accumulation of errors over the months but is inherent in the analysis of each single month. The cause of the instability is the following: The system of equations solved tends towards linear dependencies as soon as velocities and mixing coefficients are to be retrieved simultaneously. The matrix to be inverted has an extremely high condition number. This can, in principle, be remedied by regularization. We found out, however, that in this case (contrary to the velocity-only analysis) the result depends strongly on the chosen regularization and is, thus, not robust. As a consequence, we have decided to constrain the mixing coefficients to zero and to re-interpret the resulting velocities as those 2D-velocities which best describe the combined effect of advection, eddy transport and eddy mixing. It cannot be expected that these effective velocities equal the zonal mean advective velocities.

Action: A clarifying sentence has been added.

Review: Line 88: What does the word “efficient” in ”efficient 2D circulation” mean? Do you mean effective? If not, the meaning should be clarified.

Reply: This is a wording error and should read ‘effective’ instead. Thanks for spotting!

Action: This wording error has been corrected.

Review: Line 89: I have never seen the term “Fickian mixing” before. Having done some searching, I think what you are referring to is more commonly called diffusion. If that’s the case, I would use that term. Otherwise, the meaning should be explained.

Reply: We intentionally avoid the term ‘diffusion’ in this context for the following reason: ‘Diffusion’ we understand is a physical process happening on a molecular scale. The processes we describe still abide to Fick's law of diffusion but are macroscopic processes. Thus we consider the term 'diffusion' in this context as misleading.

Action: We have added a footnote explaining the meaning of 'Fickian mixing'.

Review: Section 2.3: Why do you average every pair of months? I would guess that is due to interannual variability of the phase (and I use that word very loosely here, perhaps it would be better to say timing) of the circulation. Whatever the case is, it should be stated.

Reply: There seems to be a fundamental misunderstanding. We do not average over two months. The velocity field labelled, say, March-April, is the velocity field that best reproduces the change of the monthly mean March mixing ratio field to the monthly mean April mixing ratio field.

Action: We have added some clarification to avoid this misunderstanding. We think, however, that this clarification fits much better in the Section 'The General Approach' than here; thus we have included it there.

Review: Figures 1,2,3, and 4: I find these figures very difficult to interpret. First, the changing color scale does not seem necessary, as the maximum values do not vary strongly between the figures - most of them are around 11/12 - although it would create an issue for the December-January figure. At the moment, however, it is difficult to assess how the magnitude of the circulation changes at each point, month-to-month, except in the most starkly contrasting cases.

Reply: We do agree that the changing colour scales of the original submission were disadvantageous.

Action: New plots with fixed colour scales have been included.

Review: Second, it is difficult (if not for most cases pratically impossible) to obtain even a rough magnitude of the vector components because the color scale shows a norm of the vectors. I suggest using contours or heatmaps of the separate vector components instead.

Reply: The length and direction of the arrows represent the velocity components. The colour scale was meant just as an additional guide of the eye. The length units of the arrows are ad hoc, that is to say, they are not consistent with the ϕ and z axes intervals of the plots.

Action: The original data will be made available in digital form on tha data repository 'KITOpen', as described above.

Review: Third - and this has nothing to do with interpretation - you show the boundary velocities of these results although it is clear from CG16 that the vectors at the boundaries are difficult for the inverse model.

Reply: As already stated above, within the reply to the general comments, the problem at the boundaries is not a problem of the inversion scheme but a problem of inconsistent test data which represent non-realistic circulations where air accumulates at the boundary of the domain. By the way, the arrows in the boundary tiles refer to transport in the 80-90 degrees latitude band (and not to the 90 deg. latitude; i,e., we have no northward transport at the North pole.)

Action: None.

Review: Figures 5 and 6: These figures are unusual and require some considerable effort to comprehend. I assume the width versus height of the bubbles shows the stardard deviation in the meridional and vertical directions, and that the colors show the standard devation of the norm, but no information is given about that. I would suggest simply replacing these with contours and/or heat maps.

Reply: Agreed.

Action: We now show variabilities in v and w in separate figures.

Review: All figures: I suggest using a perceptually uniform colorscale, which makes viewing much easier for those who do not have a standard perception of color.

Reply: We have tried many different colour scales but the alternatives did not seem convincing to us.

Action: We now present the same plots in a different color scale in the supplement. Beyond this, we will make the original data available, thus the readers can plot then in their preferred representation.

Review: Line 133: I am not sure that I can agree that the vertical motion over this range creates a transport barrier. I would rather say it suggests one, at the most. But it could also be interpreted as a latitude (or a section of a latitude) where the circulation splits. In that case, there's not really a barrier to horizontal transport, but only relatively little forcing towards horizontal transport / a stronger forcing towards vertical transport. I'm not sure what the case truly is, but I dont think it's certain that this represents a barrier.

Reply: We will rephrase this sentence to avoid misunderstanding.

Action: We have rephrased lines 133-134 to: "The direct vertical motion over 30°S suggests the existence of a region where horizontal transport is minimal compared to vertical transport; the location of this region is in good agreement with the location of the subtropical transport barrier (e.g. Stiller et al., 2017)."

Review: Line 138: "would likely look" - I think it's highly likely, even, but no definitive statement can be made until the analysis is done. On that topic, I think that analysis would be very interesting for future work.

Reply: Agreed.

Action: We have reworded this: "Representation in equivalent latitudes would be more adequate to analyze this phenomenon but since that representation would not be optimal for global analyses, it is deferred to a future study."

Review: Line 142: You might consider showing the tropopause and stratopause levels in your figures. I think that would be very helpful, and could alleviate a lot of confusion.

Reply: Monthly averaged tropopause altitudes can be very misleading.

Action: none

Review: Line 150: It would be more useful to replace the values shown in Figures 5 and 6 with the values discussed in this sentence. That would be a more direct indication for the reader of where the circulation is consistent. Otherwise, they need to compare these values themselves, which is rather tedious if a thorough comparison is desired.

Reply: If we understand correctly, the reviewer recommends to present the ratio between variability and absolute velocity instead of the variabilities themselves. (in the sense "inferred velocities exceed their variabilities by a factor of ..."). We tried this but due to the often small velocities, this representation is not easy to interpret either. The plot would be dominated by large but meaningless ratios related to tiny velocities while regions of interest with large absolute variabilities would no longer be obvious. That is why we didn't choose this representation.

Action: none

Review: Line 189: Leaving aside the term "latitudinal barrier" (again, I am not sure how to distinguish between a barrier to latitudinal transport or a region of weak latitudinal transport), I do not see that agree that with the term

“contribute to the formation”.

Reply: We have rephrased this sentence.

Action: Lines 189-190 have been rewritten as “This feature will evolve in the following months as a region where uplift motion clearly overtakes horizontal transport around 60°N.”

Review: Line 234: I’ve mentioned this already, but I think this case shows clearly why the variability should be depicted in another way. It’s too difficult to compare the standard deviations here to the circulation strength, for the most part. But your argument does seem plausible.

Reply: We agree that this is difficult with the original plots.

Action: We now quote the numbers in the text and and rephrase to make it clearer that the figure illustrates our argument rather than quantify it.

Review: Line 237: It seems like you wanted to specify a figure in Ploeger et al. 2017. I suppose you mean Figure 5? You should specify the figure.

Reply: Agreed. Indeed we mean Figure 5.

Action: The Figure has been specified.

Review: Line 323: What is independent about the ANCISTRUS results?

Reply: ANCISTRUS results are independent from each other in the sense that the result of an ANCISTRUS run for one month is never used a first guess, a priori, or similar of an ACISTRUS run of another month. All ANCISTRUS runs can thus be performed independently, and any artificial autocorrelation of the results is thus excluded.

Action: We have slightly reworded this for clarity: “from the results of independent ANCISTRUS runs".

Review: Line 323: "resulting fields are stable" – The statement regarding field stability should be more nuanced. Some parts of the fields do seem to be stable, sure, but this statement suggests that the fields are generally/always consistent.

Reply: Agreed.

Action: This statement has been made more specific: "resulting fields are stable over the years of the MIPAS mission (2002–2012) in the sense that the annual variation of the resulting circulation patterns is large only in regions where one would expect large natural interannual variability.

Review: Line 324: "increases confidence in the robustness of the analysis method" - I do not agree. If the method is robust, then a rather stable circulation field over the approx. decade of measurements in one region would suggest that the circulation field is a typical phenomenon for that region, at least for that decade. However, the robustness of the inverese method cannot be assessed by seeing consistency in its results without a second point of reference (preferably, other observation-based circulation estimates, which - to my knowledge - do not exist).

Reply: Well, this depends what how the term 'robustness' is understood. We understand 'robustness' as the characteristic that the solution is not overly sensitive to varying input. We do not claim here to have shown that the method is accurate.
That is also why our initial wording was "increases confidence in the robustness" instead of "shows the results are robust".

Action: We have clarified what we mean: " The stability of results from independent ANCISTRUS runs increases confidence in the robustness of the analysis method in the sense that it produces similar results for similar input fields."

Review: Line 330: It's not clear to me if a clear separation between these two pathways would be expected or not. Could you provide any context on that, in terms of earlier literature?

Reply: Agreed

Action: we have inserted: "..., as suggested by the schematic shown in Fig. 1 of Boenisch et al. (2011)..."; Reference: Atmos. Chem. Phys. 11(8), 3937-3948, doi10.5194/acp-11-3937-2011, 2011),

Review: Line 333: "consistent with the assumption" - Has anyone previously suggested this idea, or are you saying that your results would only be consistent with a northward pole-to-pole circulation if it was above the domain of MIPAS? If nobody has suggested this, then this statement should be written differently to clarify the novelty of the result.

Reply: Well, we think that the existence of the pole-to-pole overturning circulation is well established. We see velocities going up in the north and downward velocities in the south, but the meridional velocities which would close this circulation are above our data domain. We neither claim to have found a novel circulation path nor do we refer to a specific assumption written in the literature. Thus our careful wording.

Action: We have rewritten this without the term 'assumption': "Our data are consistent with - but do not directly support - a southward pole to pole circulation from March to May at altitudes not covered by MIPAS data"

Review: Line 337: To my understanding, this intrepretation of the tropical pipe would be novel. I only wish to note that here.

Reply: Yes, indeed. We have intentionally chosen a very careful wording here ('suggests'...'may not be'...). We have now made the wording even more careful.

Action: We have changed the wording to “This seems to suggest that...not always...

Review: Line 341: This could be consistent with some earlier results. See Butchart 2014 (The Brewer-Dobson Circulation, Rev. Geophys.) Figure 6 and discussion of that figure. If mean downwelling during winters where the polar vortex is not disturbed is the same between both hemispheres, then one would expect stronger climatological descent in the southern hemisphere because the vortex is disturbed less often there.

Reply: We understand our (old) lines 340-341 as an introductory sentence for the five following more specific points. Thus the quite specific comment seems to refer to line 342 (#1 in the list) rather than to line 341. We have added a sentence there.

Action: We have added to #1: “This is consistent with stronger southern than northern polar winter subsidence which is associated with less perturbed polar vortices there (Butchart 2014, Section 5.1).” Reference: Rev. Geophys. 52(2), doi10.1002/2013RG000448, 157-184 (2014)

Review: Line 343: To my knowledge, this result is not expected.

Reply: Ok, we have now mentioned this.

Action: We have added: “To the best of our knowledge these altitude differences have not been reported before either.”

Review: Line 347: I’ve mentioned it already, but I do not think the term “barriers” is justified in this context.

Reply: Agreed

Action: We will replace the term ‘barriers’ by ‘areas with near zero ... velocities.’

Review: Line 348: Same to point 2.

Reply: agreed.

Action: We have added: "To the best of our knowledge this also has not been reported before."

Review: Line 364: In the broad stroke, I agree with this statement. However, the absence of a southward mesospheric overturning circulation means that this statement cannot be written in the absolute. Furthermore, the results do not characterize these patterns in an expected fashion (tropical pipe, for example). This statement should be rewritten to reflect those points.

Reply: The overturning circulation is not absent but just not covered by the MIPAS measurements. But we agree to reword our statement.

Action: We have rewritten: "The ANCISTRUS method applied to MIPAS data broadly reproduces well the known atmospheric meridional circulation patterns, although with some unexpected features. Additional information ..."

Review: Technical Comments

Review: Abstract, line 1: HCFC-22.

Reply: Thanks for spotting!

Action: Corrected.

Review: Line 14: The citation of Brewer and Dobson 1949 is incorrect. That's a single-author publication, just from Brewer.

Reply: Thanks for spotting!

Action: Corrected.

Review: Line 14: I think it's better to write abbreviations in a separate set of parentheses, just so it's clear that the abbreviation isn't some part of a citation.

Reply: This comment has become obsolete after rewriting in reply to a specific comment (see above).

Action: No additional action.

Review: Line 16: The last part of this sentence seems to suggest that only aerosols affect major chemistry-climate processes. It would be more clear with "as aerosols, all of which affect major chemistry".

Reply: Agreed.

Action: Rephrased as suggested.

Review: Line 19: This sentence is a bit of a run-on. It would be better to write one sentence for Engel's balloon studies and another for the satellite studies.

Reply: We agree that the original sentence was too long. We prefer, however, to split the sentence immediately after the Butchart reference.

Action: Will have changed this to "...Butchart et al. (2006). This triggered..."; Reference: Clim. Dyn. 27(7-8), 727-741, doi10.1007/s00382-006-0162-4 (2006).

Review: Line 22: "Offline model simulations ... analysis data have also confirmed ...", or add a comma after "Also".

Reply: Thanks!

Action: A comma has been inserted.

Review: Line 28: It looks like you meant to write "has been investigated" or something similar. At the moment, the sentence doesn't make sense.

Reply: Agreed.

Action: Corrected.

Review: Line 30: If Funke et al. (from all those years) showed this, then I would write "has been" not "could be".

Reply: Agreed.

Action: Corrected.

Review: Line 35: It would be more precise to simply say that the picture of the middle atmospheric circulation is better resolved in space and time, cutting out the "more detailed" part.

Reply: Agreed.

Action: Corrected.

Review: Line 38: The ending, "over the years", isn't necessary here.

Reply: We had added 'over the years' to make clear that we do not talk about the inter-annual, not the intra-annual (month to month) variability. We have now reworded this in a clearer, less clumsy way.

Action: 'over the years' has been deleted, and 'inter-annual' has been inserted before 'variability'.

Review: Line 46: I would say not just monthly but "monthly-mean". Furthermore, the sentence suggests that this is the only way to infer the circulation, so you should specify "is inferred in this work".

Reply: Agreed for “in this work”. The original text already reads “monthly zonal mean” and we think that it is clear that averaging was made in both domains.

Action: “in this work” has been added.

Review: Line 49: “The resulting circulation fields...”

Reply: Thanks!

Action: Corrected.

Review: Line 62: I don’t understand what “related software” refers to. That’s the inversion method, right?

Reply: Yes, it is.

Action: This has been reworded as suggested.

Review: Line 79: “source reactions were also considered”

Reply: Thanks for spotting!

Action: Corrected.

Review: Line 83: “the neglect of sinks above that altitude”

Reply: Thanks!

Action: Corrected.

Review: Line 91: See comment on line 14 about abbreviations.

Reply: As far as we know, our way to set the parentheses here is the one which complies with the COPERNICUS rules. I think here the copy editors will have the last word.

Action: None so far. We will wait what the copy editors say.

Review: Line 103: "From MIPAS, measurements"

Reply: MIPAS here is a sort of attribute or specifications. With the comma inserted, the meaning would change towards "measurements are calculated from MIPAS", which is not what we mean. We mean "...were calculated from MIPAS measurements..."

Action: None

Review: Line 104: You explained the data gaps in the last section.

Reply: Yes, indeed.

Action: we have included the 2006 data gap in line 95 and have reword here: "... with data gaps as reported above ."

Review: Line 116: "up to 30 km"

Reply: Agreed.

Action: Corrected.

Review: Line 123: move "also" from "also the standard..." to "are also shown"(...).

Reply: Thanks!

Action: Corrected.

Review: (...). Furthermore, it should be clear to all readers that standard deviations are a measure of variability, so the "which are a measure of their variability" is not necessary.

Reply: A standard deviation is a measure of the width of a distribution but it is not clear if it represents variability, uncertainty, probability, or other. In particular in our community, uncertainties and estimated errors are often reported in terms of standard deviation. Thus, we find it necessary to be specific here.

Action: The text has been reworded.

Review: Line 127: You can just say northern hemisphere or winter hemisphere.

Reply: Agreed.

Action: "local winter" has been deleted.

Review: Line 146: "has its maximum ... and at 30°S"

Reply: Agreed.

Action: This has been reworded as suggested.

Review: Line 155: You are clearly comparing this month-pair with the previous, but this sentence should make that explicit.

Reply: Agreed.

Action: "seen in January-February" has been inserted.

Review: Line 167: "will give rise"

Reply: Thanks!

Action: Corrected.

Review: Line 170: The abbreviation SH was already used before this point. The notification of the abbrevation should be shifted to the first usage of "southern hemisphere". Ditto for NH.

Reply: Thanks for spotting.

Action: Corrected.

Review: Line 379: "their figure" - This part of the sentence addresses a particular figure, but the earlier part speaks generally of schematics. I suggest sticking to one approach or the other.

Reply: Agreed.

Action: We have split the sentence to make clear what refers to such schematics in general and what refers to this particular figure.

