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Geoscientific Model Development Discussions

Interactive comment on "Detection, tracking and event localization of interesting features in 4-D atmospheric data" *by* S. Limbach et al.

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Thank you very much for your very constructive, helpful and detailed comments on our paper. We worked thoroughly through all the points and tried to fix and improve the mentioned aspects. Especially pointing us to all the articles on flow visualization was very helpful for setting our work into a better context, since we approached the problem more from an atmospheric sciences- and image processing point of view.

General comments

1) The authors do a good job in presenting literature that in the atmospheric domain has appeared on feature detection. In other domains, however, significantly

more literature has been published on the topic. In my opinion, the developed algorithm is not sufficiently put into the context of existing algorithms for similar purposes. In particular in flow visualisation, a number of studies have been published on feature extraction and tracking, including 4D flow data. I acknowledge you have cited the work of Reinders (3016/15). To name a few others, I refer to the overview by Post et al. (2003) and, more specifically, to the works of Samtaney (1994), Ji et al. (2003), Fuchs et al. (2008), Muelder and Ma (2009) and references therein. I suggest to complete the literature review in Sect. 1 (3016/5ff.) and, in particular, to detail on how the content of Sects. 2 and 3 relates to these works.

We completely revised the introduction section from 3916/5 on. We compare our method with the approaches from the field of flow visualization and emphasize the differences, shortcomings and strengths of our method compared to the other approaches. Throughout the document we now refer to these approaches.

2) Please clarify your contribution. The three points mentioned in 3016/16-23 misleadingly suggest to the reader that are no other algorithms that operate on time series of 3D data and that are able to track more than a single feature. In Sects. 2 and 3, it is not clear to me which parts of the algorithm are similar to existing methods and what is new. As a suggestion, you could put your contribution to event tracking in grid point space into the centre of the manuscript and stress which kind of atmospheric studies it enables.

As part of our complete revision of the introduction on our method, we removed the three mentioned points and emphasize now the event localization as our main contribution. In addition, we mention that we were able to apply a simpler method for the detection and tracking of the atmospheric features we were interested in, compared to other methods. The point is that in any of the algorithms mentioned in the introduction, at least one iteration over the whole data set is necessary. Muelder and Ma require the iteration for the detection of holes inside features and birth events (though they argue that one does not need to scan for birth events during every time step, but this way they may always miss short living segments). But if they have to scan the whole data set (minus the already detected boundaries) anyway, the advantage of using the boundary shrinking/growing-technique compared to the "traditional" region growing technique becomes obsolete (for this specific scenario). Silver and Zabusky and Wang build an octree which speeds up the search for seed points. Additionally, it allows a fast evaluation of multiple different thresholds and fast set operations, as well as fast visualization and efficient caching. However, our method avoids the creation of the spatial data structure since we do not require the additional speedup later on. Instead, we directly select and cluster the regions during our single-pass iteration. A closer analysis of the algorithms computational and memory costs is added to the new sub-section 3.4.

3) Your rationale for using region growing as segmentation strategy is not clear to me as well. In 3016/9ff you state that your development was inspired by the work of Siegesmund (2006). Please elaborate on why his approach was favourable to you over other segmentation methods. Which other segmentation methods would have been an alternative? Are there types of atmospheric flow features that are not detectable with region growing? In 3016/7 you mention that there are different variations of region growing. I suggest to motivate your approach in Sects. 2 and 3 in the context of these variations.

We prefer to no longer state that our algorithm is an extension of region growing, based on the information from the additional articles on flow visualization. Instead we either removed or rephrased the corresponding sentences in our article such that they now state that we were inspired by the ideas of region growing. What we do for detection and tracking of features is similar to the selection/clustering steps described by van Walsung. We also revised the corresponding parts of Section 2 and 3 accordingly.

4) You claim your algorithm to be efficient (e.g. 3014/2, 3016/16, 3026/9). How-

ever, the only paragraph providing vague information on the computational performance is 3033/24-29. I suggest to add supporting facts and statements to the manuscript (e.g. information on the run-time, properties of the used data structures).

