Answers to comments by Anonymous Referee #1

We thank the reviewer for his/her careful reading and his/her comments on our manuscript.
The point-by-point replies to the comments are provided below:

1. General comments:

Comment #1: *section 1: It should be better motivated why the non-conservation in a specific time interval is problematic. An interesting example could be the spatio-temporal pattern of wet scavenging, something the authors have on mind here anyway.*

Answer: Being a numerical error (which is often not small as we are showing), it is always negative. Also in the course of the paper the importance for wet scavenging should become very clear for the readers. Nevertheless, we have added additional text as proposed so that this becomes more clear from the beginning on.

Changes in manuscript: Added the following sentence after the first paragraph in Section 1.1: *This is obviously undesirable as it will affect wet scavenging, a very efficient removal process for many atmospheric trace species. Wet deposition may be produced in grid cells where none should occur, or too little in others.*

Comment #2: *section 3: There are plenty of very short sections and the overall structure does not become very clear. I would suggest remove sections 3.2 and 3.7 as these paragraphs have only a few lines, which would fit well within preceding paragraphs (3.2) or are probably not needed (3.7). Also, the numbering of section 3.4 to 3.6 is misleading, as 3.5 and 3.6 should be subsections of section 3.4 (general case).*

Answer: We admit that the structuring of section 3 can be improved. However, we prefer shorter sections as we think that they support comprehension by the reader. Thus, we have restructured the subsections as follows. Following the referee's suggestion, 3.1 is merged with 3.2 and 3.5, 3.6, 3.6.1 and 3.6.2 are integrated into subsection 3.4. Furthermore, we eliminated the old 3.6 and merged the short paragraph from there into 3.1 (the part of the previous 3.6.1). Considering comment 4 of referee #2, we rephrased some subsection headings. However, we want to keep subsection 3.7, the outcome of the derivation. With Fig. 9 and Table 1, an easy-to-comprehend overview of the algorithms derived is provided which forms the base for the remainder of the paper, and possible implementations in other contexts. Without this, the single components would have to be pulled together from various pages..

Changes in manuscript: We changed the structure and headings of section 3 as follows:
3 Derivation of the interpolation algorithm
3.1 Notation and basic requirements
3.2 Isolated precipitation in a single time interval
3.3 General case
3.3.1 Boundary conditions
3.3.2 Prescribing the central slope
3.3.3 Using the equal-area condition
3.3.4 Closing the algorithm under the condition of non-negativity
3.3.5 Monotonicity filter as a post-processing step
3.3.6 Alternative monotonicity filter yielding a single-sweep algorithm
3.4 Summary of the interpolation algorithms IA1 and IA2
3.5 The two-dimensional case

Additionally, we moved the short paragraph of the old 3.6 section right at the beginning of the new section 3.3.1.

Comment #3: *section 3.1: It should be made clear that the physical interpretation of g is the mean precipitation rate. If this is not the case, eq. (4) is not physically meaningful in the context of the discussion in the reminder of the paper.*

Answer: Yes, this was a sloppy wording.

Changes in manuscript: *Precipitation can then be represented* replaced by *The precipitation rate is then represented*

Comment #4: *section 3.1 and 3.2: I think you should at f(t) ≥ 0 as third condition for the construction of the algorithm. Also, it would be good to reference Tab. 2 in this section already.*

Answer: Thank you for this suggestion. You are right. This is necessary to be consistent and precise throughout the paper.

Changes in manuscript: We added the non-negativity condition f ≥ 0 as the second condition in the list of requirements in section 3.1. We also reference Table 2 in this context.
Our aim is to find a piecewise linear function f: [0, T] → R to serve as interpolation. We require it
1. to be continuous,
2. to preserve the non-negativity such that f satisfies
f ≥ 0 , and
3. to conserve the precipitation amount within each single time interval I_i , i. e.
Int_I_i f dt = g_i Δt
In particular,
… Eq(7) …
These conditions are also listed in Table 2 as the three strict and main requirements of the algorithm.
In accordance with this change we modified the sentence in Section 3.1 (old Section 3.2) right before Eq. (12) as follows*: In order to fulfil Eq. (5) (non-negativity) we need a solution satisfying …*

Comment #5: *section 4.2.3: Instead of comparing the global maximum (which is only one data point), it would be interesting to investigate the statistics of the maximum value during all events.*

Answer: We agree. The global maximum is indeed not very significant statistically. Therefore, from the R3h time series we derived precipitation events consisting of consecutive precipitation intervals with a minimum of 0.2 mm/h. The mean of the maxima of all these event is not used as the statistical parameter.