Review #2:

Review: The authors present an estimate of meridional circulation patterns in the middle atmosphere based on measurements from 2002 though 2012 by the MIPAS instrument of a range of trace gas species. The estimate is based on an inverse method that infers an effective flow field in the meridional plane from the continuity equation along with an estimate of chemical sources and sinks. The methodology is updated from previous work by the first two authors through inclusion of further chemical sources and sinks, and by inferring only an 'effective' meridional flow that includes the effects of mixing/eddy transport.
The main results shown are the month by month estimates of the decadal-averaged meridional flow, as well as an estimate of the interannual variability of the flow. In as much as this estimate is a relatively direct observational estimate of a difficult to measure quantity, this result is of potential value to the broader community.

Reply: We thank the reviewer for this encouraging evaluation.

Action: None.

Review: My main concern is that if this is to be the case, enough quantitative details should be given in order to facilitate comparisons with these results; this is largely the case but there are a few ambiguities that should be addressed (see below).

Reply: Agreed.

Action: See specific actions below.

Review: Beyond this I have a few questions and comments about the presentation of these results (in particular I find the presentation of the interannual variability difficult to understand), but otherwise feel this is appropriate for publication with some minor revisions.

Reply: We agree that the presentation of the inter-annual variability was insufficiently explained. In reply to reviewer #1 we have decided to present the variabilities separately for vertical and horizontal effective velocities.

Action: See specific actions below.

Review: Specific comments
1) As mentioned above there are a few points that would be helpful for making quantitative comparisons with these results. Firstly, does the inferred circulation conserve mass?

Reply: Yes, it largely does, except for transport into and out of the model domain at the upper and lower boundary, which may not necessarily be balanced. But besides the continuity equation of species, also the continuity equation of air density is one of the determining equations of our system.

Action: None.

Review: If so the authors may want to consider showing a mass stream function instead of the vector plots.

Reply: Any representation which involves weighting by air density suffers from the large dynamical range of air density with altitude. We have tried various representations of this type but always all structure and information in the middle atmosphere was lost. Only values at the lowermost layer were discernable in such representations.

Action: None

Review: If not, the choice of units for Figs. 1 through 4 are a bit confusing; surely the velocities should be homogeneous in units (e.g. m/s)?

Reply: With homogeneous units the vertical velocities would be invisible, although important. The norm we use for the colour scale and for the direction of the arrows roughly corresponds to the aspect ratio of the plots where the vertical axis does not represent the true geometric conditions either but is heavily exaggerated.

Action: The original data will be made available in digital form. With this the user can represent the data in the preferred way, most suitable for the respective application. The original data are actually provided in units of m/s.

Review: The note regarding the colour scales in the Figures 5 and 6 show standard deviations of the inferred effective velocities, but the visualization is not explained.

Reply: The explanation was indeed missing in the original submission.

Action: In reply to Reviewer #1, the standard deviations will be represented as heat-maps.

Review: One assumes that the axes of the ellipses are scaled relative to the variance of the y and z components of the velocities but it seems no account is being taken of their covariance if that is the case. How are the colors chosen?

Reply: The axes of the ellipses represented the standard deviations in the the y and z components. The covariances were not represented. The colours had been chosen by adjusting the colour scale to the maximum value of the individual plot.

Action: We have decided to represent the variabilities in separate plots for v and w. A common colour scale is now used for the entire series of plots. Further, we mention that the same norm is applied to the standard deviations as for the effective velocities.

Review: More importantly, are these estimates of the standard deviation of the mean (implied by the figure caption) or sample standard deviations?

Reply: The title was indeed misleading. We present the sample standard deviations, not the standard error of the mean. This is because we are interested in the variability, not in the uncertainty. The standard error of the mean would become lower for a larger sample and is thus not the adequate measure.

Action: Titles in the plots have been corrected.

Review: In sum the interannual variability is difficult to assess in comparison to the mean circulation from these figures and is not very satisfyingly discussed in the text.

Reply: Agreed.

Action: New plots are now provided and adequately described.

Review 3) In all figures, different years are included in each panel with no discussion; why?

Reply: First we have some data gaps in the MIPAS data, and second, a (small) number of the inversions did not converge.

Action: This information is now provided in the figure caption.

Review: 4) The methodology used in the present work includes the role of chemical sources and sinks; this has been updated from von Clarmann and Grabowski (2016). The value of these updates should be demonstrated.

Reply: The impact is indeed substantial, and we are happy to show respective plots. However, we think that this fits in much better with the paper on validation and sensitivity studies discussed in reply to reviewer #1.

Action: This issue has been deferred to a validation paper of which the draft is made available to the reviewers, and reference to that paper together with a brief explanation has been included to the current manuscript.

Review: It would also be useful to make some assessment of

the role of mixing, again in order to facilitate quantitative comparisons with the mean meridional flow from models, for instance.

Reply: We agree that this is interesting, and we have actually submitted a research proposal which will tackle exactly this question. We think that this is a research topic in its own right and defer this to a future paper.

Action: none for this paper.

Review #3 (This reply refers to the uploaded comment, not to the comment sent to the editor. There are differences between these):

Review: In this paper, the authors use measurements of a variety of trace gases from MIPAS to infer the stratospheric and mesospheric circulation. They calculate a climatology and determine that the deep branch of the Brewer Dobson circulation is connected to the mesospheric pole-to-pole circulation. They verify a number of known characteristics of the circulation, such as sudden stratospheric warmings increasing variability.

Reply: We are happy that the reviewer confirms that the presented climatology verifies a number of characteristics of the BDC.

Action: None to this point.

Review: Using chemical tracers to infer the circulation is an excellent idea. Tracers are what we can measure from space, so to validate any model, we need to quantitatively relate the tracers to the dynamical output from climate models.

Reply: We agree that tracer measurements are essential for an empirical assessment of circulation. However, validating modelled tracer distributions is not enough, particularly if there are discrepancies between the model prediction and the observed atmospheric state. We are primarily studying the atmosphere but not (climate) models that try to reproduce the atmospheric processes correctly. Adjusting the models to the observed processes is a second, nevertheless necessary step that is, however, not our primary concern in this paper.

Action: None to this point.

Review: The inverse methods used here are promising. Unfortunately, the approach from the authors is lacking in a number of ways. 1) The validity of the method has not

been established.

Reply: Our method is clearly based on the established validity of the continuity equation. And as the Reviewer acknowledges here above the results we obtain successfully reproduce a number of BDC characteristics. In addition a validation paper has been submitted.

Action: None to this point. However, the validation of the algorithm has been described in a separate manuscript that has just been submitted to ACP; the manuscript number is acp-2020-72; see reply to reviewer #1.

Review: 2) Uncertainties are not calculated and [...],

Reply: Reviewer #1 has raised a similar concern before. We consider the estimated uncertainties as largely redundant. We present the variabilities of the results. These include both the precision of the results and the natural variability. The variance describing the precision of the results cannot be larger than the variance describing the variability of the results. Thus, our presented variabilities are an upper estimate of the precision of our method.

Action: See our related reply to Reviewer #1.

Review: perhaps most importantly, 3) The utility of the resulting product from the method is unclear.

Reply: The utility is that we provide an empirical diagnostic of the stratospheric circulation which does not suffer from the main drawbacks of either the direct comparison of modeled versus observed trace gas fields or the age-of-air based methods. While the former is very unspecific with respect to causes of discrepancies, the latter's drawbacks are the dependence of assumed age of air spectra and artificial overaging to unaccounted mesospheric sinks of tracers. Our results contain considerably more information than the trace gas fields and their variation with time, and they provide a better time-resolved understanding of the circulation than the age-of-air method (which integrates over the time an air parcel spent in the stratosphere).

Action: We have included a couple of sentences specifically stating the utility of our product and the capability of our method.

Review: The authors have not done any test that would demonstrate that this inversion does actually recover velocity fields in a model.

Reply: Any comparison with model results would suffer from the fact that in the case of discrepancies it is not clear if they are caused by a failure of the new method or the inadequacy of the model. Furthermore, the interpretation of 2D fields inferred from 3D model output depends on certain approximations (see Appendix of von Clarmann and Grabowski, Atmos. Chem. Phys. 16(22), 14563-14584, doi10.5194/acp-16-14563-2016", 2016). Nevertheless, we have tested in the validation paper mentioned how far velocity fields can be recovered by our inversion.

Action: Model recovery tests are included in a separate validation paper whose draft is available to the reviewers.

Review: The closest is a very idealized case in their 2016 paper and even in that case, idealized tracers are used instead of real tracers.

Reply: The idealization was made on purpose. Only in these simple cases it is possible to predict (without the help of another model) what the result should be, and to check if, e.g., the transport scheme does what it is supposed to do. In a simple test, with a constant velocity field of x degrees per month it is straight forward to check if a structure has actually moved by x degrees in a month; how the shape of the structure is conserved; what kinds of wiggles are created. With any close-to-realistic fields it is virtually impossible to judge if any wiggles are caused by diffusion or dispersion or are real phenomena. Also the over-exaggerated structures in the idealized test are, due to the large gradients in the fields, a particular challenge for the transport scheme, and can be considered almost as a worst case study. All methods used (the McCormack transport scheme, matrix inversion, etc) are well established methods.

For the transport medelling we consider tha tests presented in von Clarmann and Grabowski, 2016, as severe. The validation of the inversion scheme is included in the validation paper mentioned before.

Action: The validation paper with further validation test cases is made available to the reviewers.

Review: In order to use the method on data, essentially an entire separate modeling study needs to be performed: a) using a CCM, with full knowledge of the tracer fields used here, the inversion needs to be performed and compared to the model velocity and stream function.

Reply: We agree that such a modelling study is interesting, and it is actually under way. We object, however, that such a modelling study is the only possible approach to corroborate the validity of our scheme.

Action: Model recovery tests are included in the validation paper mentioned above.

Review: If this is successful, then the next step is: b) with the same CCM, the sampling characteristics of MIPAS (coverage and averaging kernels) need to be applied to the tracer fields so that now the limitations due to sampling and retrieval characteristics are applied. This seems especially important for vertical and horizontal resolution.

Reply: MIPAS provides dense sampling. Of course the sampling varies slightly from year to year. Still the year-to-year variability of the inferred circulation is quite small. If sampling was an issue, how can it be then explained, that in different years so similar circulation patterns are obtained?
By the way: Different standards seem to be applied to different methods. MIPAS sampling is dense, and we have representative zonal means. Other observational studies use single snapshots of the atmosphere obtained by balloon observations (e.g. Engel et al., Engel et al., 2009, 10.1038/ngeo388; cited approvingly by the reviewer) to infer the strength of the Brewer-Dobson circulation. What is the

purpose of applying such a different standard to different methods? The issue of vertical resolution and related implications have already been discussed and solved in von Clarmann and Grabowski, Atmos. Chem. Phys., 16, 14563-14584, Section 3.5.
Again, why is our work judged by a different standard than other work? We do not know any age-of-air related work where vertical resolution has been considered. In the work of the reviewer, quoted in her review, vertical resolution is not even mentioned. We expect our work to be judged by the same standards as previously published work on this field. This preaching-water-and-drinking-wine stance does not fit into a neutral review!

Planned Action: None to this point.

Review: Then the inversion needs to be done and compared once again to the model velocity and stream function output. This test will illuminate what the method actually means.

Reply: What the method actually means is quite clear: it provides the most possible direct observational access to the temporally and spatially resolved effective 2D circulation. The appendix of the paper explains how the same quantities shown in the paper can be derived from 3D model fields. This allows a direct comparison when a model validation is the topic of further work.

Action: see the discussion of the model recovery tests and the reply to reviewer #1.

Review: The errors caused by the method with full tracer fields and then with the limited sampling can then be characterized for the model as well, hopefully beginning to address point 2) above.

Reply: The sampling in one month over the years does vary. Still we get small standard deviations. This furnishes evidence that the method is not sensitive to MIPAS sampling issues.

Action: We have included this argument in the paper.

Review: This would also work towards addressing point 3) above. This "transport circulation" that the authors obtain is not obviously relevant. Without being able to meaningfully compare values to model output or reanalysis products, this quantity does not seem to be of interest,[...]

Reply: This is a presumptuous statement from a biased modeler's perspective. Our study does provide a new dataset based on observations to characterise atmospheric circulation processes, which will also additionally serve for model and reanalysis comparisons. The appendix of the paper explains how the same quantities as presented from observational data can be produced from model data or reanalyses. This allows a far more detailed comparison/model validation than age of air or the quantity "strength of the BDC". Since the BDC was posited to explain the effective transport of trace gases from low to high latitudes, our effective velocities capture the essence of the BDC, and every move towards quantities represented in 3D models would move away from this nature of the BDC. Actually the models fall short to predicting temporally and spatially resolved measures of the circulation which can be directly validated by observations. The stance that only observations which are related to model output are relevant is not tenable. Since Ian Hacking (1983, Representing and Intervening, Cambridge University Press) it is established that the task of observations goes beyond the mere verification of model predictions and that empirical science is a science in its own right.

Planned Action: None.

Review: [...] and so the authors claims of being able to assess quantitatively the variability of the circulation fall flat.

Reply: In the original paper this claim has not been made.In this paper we have focussed on the structures and the seasonal variations of these structures of the BDC. We would like to point out that between purely qualitative work and fully quantitative work, there is the wide field of work on structures (often ignored. Too many people misconceive qualitative vs. quantitative as a dichotomy!). Further, the conclusions of our paper do not depend on the absolute accuracies of the inferred effective velocities.

Planned Action: none

Review: In fact, this is the reason that age of air is such a useful tracer – it has been quantitatively related to the circulation of the stratosphere in a way that allows direct comparison of data (including the MIPAS data) to models (Linz et al. 2017).

Reply: The age of air cannot be directly observed, it must be inferred from tracer measurements. This inference of the age of air from tracer measurements is based on assumptions, some of which we challenge. The method we present in this paper does not make these assumptions. We do not state that age-of-air based methods are not useful or should not be used by models, but we have used age-of-air based methods long enough to know their weaknesses and to find legitimate to search for alternative methods which avoid some known weaknesses. And as said above, the quantities derived from observations in this paper can all be calculated from models and reanalyses as well, as described in the Appendix.

Planned Action: None.

Review: I would strongly encourage the authors to perform such a study and then to rethink their results for this work in the context of the information provided by their validation study. That would be an excellent paper that I would be truly excited to see.

Reply: A validation study (model recovery test) has been performed and the related paper has been submitted. This paper furnishes evidence that our method is robust enough for all the conclusions in the paper under discussion. For reasons discussed above, we do not consider a model-based validation study as the optimal approach.

Action: See reply to reviewer #1.

Review: Beyond this overall assessment, I have included more detailed comments below: 24: What about the lifting of the circulation? (e.g. Oberlander-Hayn 2016)

Reply: In our paper, we deal with the climatology of transport vectors and their year-to-year variability. Long-term trends as tackled in the Oberländer-Hayn et al. paper are beyond the scope of our paper.

Action: Nevertheless, we now mention their paper in the introduction.

Review: Overall introduction: What is the gap that this research is filling? The introduction reviews the literature but does not identify any motivation for the present study.

Reply: It does. The motivation is clearly stated in the sentence criticised before: "In this study we aim to provide a picture of the meridional middle atmospheric circulation (better resolved in space and time than that provided by age-of-air based methods.)"

Action: Included "(better resolved in space and time than that provided by age-of-air based methods.)"

Review: 2.1 This discussion of age of air is surprising. What is this so called "traditional observation-based characterization of the circulation"? The authors do not provide a citation.

Reply: The review paper by Waugh and Hall (Rev. Geophys. 40(4), doi10.1029/2000RG000101, 2002) gives an excellent introduction.

Action: We have included this reference.

Review: Some recent work that uses age of air observations to characterize the circulation is Linz et al. 2017. Recent work by Ray et al 2016 combines the TLP with chemistry

to examine transport, and the improvement this offers over that method should be addressed. Ray et al. 2010 is also a relevant comparison here.

Reply: Linz et al (10.1038/NGEO30132017, 2017) have characterized the BDC by a single profile. Ray et al. (10.1029/2010JD014206, 2010 and 10.1002/2015JD024447, 2016) introduce the leaky pipe model to explain age of air, ozone, CFCs, and their trends. However, since we do not deal with age of air in this paper, we do not see how these papers are related to our work. The reviewer seems to assume that we are not familiar with the current literature and the approaches used so far. We wish to state that the contrary is true, and our previous work with age of air has made us aware of the weaknesses of this approach and the need to find an improved observation-based access to the BDC.

Action: None.

Review: Furthermore, it is not clear how the method can reveal causes of "discrepancies" between these age and chemical tracer based methods since there are no error estimates.

Reply: The standard deviations representing the precision are by definition smaller than the standard deviations that we show. Thus the standard deviations can serve as upper estimates of the random errors of each monthly field. The uncertainty of the average over the years is accordingly smaller. The rationale behind our claim that our quantities are better suited to determine causes of discrepancies than age of air is fairly trivial. If, say, in the polar stratosphere there is a discrepancy, we still do not know when (since the air entered the stratosphere) or where (along the trajectory of the air parcel) the discrepancy was caused. Our method provides quantities that are resolved latitudinally, vertically and temporally. Thus a much clearer idea can be developed where the model world and the observational world begin to diverge. This is exactly where our method provides an advantage over the age-of-air based methods.