We cannot run a full set of benchmarks of the algorithm for this paper. However, we now describe the used method and data structures in more detail in Section 3, and we added Section 3.4 which contains a more detailed discussion of the required memory and on the computational complexity.

5) Language: I have listed a number of suggestions to improve the manuscript below. Nevertheless, I recommend you to recheck the correctness of the text. Some complicated sentences could be written in a more concise manner to make them better understandable, and a number of redundant words (e.g. "so-called") should be removed.

We already applied some checks and we will further check our manuscript in order to improve the language of the text. We removed all occurrences of "so-called".

Specific comments

Title

I recommend changing the title of the paper to "Detection, tracking and event localization of jet stream features in 4-D atmospheric data". This much better reflects the actual content of the paper. Alternatively, at least the word "interesting" should be removed from the title (and any other parts of the manuscript), as it in my opinion is a too vague adjective: what is "interesting"? I suggest to rather explain in the text why the detected features are interesting.

We agree and changed the title accordingly.

Abstract

- Take care to use consistent time (e.g. "we extended", "we compare", etc.)

ok

- 3014/2 I suggest to remove "interesting" (see title)

removed

- 3014/5 change "we extended the basic idea", to "we extend the method ..."

We rephrased the whole sentence, the beginning of the abstract now reads: "We introduce a novel algorithm for the efficient detection and tracking of features in spatiotemporal atmospheric data, as well as for the precise localization of the occurring genesis, lysis, merging and splitting events. The algorithms works on data given on a four-dimensional structured grid. Feature selection and clustering are based on adjustable local and global criteria, feature tracking is predominantly based on spatial overlaps of the feature's full volumes."

- 3014/9 remove "so-called", I suggest to state explicitly what an event graph is (e.g. "a directed acyclic graph containing..")

done

- 3014/13 "tested" sounds odd. I suggest "we present a case study of"

rephrased

- 3014/16 change "previous" to "a climatology from a previous study"

ok

Sect. 1

- 3015/1 remove "Therefore, " and add a paragraph break. This increases the strength of the argument in the following sentence

ok

- 3015/3 remove "so-called"

ok

- 3015/8 remove "s" in "considers"

Here we refer to one ("the earliest") study and therefore think that "considers" is correct.

- 3015/10 remove "In addition, the"

ok

- 3015/25-27 check grammar

Rephrased: "As a consequence, these feature identification and tracking algorithms treat the spatial and temporal dimensions of atmospheric data very differently."

- 3016/1 change "of this study was" to "of these studies were"

ok

- 3016/5-24 This paragraph should be revised (cf. general comments 1-3)

Done. We reformulated and extended this paragraph considerably based on the recommended papers and some of the articles referenced there within.

- 3016/25-26 The sentence suggests that the ozone hole segmentation is also part of this paper. I suggest to not mention the ozone hole study at all (this also applies to Sect. 5), as it appears confusing. Why do you not present any results from that study? Alternatively, is there a citable reference in which results from the ozone hole study were used? Could you include any results?

All of these studies were internal, informal tests of our method, so there are no citable sources. We removed the reference from this section.

- 3017/4 What do you mean by "objects"?

Replaced by "In the upcoming section, we provide definitions of some fundamental terms and structures required for a formal description of our algorithm.".

Sect. 2.1

- 3018/23 insert "have", "we have worked"

done

- 3018/23 Is your algorithm able to handle grid topologies other than regular lat/lon as well?

Any grid works as long as grid indices reflect cell adjacencies, and the mass and center of mass attributes of features can be computed (they don't need to be exact, only comparable) if the additional attribute-based feature-tracking mentioned in section 3.2 should be applied.

Sect. 2.2

- Please put the definitions in this section in the context of related work (general comment 1). For instance, the event graph terminology has also been used by Reinders et al. (2001); Samtaney et al. (1994) describe feature evolution by means of a directed acyclic graph.

We added some references, including the two mentioned here.

- 3019/24 remove "so-called"

ok

- 3020/12 I assume "small and fast moving" depends on grid and time resolution, you might want to state this

We now explicitly state this.

- 3020/12 I suggest to refer to the literature to indicate what more involved techniques could be

Thank you for this useful suggestion. We extended the paragraph and added some references related to the additional tracking technique we use.