Changes in manuscript: We exchanged the maximum with the mean of the event maxima in Table 3. Additionally we removed the description of the maxima from the second paragraph in section 4.2.3 and added: *Instead of the global maximum, we use the mean value over all precipitation event maxima. The precipitation events are derived from R3h and defined as consecutive intervals with a minimum value of 0.2 \unit{mm\,h^{-1}} in each precipitation interval bounded by at least one interval with less than 0.2 \unit{mm\,h^{-1}}. The same periods are also used for the 1-hourly time series. The mean of all event maxima in R1h is best reproduced by the IA1 algorithm whereas IFP underestimates it by about 20 %.*
We also removed Figure 15 and the corresponding text since it is no longer needed. It was just used to describe the specific discrepancy in the global maxima values.

2. Specific comments:

Comment #1: *p. 2., l. 10ff: It sould be made clearer from the start that any linear interpolation will conserve the total precipitation amount globally, but not with in each time interval. While 1this becomes clear in the course of the discussion, clarifying this from the start will allow the reader to understand the problem more quickly.*

Answer: The reviewer says that “any” linear interpolation would have the property of global conservation. It is not very clear to us what this should mean exactly, and how this should eventually be proved. Therefore, we refrain from introducing such claims. However, we have added “in each time interval” for clarification in the line referred to, assuming that this will suffice to achieve the desired clarification.

Changes in manuscript: … as it does not conserve the total amount *in each time interval*, as will be shown below.

Comment #2: *Figure 1: Whue using supporting points shifted by half a grid-point? This is not reflective of the IFP algorithm as suggested by later plots.*

Answer: As explained both in the text and the caption, this figure serves to show the simplest possible reconstruction, not the IFP algorithm (which is shown in Fig. 2). It also makes clear why this simple solution was not adopted for FLEXPART - precisely because of the shifting of the supporting points which then are out of phase with the other input variables.

Changes in manuscript: No change as we think the text and caption are clear enough.

Comment #3: *p. 3, l. 7: You refer to the asymmetry of problem in the time coordinate. This has not been mentioned before and needs some more explanation.*

Answer: “Asymmetry” was referring to the half-interval shift of the supporting points. As this may be misleading, and in order to clarify the situation, we have rephrased the paragraph. Also, a footnote was added with respect to what is happening upstream, as spatially, the precipitation values in a lat-lon grid are not truly integrated quantities in the current version of ECMWF's MARS.

Changes in manuscript: Horizontally, the precipitation values are averages for a grid cell around the grid point to which they are ascribed*, and FLEXPART uses bilinear interpolation to obtain precipitation rates at particle positions. This causes the same problem of spreading out the information to the neighbouring grid cells and implied smoothing.\footnote{In reality, the problem is even more complex. In ECMWF's MARS archive, variables such as precipitation are stored on a reduced Gaussian grid, and upon extraction to the latitude-longitude grid they are interpolated without paying attention to mass conservation. This needs to be addressed in the future on the level of the software used internally by the MARS system. Our discussion here is assuming that this would already have happened, and even if that is not the case, adding another step of non-mass-conserving interpolation makes things even worse.} However, the supporting points in space are not shifted between precipitation and other variables as it is the case for the temporal dimension.*

Comment #4: *p. 6, l. 10: Why four conditions of mass conservation?*

Answer: This refers to Eq. 15 in Zerroukat et al., 2002. For clarification we rephrase the sentence as shown below.

Changes in manuscript: The function values at the left border points are determined by an additional spline interpolation *using the condition of mass conservation in the two preceding, the current and the following intervals*.

Comment #5: *p. 9, l. 18ff: T has not been defined.*

Answer: Right, it is missing. However, *T* was already used on page 6 at the beginning of Sec. 3.1. Hence, we added the definition there.

