# Reply to anonymous reviewers and list of changes

Gabriel M P Perez

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## 1 Response to Reviewer 1

### 1.1 General comments

We appreciate the Reviewer's insightful comments and suggestions. The Reviewer pointed out the following general issues:

**1 - Connection between sections**: We have added transition paragraphs at the end of each section to motivate the next. The text now reads more seamlessly.

**2 - Motivation for going to a climatological study**: We have now made it more explicit in the introduction the need for running the LCS detection algorithm in a climatology. We have incorporated the Reviewer's suggestion to motivate it through the need of investigating the impact of LCSs in moisture and rainfall at different scales.

**3 - Conclusion improvements**: We have expanded the conclusion section adding more on the potential applications of the methodology for convergence zones in other regions as well as forecast applications.

Other issues pointed in the Reviewer's general comment are addressed in the original submission. For example, the reviewer questions about the period employed in the climatological analysis. The period is stated in Line 161 of the original submission. Similarly, the Reviewer questions about how the methodology was applied in the entire climatology. This is expressed in the methodology diagram in Figure 3: the method is repeated in sliding time windows of 2 days separated by 6 hour intervals.

### 1.2 Specific comments

**Line 22** We appreciate the Reviewer's suggestion to use "coherent winds" instead of "coherent trajectories". However, trajectories are used to highlight the Lagrangian nature of historical definitions of the ITCZ: it was considered to be and interface of air parcels originated from both hemispheres; thus the use of "coherent trajectories".

**Line 23** We thank the Reviewer for the question. We consider that previous studies were focused on both quantitative and qualitative analyses. However, the automated methodologies employed by them required previous knowledge of the phenomena, such as the typical shape and intensity of the SACZ cloud band. Thus, heuristic rules were developed to identify SACZ events that attended their existing expectations.

**Line 130** We thank the Reviewer for this suggestion. The formulation of the Cauchy-Green tensor was done in 3D Cartesian space by transforming the lat-lon departure points in x, y, z coordinates. We have added this information in the revised version.

**Line 169** : We thank the Reviewer for this suggestion. We have performed sensitivity tests to identify the smallest relaxation angle able to still capture LCSs associated with convergence zones attempting to preserve properties of Shadden's (2005) LCSs. Peikert and Sadlo (2008) suggest 45°, but we found that 15° sufficed for our case. We have included this brief explanation in the revised manuscript. We haven't performed further analysis regarding shear regions along the Andes, but we plan to do so in future studies.

**Line 176** : No, the +-20% sensitivity tests refer only to the intensity and length filters. We thank the r for this suggestion and included a short table summarising the parameters employed in the methodology.

**Figure 6** : As suggested by the Reviewer, we have now included a definition of "frequency of occurrence" in the manuscript.

**Line 202** : We appreciate the Reviewer's suggestion and have rephrased the definition of LCS accordingly.

**Line 210-214** : We agree with the Reviewer that LCSs in the neighborhood of the Andes can be shear LCSs. However, we do not believe this to be the case of the structure labeled as "1" in Figure 5. This structure originates around a cyclonic circulation feature in South Atlantic and progresses with the confluence of the front associated with the cyclone. Furthermore, this event, as described in Line 191 of the original submission, was classified by Brazilian meteorology agencies to be an event of South Atlantic Convergence Zone.

We think that the source of confusion is that we positioned the label "1" in Figure 5 at an unfortunate location. We have replaced it to make it clear that we refer to the attractive LCS described by the Reviewer and we have attempted to clarify its interpretation in the text.

**Line 241** : We thank the Reviewer for this comment and provide relevant citations as requested. However, we disagree with the Reviewer's comment about the relationship between FTLE and mixing. The backwards FTLE at a given time is an integrated measure of the attraction of trajectories arriving in a neighborhood. Thus, ridges of the backwards FTLE can diagnose high mixing efficiency because arriving air parcels underwent substantial stretching. This is consistent with the concept of mixing proposed by Ottino (1989): "Mixing is stretching and folding".

### 1.3 Technical comments

We appreciate the Reviewer's suggestions about Figures 8 and 4. We have improved these figures accordingly as well as provided an improved color palette in Figure 1.

### 1.4 References


1. Ottino, Julio M., and J. M. Ottino. The kinematics of mixing: stretching, chaos, and transport. Vol. 3. Cambridge university press, 1989.

2. Peikert, Ronald, and Filip Sadlo. "Height ridge computation and filtering for visualization." 2008 IEEE Pacific Visualization Symposium. IEEE, 2008.

3. Shadden, Shawn C., Francois Lekien, and Jerrold E. Marsden. "Definition and properties of Lagrangian coherent structures from finite-time Lyapunov exponents in two-dimensional aperiodic flows." Physica D: Nonlinear Phenomena 212.3-4 (2005): 271-304.