Sect. 2.3

- 3022/10 It is not clear to me on which literature this paragraph is based. What are "many traditional .. methods"?

Due to the revision of the previous paragraphs, we decided to completely remove Section 2.3 from the article, and to replace it by a new Section 2.3 focused on the definitions of the several criteria for the characterization of the objects to be segmented. I moved most of the content of the introduction of Section 3 into this new Section 2.3. I also renamed the “restricted homogeneity criterion” to “local homogeneity criterion”, as this name better reflects the idea behind it. Here is a preliminary version of this new section:

“The way in which our algorithm selects and clusters the samples of the input data set to create the relevant three-dimensional features depends on the formulation of three different predicates. We incorporated ideas from region growing and other segmentation methods that use different types of binary predicates for feature detection. The “selective visualization” method proposed by van Walsum (1995) uses a *selection criterion* and a *connectivity criterion* in order to select and cluster samples from the input data set. In other methods, a *global homogeneity criterion* is used for the identification of connected regions of interest, see Zucker (1976), Jain et al. (1995), Pal and Pal (1993).

Our method selects single samples of our input data set using a *local selection criterion* (l). Samples are clustered by means of a *local homogeneity criterion* (h). A *global selection criterion* (g) is used to select potential segments at the end of the segmentation process. The main task to be fulfilled before the algorithm can be applied to different types of atmospheric phenomena is to find adequate and applicable predicates h, l and g.

[Local selection criterion] The *local selection criterion* $l : X \rightarrow \{\text{TRUE}, \text{FALSE}\}$ decides whether or not a single sample belongs to a potential three-dimensional feature, based on any of its local characteristics.

This criterion can be applied to discard unsuitable samples right from the start. Depending on the objects to be detected, the formulation of a local criterion may be sufficient for a full classification of the features we want to identify. A simple, but nevertheless powerful, formulation of such a selection criterion is the test of whether the samples lie above or below a given fixed threshold. In our case study on jet streams,

for example, we used a height-dependent threshold on the wind speed.

For the clustering of the selected samples, we use a binary predicate called the *local homogeneity criterion*. We define it as follows:

[Local homogeneity criterion] The *local homogeneity criterion* $h : X \times X \rightarrow \{\text{TRUE}, \text{FALSE}\}$ decides whether a given pair of neighboring samples $x := x_{i,j,k,t} \in X$ and $x' := x_{i+i',j+j',k+k',t+t'} \in X$ with $i', j', k', t' \in \{-1, 0, 1\};\ |i'| + |j'| + |k'| + |t'| = 1$ belongs to the same segment, or not. h has to be commutative.

For scalar sample values, an obvious formulation of such a predicate could be a threshold on the difference between the sampled values of x and the adjacent sample x'. If we analyze a vector field, we could impose a threshold on the angle between the directions of x and x'. In many of our applications, however, we know in advance that our input data field is homogeneous, such that we may assume $h(x, x') := \text{TRUE}$ for all pairs of adjacent samples x, x'.

Many applications based on region growing methods, for example Silver and Zabusky (1993), start the segmentation with sets containing single seed points. Neighboring sample points are added iteratively to these sets, as long as they are still associated with the same features (for example based on thresholding or on a global homogeneity criterion). The initial seed points often correspond to extremal points, such as local minima or maxima, of the underlying data. Since we aim for a segmentation in only one iteration over the data set, we cannot know in advance whether a connected set of samples will contain any such extremal point or not. To compensates this, we use an additional predicate to discard segments at the end of the iteration based on any of its global attributes. This predicate is the *global selection criterion*:

[Global selection criterion] The *global selection criterion* $g : \mathcal{P}(S) \rightarrow \{\text{TRUE}, \text{FALSE}\}$ decides whether or not to keep a candidate four-dimensional segment based on any of its global characteristics.

For the segmentations of jet streams, we decided to use the global selection criterion as a filter on the lifespan of the detected wind events. In order to exclude short peaks of wind speed, we decided to discard segments with a lifespan of less than 24 hours."