Action: see reply to reviewer #1

Review: 2.1.2 There is no discussion of degrees of freedom. How much independent information is gained by including additional tracers?

Reply: Tests have been shown that inclusion of further species predominantly reduce the error estimates. This effect is seen even in cases where the resulting circulation does not change. For more details, see response to Reviewer #1.

Action: see validation paper.

Review: Specifically, how are sinks included?

Reply: This is described in Section 2.1.2.

Action: Some clarifying amendments as requested by reviewer #1 have been included in the description of the sinks.

Review: 3.1: Plots are very hard to understand. Streamfunctions would be much better.

Reply: We concede that the changing colour scales between the panels of a figure were not optimal. To better serve the needs of the data users, we make the data available in digital form. Then every user can represent the data in their favourite way. Our vector representation offers the advantage that it can directly be compared to the often reproduced schematic by Boenisch et al.

Action: Colour scales have been homogenized.

Review: 3.1.1 How are horizontal transport barriers identified? Why, physically, are they associated with this vertical motion? Is this purely a result of continuity and the fact that this is a 2-D calculation? If so, this should not be referred to as a barrier.

Reply: We have identified horizontal transport barriers as consecutive latitude/altitude bins where the meridional transport velocity is zero, while meridional transport vectors point in opposite directions in the two meridionally adjacent bins. We agree with Reviewer #1 that this might indeed just identify a splitting or bifurcation and that our wording needed editing.

Action: We have rephrased lines 133-134 as specified in reply to reviewer #1.

Review: 3.1.6 How precisely do you identify that this circulation is associated with the monsoon? Are there particular tracers (e.g. water vapor) that mark this as a monsoon signal? Or is it just about the timing and the fact that it's in the Northern Hemisphere, in which case the link is suggested at best. "Our results show overall agreement with the one shown by Ploeger et al. (2017)[...].";

Reply: Indeed it is the timing, the altitude range and the fact that it appears in the NH only, that we link this to the monsoon.

Action: We have edited the main text to make this clearer.

Review: What "one"?

Reply: Their Fig. 5

Action: see reply to reviewer #1.

Review: What is meant by "overall agreement"?

Reply: We mean agreement related to the structures.

Action: We have changed this to "agreement [...] with respect to the circulation structures."

Review: 3.2.1 337: What is meant by this? How does this reconcile with the well-established water vapor tape recorder results?

Reply: We concede that our wording may lead to misunderstanding.

Action: We have reworded this statement.

Review: 368-374: This seems to be saying that this study is a good validation of the method. That may be, but it's not the stated goal, and more stringent validation is needed especially so as to be able to actually interpret the resulting "effective velocities".

Reply: We think that these indicators of robustness are an important piece of information. They are by no means obsolete, even with a model recovery test in place. The validation will be published in a separate paper.

Action: Model recovery tests have been performed and the related paper has been submitted to ACP. The manuscript is be made available to the reviewers.

Review: 384: What applications would use these effective velocities?

Reply: The Brewer-Dobson circulation explains large ozone amounts over the poles while ozone is predominantly generated at low latitudes. In other words, it uses the effective 2D transport as an explanation of the trace gas distributions in the stratosphere. Thus, the effective 2D transport velocities are the natural measure of the BDC because they directly capture the essence of the BDC.
Further, these effective velocities can be understood as inverse age increments per segment of a mean trajectory. They can thus be related to the age of air but are time-resolved. The effective velocities are an empirical diagnostic in their own right. And in the appendix we relate them to the usual model quantities. Review #2 provides evidence that a significant part of the community regards this quantity as useful.
Regardless if models are able to produce such quantities or not, we think that we can learn a lot from them: Trends, variabilities etc. In this first scientific application paper we have restricted ourselves to climatologies, because these depend less on quantitative valida-

tion. The observed transport patterns and their variation contain a wealth of information in a structural sense even if one is sceptical about the associated numbers.

Action: Some sentences on possible future work have been included.

Manuscript prepared for Atmos. Chem. Phys.
with version 2015/04/24 7.83 Copernicus papers of the LaTeX class copernicus.cls.
Date: 12 February 2020

An observation-based climatology of middle atmospheric meridional circulation

Thomas von Clarmann[1], Udo Grabowski[1], Gabriele P. Stiller[1], Beatriz M. Monge-Sanz[2,3], Norbert Glatthor[1], and Sylvia Kellmann[1]

[1]Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Karlsruhe, Germany
[2]University of Reading, Department of Meteorology, Reading, UK
[3]Now at Physics Department, University of Oxford

Correspondence to: T. von Clarmann (thomas.clarmann@kit.edu)

Abstract. Measurements of long-lived trace gases (SF_6, CFC-11, CFC-12, ~~HCFC-12~~HCFC-22, CCl_4, N_2O, CH_4, H_2O, and CO) performed with the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) have been used to infer the stratospheric and mesospheric meridional circulation. The MIPAS data set covers the time period from July 2002 to April 2012. The method used for this purpose was the direct inversion of the two-dimensional continuity equation. Monthly climatologies of circulation fields are presented along with their variabilities. Stratospheric circulation is found to be highly variable over the year, with a quite robust annual cycle. The new method allows to track the evolution of various circulation patterns over the year in more detail than before. The deep branch of the Brewer-Dobson circulation and the mesospheric overturning pole-to-pole circulation are not separate but intertwined phenomena. The latitude of stratospheric uplift in the middle and upper stratosphere is found to be quite variable and is not always found at equatorial latitudes. The usual schematic of stratospheric circulation with the deep and the shallow branch of the Brewer-Dobson circulation and the mesospheric overturning circulation is an idealization which best describes the observed atmosphere around Equinox. Sudden stratospheric warmings cause increased ~~year-to year variability~~ year-to-year variability of the vertical component of the circulation.

1 Introduction

The meridional circulation of the stratosphere was discovered by Brewer (1949) and Dobson (1956) and is called ‘Brewer-Dobson circulation~~(BDC, Brewer 1949; Dobson 1956) , with~~’ (BDC) today. With its lower and upper branch as well as the mesospheric overturning circulation, it is the major transport pattern in the ~~stratosphere~~middle atmosphere (Butchart, 2014). As such it governs the distribution of atmospheric constituents in the stratosphere. The BDC therefore controls the distribution of radiative gases, such as ozone and water vapour, as well as aerosols, ~~affecting~~ all of which affect major chemistry-climate processes (Dunkerton, 1978; Plumb, 2002).

Possible changes in the intensity of the BDC as a consequence of climate change have been proposed by, e.g., Butchart et al. (2006)~~and~~. This triggered observation-based studies by Engel et al. (2009), using balloon-borne observations, and Stiller et al. (2012b), as well as Haenel et al. (2015), using satellite data. These studies based on satellite data suggest that the true picture of middle atmospheric circulation is ~~far~~ more detailed and ~~far~~ too complicated to be characterized ~~merely~~ by a scalar intensity of the circulation. Also, offline model simulations driven by ERA-Interim analysis data confirmed this heterogeneous picture for the stratosphere (Diallo et al., 2012; Monge-Sanz et al., 2012; Ploeger et al., 2015b). A shift of the entire circulation pattern by 5° to the South below 800 K and a widening of the tropical pipe above that altitude have been detected by Stiller et al. (2017).

The relative importance of transport versus mixing has been investigated by, e.g., Garny et al. (2014) or Ploeger et al. (2015a). Structural changes of the BDC and evidence of a transition branch situated below the shallow branch have been reported by Lin and Fu (2013) and Diallo et al. (2019). (Oberländer-Hayn et al., 2016)derived an upward shift of the BDC from model simulations and concluded that it could explain the apparent acceleration of the BDC in models.

The polar winter downward branch of the mesospheric overturning circulation which brings large amounts of mesospheric NO_x-rich air down into the stratosphere where it participates in ozone chemistry has been ~~analyzed~~ investigated in depth by, e.g., Funke et al. (2005). It ~~could be~~ has been shown that the NO_x flux into the stratosphere depends both on the thermospheric source strength which depends largely on solar particle precipitation and the strength of subsidence of air into the stratosphere in the polar winter vortex (Funke et al., 2008, 2011, 2014b, a, 2017). In this context, major stratospheric warmings play an essential role and are coupled with the lower atmosphere (Funke et al., 2010). Perturbations of stratospheric composition by downward transport of air into the middle atmosphere have also been investigated by Smith et al. (2011).

While the direct comparison of modelled trace gas fields with measured ones is very unspecific with respect to causes of discrepancies, the drawbacks of age-of-air based methods are the dependence on assumed age of air spectra and artificial overaging to unaccounted mesospheric sinks of tracers. Our results contain considerably more information than the trace gas fields and their variation with time, and they provide a better time-resolved understanding of the circulation than the age-of-air method (which integrates over the time an air parcel spent in the stratosphere).

In this study we aim to provide a ~~more detailed~~ picture of the meridional middle atmospheric circulation better resolved in space and time than that provided by age-of-air based methods. For this purpose, we infer circulation vectors from measurements of long-lived trace gases from July 2002 to April 2012 obtained with the Michelson Interferometer for Passive Atmospheric Sounding

(MIPAS, Fischer et al. 2008). From these we calculate a climatology[1] of the circulation in terms of multi-annual monthly means along with their ~~variability over the years~~inter-annual variability.

First we present the methods and data sets used for our analysis (Section 2). This includes a description of the method of the direct inversion of the continuity equation (Section 2.1), of the trace gas data sets used (Section 2.2) ~~,~~ and our scheme to calculate climatologies from the monthly circulation patterns (Section 2.3). Our derived climatologies of middle atmospheric circulation are discussed along with related variabilities in Section 3. Finally, in Section 4, we summarize our results, draw conclusions on their plausibility, and identify possible future work.

2 Method and Data

Stratospheric circulation is inferred in this work from monthly zonal mean mixing ratio distributions of long-lived tracers by the direct inversion of the continuity equation, using the method by von Clarmann and Grabowski (2016). Zonal mean volume mixing ratio fields are calculated from global trace gas distributions retrieved from limb emission spectra measured with MIPAS. ~~Resulting~~ The resulting circulation fields are analyzed in terms of first and second moment statistics to provide a climatology of the middle atmospheric circulation.

2.1 The Direct Inversion of the Continuity Equation

The direct inversion of the continuity equation uses the scheme developed by von Clarmann and Grabowski (2016). This approach avoids certain limitations associated with the traditional observation-based characterization of the circulation via the mean age of stratospheric air. These are: (a) no age spectra (Andrews et al., 1999; Waugh and Hall, 2002) are required; (b) the so-called 'over-aging' due to subsidence of mesospheric air depleted in tracer concentrations (Stiller et al., 2012b; Reddmann et al., 2001; Ray et al., 2017) does not bias the analysis because observation-based upper boundary mixing ratios of these gases are used~~, and~~. Any calculation of mixing ratio gradients relies on measurements of air already depleted in SF_6 and no direct reference is made to undepleted tropospheric air. And (c) we provide circulation fields resolved in space and time. By doing so we can trace back the causes of possible discrepancies between model data and observation-based data better than with the age-based method. The observational information provided by the age-of-air method is only available as the integrated travel time of the air parcel since it entered the stratosphere.

[1]Conceding that ten years is often not considered as a climatologically relevant period of time, we still call these multi-year monthly mean circulation patterns 'climatologies', mainly in order to distinguish them from 'monthly means' which commonly are understood to refer to a specific year, as compiled, e.g., by the SPARC Data Initiative by Hegglin and Tegtmeier (2011); Hegglin et al. (2013); Hegglin and Tegtmeier (2017) or Tegtmeier et al. (2013, 2016). Doing this, we use the term 'climatology' in its widest sense.

In the next subsection we shortly summarize the basic rationale behind this approach. Thereafter, updates of the related ~~software~~ inversion method (Analysis of Stratospheric Circulation Using Spectroscopic Measurements, ANCISTRUS) are described.

2.1.1 The General Approach

The prognostic formulation of the continuity equation allows to predict later trace gas and air density distributions when their initial values as well as the velocities, mixing coefficients and source/sink terms are known. We invert this equation to obtain velocities and (optionally) mixing coefficients from given air density and trace gas distributions at different times. For this purpose, first the prediction step is formalized, using a matrix which contains the partial derivatives of the later atmospheric state with respect to the initial atmospheric state. From this we calculate the Jacobian containing the partial derivatives of the final atmospheric state with respect to the velocities and mixing coefficients. A constrained inversion of the prognostic equation involving the latter Jacobian finally gives the field of velocities and mixing coefficients.

For example, we use a monthly mean mixing ratio fields of March in a certain year, solve the prognostic form of the continuity equation for an initially guessed velocity field to calculate the expected mixing ratio fields for April. The residual between the measured mixing ratio fields for April and the predicted one contains the information needed to adjust the velocity field. This process ist started with all-zero velocity fields and iterated until convergence. The finally resulting velocity field is then labelled ‘March-April’.

Since, due to correlation of velocities and atmospheric composition, inferred velocities are not the zonally averaged velocities but include eddy transport effects, we call the inferred velocities ‘effective velocities’. For further details, see von Clarmann and Grabowski (2016), and Appendix A.

2.1.2 Recent Updates and Current Setup

The major amendment to the code since von Clarmann and Grabowski (2016) has been the inclusion of sinks of CCl_4, CFC-11, CFC-12, CH_4, CO, HCFC-22, H_2O and N_2O. For each month, latitude band and altitude a chemical box model has been run to calculate which fraction of the initial concentration was still present after one month. The following sink reactions were considered: Photolysis with TUV-based photolysis rates (Madronich and Flocke, 1998), ~~and~~ as well as reactions with OH, $O(^1D)$, and atomic chlorine (Sander et al., 2010). The OH concentrations were estimated using the parametrization scheme suggested by Minschwaner et al. (2011). $O^1(D)$ mixing ratios were estimated using the equilibrium (Equation 5.38 in Brasseur and Solomon 2005), applied to MIPAS ozone. Atomic chlorine was estimated by application of a diurnal cycle to the noon profile shown in Figure 5.50 in Brasseur and Solomon 2005. Inaccuracies in the latter estimates are deemed tolerable due to the minor relevance of the Cl sink compared to the other sinks.

For H_2O and CO also source reactions were also considered, namely methane oxidation and photolysis of CO_2, respectively. In cases where these source reactions outweigh the sinks, the monthly survival rate can be larger than unity. These box model calculations were performed offline and results were tabulated, allowing the ANCISTRUS code to operate with reasonably large time steps. For SF_6, no sinks were considered. Since values at the upper boundary are prescribed using MIPAS measurements, the neglect of sinks above that altitude will not cause artificial 'over-aging' as described by Stiller et al. (2012b). The relevance of the inclusion of sinks and sources is demonstrated in von Clarmann and Grabowski (2020, submitted to Atmos. Chem. Phys.).

While in principle ANCISTRUS is designed to infer both effective 2D velocities and mixing coefficients, in the current version a regularization has been chosen to impose the mixing coefficients to be zero. This choice stabilizes the inversion although it does not provide full information on how mixing propagates onto the velocities. Thus the derived velocities have to be understood as the efficient effective 2D circulation velocities which best describe the redistribution of trace species, under the constraint that Fickian mixing[2] makes no contribution.

The ANCISTRUS method has been validated by von Clarmann and Grabowski (2020, submitted to Atmos. Chem. Phys.). The validation study has shown that below 30 km altitude, results are robust even in a quantitative sense. Above, where less reliable measurement information is available, all structures and patterns are still reliably reproduced. Peak velocities, however, are not always reproduced accurately. They are more frequently underestimated than overestimated. The latter effect is attributed to the regularization of the inversion. In no case, the inversion procedure generated artificial circulation patterns which were not present in the reference data. The method proved to be sufficiently robust with respect to missing input data. That is to say, effective velocity differences between a full ANCISTRUS run and a run with information on one particular species missing were considerably smaller than the effective velocities retrieved with a full ANCISTRUS run. For the purpose of this paper, ANCISTRUS proved to be an adequate tool.

2.2 MIPAS

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS; Fischer et al. 2008) is a Fourier transform infrared limb emission spectrometer on Envisat. The sun-synchronous polar orbit of the satellite, with an inclination of about 98.5°, allowed global measurements of trace gases with dense coverage. MIPAS was operational from July 2002 to April 2012, with some sizeable data gaps in 2004 and 2005. to 2006. Due to a failure of the interferometer mirror slide in 2004, operation at high spectral resolution was stopped in March 2004. In January 2005 operation was resumed, however at degraded spectral resolution. This went along with an improvement of spatial sampling.

[2] We use the term 'Fickian mixing' for any mixing which abides to Fick's law of diffusion. While 'diffusion' (without further qualification) is often understood as a physical process on a molecular scale, Fick's law is also applicable to some macroscopic processes. For this reason we think that the term 'Fickian mixing' is more adequate in this context than 'diffusion'.

The altitude coverage of useable tangent altitudes in the nominal measurement mode of MIPAS ranges from cloud top altitude to the middle mesosphere. Data products relevant to this study are temperature and H_2O (von Clarmann et al., 2003, 2009), CH_4 and N_2O (Plieninger et al., 2015), CFC-11, CFC-12 (Kellmann et al., 2012), HCFC-22 (Chirkov et al., 2016), CCl_4 (Eckert et al., 2017), SF_6 (Stiller et al., 2012b; Haenel et al., 2015), and CO Funke et al. (2009). The products have been widely validated, e.g., by Stiller et al. (2012a); Plieninger et al. (2016); Eckert et al. (2016), just to name a few.