Changes in manuscript: Added definition of T in Sec 3.1 as *the time at the end of the period of precipitation input data.*

Comment #6: *p. 11, l. 5: Do you mean cases with either $g_i = 0$ & $g_{i+1} > 0$ or $g_i > 0$ & $g_{i+1} = 0$?*

Answer: There was a typo. For a positive data value $g_i > 0$ one has to distinguish between $g_{i+1} > 0$ and $g_{i+1} = 0$, leading to a lack of continuity.

Changes in manuscript: … *a case distinction is required to deal separately with $g_{i+1} > 0$ and $g_{i+1} = 0$ for a given $g_{i} > 0$.*

Comment #7: *p. 12, l. 13: The derivation of Eq. (24) needs a bit more explanation, as it does not directly follow from Eq. (16). It would be good to explain that you use the conditions for the two intervals on which f_{i+1} borders.*

Answer: In fact, the choice of slope enters the argument already earlier in Eqs. (11) and (12), which are used when deriving Eq. (23). From Eq. (23) it can then be directly inferred that condition (24) is sufficient. Note that the numbering of equations changed.

Changes in manuscript: (starting p.12, l. 9 after $f_{i}^{(1)} \ge 0 \wedge f_{i}^{(2)} \ge 0$). *For the central slope being defined as the mean Eq. (17), the subgrid function values are given by Eq. (12) and Eq. (13). The requirement of non-negativity of $f_i^{(1)}$ (Eq. (21)) and $f_i^{(2)}$ (Eq. (22)) then amounts to*
… Eq (24) …
Thus, a sufficient condition for the algorithm to preserve non-negativity is the restriction
… Eq (25) …

Comment #8: *Fig. 8b: It would be nice to have the original reconstructed precipitation curve plotted in the background to illustrate that also f_{i}^{1} changes.*

Answer: Thank you, that is a good idea. We added the curve in the plot.

Changes in manuscript: We changed figure 8 by adding the original reconstructed curve in orange.

Comment #9: *p. 14. l. 3: Add reference to left hand side of Table 1.*

Answer: Good idea. We added a reference to the Table (not explicitly "left side", as this is obvious).

Changes in manuscript: Added a reference at the end of the sentence: … *and is summarised in Table 1.*

Comment #10: *section 3.6.2: State explicitly that the main difference to IA1 is that the monotonicity* *filter is applied to all intervals not only does exhibiting a "M-" or "W-"shape. Als add a reference to the right hand side of Table 1.*

Answer: Yes, this can be made clearer.

Changes in manuscript: added reference to Table 1 after IA2 definition: … *henceforth and is summarised in Table 1.*
Also add the statement: *It applies the filter to all the intervals rather than to `M'- or `W'-shaped parts of the graph only, as it is the case in IA1.*

Comment #11: *p. 18, l. 7ff: Reorder the discussion in this paragraph so the requirements are discussed in the same order as listed in the Table.*

Answer: We agree with this suggestion, it will be easier to follow in this way. We rephrased subsection 4.1 so that it follows the correct order. We also found that the legends of Figures 10-13 still referred to the synthesised 3-hourly time series as R3h, even though they are called I3h (Ideal 3-hourly) in the text. Since I3h might be misleading considering the meaning of IA1 and IA2, we decided to call this time series S3h ("Synthesised 3-hourly").

Changes in manuscript: Rephrased the complete section 4.1. Additionally we exchanged I3h with S3h (Synthesised 3 hourly) and changed the figures accordingly.

Comment #12: *p. 21, l. 9: Can you reformulate this sentence, it is not clear to me what you mean with "precipitation rate weakened within two 3-h intervals"?*

Answer: We agree, this is not clearly formulated.

Changes in manuscript: … strong increase of the precipitation rate is *followed by a weakening* within two 3-h intervals.

Comment #13: *p. 22, l. 1f.: Do you mean you are using the data from the operational deterministic forecasts? Please reformulate accordingly.*

Answer: Yes, we rephrased the sentence.

