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Interactive comment on "Lagrangian coherent structures in tropical cyclone intensification" *by* B. Rutherford et al.

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The authors would like to thank the referees for their helpful comments which have improved the quality of the manuscript. We also appreciate the literature review. We have carefully considered the comments and are submitting a revised paper. We will first address the general format of the revised paper, and then address each of the comments from the individual referees.

The format of the manuscript has been changed so that there are now two results sections. The first results section, now Section 4, shows the structure of the Lagrangian flow field. The second results section, now Section 5, shows the time evolution of the structures. Section 5 has been simplified to show the evolution of the structures without strong language regarding the causal effects of the structures. Confusing labels in the

figures have been removed. In addition, the section on mathematical details, Section 2, has been expanded. The abstract and conclusions reflect the new results.

Comments to referee 1: We appreciate the comments from referee 1 and have carefully considered the suggestions. The new manuscript reflects these suggestions, and aims to reduce strong statements and provide the proper observational support. The section on vortex interactions has been reduced. We will address each of the main comments individually.

1. The abstract has been changed to make the statement about what we learn from the flow field surrounding the VHTs rather than the VHTs. We now support the statements with figures showing trajectory locations in relation to the VHTs to demonstrate the local mixing properties. We refrain from the use of the term turbulence in regards to the local environment around VHTs.

2. We have removed the strong statements which are not supported by figures.

a. We will show and explain that LCSs are coherent to 4 km based on updraft and vertical vorticity structure.

b. This statement has been removed.

c. We now further differentiate VHTs and LCSs, and state that LCSs which remain with vortical remnants may last for longer intervals. LCSs are a property of the flow field surrounding the VHT and are not necessarily a property of the VHT itself as defined by its locally enhanced vorticity and updraft. The 1 hour time span is both from visual inspection of the simulated convection and enhanced vorticity and is shown in other studies, e.g. Nguyen 2008.

d. We have changed paragraph 4.1 to state that VHT merger changes the surrounding flow field, which in turn changes the LCS. This change will be made throughout the paper.

e. We will change this sentence to make it more clear that the Lagrangian values are in this case higher in the repelling fields.

3. VHTs are coherent through the time dependent flow field, i.e. these structures can be tracked readily on constant z-surfaces for times on the order of 1 hour.

4. We have discussed that the basis for the coordinate system is not Galilean invariant and that a uniform translation could change the direction of the basis vectors relative to the flow. We now suggest also that a co-moving frame of reference may be necessary for simulations where the storm is not stationary.

5. We have addressed the physical meaning of the matrices A and Psi, and have added supporting references. We will also further emphasize the meaning of the shear term.

6. We show log(Psi22). The caption has been changed.

Minor points

1. We have included a practical method for identifying VHTs based on updraft maxima and enhanced vorticity so that VHTs can be identified in the figures.

2. The proper citation has been added

3. The citations have been added

4. The citation has been added.

5. The citation has been added.

6. This citation has been changed to Ottino (1991).

7. The citation has been added.

8. A subsection discussing the sensitivity to integration time has been added.

9. The statement will be changed to avoid confusion by the readers.

10. The LCSs are tracked primarily by visual inspection on constant z-surfaces.

11. The study of Velasco Fuentes (2005) is now acknowledged.

Comments to referee 2: We very much appreciate the comments from referee 2, which have helped in the organization and content of this paper. We have revised the manuscript to emphasize the exploratory nature of the study and to focus on the main features. We will address each comment individually.

1) We have attempted to reduce the over-interpretation in the revised manuscript. By focusing more on the flow structure and less on the causality and tracking structures, we have tried to remove any biased results and generalizations. We have simplified also the labeling and have eliminated the mention of turbulent regions since tracking them beyond approximately 1 hour is futile.

2) We have clarified that the LCSs are part of the flow field, and are therefore not independent of the vortices, which are also part of the flow field. The boundaries of the vortices are marked by the LCSs but the vortices are not formed by the manifolds. We have clarified this point, and emphasized that LCSs are a diagnostic of the flow field.