2.3 The Climatology of middle atmospheric meridional circulation

From MIPAS measurements of the considered trace species, monthly zonal mean distributions were calculated for latitude/altitude bins of 6°/3 km. Monthly distributions were available from July 2002 to April 2012 with data gaps ~~in 2004, 2005 and 2006.~~ as reported above. Therefore, the velocity field of each month is constructed from its own set of years of available data. For each pair of subsequent months, two-dimensional circulation fields were calculated, using the ANCISTRUS-tool described above. This resulted in 89 circulation fields, the first representing August to September 2002, the latest March to April 2012. Then, all ~~January-February~~ January to February fields were averaged, all ~~February-March~~ February to March fields, etc., to form the 12-monthly climatology.

The use of language is not uniform in the community. For the description of the figures, we use the following terminology: The 'overturning circulation' we understand is the mesospheric pole to pole circulation, consisting of one single rotation cell and mainly driven by gravity wave breaking (Plumb, 2002; Dunkerton, 1978).

The 'deep branch of the BDC' is the circulation from the equator to the poles in the middle/upper stratosphere with uplift in the tropics and subsidence over the poles, (Plumb, 2002; Birner and Bönisch, 2011; Bönisch et al., 2011). For the transport pattern from the tropics to midlatitudes in the lower stratosphere we use the term 'shallow branch of the BDC'.

3 Results

Figures 1–2[3] show the resulting circulation fields in the full altitude range from 6 to 68 km. We also show the circulation patterns ~~only for altitudes~~ for altitudes up to 30 km only (Figs. 3–4), where the reduced altitude range along with the reduced maximum velocities allows to better resolve the smaller effective velocities found in the UTLS and troposphere.

Since these monthly circulation patterns are built from averages covering the period August 2002 to April 2012, the following characteristic has to be kept in mind when interpreting these results. A strong circulation feature which appears in every year but not always exactly at the same latitude,

[3] In the supplement, all figures of this paper are reproduced with a colour scale that is better legible for readers with a non-standard colour perception.

altitude, or time appears weaker in these climatologies. Conversely, a weaker pattern, which appears every year at the same latitude, altitude, or time will appear stronger.

To diagnose this effect, ~~also~~ the standard deviations of the components of the circulation vectors, which are a measure of their variability, are ~~shown~~ also shown for meridional and vertical effective velocities, respectively, in Figs. ~~??~~5–~~??~~6 for January to June, and in Figs. 7–8 July to December. These variabilities are caused both by the natural variability of the circulation over the years and its random uncertainty. The latter is the random uncertainty of the MIPAS measurements propagated onto the circulation vectors.

3.1 An average year of middle atmospheric circulation

3.1.1 January-February

The circulation pattern inferred from the change of trace gas distributions from January to February shows two major circulation cells with opposite rotation (Fig. 1, upper left panel). In the Northern ~~, local winter, hemisphere~~ hemisphere (NH) there is strong transport from the Southern tropics (up to 30°S) to the Northern subarctic latitudes, with maximum effective velocities in the upper stratosphere, between 40 and 45 km altitude. This can be associated with the upper branch of the BDC. Separated by a local minimum of effective velocities at 30 km altitude, there is a further branch of the Brewer-Dobson circulation in the lower to middle stratosphere. While its velocities and vertical extension are smaller, its contribution to the airmasses transported to higher latitudes is still significant due to the larger air density at these lower altitudes. The direct vertical motion over 30°S ~~creates a sort of transport barrier to horizontal circulation for the 30-55 km altitude range.~~

suggests the existence of a region where horizontal transport is minimal compared to vertical transport; the location of this region is in good agreement with the location of the subtropical transport barrier (e.g., Stiller et al., 2017). Above 50 km at Northern polar latitudes there is some subsidence. Associated year-to-year variability in vertical effective velocities is large, reflecting the irregular appearance of sudden stratospheric warmings (~~Figure ??~~Fig. 6, upper left panel). In the middle and lower Northern polar stratosphere there is no clear signal of subsidence. This can be explained by the fact that the northern polar vortex is known to be regularly displaced from the pole, which causes subsidence effects to be averaged out when latitudinal averages are considered. ~~In equivalent latitudes this would look different but this~~ Representation in equivalent latitudes would be more adequate to analyze this phenomenon but since that representation would not be optimal for global analyses, it is deferred to a future study.

At the same time, we find in the ~~SH~~ Southern hemisphere (SH) a region of southward/poleward transport around 60 km altitude starting around 30°S, and subsidence over high Southern latitudes in the mesosphere and upper stratosphere. It would be bold to associate it with the Brewer-Dobson circulation, because measured temperature profiles suggest that the stratopause during this time is

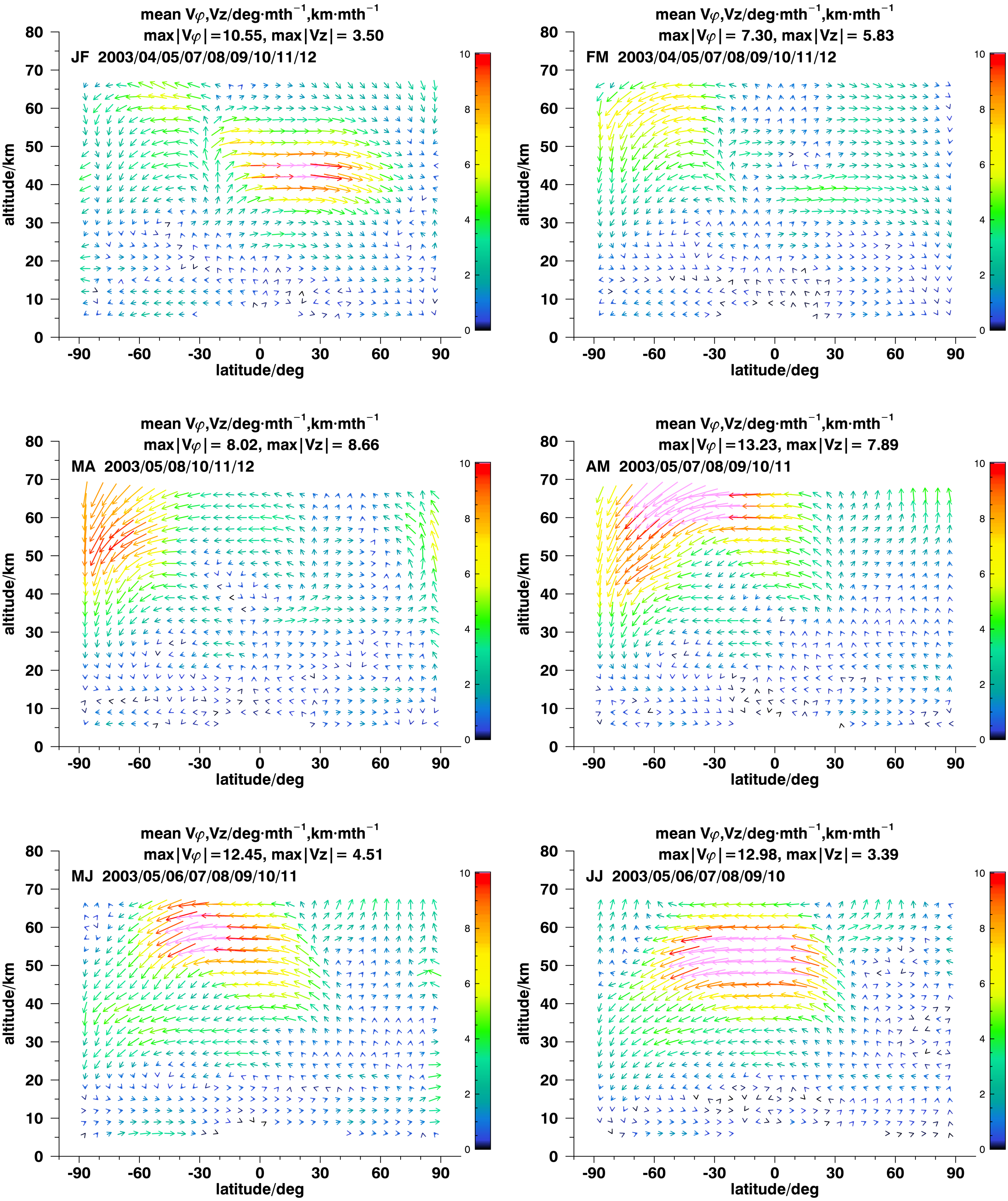

Figure 1. : Mean monthly circulation patterns from January–February (top left, JF) to June–July (bottom right, JJ). The headers give quantitative information about maximal effective velocities, the months and years considered. ~~Note the different colour scales of the plots~~Missing years are due to MIPAS data gaps and non-converged inversions. Missing species are indicated. The colour scales refer to $\sqrt{(v_\phi \mathrm{deg}^{-1}\mathrm{mth})^2 + (v_z \mathrm{km}^{-1}\mathrm{mth})^2}$ for v_ϕ and v_z in units of deg mth^{-1} and km mth^{-1}. Pink arrows refer to velocities higher than representable by the colour scale chosen.

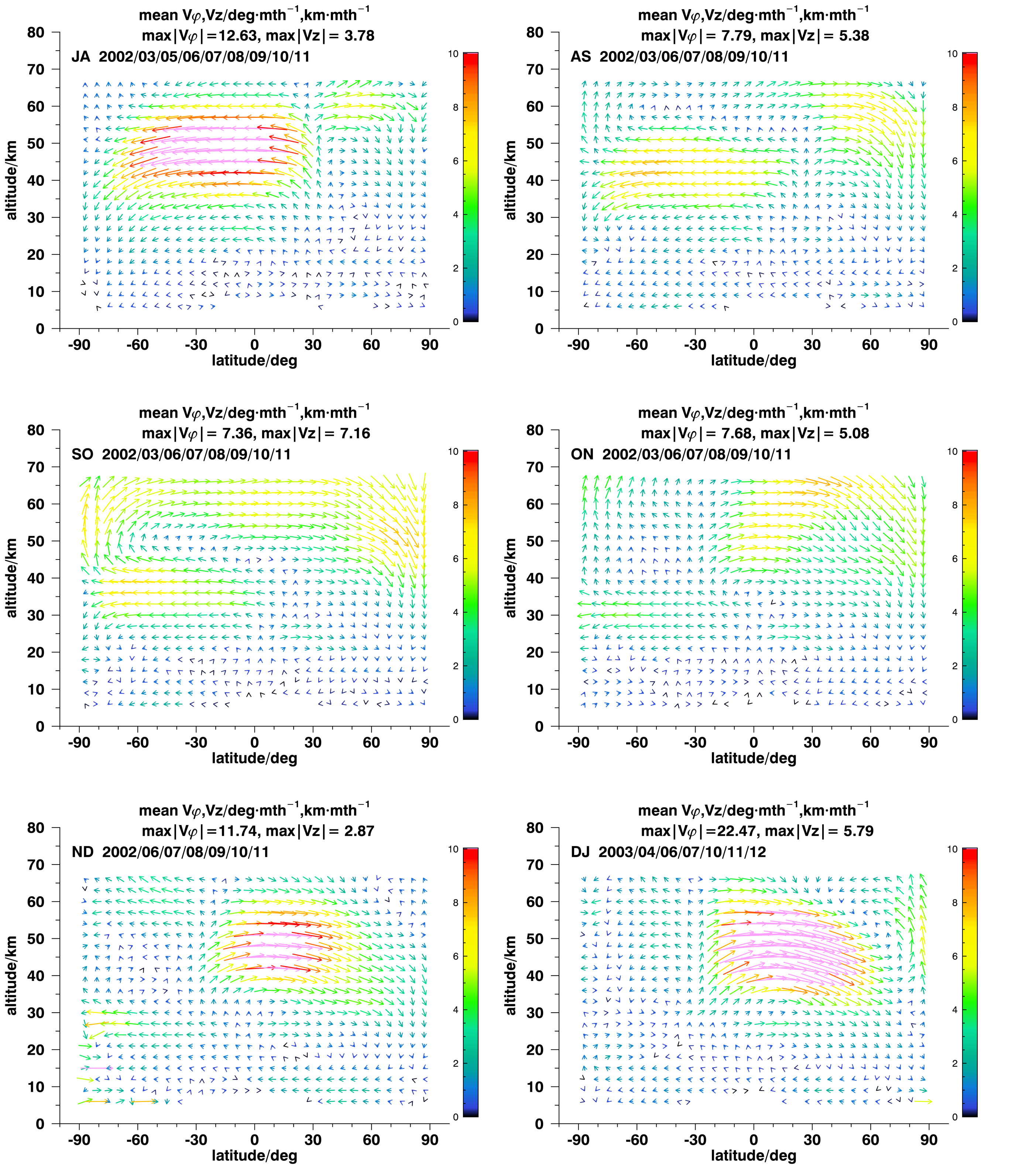

Figure 2. : Mean monthly circulation patterns from July–August (top left, JA) to December-January (bottom right, DJ). For details, see Fig. 1.

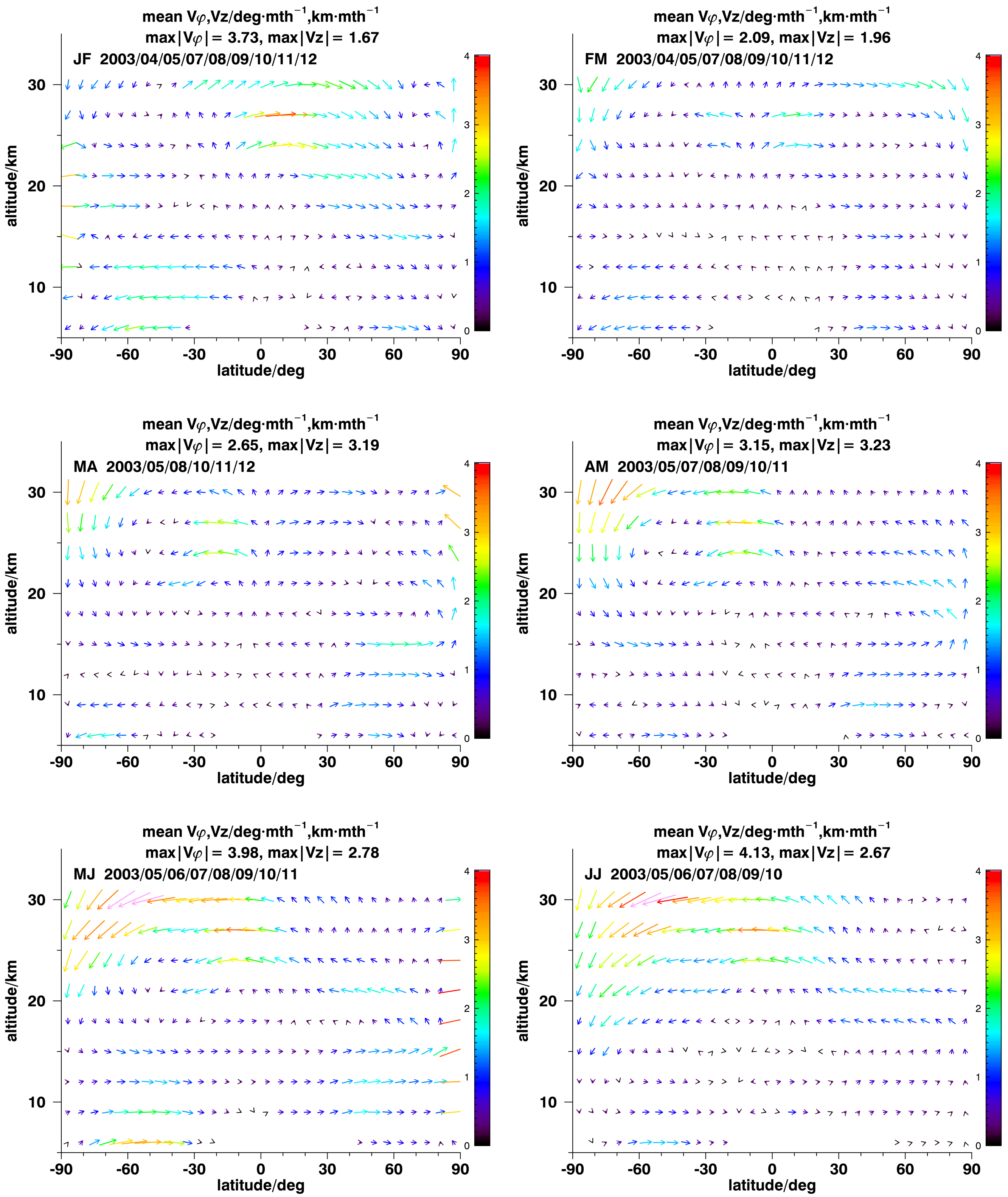

Figure 3. : Same as Fig. 1 but for altitudes up to 30 km only.