## 2 Reviewer 2

### 2.1 General comments

We appreciate and thank the Reviewer for the insightful comments and suggestions. The Reviewer pointed out the following general issues:

**1 - Abbreviations** We have addressed the issue of unexplained abbreviations in the revised manuscript.

**2 - Title** We have considered the Reviewer's suggestion about including "Coherent structures" in the title. We will be adding these as keywords for the final manuscript. However, our analysis is not limited to coherent structures (FTLE ridges). It also includes correlations between a metric of mixing efficiency (the FTLE scalar field) and water vapour and rainfall. Since "coherent structures" can be studied within the framework of chaotic mixing, we believe that the current title better express the contents of the paper.

### 2.2 Minor comments

**Line 45** We thank the Reviewer for this suggestion. We have detailed the definition of convergence zone as suggested.

**Further approaches do not count elongated structures as coherent sets, why does this work here?** We thank the Reviewer for this comment. However, we are not entirely sure about which part of the manuscript the Reviewer is referring to here. We do describe the LCSs on our case study as a "coherent ensemble" because they last for a considerable amount of time and seem to move as a group. To avoid confusion we have removed the word "coherent" from this sentence (Line 221).

**"Are there further approaches to identify coherent structures of meteorological phenomena besides the FTLE?"** We thank the Reviewer for this question. In meteorology there are many methods to identify coherent structures such as hurricanes and extratropical cyclones. However, from a purely kinematical point of view, there is a limited but growing number of approaches, such as the geodesic transport barriers of Haller and Beron-Vera (2012).

**Fig 4** Here the departure positions are shown in units of degrees Latitude and Longitude. We have now clarified this in the figure caption.

**TCWF** We thank the reviewer for this observation. We have specified this abbreviation in the revised version.

**"figures are often placed far away in the paper"** We thank the reviewer for this comment. We have rearranged the figures in the revised version.

**Figure 5** We appreciate the Reviewer's comment and have added a brief explanation of the LCS computation. However, this computation is described in detail in the Methodology section.

**Are $x_0$ and $x_1$ in $\mathbb{R}^2$?** Yes, $V_{\rho_v}$ is vertically integrated such that $V_{\rho_v} = V_{\rho_v}(x, y)$ where $x, y$ are points in $\mathbb{R}^2$ as they correspond to locations in the Earth's surface. Thus, the points $x_0$ and $x_1$ are in $\mathbb{R}^2$. We have clarified this in the revised version.

**Page 8 "How do you identify the trajectory"** Here we integrate trajectories for every grid point available in ERA5 grid. So there is no prior choice of trajectory. This have been clarified in the revised version.

**"Why is the rate sigma exponential and not logarithmic"** Lyapunov exponents are typically defined exponential rates connecting the separation of trajectories at two different times. In the case of the backwards FTLE, we formulate that the separation $\delta$ at the departure time $t = t_0$ is equal to the the separation at the arrival time $t = t_1$ multiplied by an exponential term:

$$\delta(t_0) = \delta(t_1)e^{\sigma \Delta t} \tag{1}$$

The separation ratio $\delta(t_0)/\delta(t_1)$ is expressed by the largest eigenvalue of the Cauchy Green tensor. Thus, Equation 4 in the original submission can be obtained by applying the logarithm in the equation above and isolating the exponential rate $\sigma$, i.e., the FTLE.

**Why is $\lambda_{max}$ at the same time an eigenvalue and a norm?** We thank the reviewer for this comment. $\lambda_{max}$ is not a norm and we have fixed this in the revised manuscript.

**Page 8: time resolution** 2 days is the length of the time window, the time resolution employed to compute the trajectories was 6 hours. We have clarified this in the revised version.

**Line 160** We thank the reviewer for this suggestion. We have referred to Eq. 1 in the revised version.

**How does this method handle sources and sinks** The flow $V_{\rho_v}$ used to calculate the trajectories should not be affected by the total amount of water in the column as the water vapour density $\rho_v$ is both in the numerator and denominator of Eq. 1, yielding a flow that is not dependent on the horizontal water vapour distribution. The role of $\rho_v$ is only to provide a vertical scaling that favours moist levels. Therefore, we hope that sources and sinks do not affect our detection of LCSs. We have added this discussion on the revised manuscript.

**What is the absolute number of events?** The absolute number of events would depend on the size of the boxes and the time interval in which the events are accounted for. The fine grid we considered in this work results in the low fraction of events per box shown in Figure 6. A first order guess of the absolute number of days in which an event occurred would be something between 0 and 50 days per year, depending on the region of the domain.

**Motivate the correlations in 6.2** We thank the reviewer for this comment and have included a motivating sentence as suggested.

**Figure 8** : We have enhanced the size of the VIMF vectors so they are clearer.

**Lines 303-304** We have added references as requested.

**Lines 311-312** We have added references as requested.

## 3 Response to Short Comment 1

We thank Dr. David Schultz for his insightful comments and for his inerest in our study. Here we will be addressing each of the three parts of his comments.