3) We have revised the mathematical methods section and numerical methods section to explain how each field is computed, and offer physical interpretation of the fields. Section 3 shows the difference between the Psi_22 calculation, which is completely 3D and the planar approximation to FTLEs.

4) A, B)Does Psi22 measure three-dimensional separation or separation in one plane? It measures three-dimensional separation.

C) What wind field? The fully 4D wind field is used for all trajectory computations, including those trajectories used to compute FTLEs. This is now stated clearly in the first sentence of the subsection on Lagrangian field computations.

D) The vertical motion affects trajectories, therefore its effects are incorporated into the Lagrangian fields. In the revised manuscript, we have elaborated further on the role of the vertical velocity component in each of the individual Lagrangian fields.

E) The helical coordinate system is a simplification that allows the Psi fields to be computed much more easily than with a general TNB coordinate frame.

F, G) When there is no shear, ridges of Psi22 are in the same locations as ridges of FTLEs. The relationship between Psi22 and FTLEs was first shown by Haller and Iacono (2003) for a two dimensional flow. We have added additional references to this study and further described the physical meanings of the fields.

5) The local coordinate system follows the trajectory. Not all time dependencies in Equation 2 are contained within B. Even for steady flows, the operator A implicitly contains the time dependencies associated with the changing velocity field following fluid particles. In the case of a steady flow B does indeed vanish. The time dependencies contained in B are small compared to the terms in A for sufficiently small integration times. Also, the time change of the local coordinate system is small compared to the change caused by the spatial variation of trajectories. We have made this more clear.

6) We have added a subsection and a figure demonstrating the sensitivity of LCS structure to the integration time. Based on the results shown, 1 hour falls within a range of acceptable integration times.

7) The revised presentation has been modified to avoid confusion between facts (what has been established previously) and results (what we show here).

Minor Comments: Responses are given below the comments

Sec. 1: Footnote 3: "previous footnote" → "footnote 1" We have made this correction.

pg 131, line 1: not clear to what "new model" you refer The new 3D model of 3D cyclone intensification.

Beginning of Sec. 1.2: the change to dynamic-system jargon is rather abrupt pg 131, last sentence: Neither the FTLE nor the Psi22 field is later "visualized in a reference frame moving approximately with the speed of the Lagrangian boundary through the time dependent flow ..." This sentence is confusing to me. We have simplified the

sentence to say that flow boundaries move with the flow. We have also attempted to reduce the dynamical systems jargon without precise definitions.

pg 132, line 6: "generalized, frame-independent" (?) We have removed this wording.

pg 133 ff, paragraph starting at end of page: At this point in the manuscript, this information is not digestible for the reader. We have moved this material to Section 2 where it is introduced further.

Pg 135, line 1: If a reader followed your suggestion, he/she would never learn what your main diagnostic (Psi22) actually is! We have removed this suggestion.

Sec. 2: end of pg 135: I suggest to give the formula for the FTLE as used in this manuscript. We have provided the formulation for the flow map from which the planar FTLE is computed. The planar FTLE is then computed as the standard FTLE on the new flow map.

pg 136,line 4: in what sense can the radial velocity be dominated by the radial shear of the tangential wind? Radial separation of trajectories at different radii relative to the shear or vortex center. We have simplified the wording to "radial shear."

Line 11: "moving frame of reference" Aren't we moving along the trajectory already? Do you mean that the orientation of the coordinate system may change? Orienting the coordinate system along the trajectory path. We have tried to make this more clear.

Sec. 3: Pg 141, line 19: For comparison, can you give an approximate number of VHTs during rapid intensification? There are initially 12 VHTs in this simulation using the current initialization and grid-spacing choices.

Pg 141, line 24: 'to the to the' We have corrected this error.

pg 142, line 1: Are you sure that the sigma-levels in your version of MM5 vary with time? The heights relative to the sea-surface are computed from the pressure field which varies in time. The grid output of velocities are on constant Sigma-levels.

Pg 143, line 10, heating gradient and radial influx: We have added references that support this statement.