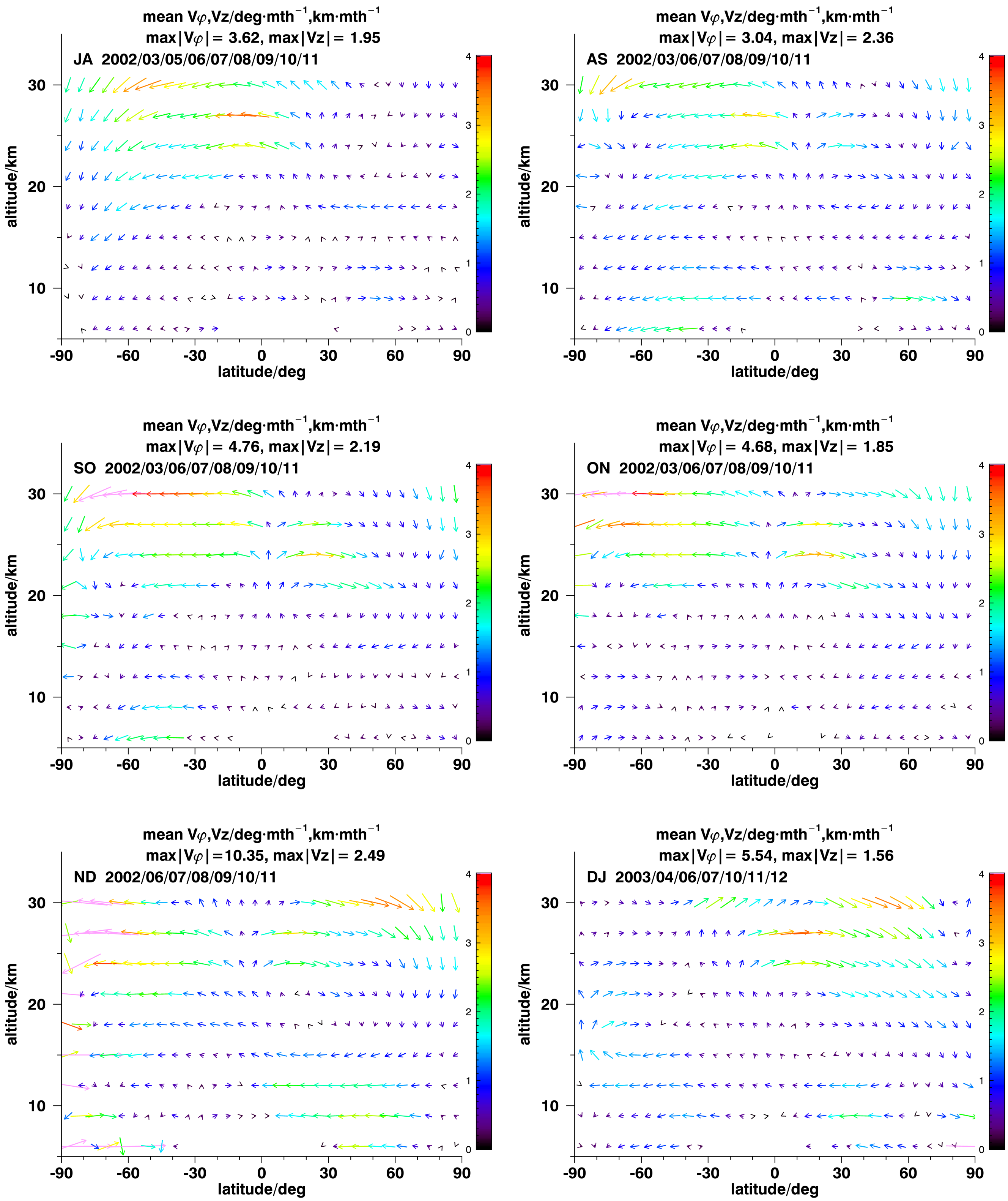

Figure 4. : Same as Fig. 2 but for altitudes up to 30 km only.

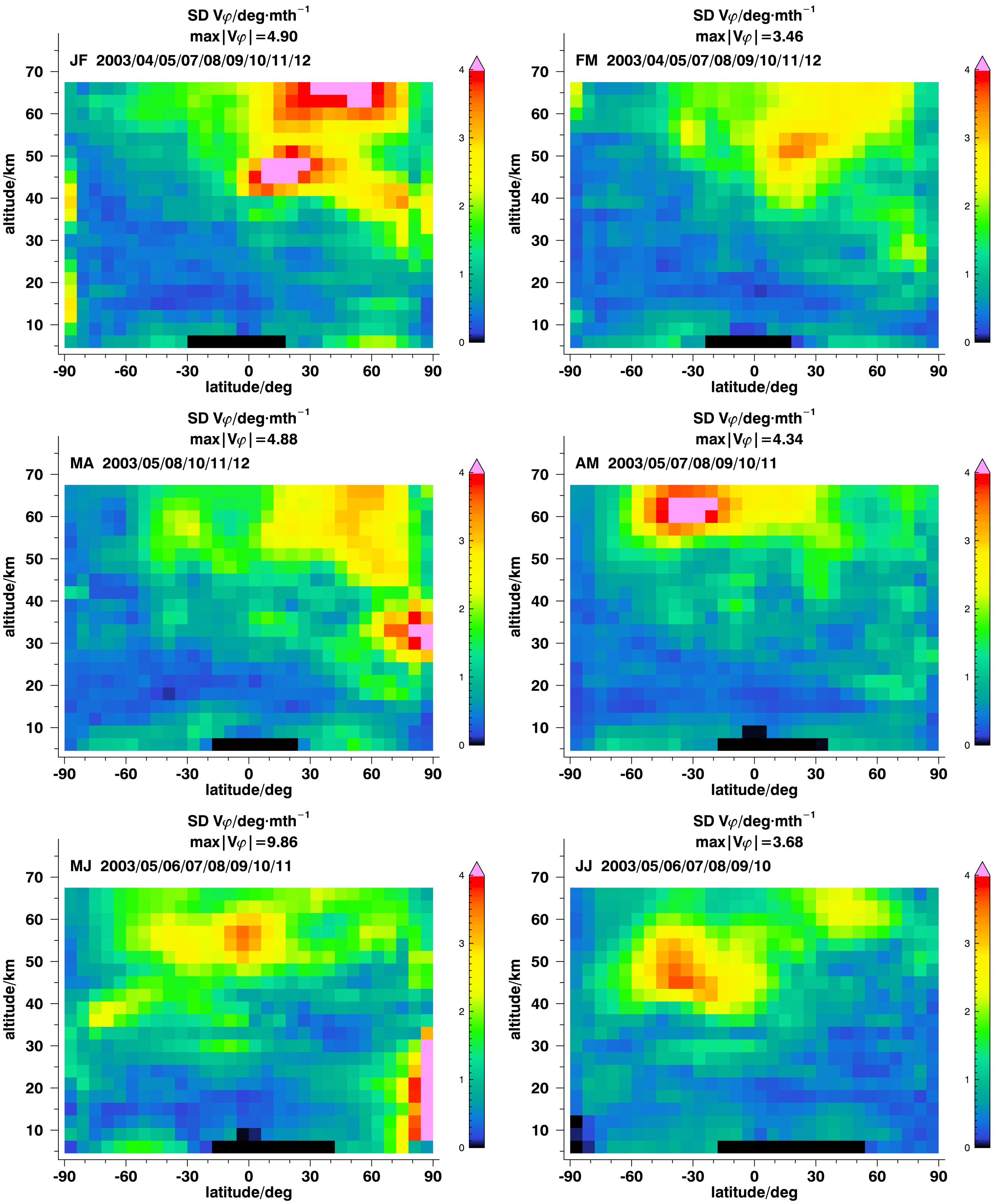

Figure 5. : Inter-annual variability of the middle atmospheric ~~circulation~~ meridional effective velocities in terms of sample standard ~~variations~~ deviations from January–February (top left, JF) to June–July (bottom right, JJ).~~For details, see Fig. ??~~

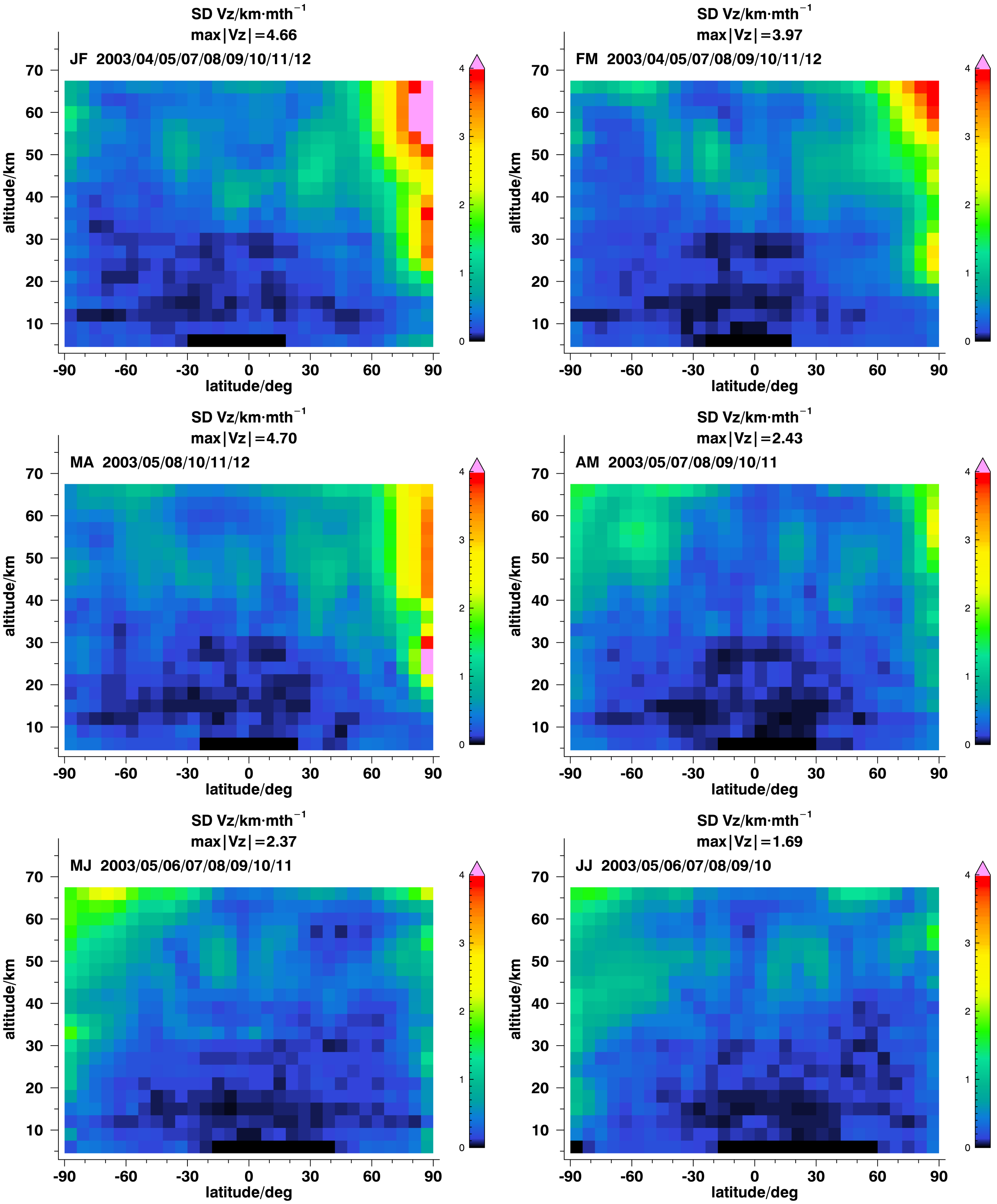

Figure 6. : Inter-annual variability of the middle atmospheric ~~circulation~~ vertical effective velocities in terms of sample standard ~~variations~~ deviations from ~~July–August~~ January–February (top left, ~~JA~~JF) to ~~December-January~~ June–July (bottom right, ~~DJ~~JJ). ~~For details, see Fig. 1.~~

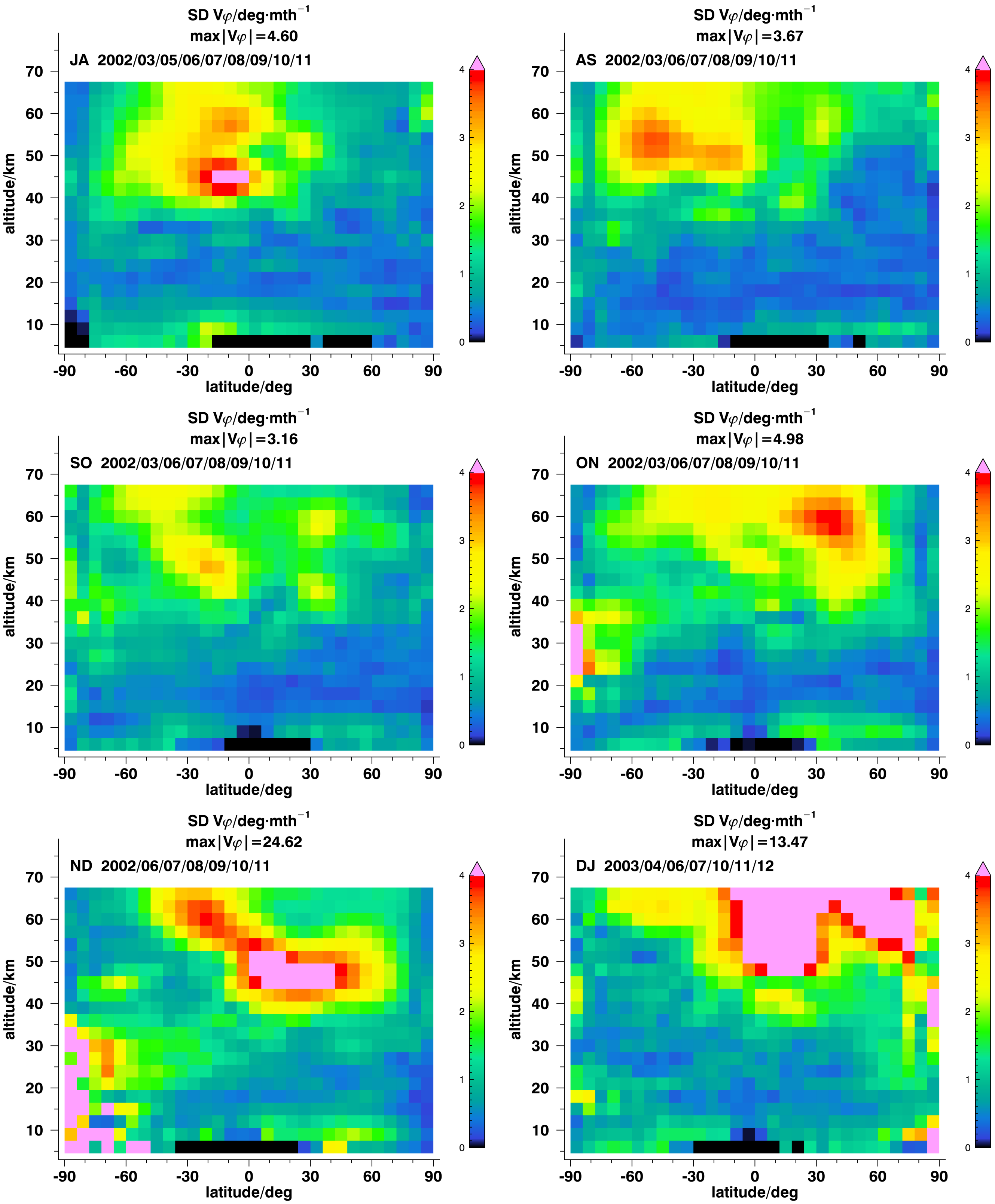

Figure 7. : Inter-annual variability of the middle atmospheric meridional effective velocities in terms of sample standard variations from July–August (top left, JA) to December–January (bottom right, DJ).