### 3.1 Part A - Literature that should be cited

It is suggested that we cite a wide body of literature regarding flow kinematics, atmospheric rivers and fronts; many of such studies were produced by Dr. Schultz's group and collaborators. We appreciate the quality and value of the contributions presented in these suggestions and will considering adding some of them in the revised manuscript. However, we do not aim to provide an extensive review on each of the concepts we explore: our aim is to introduce the FTLE and the concept of LCSs to the broad meteorology community as well as providing sufficient background literature to support the interpretation of our novel results. Moreover, most of the suggested literature is around Eulerian metrics, such as the Okubo-Weiss criterion or the instantaneous Lyapunov exponent. While these are powerful diagnostics for instantaneous features or steady flows, they have limited ability to diagnose structures of tracer accumulation in unsteady flows. This is especially the case considering that moisture in the atmosphere has an average residence time of at least a few days, which is enough time for the moist parcels to explore large-scale turbulence and be shaped accordingly.

It is suggested that Figure 15 of Thomas and Schultz (2019) is, quoting Dr. Schultz, "very similar" to our Figure 6. Albeit somewhat related through the concept of airmass interface, the figures differ in more than one aspect: (1) the Atlantic ITCZ is not visible in their plot; (2) they capture a signal dominated by topography over South America. We believe that the difference between our results reflect that different methodologies were employed. The authors employed the asymptotic contraction rate, which is equivalent to the instantaneous local Lyapunov exponent, and, therefore, an Eulerian quantity. The authors also perform their analysis at the vertical level of 850 hPa. Our methodology employs a fully Lagrangian metric in a vertically integrated flow.

### 3.2 Part B - Consistency of the manuscript with previous literature

Here it is suggested that some abbreviations that we have employed in the original manuscript are not in accordance with what is usually employed in the moisture transport literature. These abbreviations have now been spelled out fully, also complying with the Editor's comments.

It is also suggested that we provide a reference about the derivation and mathematical notations of the strain tensor. In this study we have adopted the notations presented in Haller (2015), which is a comprehensive review about Lagrangian coherent structures. We have accepted the suggestion and added this reference in Section 2.

The commentator also states that Cohen and Kreitzberg (1997) employed a 12 hour timescale to identify transport barriers and asks for our rationale for a 2-day time scale. Our rationale is described in the last paragraph of Section 2.2 of the original submission: we used a timescale that is long enough to explore large-scale structures and not be influenced by diurnal circulations. But it is not too long as to filer out the effect of extratropical cyclones, as we are interested in this type of structure. Moreover, as we stated in the original submission, we tested a range of timescales (1, 3 and 4 days) and obtained robust results.

### 3.3 Part C - Terminology and Readability

Here the commentator points to aspects related to the readability of the manuscript. Some of these, such as reducing the number of acronyms and improve the connectivity between chapters, have been addressed in the revised version, also complying with the reviewers' comments. We have also improved the discussion in Section 7, especially regarding potential applications of the method.

The commentator criticises the title of our last section: "Summary and Conclusions" by suggesting that the two words are the same. Here we point to the dictionary definition of summary: "a compendium of previously stated facts or statements" (`https://www.dictionary.com/browse/summary`). In the final section we aim to repeat the discussion in a more concise way as well as presenting the main conclusions, hence "Summary and Conclusions".

The commentator suggests that we use the word "automated" instead of "objective" to describe our methodology. We disagree with this. We suggest the reading of the seminal work of Shadden et al. (2008) on Lagrangian Coherent Structures (LCSs). The authors demonstrate the objectiveness of FTLE ridges by deriving a formula for the flux across them; they go on to show that FTLE ridges are material lines to a very good degree of approximation.

## 4 Response to editor comments

We thank the editor for his comments. To improve readability by reducing the number of abbreviations. The following abbreviations were removed in the revised version: SASH, TCWF, VIMF.

## 5 List of relevant changes in manuscript by order of appearance in the document

The following items are the relevant changes in the revised manuscript, according to the Reviewer's suggestion. The figures were rearranged to be closer to where they are cited in text as requested by a reviewer. The major improvements are discussions on the justification of a climate study and the potential applications of the methodology.

1. Section 1.1: enhanced discussion of mixing and coherent structures

2. Section 1.2:

   Improved color palette for Figure 1

   Justification for the need of a long-term study

3. Section 2.1:

   Added discussion about sources and sinks

   Added sentence in the final paragraph to connect with the following section

4. Section 2.2: Added details about the Cartesian and spherical coordinates

   Referencing Haller 2015 about the derivation of the strain tensor and FTLE metrics.

5. Section 3:

   Included a table summarising the relevant parameters of the methodology

   Added a short sentence about the choice of tolerance angle for the ridge detection

6. Section 4: Added a short sentence in the final paragraph to introduce the next section

7. Section 5: Added a paragraph in the end to justify the need to perform a climatological study and to introduce the next section

8. Section 6.1:

   Included a definition of frequency of occurrence

   Included a final paragraph to justify the next section

9. Section 6.2:

   Included a reference about correlating FTLE with atmospheric variables

   Included a final paragraph to justify the next section

10. Section 6.3:

    Renamed the section

    Added introduction to the next section in the last paragraph

11. Section 6.4:

    Renamed the section

    Enhanced the discussion on the connection between Rossby waves and large-scale mixing

12. Section 7:

    Expanded the discussion about the application of the method on other locations and its use in operational weather forecasting.