Pg 143, line 11: It is hard to identify an eye in this figure. The eye can be seen as the interior of the ring of enhanced cyclonic vorticity at the vortex center.

Pg 143, last paragraph: This overview of the role of LCSs is vague and not particular helpful at this point in the manuscript. E.g. what means "LCS ... contribute to the fluid dynamics by ... convergence in the boundary layer ..."? I suggest deleting this paragraph. We have deleted this paragraph.

Pg 144, line 3, "fixed-time Lagrangian scalar fields": The Lagrangian fields at fixed times are computed from the backward integration of time-dependent trajectories from that fixed time. Please clarify. The fixed time Lagrangian fields refer to the initial time for integration. Integrations are performed using the full 4D wind fields. We have made this more clear.

Pg 144, Sec. 3.3.1, vertical separation: This seems conceptually important and should be discussed more focused and more clearly (see also 'Major concern' comment above). This is addressed in earlier comments, and we now comment on the importance of the vertical component.

Pg 145, first sentence: I understand that shear adds to particle separation but why does shear exclude hyperbolic stability? Shear does not exclude hyperbolicity. However, shear does make the detection of hyperbolic LCSs difficult. It causes high FTLE values regardless of the existence of LCSs.

Sec. 4: Pg 145, Sec. 4.1: For a reader without good knowledge of LCS, this subsection is not helpful. Again, in this subsection it is not clear what is already known about LCS and what is a result of the current study. Please revise carefully, potentially move subsection to a later part of the manuscript or clarify using examples. We have revised this paragraph to make the ideas more clear.

Pg 145,first sentence of Sec. 4.2: I assume the coherence of LCS follows from the coherence of the VHTs. Your readers, as I did, may become somewhat frustrated by your presentation at this point: Would we expect such coherence in the LCS from theoretical considerations? Has the coherence been documented before? Is it merely an observation in your idealized case? It is due to the coherence of flow features that are associated with the LCSs. The overall changes in wording (see main point #1) should improve this explanation. Coherence of VHTs and LCSs are not completely dependent or independent of each other, but both rely on a persistent property of the flow field.

Pg 146, paragraph star ting at line 6: The message of this paragraph is unclear to me. The paragraph will benefit from a better introduction of the 'planar projection'. And again: it is unclear whether 'typically' refers to your study or whether 'tangles of FTLEs' have been associated with convective, rotating structures in previous work. The revised description of the methodology should solve this problem. 'Typically' refers to several cases of this specific study. We now clarify this point. The finding of a tangle of LCSs marking turbulent region is now further explained, and will be supported by an additional figure.

Pg 146, Sec. 4.3: For the reader, at this point in the manuscript, the discussion of the azimuthal averages is unintelligible. The azimuthally-averaged wind fields for both Lagrangian quantities and Eulerian quantities show similar and consistent tendencies during intensification. We have tried to make the text clearer.

Why should Psi22 mix inwards? Rutherford and Dangelmayr (2010) showed that a maximal Psi22 ridge was found in the eyewall.

Why is Psi22 associated with the eyewall? RD2010 showed that a maximal Psi22 ridge was found in the eyewall. What do we learn from a comparison of the azimuthal averages anyways? The azimuthal averages broadly characterize the various quantities for the azimuthally averaged vortex and show the relationship between the Lagrangian quantities and the mean flow features.

Pg 147, line 12 and Fig. 6a): What are the proper ties of the assumed flow in which the vortex is embedded? We have removed the subsection on a convergent vortex.

Pg 148, line 1-4: Again, is this known from previous studies? Or is this a concept of vortex interaction that you have developed based on the current study? This interaction concept is a result that emerged from the current study. We have tried to make this more clear.

Pg 148, line 20: Why would the LCSs vanish while the vortices persist? Flow properties inside a VHT approximately decouple from those outside. Other examples of flow features and vortices that approximately decouple while remaining intact include cases of TC genesis via Easterly waves (Dunkerton et al. 2009).