- 3022/10-20 The terminology in this paragraph confuses me. Why do you add samples to a segment ("S") instead of a feature, as defined in Def. 3? Or does S denote a set of samples, as line 19 suggests? In line 13, do you mean eight neighbouring samples for a TWO-dimensional case (four-dimensional would be more, I assume)?

We introduce the predicates without going into details of region growing segmentation in the new Section 2.3. now which is hopefully less confusing.

- 3022/Def.11 Similar definitions for a homogeneity criterion are used in the literature as well (e.g. Pal and Pal, 1993)

We removed the explicit definition of the homogeneity criterion, but added the new reference to Pal and Pal when the homogeneity criterion is mentioned in new Section 2.3.

- 3022/26 "typical" in which respect?

This phrase is no longer present in the revised version of Section 2.3.

- 3023/5 "common approach" in which respect?

We rephrased that sentence, using the adjective "obvious" now, instead of "common".

Sect. 3

- 3023/17 I suggest rephrasing the sentence to "The region growing methods introduced by XYZ require one or more.."

Sentence was moved to Section 2.3, we revised it and added a reference.

- 3023/23 replace "applicable" by "practical" or "feasible"

Now invalid (sentence removed).

- 3023/23-25 What is an "automatic search" in this context? Why is it inefficient?

Now invalid (sentence removed). The way the algorithm is implemented, including the one-pass over the 4D data set, is now motivated and set into context at the beginning of section 3. Here is the preliminary version of this beginning:

"In the previous section, we defined the input and output of our algorithm, as well as all required predicates for the characterization of the features we want to detect. This is the basis for the detailed description of the implementation of our algorithm in this section.

In contrast to existing methods used for the detection of *atmospheric* flow features, our new method is capable of efficiently detecting three-dimensional atmospheric features and their development over time. We adopted ideas from several methods from the field of flow visualizations. However, our method is unique in that it is capable of estimating the locations of merging and splitting events in grid space. In addition, we could simplify the implementation to the point that we only need one iteration over the data set. By selecting and clustering the data during this one iteration, we avoid the construction of additional spatial data strutures, as for example done by Silver and Zabusky (1993). Muleder and Ma (2009) track single features very efficiently by operating on the boundary of the feature only. If new features, as well as holes inside existing features should be detected, however, a full iteration over the data set (except for the already detected boundaries) is unavoidable. Due to the simplicity of our method, it is potentially well suited for parallel processing.”

- 3023/26 I do not understand what exactly you mean by “only require one sequential iteration”. The text suggests that your algorithm differs in this respect from the approaches used by other authors. How does it differ, for instance, from Muelder and Ma (2009), who at any timestep iterate through all unsegmented grid points to detect any new features (Sect 2.3 in their paper)?

This is now discussed at the beginning of Section 3.

- 3023/26 “efficiency considerations”: can you support this by numbers? What speedup can be achieved?

The role of the local homogeneity criterion is now discussed in the new Section 2.3. The efficiency is briefly discussed in the new Section 3.4.

- 3024/23-25 This is an important statement. I suggest to put more emphasis on it and to support it by examples of how the predicates could look like. Sect. 3.1

Sentence moved to Section 2.3. We added examples for all predicates.

- 3025/5 replace “previous algorithm outline” by “Algorithm 1”; sentence can be split into two

done

- 3025/7 “On the way” sounds unscientific, I suggest “During execution”

Yes, this sounds better.

- 3025/8 “later” is redundant

Ok, we rephrased the sentence.

- 3025/12 “any .. any”: I suggest to rephrase this in a more concise manner; what is “any candidate feature”?

We removed this sentence.

- 3025/13 rephrase “we look at all”

Replaced by “we examine...”.

- 3025/19 What is an “appropriate data structure”? Please specify.