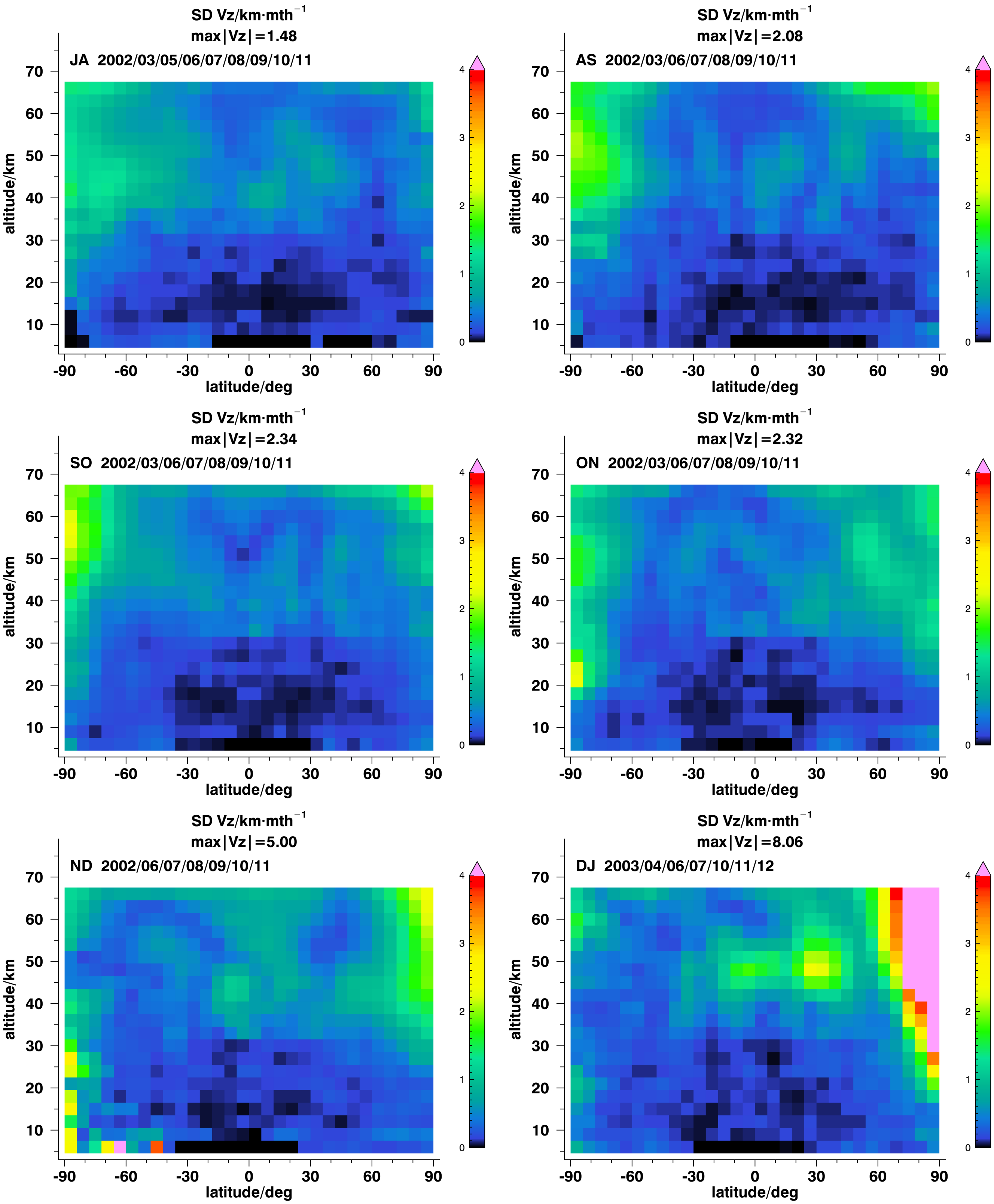

Figure 8. : Inter-annual variability of the middle atmospheric vertical effective velocities in terms of sample standard variations from July–August (top left, JA) to December-January (bottom right, DJ).

at about 50 km. Instead, this is a mesospheric branch of an Equator-pole circulation. Most parts of the ~~Southern hemispheric~~ SH stratosphere are quite calm. Low variabilities indicate that this is a very typical condition. At Southern midlatitudes there is an isolated cell of pronounced poleward transport at tropospheric altitudes between 8 and 12 km (Fig. 3, top left panel). We associate this with the transition branch of the BDC reported by Lin and Fu (2013) and Diallo et al. (2019).

Tropical uplift, which separates the anti-parallel circulation patterns described above, has ~~largest effective velocities~~ its maximum at 50 km altitude and ~~is situated~~ at 30°S. At lower altitudes effective uplift velocities are small and maxima seem to be found further equatorward compared to higher altitudes. This leads to a warped tropical pipe.

In the altitude range covered by our data no indication of a pole to pole overturning circulation is seen.

Except for the highly variable subsidence at Northern polar regions and its feeding in the Northern midlatitudinal mesosphere, inferred velocities largely exceed their variabilities by a factor of 3, indicating that these results are robust and, due to only moderate year-to-year variability, are fairly representative for the atmospheric state at this time of the year.

3.1.2 February-March

The upper stratospheric transport pattern from the tropics to the North pole seen in January to February around 40 km has considerably weakened, and at least in the middle stratosphere (around 30 km) there is now a stronger signal of Northern polar subsidence (Fig. 1, right upper panel). The ~~Southern hemispheric~~ SH circulation pattern has become considerably stronger. Southern polar subsidence is more clearly pronounced than the month before and is seen to reach lower altitudes. Effective velocities decrease towards lower altitudes which is an immediate and expected effect of increasing air density during subsidence. The NH middle stratospheric poleward circulation pattern below 30 km remains intact, and a ~~Southern hemispheric~~ SH counterpart has emerged. The deep branch of the BDC starts to form from the tropical region above 20 km.

Roughly following the seasonal movement of the solar zenith, the tropical pipe has moved slightly towards the equator. Between 40 and 45 km there is still a poleward offset of the latitudinal region of uplift which separates the northern and southern circulation patterns at 18°S. Between 45 and 55 km the upward movement bifurcates into a Northern and Southern transport branch. The Northern one feeds into a mesospheric circulation pattern that exists above the deep branch of the BDC (at 55 km and above), while the Southern branch feeds into the dominating circulation pattern of the SH upper stratosphere and mesosphere. At 55 km a reverse offset of the latitude of strongest uplift is observed towards northern latitudes. This movement will proceed further in the following months and will give ~~raise~~ rise to a mesospheric overturning pole-to-pole circulation later in the year.

Shallow branches of the BDC are seen in both hemispheres. In northern midlatitudes this pattern extends higher up into the stratosphere while in the ~~southern hemisphere (SH)~~ SH it is confined to the lowermost stratosphere. Arguably, the classification of this feature as the lower branch of the BDC is not straightforward because it is not clear enough whether this feature is fed by the tropical uplift. In the lower southern midlatitude stratosphere there is even an altitude region (~ 15 km) where equatorward backflow is observed which possibly closes the loop of the circulation above.

Again the regions of large variability are confined to high Northern polar latitudes and a small region at 53 km altitude, 26° latitude. This again shows moderate year-to-year variability and representative results elsewhere.

3.1.3 March-April

An overturning circulation feature forms which is also fed by tropical air above about 30 km (Fig. 1, left middle panel). The uplift barrier between 40 and 60 km has moved to 30°N and makes this overturning circulation feature bifurcate into two branches, one developing into the deep pole-to-pole circulation above 65 km, and another one from the tropics to the southern high latitudes below 65 km. In the SH, a deep BDC branch has clearly developed from the subtropical pipe cell above 20 km (Fig. 3), and adds poleward and subsidence motion to the overturning circulation branch over the Southern Pole. This subsidence reaches further down than in the preceding month. At 15 km altitude there is some back-flow of southern polar air towards lower latitudes.

In the NH, the overturning circulation seems to be fed from a second altitude region. Besides the deep branch of the BDC around 35 km, poleward transport in the lower stratosphere (10 - 15 km) from the subtropics (30°N) to the high latitudes is feeding into the uplift over the North Pole as well. Above 15 km the arriving air is uplifted, while air arriving at lower altitudes subsides (Fig. 3,middle left panel).

The structure of circulation over the NH midlatitudes leaves an isolated region between 35°N-65°N in the altitude range of 30-65 km without a sizeable vertical velocity component (Fig. 1). ~~This seems to contribute to the formation of the uplift latitudinal barrier that will appear~~ This feature will evolve in the following months as a region where uplift motion clearly overtakes horizontal transport around 60°N~~in the following months~~.

Large variability in the lower stratosphere in high northern latitudes (~~Fig. ??~~Figs. 5-6, middle left ~~panel~~panels) is attributed to late winter vortex dynamics.

3.1.4 April-May

In the southern polar stratosphere there is still strong subsidence (Fig. 1, right middle panel). Maximum velocities have shifted higher up (around 70 km) and towards lower latitudes. The northern polar uplift branch of the mesospheric overturning circulation has also moved upwards and broadened so that it covers NH middle and high latitudes now. It does not show the tropical origin anymore, i.e., this part of the pole-to-pole circulation branch is now disconnected from the tropical pipe. Instead, a strong transport branch from the Northern subtropics (30°N) to the South Pole has developed for altitudes above 40 km. This transport path avoids the detour over the Northern polar latitudes but feeds into the mesospheric circulation at about 30°N.

In the Northern lower stratosphere between 10 and 25 km a circulation has established with poleward transport below 15 km and upward and southward transport between 15 and 25 km (see Fig. 3, middle right panel). In the SH there exists a second transport branch from the equator to subarctic latitudes between 20 and 30 km, the deep branch of the BDC, that has strengthened compared to the previous month (see Fig. 3, middle right panel). As in the preceding month, some back-flow of polar air towards low latitudes is detected in the SH at 15 km, most pronounced in sub-polar regions. Large interannual variability is observed above 55 km at SH mid and lower latitudes (Fig. ~~??~~5, middle right panel), related to the varying vertical extent of the pole-to-pole overturning circulation.

3.1.5 May-June

The mesospheric branch of the BDC in the SH is still there, now with maximum velocity shifted towards subtropical latitudes and lower altitudes (Fig. 1, lower left panel); this circulation branch now causes subsidence over SH midlatitudes at higher levels. At about 30–40 km descending air encounters the lower deep branch of the BDC. Air is further transported towards the polar region where these merged branches of the BDC result into subsidence. While in the preceding month subsidence over the Antarctic was observed up to the highest altitudes, now the circulation above 60 km starts to reverse, which will lead to a south-north pole-to-pole circulation in the next six months. There is indication of a reversal of the shallow branch in the SH with strongly increased equatorwards transport velocities (compared to the previous month) in the range below 15 km.

Again, the NH is quite calm in terms of absolute velocities but the circulation of air with transport towards the pole below 15 km and back to the mid-latitudes and subtropics around 20 km has strengthened (Fig. 3, lower left panel). The region of vertical transport around 30°N has moved down to altitudes between 30 and 50 km. Vertical uplift in between 40°N - 60°N in the altitude range of 40-60 km feeds the SH mesospheric circulation branch.

3.1.6 June-July

A clear pattern of the deep branch of the BDC has established in the SH, with transport from the Northern subtropics (35°N) to the South Pole and subsidence there below 40 km (Fig. 1, lower right panel). Relatively large variability in the range of 30° – 60° S and 45 to 55 km altitude indicates that the extent of high transport velocities towards the South Pole varies from year to year (~~Figure ??~~Fig. 5, lower right panel). A very weak backward flow to the equator is present below 13 km (Fig. 3, lower right panel). The southern polar uplift now starts already at 50 km altitude. It will intensify during the following months. Eventually, three months later, it will form the upwelling branch of the overturning pole-to-pole circulation.

The middle to upper stratosphere in the NH is rather quiet. Some uplift is still present in mid-latitudes above 55 km that is fed from the subtropical region (30°N). An area of uplift from 25-50 km above 30°N forms a horizontal transport barrier in the sense that air southward of this barrier is transported in direction to the South Pole; this feature persists until August-September.

The circulation pattern in the lower Northern stratosphere is still present. The poleward transport in the lower branch as observed the month before has weakened. Now we observe an upwelling pattern from 30–40°N that transports air upwards and polewards up to around 75°N before turning towards the tropics at about 20 km altitude (Fig. 3, lower right panel). This feature is also observed in the following month, but loses strength in August-September, when this pathway is overpowered by the descent of the already forming overturning circulation in the ~~Northern Hemisphere (NH)~~ NH high latitudes. The low standard deviations ~~corresponding to~~ of meridional effective velocities, which are about a factor of three smaller than the effective velocities in this region and time of the year indicate that this is the usual ~~path~~ pathway tracers follow (Fig. ~~??~~5, lower right panel.). This, together with the lack of a SH counterpart, allows us to link this pattern to the occurrence of the Asian Monsoon, which has been recently shown to be an effective pattern for transport of tropospheric tracers into the stratosphere (e.g. Randel et al., 2010; Ploeger et al., 2017; Yu et al., 2017). Our results ~~show overall agreement with the one~~ are in agreement with Fig. 5 shown by Ploeger et al. (2017) with respect to the circulation structures. Differences related to the transport of tracers during the monsoon period can be attributed to the different time resolution in our study and theirs.

3.1.7 July-August

In general, the circulation patterns resemble those of the previous month, although shifted towards lower altitudes (Fig. 2, upper left panel). The only exception is the uplift barrier at 30°N which is displaced to higher levels. The circulation branch above 50 km from 30°N to the poles is strengthening. While in the previous month it seemed to feed chiefly the overturning pole-to-pole circulation, it now establishes the onset of northern polar subsidence, which will continue to gain importance during the subsequent months. That is to say, what looked like overturning circulation the month before becomes more and more a BDC-like symmetric feature. The maximum updraft is located at 30°N. In the second half of the year, the patterns observed during the first six months are largely mirrored to the other hemisphere, however shifted in altitude, and the transport velocities are somewhat larger. The July-August patterns resemble widely the mirrored patterns seen in JF (Fig. 2, upper left panel). The pronounced deep branch of the BDC resides in the middle to upper stratosphere of the SH (35 to 60 km). A zone of vertical transport around 30°N and between 30 and 55 km forms a horizontal transport barrier. Above this barrier, upward and poleward transport with a source region in the Northern subtropics has established. Indication of uplift over the South Pole is seen above 60 km.

The circulation pattern in the Northern lower stratosphere with poleward transport below 15 km and equatorward transport around 20km is still existent. As in the previous months we assign this circulation cell to the NH monsoon systems (Fig. 4, upper left panel).

~~Variability~~ The variability of meridional effective velocities in the upper stratosphere over tropics and southern midlatitudes is ~~larger than~~ similar to the NH counterpart in January-February (Fig. ~~??~~7, upper left panel). Although small, there is a sizeable variability in vertical velocity over the South pole related to year-to-year variability of the descent inside the polar vortex ~~.~~ (Fif. 8, upper left panel).

3.1.8 August-September

The general circulation pattern resembles that of the preceding month (Fig. 2, upper right panel). However, the maximum of peak velocities of the SH circulation branch are now found at lower altitudes. A bifurcation of the circulation is found near the southern polar stratopause. This poleward circulation branch around 45 km altitude feeds both the mesospheric overturning circulation which now has established in south north direction, and the southern polar subsidence. In the northern polar upper stratosphere and mesosphere strong poleward transport and subsidence starts to establish, which is fed by the mesospheric overturning circulation, by tropical uplift south of 30°N from above 55 km, and by Northern mid-latitude air from 35 to 55 km. Meridional velocities in the winter hemisphere are stronger in the 0-70°S, 40 km altitude range in August-September compared to the NH counterpart in February-March.

In the lowermost stratosphere, we see isolated shallow branches of the BDC below 15 km transporting air from the subtropics to the poles in both hemispheres (Fig. 4, upper right panel). Similar to February-March and March-April, vertical transport is present over the equator up to about 27 km; this vertical transport feeds into two rather weak circulation cells in midlatitudes below 25 km. In the SH this circulation merges with the poleward transport further down, while in the NH, the circulation merges with the weakened equatorward transport around 20 km that was observed in the previous months.

We can see a reversal in the horizontal velocities in the NH lower stratosphere above about 10 km from around 40°N to the equator. We associate this with Asian-monsoon-related transport.

3.1.9 September-October

The circulation in September-October is dominated by a pronounced overturning pole-to-pole circulation feature, being lower in altitude than its boreal spring counterpart (Fig. 2, middle left panel). All transport above 55 km is directed upwards and towards the North Pole. The deep branch cell of the BDC in the SH observed in the previous months has moved further down (25 to 40 km) and further polewards and feeds, by bifurcation, into the overturning circulation in its upper part. The lower part still feeds into the subsidence area in the middle to lower South polar atmosphere (below 30 km). The uplift region that forms a horizontal transport barrier is now located between 25 and 40 km and closer to the equator, at about 20°N. Above this barrier, all transport in the NH is directed towards the North Pole. A second region of purely vertical transport is found directly above the equator between 20 and 30 km. This region of vertical transport separates two weak circulation cells in both hemispheres. The SH one merges with the deep branch of the BDC, while the NH counterpart provides poleward and downward transport towards 60°N and then turns into equatorward transport around 15 to 20 km. In the lowermost stratosphere and UTLS (below 13 km, Fig. 4, middle left panel) we observe some poleward transport in the SH while the NH atmosphere in this altitude range is rather quiet.

3.1.10 October-November

The transport cell related to the deep branch of the BDC in the SH has weakened considerably, and has shrunk and moved further down to 25 to 35 km (Fig. 2, middle right panel). Although its upper part still feeds into the uplift over the South Pole, it is now more separated from the above regions and more clearly causing also air descent over the South Pole.

The horizontal transport barrier formed by vertical transport has jumped back to the SH and is located around 30°S from this month on (until March-April). Its altitude range is again 45 to 65 km. It creates an isolated region at 40° – 60°S and 40-55 km, similar to the one found in the NH during March-April, although smaller now. All transport above 40 km and northward of 30°S is directed towards the North Pole and leads to subsidence there. Increased upward velocities over the South Pole above 55 km indicate the existence of an overturning mesospheric pole-to-pole circulation, but this seems to take place at altitudes mainly above 68 km and can thus not be diagnosed here. In contrast, a tropical feeding of the former overturning circulation takes over and will develop in the subsequent month into the deep branch of BDC in the NH. A second region of purely vertical transport is present over the equator between 20 and 30 km and acts as horizontal transport barrier there. It is flanked by a weak NH circulation cell transporting air into midlatitudes above 20 km and equatorwards below 15 km. (Fig. 4, middle right panel).

Largest variability at 20 to 35 km over the South pole is related to interannual variations in the timing of the SH polar vortex break-up, associated with the high values seen in ~~Figure ??~~Figures 7–8, middle right ~~panel~~panels. This had already started in the previous month in the upper stratosphere.