Pg 148, last (complete) sentence: unclear Pg 149, line 14: Usually, a saddle point is identified at the intersection of the stable and unstable manifolds, or at the intersection of FTLE-ridges. Here, you identify the saddle point by the intersection of the attracting and repelling Psi-LCS. Please clarify. This is the finite-time extension of invariant manifolds for a hyperbolic trajectory. The intersection occurs outside of the vortex where Psi22 and FTLEs are similar so the intersection point is in a hyperbolic region. We clarify this point in the revised manuscript.

Pg 149, line 16 ff, "Over the next . . .": The description in the remainder of this paragraph is absolutely insufficient to shed light on the complex conïňĄguration of vorticity and LCSs. E.g. ". . . vorticity pools and LCS travel together . . ." is vague, at best. ". . . vortices A and B come very close, yet remain separated by the attracting LCS." This is at odds with the "unstable interaction" described in Fig. 6d and rather reminiscent of "stable interaction" which, however, is supposed to occur along a repelling LCS. Furthermore, I do not see any LCS that separates vortices B and C in Fig. 7d. This section has been substantially reduced and simplified to help address these concerns. We have inserted additional figures to help strengthen the

presentation in this section.

And: in what sense are vortices B and C "not connected"? Do you imply that vortices are connected by a separatrix? There is an LCS between them but we have removed the term 'separatrix'.

(line 20). At least linguistically, this would be very confusing. Fig. 7: For the sake of clarity and simplicity, I suggest omitting the theta_e field to illustrate vortex interaction. We agree and will replace theta_e and vorticity contours, with just a plot of just vertical vorticity.

Sec. 4.5: I find it irritating that the authors first present their conclusions (ïňĄrst paragraph) before they attempt to present supporting evidence in the second paragraph of this subsection. We have removed the conclusions from this subsection, and moved the material and other supporting material to the introduction

The description in this second paragraph is insufficient to support the authors claim that "LCS reveal preferred locations for the convergence of theta_e . . .". Furthermore, it is not straightforward to see how convergence is related to theta_e gradients. We now instead say that LCSs lie along thete_e gradients. The convergence into pools of enhanced theta_e occurs at the ends of LCSs.

Pg 150, line 15: Why do these LCS have so much longer time scales/ lifetimes than the LCSs described in Fig. 7? There are fewer VHTs influencing the total flow so the signature of the VHT is not as distorted by the turbulence of neighboring VHTs.

Pg 151, line 1: Sec. 4.2 does not describe vortex merger (neither does Fig. 6). We have changed the reference to Section 4.4.2

Sec. 4.7: Is it actually possible to track the turbulent T-regions? (as suggested by the same labeling at different times) We have removed the turbulent regions (as noted above) from the plots since they are difficult to track for longer than 1 hour.

Sec. 4.7: Is it actually possible to track the turbulent T-regions? (as suggested by the

same labeling at different times) The primary Lagrangian structures are the persistent LCSs that are associated with the eyewall of the storm.

Comments to referee 3: We appreciate the helpful comments from referee 3. We have briefly addressed the question of vortex dipoles in a revised section 4. The methods used in this study are capable of diagnosing them, but their associated coherent structures are not as long lived and are thus more difficult to detect. A comparison of the relationship between cyclonic and anticyclonic vortices is a topic that was summarized heuristically in a Published Response to an Editorial Comment [add weblink address here for our responses to Michael McIntyre in ACPD 2009 paper by Dunkerton, Montgomery and Wang, 2009]. Basically, in the presence of pre-existing cyclonic circulation, the convective stretching process produces a skewed distribution of vertical vorticity with a bias of more intense cyclonic vortices (e.g. Montgomery et al. 2006, JAS). This cyclonic bias implies that their influence on the emerging cyclonic flow, while certainly not negligible, is less than that of the cyclonic vortices."

P28123 l 11-13: We will mention shear in this sentence.

P28120 l 21-24: coherent structures that grow above the boundary layer. . .

We will include all of the technical changes. TNB means tangent, normal, binormal.

Interactive comment on Atmos. Chem. Phys. Discuss., 11, 28125, 2011.