We extended this section considerably and describe the data structures used. The preliminary version of this part is now as follows:

“The algorithm represents the candidate features using a union-find data structure. This data structure corresponds internally to the node of a tree, holding a reference to a single parent node. The root of each tree is the unique representative of all the candidate features in the tree. Candidate features from different trees are merged by setting the reference from the root of the tree with smaller rank to the root of the other tree. In our implementation, each representative candidate feature internally stores a list of indices of all samples associated with the corresponding feature, as well as a set of attributes, such as center of mass and an approximation of the volume. The list of sample indices and the set of attributes are updated each time two candidate features are merged. To keep the number of candidate features, and with it the rank of the internally stored trees low, we add single samples with only one neighboring candidate feature directly to the existing feature instead of adding a new node to the tree. For the sake of simplicity, we omitted the distinction of this additional case in our algorithm outline. The union and find operations are further sped up by using path compression. For a direct access to the candidate features associated with each sample, we store the references in a three-dimensional array. At the end of each time step, the set of all representative candidate features corresponds to the set of real features F_t."

Sect. 3.2

- 3026/3-4 "many possible approaches": Please be more specific. Which types of objects can be imagined, which approaches are suitable? I suggest to refer to the literature.

We rephrased the sentence which now reads "There are different approaches to achieve this goal ..." and we specifically mention overlap and nearest neighbour approaches with references.

- 3026/8-19 It is unclear to me why checks for spatial overlapping and feature size are sufficient. For which types of features do they work? What happens if the time step of the available dataset is too large to allow for spatial overlap of the features? Are alternative checks mentioned in the literature?

This is now covered. For the jet streams, the spatial overlapping is sufficient for most cases. The extended tracking of the other cases based on attributes is discussed as well and compared to techniques described by Samtaney et al. and Reinders et al..

- 3026/9 I might have missed this, do you explain the details of the data structure that is extended?

Throughout the description of the algorithm, we now describe the data structures in more detail. The representation of the candidate edges for spatial overlaps is now more detailed. We also improved the algorithm outline to clarify how information is managed (conceptional) during the execution of the algorithm.

- 3026/11 rephrase "finish the association", e.g. "associate a sample.."

We completely changed the structure of this sentence.

- 3026/14-15 sentence sounds odd, rephrase

Rephrased.

Sect. 3.3

- I suggest you emphasize your contribution described in this section, as it is the basis for the results presented in Sect. 4: Why is it particularly interesting for atmospheric applications to determine the locations of the events? What is new compared to existing approaches (e.g. the boundary growing approach of Muelder and Ma, 2009)?

We extended the text at the beginning of Section 3.3 by adding some words about our motivation and emphasizing the difference of our methods compared to other methods. Note that the application shown in section 4 will also greatly help the reader to acknowledge the usefulness of the event localization.

- 3027/1 – 3028/4 This part is difficult to understand. You provide a very good illustration of the process in Fig. 3. I suggest to first describe the localization of a merging event in the 2D case by means of Fig. 3, then generalize the concept to three dimensions. You might also want to state at the beginning of the paragraph that (and why) in order determine the grid points at which merging has taken place, a region growing processes composed of two stages is suitable. Then describe the details.

We extended this section as well, motivating the ideas behind the estimation of the locations. We also added an earlier reference to Figure 3 and a (slightly) more detailed description of the second growing phase.

- 3027/1 “The basic idea behind ..” is redundant, e.g. “Localization of .. is based on a search ..”

We use the proposed formulation, thanks.

- 3027/2-5 Difficult to understand, “steps on the lattice”, “grow” and “touch” are unclear.

We avoid or explain these terms now, and also restructured this section.

- 3027/8-9 Difficult to understand, reads as if the feature (instead of the merging event) is identified by the edges.

We removed the end of this sentence. It should hopefully be clear at this point to the reader, that the events can be identified by looking at the number of outgoing/incoming edges at the nodes of the event graph.

- 3027/17ff. You might want to point out that this region growing process is separate from the feature detection phase

We think that it should be clear to the reader that this section is not about the feature detection and we think that referring to feature detection again might be rather misleading.

- 3027/24ff Why is the second growing phase necessary? How do you determine the number of steps? What do you mean by “fuzziness” in this context?

We explained the motivation behind the second growing phase in more detail at the beginning of the section. The second growing phase is not fundamental, but it provides more substantial events that consist of a critical number of grid points. In the end, it depends on the application whether a representation of the event as a thin border

that unlikely reflects the exact position of the event, or an extended region which likely includes the event location is preferred.