3.1.11 November-December

The most pronounced feature in this month is the deep branch cell of the BDC in the NH at very high altitudes (35 to 60 km), transporting air from the Southern subtropics (30°S) to the North Pole (Fig. 2, lower left panel). Subsidence over the winter pole is present below 50 km. Some upward and Southern poleward transport is present over the SH midlatitudes above 55 km, similar to the May-June and June-July situation in the NH. A very weak remnant of the deep branch of the BDC is present in the SH between 20 and 30 km. In the lowermost stratosphere, a reversal of the shallow branch of the BDC with transport towards the equator can be seen (Fig. 4, lower left panel). This is especially clear for the NH. This equatorward transport seems to be fed by the subsidence over the North pole. A similar but weaker feature was observed in the SH in March-April.

3.1.12 December-January

The deep branch of the BDC is still seen as the main circulation feature near the Northern tropical and midlatitudinal stratopause. However, it has shrunk in latitudinal extension and feeds the subsidence over the North Pole only below 25 km (Fig. 2, lower right panel). In the northern polar upper stratosphere the vertical velocity has reversed, showing upward velocities. Interannual variability, however, is high here, probably caused by frequent sudden stratospheric warmings appearing at different times of the NH winter (Figure ??7, lower right panel). In the shallow branch of the BDC, equatorward transport in the NH midlatitudes below 15 km and poleward transport in the SH at the same altitude range is present. In the SH, the circulation pattern is closed by upward and equatorward transport in the 15 to 25 km region (Fig. 4, lower right panel).

3.2 Summary

We have presented here a new climatology of middle atmospheric circulation fields, derived from long-lived tracer measurements from MIPAS. The climatologies have been constructed from independent ANCISTRUS results the results of independent ANCISTRUS runs (von Clarmann and Grabowski, 2016) with a latitudinal/vertical resolution of 6°/3km; resulting fields are stable over the years of the MIPAS mission (2002–2012) . This both in the sense that the annual variation of the resulting circulation patterns is large only in regions where one would expect large natural interannual variability. The stability of results from independent ANCISTRUS runs increases confidence in the robustness of the analysis method and in the sense that it produces similar results for similar input fields. This shows that the patterns displayed are indeed typical phenomena of the middle atmospheric circulation, which remain after the calculation of the multi-year averages. Further, it furnishes evidence that the results do not depend in any sizeable way on the MIPAS sampling in a particular year. Other phenomena, which also appear on a regular basis but vary in the exact latitude or time where/when they appear, average out. This issue is further discussed in Section 3.2.3. In the following, we present a synopsis of the main phenomena found.

3.2.1 The BDC and the Overturning Circulation

The upper branch of the BDC and the overturning pole-to-pole circulation are not, according to our data, two independent phenomena as suggested by the schematic shown in Fig. 1 Bönisch et al. (2011), but we observe quite smooth transitions between both. While from July to September there are still two major, roughly antiparallel circulation cells below 68 km, in September-

October we have one single northward circulation pattern above 50 km. Our data are consistent with ~~the assumption~~ - but do not directly support ~~it~~ - ~~that from March to May there exists~~ a southward pole to pole circulation ~~which is situated at altitudes not~~ from March to May at altitudes above those covered by MIPAS data.

From our data, the direct uplift of air from the tropopause above the equator seems not to be the preferred tracers' path in shorter timescales. Such tropical uplift is clearly seen only in January-February and October-November. On the other hand, this uplift is known to be slow and robust in a statistical sense. This ~~suggests~~ seems to suggest that the tropical pipe may not be an actual transport path but instead a residual which emerges when fluctuations at shorter timescales cancel out.

3.2.2 Inter-hemispheric Differences

While we see corresponding features in the SH and NH, NH atmospheric circulation is not merely a mirrored ~~southern hemispheric~~ SH circulation phase-shifted by six months. The main differences are:

1. The deep branch of the BDC in the local winter stratosphere is stronger in the SH than in the NH. This is consistent with stronger southern than northern polar winter subsidence which is associated with less perturbed polar vortices there (Butchart, 2014, Section 5.1).

2. While the major patterns can be found in both hemispheres, their typical altitude is different in the NH compared to the SH. Overall, they appear at higher levels in the SH. This applies for instance to the low-midlatitudes feature in May-June and June-July in the SH, and ~~in~~ to the November-December and December-January feature in the NH. Another example is the overturning circulation feature in March-April in the SH and September-October in the NH. To the best of our knowledge these altitude differences have not been reported before either.

3. The location of ~~vertical uplift separation barriers~~ the regions with near-zero vertical effective velocities is different in both hemispheres.

4. There are differences in the structure of the overturning circulation: only one pathway is observed in the SH towards NH branch in September-October while two pathways are seen in the NH towards SH branch in March-April. This creates a large region of isolated air in the NH for these months, without a SH counterpart. To the best of our knowledge this also has not been reported before.

5. In the NH we detect a summer signal (June to September), that has no SH counterpart, which we attribute to the Asian monsoon.

3.2.3 Variable Phenomena

The variability of atmospheric transport is largest particularly large at winter polar latitudes. This applies both to the lower mesosphere/upper stratosphere region and the middle stratosphere and the connected midlatitudinal mesospheric reansport pattern (Figs. ??5–??8). In the NH this variability is related to sudden stratospheric warmings. This variability causes an underrepresentation of the related transport pattern in the climatology. Conversely, in the SH, the interannual variability in the polar vortex break-up is associated with very high variability in transport in October–November in the SH polar region between 20-35 km, as this is also affecting the highest latitude the deep branch of the BDC can reach.

Another region of large variability in meridional effective velocities is found over mid-low latitudes in the winter hemisphere (Figs. ??5–??8, January-February in the NH, June-July and July-August in the SH), reaching maximum standard deviation values between 40-50 km of altitude. In the SH this high variability pattern persists also in August-September and September-October. A further region of large variability appears in August-September above 45 km, centred around 50°S and is associated with the same circulation pattern.

4 Discussion and Conclusion

The ANCISTRUS method applied to MIPAS data broadly reproduces well the known atmospheric meridional circulation patterns. Beyond this, additional , however with some unexpected features. Additional information has been obtained from this new climatology regarding how some of these patterns evolve over the year. Compared to established methods, it provides circulation fields at largely improved temporal and spatial resolution and at altitudes not accessible by the classical methods such as age-of-air analysis on the basis of air sampling instruments of satellite based SF_6 measurements. The results are stable in a sense that the interannual variability of a pattern seen at a certain time of the year is small, that is to say, the patterns do not average out when the mean circulation is calculated although the input circulation patterns for the averaging process have been generated independently. No common a priori velocity distribution has been used to push the results towards the expected circulation patterns. Furthermore, transitions between the circulation patterns of subsequent months are reasonably smooth, which is another indicator of the robustness of the results. Large interannual variability is mainly limited to situations where it can be explained by processes known to have large interannual variability in themselves, e.g. sudden stratospheric warmings.

The main features seen in these climatology fields are that the upper branch of the BDC and the overturning pole-to-pole circulation are heavily intertwined phenomena; the latitude of stratospheric uplift in the middle and upper stratosphere is more variable than previously established; and the schematics of the BDC usually shown (e.g. Fig. 1 of Bönisch et al. 2011) seem to be representative for certain months only~~, actually rather spring/autumn months instead summer/winter months as indicated in their figure, ~~.and do not capture enough detail and interactions between the various circulation branches. The particular figure quoted seems to represent rather spring/autumn months instead summer/winter months as indicated.

~~Oncoming future steps~~ Obvious future steps are the analyses of the interannual variability of transport patterns. Further planned activities consist in the application of this method to data from other space missions, ~~like~~ such as the Microwave Limb Sounder (MLS) on the Aura satellite (Waters et al., 2006) and the distinction of transport versus mixing. Researchers optimistic with respect to funding issues even plan an ANCISTRUS model in other than geometric altitude coordinates or even a three-dimensional version of ANCISTRUS, which would be a very versatile tool to infer velocities from concentration distributions for various applications.

Appendix A: The interpretation of 'effective velocities'

The effective velocities presented in this study cannot be interpreted as zonal mean velocities. The reason is twofold.

First, due to possible correlations between velocities and mixing ratios, products of prime terms in the zonal mean of the Reynolds decomposition of the tendency formulation of the continuity equation do not cancel out. Following Tung (1982)[4] and applying approximations suggested therein, von Clarmann and Grabowski (2016, Appendix A) rewrite the continuity equation as

$$\frac{\partial}{\partial t}\overline{\mathrm{vmr}_g} = -\frac{v^*}{r}\frac{\partial}{\partial \phi}\overline{\mathrm{vmr}_g} - w^*\frac{\partial}{\partial z}\overline{\mathrm{vmr}_g} + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left[K^*_\phi \frac{\partial}{\partial \phi}\overline{\mathrm{vmr}_g}\right] + \frac{\partial}{\partial z}\left[K^*_z \frac{\partial}{\partial z}\overline{\mathrm{vmr}_g}\right], \tag{A1}$$

where, contrary to the notation of the main text, velocities, mixing coefficients and state variables with a bar indicate zonal averages while quantities without a bar indicate longitudinally resolved quantities, and where

$$v^* = \overline{v} - \frac{1}{\overline{\rho}}\frac{\partial}{\partial t}\overline{\rho'\eta'} - \frac{1}{\overline{\rho}r}\frac{\partial \overline{\rho}}{\partial \phi}K_{\phi\phi} - \frac{\partial}{\partial z}K_{z\phi} - \frac{1}{\overline{\rho}}\frac{\partial \overline{\rho}}{\partial z}K_{z\phi}, \tag{A2}$$

$$w^* = \overline{w} - \frac{1}{\overline{\rho}}\frac{\partial}{\partial t}\overline{\rho'\Phi'} - \frac{1}{\overline{\rho}}\frac{\partial \overline{\rho}}{\partial z}K_{zz} - \frac{1}{r}\frac{\partial}{\partial \phi}K_{\phi z} - \frac{1}{\overline{\rho}r}\frac{\partial \overline{\rho}}{\partial \phi}K_{\phi z}, \tag{A3}$$

$$K^*_\phi = K_{\phi\phi}, \tag{A4}$$

and

$$K^*_z = K_{zz}, \tag{A5}$$

[4]There exist other approaches than that of Tung (1982) to interprete 2D circulation, using different approximations. Depending on the approach chosen, the calculation of effective 2D velocities from 3D fields involves different terms.

$$K_{\phi\phi} = \frac{1}{\overline{\rho}}\overline{(\rho v)'\eta'}, \tag{A6}$$

$$K_{zz} = \frac{1}{\overline{\rho}}\overline{(\rho w)'\Phi'}, \tag{A7}$$

$$K_{\phi z} = \frac{1}{\overline{\rho}}\overline{(\rho v)'\Phi'}, \tag{A8}$$

and where η', Φ' and σ' are defined by

$$\left(\frac{\partial}{\partial t} + \frac{\overline{u}}{r\cos\phi}\frac{\partial}{\partial\lambda}\right)\eta' = v', \tag{A9}$$

$$\left(\frac{\partial}{\partial t} + \frac{\overline{u}}{r\cos\phi}\frac{\partial}{\partial\lambda}\right)\Phi' = w', \tag{A10}$$

and

$$\left(\frac{\partial}{\partial t} + \frac{\overline{u}}{r\cos\phi}\frac{\partial}{\partial\lambda}\right)\sigma' = S'. \tag{A11}$$

To generate effective quantities comparable to our results from 3D fields requires not only the calculation of the zonal mean velocities but also the evaluation of the second to fifth terms of Equations (A2) and (A3).

The second reason why our results cannot be understood as zonal mean velocities is that in our inversion we constrain to zero the effective mixing terms $\frac{1}{r^2}\frac{\partial}{\partial\phi}\left[K^*_\phi \frac{\partial}{\partial\phi}\overline{vmr_g}\right]$ and $\frac{\partial}{\partial z}\left[K^*_z \frac{\partial}{\partial z}\overline{vmr_g}\right]$, i.e., those terms in the continuity equation (Eq. A10 in ~~von Clarmann and Grabowski 2016~~von Clarmann and Grabowski, 2016) which act upon second derivatives of state variables. Thus, their effect is aliased onto our effective velocities. From comparison of our effective velocities with zonal mean velocities information on the relevance of eddy transport and eddy mixing can be gained.

Acknowledgements. We thank the reviewers for their thorough, detailed and insightful reviews.

References

Andrews, A. E., Boering, K. A., Daube, B. C., Wofsy, S. C., Hintsa, E. J., Weinstock, E. M., and Bui, T. P.: Empirical age spectra for the lower tropical stratosphere from in situ observations of CO_2: Implications for stratospheric transport, J. Geophys. Res., 104, 26,581–26,595, 1999.

Birner, T. and Bönisch, H.: Residual circulation trajectories and transit times into the extratropical lowermost stratosphere, Atmos. Chem. Phys., 11, 817–827, doi:10.5194/acp-11-817-2011, 2011.

Bönisch, H., Engel, A., Birner, T., Hoor, P., Tarasick, D. W., and Ray, E. A.: On the structural changes in the Brewer-Dobson circulation after 2000, Atmos. Chem. Phys., 11, 3937–3948, doi:10.5194/acp-11-3937-2011, 2011.

Brasseur, G. and Solomon, S.: Aeronomy of the Middle Atmosphere–Chemistry and Physics of the Stratosphere and Mesosphere, Atmospheric and Oceanographic Sciences Library 32, Springer, P. O. Box 17, 3300 AA Dordrecht, The Netherlands, third edn., 2005.

Brewer, A. W.: Evidence for a world circulation provided by measurements of helium and water vapour distribution in the atmosphere, Quart. J. Roy. Meteorol. Soc., 75, 351–363, 1949.

Butchart, N.: The Brewer-Dobson Circulation, Rev. Geophys., 52, 157–184, doi:10.1002/2013RG000448, 2014.

Butchart, N., Scaife, A. A., Bourqui, M., de Grandpre, J., Hare, S. H. E., Kettleborough, J., Langematz, U., Manzini, E., Sassi, F., Shibata, K., Shindell, D., and Sigmond, M.: Simulations of anthropogenic change in the strength of the Brewer-Dobson circulation, Clim. Dyn., 27, 727–741, doi:10.1007/s00382-006-0162-4, 2006.

Chirkov, M., Stiller, G. P., Laeng, A., Kellmann, S., von Clarmann, T., Boone, C., Elkins, J. W., Engel, A., Glatthor, N., Grabowski, U., Harth, C. M., Kiefer, M., Kolonjari, F., Krummel, P. B., Linden, A., Lunder, C. R., Miller, B. R., Montzka, S. A., Mühle, J., O'Doherty, S., Orphal, J., Prinn, R. G., Toon, G., Vollmer, M. K., Walker, K. A., Weiss, R. F., Wiegele, A., and Young, D.: Global HCFC-22 measurements with MIPAS: retrieval, validation, global distribution and its evolution over 2005-2012, Atmos. Chem. Phys., 16, 3345–3368, doi:10.5194/acp-16-3345-2016, 2016.

Diallo, M., Legras, B., and Chédin, A.: Age of stratospheric air in the ERA-Interim, Atmos. Chem. Phys., 12, 12 133–12 154, doi:10.5194/acp-12-12133-2012, 2012.

Diallo, M., Konopka, P., Santee, M. L., Müller, R., Tao, M., Walker, K. A., Legras, B., Riese, M., Ern, M., and Ploeger, F.: Structural changes in the shallow and transition branch of the Brewer–Dobson circulation induced by El Niño, Atmos. Chem. Phys., 19, 425–446, doi:10.5194/acp-19-425-2019, 2019.

Dobson, G. M. B.: Origin and distribution of polyatomic molecules in te atmosphere, Proc. R. Soc., A236, 187–193, 1956.

Dunkerton, T.: On the mean meridional mass motions of the stratosphere and mesosphere, J. Atmos. Sci., 35, 187–193, doi:10.1175/1520-0469(1978)035<2325:OTMMMM>2.0.CO;2, 1978.

Eckert, E., Laeng, A., Lossow, S., Kellmann, S., Stiller, G., Clarmann, T., Glatthor, N., Höpfner, M., Kiefer, M., Oelhaf, H., Orphal, J., Funke, B., Grabowski, U., Haenel, F., Linden, A., Wetzel, G., Woiwode, W., Bernath, P. F., Boone, C., Dutton, G. S., Elkins, J. W., Engel, A., Gille, J. C., Kolonjari, F., Sugita, T., Toon, G. C., and Walker, K. A.: MIPAS IMK/IAA CFC-11 (CCl3F) and CFC-12 (CCl2F2) measurements: accuracy, precision and long-term stability, Atmos. Meas. Tech., 9, 3355–3389, doi:10.5194/amt-9-3355-2016, 2016.

Eckert, E., von Clarmann, T., Laeng, A., Stiller, G. P., Funke, B., Glatthor, N., Grabowski, U., Kellmann, S., Kiefer, M., Linden, A., Babenhauserheide, A., Wetzel, G., Boone, C., Engel, A., Harrison, J. J., Sheese, P. E., Walker, K. A., and Bernath, P. F.: MIPAS IMK/IAA carbon tetrachloride (CCl_4) retrieval and first comparison with other instruments, Atmos. Meas. Tech., 10, 2727–2743, doi:10.5194/amt-10-2727-2017, 2017.