Changes in manuscript: *Fields of both large-scale and convective precipitation in the operational deterministic forecasts were extracted from ECMWF's MARS archive with ...*

Comment #14: *p. 22, l. 14: "Convective precipitation occurs less frequently". Presumably you refer to periods with only convective precipitation in the ECMWF forecast? Also, is this statement true globally?*

Answer: This statement is generally true as can be seen from Table 5 (lower threshold) and from the standard deviation in Table 3, where values are higher for convective precipitation. Nevertheless, we eliminated the second part of the sentence in question and merged the sentence with the following one.

Changes in manuscript: *Convective precipitation occurs less frequently and its variability is higher (cf. Table 3) than in the case of large-scale precipitation which is more continuous and homogeneous.*

Comment #15: *p. 24, l. 18: This may also be due to the convection parameterisation used in the*

ECMWF global model. It is well known that parameterised convection is too weak and too frequent compared to either observations or convection-permitting model simulations.

Answer: While we agree with the reviewer's statement, it is not relevant here as we are just comparing the model's original precipitation with reconstructed precipitation. Our statement is true as can be seen from Table 5 for the lower threshold. We removed "*often falls only during a few hours per day.*" as this was not evaluated. The standard deviation is higher for convective precipitation as shown in Table 3; we have added this information.

Changes in manuscript: Convective precipitation occurs less frequently (cf. Table 5) and its variability is higher (cf. Table 3) than in the case of large-scale precipitation which is more continuous and homogeneous.

Comment #16: *p. 28, l. 1: This is not only true for the "light-blue region"! Frequency values are generally shifted towards higher IFP values in the first R1h bin compared to the second R1h bin.*

Answer: We have rephrased this paragraph, addressing the reviewer's comment and done some minor corrections.

Changes in manuscript: *For both precipitation types, but especially for convective precipitation, an overestimation of very low intensities is noticeable. Zooming in, the first R1h bin for the convective precipitation shows enhanced values corresponding to the bias towards wet cases in Table \ref{tab.drywet}. This is continued ...*

3. Technical corrections:

Comment #1: *p. 2, l. 15: "... quantification of atmospheric **transport**, such ..."*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #2: *p. 3, l. 22: remove "see" from figure reference*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #3: *p. 5, l. 19: ... ones (**e.g., Hämmerlin and Hoffmann, 1994; Hermann, 2011**). The ...*

Answer: Ok

Changes in manuscript: … ones (e.g., Hämmerlin and Hoffmann, 1994; Hermann, 2011). The …

Comment #4: *p. 5, l. 21: ... out **for example** by White et al. (2009) ...*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #5: *p. 5, l. 32: no comma after "problem"*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #6: *p. 6, l. 26: "... presented in **section 1**, we ..."*

Answer: Ok

Changes in manuscript: *... presented in Section 1, we ...*

Comment #7: *p. 9, l. 10: "$g_i * g_{i+1} > 0$ " would be clearer*

Answer: Standard math notation does not use multiplication symbols between two scalars.

Changes in manuscript: We have added a thin space instead.

Comment #8: *p. 10, l. 12 & l. 19: These sentences are slightly awkward, please reformulate.*

Answer: We have rewritten the whole text from l. 10 to l. 21. However, the sentence in l. 19 was not altered as we think that it is sufficiently clear.

Changes in manuscript: *This result is quite intuitive in the sense that it corresponds to the mean slope of the interpolation function throughout the interval I_i . Letting $k_i^{(2)}$ being determined via Eq. (17), the function values $f_i^{(2)}$ are uniquely determined by $f_i^{(1)}$ through Eq. (9) as*
... Eq. (18) ...
and thus the degrees of freedom are reduced accordingly.
Other possible approaches for the central slope which have not been selected would be:

(i) *Setting $k_i^{(2)} = 0$, which is the simplest choice for $k_i^{(2)}$. It was used for the isolated precipitation event. This means that f is constant in the central subintervals $I_i^{(2)}$, and thus $f_i^{(1)} = f_i^{(2)}$. This choice, however, does not reflect a natural precipitation curve.*

(ii) *A more advanced, data-driven approach would be to represent the tendency of the surrounding data values by the centred finite difference*
... Eq. (19) ...
The problem here is to fulfil the condition of non-negativity if g_i is small compared to one of its neighbouring values.

Comment #9: *p. 11, l. 9: "**With** Eq. (2) .."*

Answer: Ok, we rephrased the sentence.