Sect. 4

- 3028/6-9 It would strengthen the manuscript if you would state for which types of phenomena the algorithm has been tested and why the jet stream case representative (cf. the comment to the ozone hole case in Sect. 1).

We now mention all the phenomena for which we performed preliminary tests of the algorithm. The jet stream application has been the first one for which we analyzed the results in great detail. Publications on applications for different flow features are however planned for the coming months.

Sect. 4.2

- 3030/18 Why did you choose 10m/s to be added to the value of Koch et al. (2006)? Can you provide any information on the sensitivity of the result on this parameter? Is it important?

Koch et al. looked at vertically averaged winds extending over the layer from 500 to 100 hPa. Since we work with local winds, a higher threshold should be used to obtain comparable results. Of course the results are sensitive to the threshold but the current values are generally accepted in the community to characterize jet streams.

- 3030/20-21 (“We do not state..”) Fine for this case study. However, as you have introduced these criteria in Sects. 2 and 3, it would strengthen the manuscript if you provided an alternative example of how they could be used.

We added a global selection criterion testing for a minimum lifespan of a 4D-segment of four or more time steps. We will update the climatology plots for the revised version.

Sect. 4.3

- 3032/15-18 The sentence "If now, looking.." sounds odd, rephrase

We removed this sentence.

- 3032/20-29 You are using a uniform lat/lon grid. Thus, the actual area represented by each grid point is not uniform (depends on latitude). Have you considered this when using the number of grid points of a segment as size indicator for the analysis?

Yes, we summed up the cosines of the latitude of the grid cells. I added a remark to clarify this.

Sect. 5

- I suggest to more strongly emphasize the contribution of the paper and the new results obtained from the case study.

In the revised version, we will consider this point and mention more clearly the meteorological importance of the results from this study.

- 3033/5 cf. comment on the ozone hole case in Sect. 1

We rephrased the corresponding sentence and clearly state that so far we only did preliminary tests of the algorithm for different features.

- 3033/12-13 Smaller than what? Faster than what?

We added more information. We meant in comparison to jet streams on grids with comparable resolutions.

- 3033/17-23 What about prediction-correction methods such as presented by Muelder and Ma (2009) and approaches that include time information in the feature detection process (e.g. Ji et al., 2003, and Fuchs et al., 2008)?

We have added references to the papers by Fuchs et al. and Muelder and Ma.

- 3033/24-29 I suggest to move any information on performance and efficiency of the method into another section (cf. general comment 4).

We added Section 3.4 for this, and slightly rephrased the paragraph here. The preliminary version of Section 3.4 reads as follows:

"Our method profits from simplifications made on the basis of the prior knowledge about the atmospheric features we want to identify and track. Other methods, for example the approach by Muelder and Ma (2009), require at least a single iteration over the whole data set, if all new features and holes in existing features should be detected. Related approaches, for example Silver and Zabusky (1993), use octrees or other spatial data structures to archive speedups. Since our algorithm selects, clusters and tracks features during a single iteration over the data set, we would not profit from the additional maintenance of a spatial data structure. The only exception would be if the available memory was very limited, such that the two additional three-dimensional arrays we use for storing the links to the candidate features of the current time step, and to the features of the previous time step, could not be allocated. In such cases, it would be reasonable to replace these two array by an appropriate spatial data structure, in order to save memory at the expense of speed."

Figures

- Fig 1: I suggest to add coastlines and/or a graticule for better readability of the figure. Rephrase the caption to "showing all detected three-dimensional features at a single time step".

This is a useful suggestion, thank you. The caption has been rephrased.

- Fig 5: The colour bar extent includes values below 40m/s, although these (according to the text) are not included in the segments. As the earth is depicted in blue, this is confusing. I suggest to have the colour bar only show values above 40m/s.

In the revised version we will improve the colour bar as suggested.

- Fig 6 and Fig 7: I suggest to add a graticule, similar to the figures in Koch et al. (2006), to improve readability.

We try to add a graticule (not straightforward with our software).

- Fig 8: What are the units of the colour bar? What are the units of "cos-weighted gridpoints"?

The color bar shows "number of sub-segments". The other unit is "number of cos-weighted gridpoints". We now mention the unit in the caption.

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