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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Advective mixing in a nondivergent barotropic hurricane model" *by* B. Rutherford et al.

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The authors would like to thank the referee for the helpful and valuable comments. We will first address the general comments, and then turn to the specific points.

The effect of radial mixing and the existence of LCSs that influence the mixing process, even through the shear, is the most important aspect of this study. In particular, we try to show that the FTLE and the Q-field do not govern trajectory transport in the presence of shear, however the R-field does provide a Lagrangian tool that is suitable in this context. Some of the main concerns of the referee were whether the Q-field was suitable as a diagnostic, and whether the azimuthal locations of coherent structures displayed any azimuthal preference. As an answer regarding the concern about the Q-field, we would like to say that while the Q-field does show instantaneous separation, it does not

show which trajectories become entrained in mesovortices. In fact, there is a distinct difference between trajectories which exhibit instantaneous high Q-values and trajectories which show persistently high Q-values. Persistently high Q-values correspond more closely to regions of high R-values than do the regions of high instantaneous Q-values. Recent studies have shown that the Lagrangian Q-field is a better hyperbolic mixing diagnostic than the instantaneous Q-field, but does not work as well as FTLE's. As a Lagrangian diagnostic for mixing, we advocate the R-field, but not the Eulerian Q-field. As an alternative, the integrated Q-field shows very symmetric structures, in similar location to the R-field structures. However, the R-field shows asymmetries that determine the interaction and preference of individual mesovortices much more quickly (likely due to the fast convergence of the method).

A key concern was also the azimuthal preference of the Lagrangian diagnostics in relation to the instantaneous location of the mesovortices. In the revised version, we will add R-field plots with superimposed PV contours marking the mesovortices, which will make the relation between the structures more evident.

Concerning the relation of our diagnostics to the GLM theory of Andrews and McIntyre (1978), we are not only looking at a way to compute a net flux, but also have in mind the relation of the Lagrangian fields to impenetrable boundaries. For sheared flows, as in this model, the boundaries are in no way impenetrable, but show persistent structures that are related to mesovortives. Viewed in the context of a larger-scale tropical storm, the mesovortices have associated LCS's that may or may not have any link to the environmental flow. The decomposition of the flow separation into hyperbolic and shear components will allow the detection of LCS's in the environmental flow (with little shear) that are also associated with the mesovortices. The idea is that structures of different stability types can be found in the environment and inner core regions, and then be linked to determine the full time-dependent structures that govern the mixing into the inner core. The paper of Dunkerton et al. (2009) proposes the idea of a dividing streamline, which is a key link between environmental flow and interaction with

the inner core. A goal for future research using the methods developed in our paper is defining this streamline as an LCS, where the structure ignores the shear in the inner core and is purely hyperbolic in the environment, providing a time-dependent Lagrangian boundary. We anticipate that this approach will make it possible to define the dividing streamlines from the time-dependent velocity field by direct computation of the manifolds, without using fixed points of the time-averaged velocity field.

The R-field has the added benefit of a moving time frame and adjustable integration time, which can also be exploited to diagnose a cat's eye mesovortex formation. The interaction of two mesovortices in relation to a subtracted mean flow involves two fixed points connected by dividing streamlines (Dunkerton et al., 2009). The dynamics near the fixed points is slow, so resolving information about the dividing streamline (manifold) away from the fixed point requires a substantially longer integration time than resolving information about a time-dependent mesovortex, which has much faster dynamics. However time-dependence of the velocity field makes it difficult to relate the Lagrangian structures associated with the mesovortices to any dividing streamlines within the environmental flow. The advantage of the way time is handled in our study is that the moving time frame not only allows detection of the constantly changing mesovortices, but also allows to associate these structures with environmental flow boundaries (not seen in this model because shear is present almost everywhere). Also, due to the fast convergence even in a time-dependent velocity field, the approximation through a time-averaged, steady velocity field is not necessary.

Regarding the tropical wave critical layer, it is clear that there is a connection between the mesovortices and VHT's, however the shear plays a different role in these two cases. The nondivergent barotropic model shows shear almost everywhere, whereas the VHT interaction does not. The use of a 3D version of the R-field adapted to study VHTs is currently being investigated. Based on the Lagrangian structural differences between the 3D model and the 2D barotropic model we prefer not to comment on VHTs in this paper, but to handle the VHT situation rigorously and properly in a

separate study.

In response to the specific comments:

1. The FTLE fields do not show clear ridges, which would be considered as manifolds. The ridges of the R-field are not invariant manifolds, but carry a greater relation to Rossby waves. They are Lagrangian though because of their persistence, both in relation to trajectories that hold persistently positive R values, and persistence across varying initial time. The relation of the structures to a tropical wave critical layer will be addressed in a later paper.

2. The relation between the Q and R fields can be best demonstrated by comparing the R-field to places where trajectories show persistently low or high Q values. Plots of the integrated Q-field along with a relationship to the R-field, including azimuthal preference will be included in the revised version, and a sentence referring to this relation will be added to the abstract.

3.-4. These comments will be added and the additional references will be included.

5. Our response to this comment is addressed in the response to ♯2, and the new figures will help to establish a better connection between the R and Q fields.

6. The GLM will be addressed as a Lagrangian mixing diagnostic, and appropriate references will be added. We will also explain in more detail our reasons for choosing the R-field as a diagnostic, since its extension to more general mixing problems is quite interesting.

7. We agree with the change in wording and will make the proposed change.

8. A further description of the stages of mixing will be given at this place (p. 16090, l. 22 in discussion paper), with further elaboration of the temporary crystalization process followed by the vortex interaction phase given in appropriate "results-sections".

9. The solutions of the variational equation involve the growth of material line elements along orthogonal subspaces. The idea of a rotation is correct, and the language will be changed to read "expansion" and "contraction".

10. We agree that in equations (6) and (7) different notations are used to denote a Jacobian. We would like to keep the ∇-notation and will change (6) and the first equation on p. 16095. The dot-notation is consistently used for scalar products of vectors. Regarding matrix-vector or matrix-matrix multiplications we prefer to write this without dots.

References

T. J. Dunkerton, M. T. Montgomery and Z. Wang. Tropical cyclogenesis in a tropical wave critical layer: easterly waves. Atmos. Chem. Phys. 9, 5587-5646 (2009).

D. G. Andrews, and M. E. McIntyre. An exact theory of nonlinear waves on a Lagrangian mean flow. J. Fluid Mech. 89, 609-646 (1978).

Interactive comment on Atmos. Chem. Phys. Discuss., 9, 16085, 2009.