Changes in manuscript: *With the additional Eq. (23) for the function value f_{i+1} , having Eq. (21) and Eq. (22) for the sub-grid values $f_i^{(1)}$ and $f_i^{(2)}$, respectively, the algorithm is now closed.*

Comment #10: *p. 11, l. 20: Add "as discussed in the following paragraphs."*

Answer: Ok

Changes in manuscript: … looked at *and are discussed in the following paragraphs.*

Comment #11: *p. 11., l. 21: Remove "thereby"*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #12: *p. 12., l. 4: “**The** preservation ... requirement, **as discussed above** . In ... for the **nonnegativity** ...”*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #13: *p. 12, l. 5: The sentence is somewhat awkward, could you reformulate just using the equations constiting the algorithm so far>?*

Answer: We agree that it is somehow awkward. We reformulated the sentence.

Changes in manuscript: *The algorithm consisting of Eqs. (21), (22), and (23) (function values f_{i+1} determined via the geometric mean) is considered as the base. It has the strong advantage not to require a case distinction between vanishing and positive values.*

Comment #14: *p. 17, l. 11: “... requirements, as **formulated** in ...”*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #15: *p. 18, l. 2: “... with **constant** precipitation ...” ?*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #16: *p. 18, l. 6: “... with t**he results from the reconstruction algorithms** ... ”*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #17: *p. 18, l. 10: “... as **the** input ...”*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #18: *p. 18, l. 22: “... both algorithms (not shown). ...”*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #19: *p. 19, l. 2: “ ... in addition **requires** some ...”*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #20: *p. 19, l. 10: Replace the phrase " go on". The current formulation is rather casual and unspecific.*

Answer: Agreed.

Changes in manuscript: … how these wiggles **would further proceed in additional intervals**, …

Comment #21: *p. 19, l. 17: "... the way, **in which the monoticity filter is applied**. In ..."*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #22: *p. 21, l. 15ff.: "... retrieved **with 1-h and 3-h** time resolution. ... algorithms, **while the 1-h data are used to validate the reconstructed** ..."*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #23: *p. 22, l. 13f.: "... one **dominated by large-scale** and another by **convective precipitation**."*

Answer: Ok

Changes in manuscript: *... dominated by large-scale and another one by convective precipitation.*

Comment #24: *p. 22, l. 17: Please reformulate this sentence, it is somewhat awkward.*

Answer: Ok.

Changes in manuscript: *Furthermore, a criterion for the selection of the sample was that it should exhibit monotonicity problems as discussed above.*

Comment #25: *p. 22, l. 18: "Characteristic" for what?*

Answer: We admit that this was the wrong word. We exchanged "characteristic" with "typical".

Changes in manuscript: *The two days are typical; they do not represent a rare or extreme situation.*

Comment #26: *p. 22, l. 26 and 30f.: Please ensure you are using a consistent nomenclature for date-times througout the paper.*

Answer: Agreed. Adapted several occurrences of dates / times.

Changes in manuscript: changed date-time to e.g. 11 January 18 UTC

Comment #27: *p. 22, l. 29: " ... last longer **(Fig. 14). This** ..."*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #28: *p. 25, l. 14: "overall averages": The column labelled "mean"?*

Answer: Do you mean p. 24, l. 14 ? Ok, we agree that it is not consistent. We changed "averages" to "means".

Changes in manuscript: … *overall means* …

Comment #29: *Table 5, caption: "Relative deviations (δ_d **and** δ_w) ..."*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #30: *p. 27, l. 1: "... more **points** fall ..." ?*

Answer: Ok

Changes in manuscript: changed as suggested

Comment #31: *p. 28, l. 19: The nomenclature of IA1m is slightly confusing, as IA2m refers to the average of forward and backward execution of IA2.*

Answer: We admit that this nomenclature might be slightly confusing. However, "m" stands for "modified" and not for "mean" in both cases, which is pointed out in section 4.3, second paragraph and section 4.1, third-last paragraph.

Changes in manuscript: No changes made as we think that the meaning of "m" is clearly stated in the manuscript.

Comment #32: *p. 29, l. 28: "... integration of **the** method ... itself **for the** temporal ..."*

Answer: Ok

Changes in manuscript: changed as suggested