Engel, A., Möbius, T., Bönisch, H., Schmidt, U., Heinz, R., Levin, I., Atlas, E., Aoki, S., Nakazawa, T., Sugawara, S., Moore, F., Hurst, D., Elkins, J., Schauffler, S., Andrews, A., and Boering, K.: Age of stratospheric air unchanged within uncertainties over the past 30 years, Nature Geosci., 2, 28–31, doi:10.1038/ngeo388, 2009.

Fischer, H., Birk, M., Blom, C., Carli, B., Carlotti, M., von Clarmann, T., Delbouille, L., Dudhia, A., Ehhalt, D., Endemann, M., Flaud, J. M., Gessner, R., Kleinert, A., Koopmann, R., Langen, J., López-Puertas, M., Mosner, P., Nett, H., Oelhaf, H., Perron, G., Remedios, J., Ridolfi, M., Stiller, G., and Zander, R.: MIPAS: an instrument for atmospheric and climate research, Atmos. Chem. Phys., 8, 2151–2188, doi:10.5194/acp-8-2151-2008, 2008.

Funke, B., López-Puertas, M., Gil-López, S., von Clarmann, T., Stiller, G. P., Fischer, H., and Kellmann, S.: Downward transport of upper atmospheric NO_x into the polar stratosphere and lower mesosphere during the Antarctic 2003 and Arctic 2002/2003 winters, J. Geophys. Res., 110, D24308, doi:10.1029/2005JD006463, 2005.

Funke, B., García-Comas, M., López-Puertas, M., Glatthor, N., Stiller, G. P., von Clarmann, T., Semeniuk, K., and McConnell, J. C.: Enhancement of N_2O during the October-November 2003 solar proton event, Atmos. Chem. Phys., 8, 3805–3815, 2008.

Funke, B., López-Puertas, M., García-Comas, M., Stiller, G. P., von Clarmann, T., Höpfner, M., Glatthor, N., Grabowski, U., Kellmann, S., and Linden, A.: Carbon monoxide distributions from the upper troposphere to the mesosphere inferred from 4.7 μm non-local thermal equilibrium emissions measured by MIPAS on Envisat, Atmos. Chem. Phys., 9, 2387–2411, 2009.

Funke, B., López-Puertas, M., Bermejo-Pantaleón, D., García-Comas, M., Stiller, G. P., von Clarmann, T., Kiefer, M., and Linden, A.: Evidence for dynamical coupling from the lower atmosphere to the thermosphere during a major stratospheric warming, Geophys. Res. Lett., 37, L13803, doi:10.1029/2010GL043619, 2010.

Funke, B., Baumgaertner, A., Calisto, M., Egorova, T., Jackman, C. H., Kieser, J., Krivolutsky, A., López-Puertas, M., Marsh, D. R., Reddmann, T., Rozanov, E., Salmi, S.-M., Sinnhuber, M., Stiller, G. P., Verronen, P. T., Versick, S., von Clarmann, T., Vyushkova, T. Y., Wieters, N., and Wissing, J. M.: Composition changes after the "Halloween" solar proton event: the High Energy Particle Precipitation in the Atmosphere (HEPPA) model versus MIPAS data intercomparison study, Atmos. Chem. Phys., 11, 9089–9139, 2011.

Funke, B., López-Puertas, M., Holt, L., Randall, C. E., Stiller, G. P., and von Clarmann, T.: Hemispheric distributions and interannual variability of NOy produced by energetic particle precipitation in 2002-2012, J. Geophys. Res. Atmos., 119, 13,565–13,582, doi:10.1002/2014JD022423, 2014a.

Funke, B., López-Puertas, M., Stiller, G. P., and von Clarmann, T.: Mesospheric and stratospheric NOy produced by energetic particle precipitation during 2002-2012, J. Geophys. Res. Atmos., 119, 4429–4446, doi:10.1002/2013JD021404, 2014b.

Funke, B., Ball, W., Bender, S., Gardini, A., Harvey, V. L., Lambert, A., López-Puertas, M., Marsh, D. R., Meraner, K., Nieder, H., Päivärinta, S.-M., Pérot, K., Randall, C. E., Reddmann, T., Rozanov, E., Schmidt, H., Seppälä, A., Sinnhuber, M., Sukhodolov, T., Stiller, G. P., Tsvetkova, N. D., Verronen, P. T., Versick, S., von Clarmann, T., Walker, K. A., and Yushkov, V.: HEPPA-II model-measurement intercomparison project: EPP indirect effects during the dynamically perturbed NH winter 2008-2009, Atmos. Chem. Phys., 17, 3573–3604, doi:10.5194/acp-17-3573-2017, 2017.

Garny, H., Birner, T., Bönisch, H., and Bunze, F.: The effects of mixing on age of air, J. Geophys. Res. Atmos., 119, 7015–7034, doi:10.1002/2013JD021417, 2014.

Haenel, F. J., Stiller, G. P., von Clarmann, T., Funke, B., Eckert, E., Glatthor, N., Grabowski, U., Kellmann, S., Kiefer, M., Linden, A., and Reddmann, T.: Reassessment of MIPAS age of air trends and variability, Atmos. Chem. Phys., 15, 13 161–13 176, doi:10.5194/acp-15-13161-2015, 2015.

Hegglin, M. and Tegtmeier, S.: The SPARC Data Initiative, SPARC Newsletter, 36, 22–23, 2011.

Hegglin, M. I. and Tegtmeier, S., eds.: The SPARC Data Initiative: Assessment of stratospheric trace gas and aerosol climatologies from satellite limb sounders, SPARC Report No. 8, WCRP-5/2017, SPARC, doi:10.3929/ethz-a-010863911, 2017.

Hegglin, M. I., Tegtmeier, S., Anderson, J., Froidevaux, L., Fuller, R., Funke, B., Jones, A., Lingenfelser, G., Lumpe, J., Pendlebury, D., Remsberg, E., Rozanov, A., Toohey, M., Urban, J., von Clarmann, T., Walker, K. A., Wang, R., and Weigel, K.: SPARC Data Initiative: Comparison of water vapor climatologies from international satellite limb sounders, J. Geophys. Res. Atmos., 118, 11,824–11,846, doi:10.1002/jgrd.50752, 2013.

Kellmann, S., von Clarmann, T., Stiller, G. P., Eckert, E., Glatthor, N., Höpfner, M., Kiefer, M., Orphal, J., Funke, B., Grabowski, U., Linden, A., Dutton, G. S., and Elkins, J. W.: Global CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) Measurements with the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS): retrieval, climatologies and trends, Atmos. Chem. Phys., 12, 11 857–11 875, doi:10.5194/acp-12-11857-2012, 2012.

Lin, P. and Fu, Q.: Changes in various branches of the Brewer–Dobson circulation from an ensemble of chemistry climate models, J. Geophys. Res.-Atmos., 118, 73–84, doi:10.1029/2012JD018813, 2013.

Madronich, S. and Flocke, S.: The role of solar radiation in atmospheric chemistry, in: Handbook of Environmental Chemistry, edited by Boule, P., pp. 1–26, Springer-Verlag, Heidelberg, 1998.

Minschwaner, K., Manney, G. L., Wang, S. H., and Harwood, R. S.: Hydroxyl in the stratosphere and mesosphere- Part 1: Diurnal variability, Atmos. Chem. Phys., 11, 955–962, doi:10.5194/acp-11-955-2011, 2011.

Monge-Sanz, B. M., Chipperfield, M. P., Dee, D. P., Simmons, A. J., and Uppala, S. M.: Improvements in the stratospheric transport achieved by a chemistry transport model with ECMWF (re)analyses: identifying effects and remaining challenges, Quart. J. Roy. Meteorol. Soc., 139, 654–673, doi:10.1002/qj.1996, 2012.

Oberländer-Hayn, S., Gerber, E. P., Abalichin, J., Akiyoshi, H., Kerschbaumer, A., Kubin, A., Kunze, M., Langematz, U., Meul, S., Michou, M., Morgenstern, O., and Oman, L. D.: Is the Brewer-Dobson circulation increasing or moving upward?, Geophys. Res. Lett., 43, doi:10.1002/2015GL067545, 2016.

Plieninger, J., von Clarmann, T., Stiller, G. P., Grabowski, U., Glatthor, N., Kellmann, S., Linden, A., Haenel, F., Kiefer, M., Höpfner, M., Laeng, A., and Lossow, S.: Methane and nitrous oxide retrievals from MIPAS-ENVISAT, Atmos. Meas. Tech., 8, 4657–4670, doi:10.5194/amt-8-4657-2015, 2015.

Plieninger, J., Laeng, A., Lossow, S., von Clarmann, T., Stiller, G. P., Kellmann, S., Linden, A., Kiefer, M., Walker, K. A., Noël, S., Hervig, M., McHugh, M., Lambert, A., Urban, J., Elkins, J. W., and Murtagh, D.: Validation of revised methane and nitrous oxide profiles from MIPAS-ENVISAT, Atmos. Meas. Tech., 9, 765–779, doi:10.5194/amt-9-765-2016, 2016.

Ploeger, F., Abalos, M., Birner, T., Konopka, P., Legras, B., Müller, R., and Riese, M.: Quantifying the effects of mixing and residual circulation on trends of stratospheric mean age of air, Geophys. Res. Lett., 42, 2047–2054, doi:10.102/2014GL062927, 2015a.

Ploeger, F., Riese, M., Haenel, F., Konopka, P., Müller, R., and Stiller, G.: Variability of stratospheric mean age of air and of the local effects of residual circulation and eddy mixing, J. Geophys. Res. Atmos., 120, 716–733, doi:10.1002/2014JD022468, 2015b.

Ploeger, F., Konopka, P., Walker, K., and Riese, M.: Quantifying pollution transport from the Asian monsoon anticyclone into the lower stratosphere, Atmos. Chem. Phys., 17, 7055–7066, 2017.

Plumb, R. A.: Stratospheric transport, J. Meteorol. Soc. Jpn. Ser. II, 80, 793–809, doi:10.2151/jmsj.80.793, 2002.

Randel, W. J., Park, M., Emmons, L., Kinnison, D., Bernath, P., Walker, K. A., Boone, C., and Pumphrey, H.: Asian Monsoon Transport of Pollution to the Stratosphere, Science, 328, 611–613, doi:10.1126/science.1182274, 2010.

Ray, E. A., Moore, F. L., Elkins, J. W., Rosenlof, K. H., Laube, J. C., Röckmann, T., Marsh, D. R., and Andrews, A. E.: Quantification of the SF_6 lifetime based on mesospheric loss measured in the stratospheric polar vortex, J. Geophys. Res. Atmos., 122, 4626–4638, doi:10.1002/2016JD026198, 2017.

Reddmann, T., Ruhnke, R., and Kouker, W.: Three–dimensional model simulations of SF_6 with mesospheric chemistry, J. Geophys. Res., 106, 14,525–14,537, doi:10.1029/2000JD900700, 2001.

Sander, S. P., Friedl, R. R., Barker, J. R., Golden, D. M., Kurylo, M. J., Wine, P. H., Abbatt, J., Burkholder, J. B., Kolb, C. E., Moortgat, G. K., Huie, R. E., and Orkin, V. L.: Chemical kinetics and photochemical data for use in Atmospheric Studies, Evaluation Number 16 : supplement to Evaluation 15: update of key reactions, JPL Publication 09-31, Jet Propulsion Laboratory, National Aeronautics and Space Administration, Pasadena, CA, USA, 2010.

Smith, A. K., Garcia, R. R., Marsh, D. R., and Richter, J. H.: WACCM simulations of the mean circulation and trace species transport in the winter mesosphere, J. Geophys. Res., 116, D20 115, doi:10.1029/2011JD016083, 2011.

Stiller, G. P., Kiefer, M., Eckert, E., von Clarmann, T., Kellmann, S., García-Comas, M., Funke, B., Leblanc, T., Fetzer, E., Froidevaux, L., Gomez, M., Hall, E., Hurst, D., Jordan, A., Kämpfer, N., Lambert, A., McDermid, I. S., McGee, T., Miloshevich, L., Nedoluha, G., Read, W., Schneider, M., Schwartz, M., Straub, C., Toon, G., Twigg, L. W., Walker, K., and Whiteman, D. N.: Validation of MIPAS IMK/IAA temperature, water vapor, and ozone profiles with MOHAVE-2009 campaign measurements, Atmos. Meas. Tech., 5, 289–320, doi:10.5194/amt-5-289-2012, 2012a.

Stiller, G. P., von Clarmann, T., Haenel, F., Funke, B., Glatthor, N., Grabowski, U., Kellmann, S., Kiefer, M., Linden, A., Lossow, S., and López-Puertas, M.: Observed temporal evolution of global mean age of stratospheric air for the 2002 to 2010 period, Atmos. Chem. Phys., 12, 3311–3331, doi:10.5194/acp-12-3311-2012, 2012b.

Stiller, G. P., Fierli, F., Ploeger, F., Cagnazzo, C., Funke, B., Haenel, F. J., Reddmann, T., Riese, M., and von Clarmann, T.: Shift of subtropical transport barriers explains observed hemispheric asymmetry of decadal trends of age of air, Atmos. Chem. Phys., 17, 11 177–11 192, doi:10.5194/acp-17-11177-2017, https://doi.org/10.5194/acp-17-11177-2017, 2017.

Tegtmeier, S., Hegglin, M. I., Anderson, J., Bourassa, A., Brohede, S., Degenstein, D., Froidevaux, L., Fuller, R., Funke, B., Gille, J., Jones, A., Krüger, Y. K. K., Kyrölä, E., Lingenfelser, G., Lumpe, J., Nardi, B., Neu, J., Pendlebury, D., Remsberg, E., Rozanov, A., Smith, L., Toohey, M., Urban, J., von Clarmann, T., Walker, K. A., and Wang, R. H. J.: SPARC Data Initiative: A comparison of ozone climatologies from international satellite limb sounders, J. Geophys. Res. Atmos., 118, 12,229–12,247, doi:10.1002/2013JD019877, 2013.

Tegtmeier, S., Hegglin, M. I., Anderson, J., Funke, B., Gille, J., Jones, A., Smith, L., von Clarmann, T., and Walker, K. A.: The SPARC Data Initiative: comparisons of CFC-11, CFC-12, HF and SF_6 climatologies from international satellite limb sounders, Earth Syst. Sci. Data, 8, 61–78, doi:10.5194/essd-8-61-2016, 2016.

Tung, K. K.: On the Two-Dimensional Transport of Stratspheric Trace Gases in Isentropic Coordinates, J. Atmos. Sci., 39, 2330–2355, 1982.

von Clarmann, T. and Grabowski, U.: Direct inversion of circulation and mixing from tracer measurements - Part 1: Method, Atmos. Chem. Phys., 16, 14 563–14 584, doi:10.5194/acp-16-14563-2016, 2016.

von Clarmann, T., Glatthor, N., Grabowski, U., Höpfner, M., Kellmann, S., Kiefer, M., Linden, A., Mengistu Tsidu, G., Milz, M., Steck, T., Stiller, G. P., Wang, D. Y., Fischer, H., Funke, B., Gil-López, S., and López-Puertas, M.: Retrieval of temperature and tangent altitude pointing from limb emission spectra recorded from space by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), J. Geophys. Res., 108, 4736, doi:10.1029/2003JD003602, 2003.

von Clarmann, T., Höpfner, M., Kellmann, S., Linden, A., Chauhan, S., Funke, B., Grabowski, U., Glatthor, N., Kiefer, M., Schieferdecker, T., Stiller, G. P., and Versick, S.: Retrieval of temperature, H_2O, O_3, HNO_3, CH_4, N_2O, $ClONO_2$ and ClO from MIPAS reduced resolution nominal mode limb emission measurements, Atmos. Meas. Techn., 2, 159–175, doi:10.5194/amt-2-159-2009, 2009.

Waters, J. W., Froidevaux, L., Harwood, R. S., Jarnot, R. F., Pickett, H. M., Read, W. G., Siegel, P. H., Cofield, R. E., Filipiak, M. J., Flower, D. A., Holden, J. R., Lau, G. K., Livesey, N. J., Manney, G. L., Pumphrey, H. C., Santee, M. L., Wu, D. L., Cuddy, D. T., Lay, R. R., Loo, M. S., Perun, V. S., Schwartz, M. J., Stek, P. C., Thurstans, R. P., Boyles, M. A., Chandra, K. M., Chavez, M. C., Chen, G.-S., Chudasama, B. V., Dodge, R., Fuller, R. A., Girard, M. A., Jiang, J. H., Jiang, Y., Knosp, B. W., LaBelle, R. C., Lam, J. C., Lee, K. A., Miller, D., Oswald, J. E., Patel, N. C., Pukala, D. M., Quintero, O., Scaff, D. M., Van Snyder, W., Tope, M. C., Wagner, P. A., and Walch, M. J.: The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite, IEEE Trans. Geosci. Remote Sens., 44, 1075–1092, doi:10.1109/tgrs.2006.873771, 2006.

Waugh, D. W. and Hall, T. M.: Age of stratospheric air: theory, observations, and models, Rev. Geophys., 40, 1010, doi:10.1029/2000RG000101, 2002.

Yu, P., Rosenlof, K. H., Liu, S., Telg, H., Thornberry, T. D., Rollins, A. W., Portmann, R. W., Bai, Z., Ray, E. A., Duan, Y., Pan, L. L., Toon, O. B., Bian, J., and Gao, R.-S.: Efficient transport of tropospheric aerosol into the stratosphere via the Asian summer monsoon anticyclone, PNAS, 114, 6972–6977, 2017.