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Interactive comment on "The genesis of Hurricane Nate and its interaction with a nearby environment of very dry air" *by* Blake Rutherford et al.

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The authors would like to thank the reviewer for the detailed comments that we have used to improve the quality of this paper. We have written a new version of the manuscript that takes all of these comments into consideration. The responses to each of the individual comments is given below. The reviewer's comments are given below in italic while the author's responses are given in standard font.

In my opinion, this paper does not achieve its goal in illustrating how Nate interacts with its environment. Many results seem to be highly dependent on the way there are obtained and some statements are incorrect. It needs a major revision. First, all the paper is based on the role of the air mass that comes from storm Lee. However, no figure is given to show the evolution and decay of this cyclone. In addition, there is no *precise definition of the air constituting Lee, and it is then difficult to see which air mass will be involved in Nate development. Second, the invariant manifolds may be highly sensitive on the way there are computed. From the different figures presented in the manuscript, small-scale motions may be very intense so as the exact position of the manifolds may change very much. Now, my more precise comments.*

We thank the reviewer for the detailed comments and we have revised the manuscript that considers all of the reviewer's comments. We have made substantial revisions to the paper that strengthen the results and have corrected the errors. In particular, we have added Figure 2a showing the potential vorticity from Lee and the Lagrangian boundaries associated with the transport of this high potential vorticity air into the Nate development region, a precise definition of the region containing high potential vorticity from Lee, and the subsequent formation of the boundary associated with the sharp moisture gradient to the north of the Nate vortex. While the manifolds are sensitive to the way they are computed, e.g. due to the choice of the time interval used for integration, the sensitivity affects filaments that have little circulation, but does not affect the larger scale transport, so our major conclusions hold regardless of small scale uncertainties. We have added more precise statements about how the manifolds are computed, and have added an additional discussion about the sensitivity in Section 4.

1) Line 31, page 2.The definition of invariant manifolds based on a moving reference frame is wrong. Following your definition, any Galilean transform (e.g. rigid-body rotation) will change the position of saddle points and of the manifolds. The second definition given page 4 which relies on the Okubo-Weiss criterion is wrong as well, for the same reasons (see Lapeyre et al. Physics of Fluids 1999, Lapeyre et al. Chaos, 2001, Koh and Legras Chaos 2002, Haller JFM 2005). In the same manner, the authors cannot say page 14 that Okubo-Weiss is Galilean invariant! A correct definition of manifolds is given in the method section page 7.

We find this comment to be a misinterpretation of our definition on page 2, as the Lagrangian manifolds used in the analysis of Nate are not defined to be those of a stagnation point in the moving frame as clearly, the manifolds only coincide with Eulerian streamlines if one can assume that the flow and reference frame are steady. We have modified the text on page 4 to make it clear that a distinguished frame is still assumed at this point. The assumption of a steady flow in a moving frame of reference used in the definitions on page 2 and 4 are not used in any of the results in this study, and only serve as a motivation for the use of the correct definition on page 7. We have changed the wording on pages 2 and 4 to indicate that these manifold definitions are only valid in the case of steady flows where the frame is specified. The wording on page 14 for the Okubo-Weiss criterion has been changed to 'translation invariant'.

2) It is quite difficult to follow the paper as one needs to understand the different air masses origin and and there is no synoptic view of Lee (add a figure, please!) and a definition of its air mass. Also, can the author show Nate in its embedded environment (i.e. in a much larger spatial region)? An example of my difficulty in reading the paper is given page 3, lines 13-14 when the authors state that "One or more vorticity filaments...". It would be very useful to see them! Same thing, about the S-shape (line 17). Can the authors illustrate the remnant air from Lee!

The new Figure 2a showing Lee and the pre-Nate region demonstrates the interaction of these different air masses. The vorticity filaments and s-curve connecting the Nate and Lee flows that are described in the paper are now shown in the figure.

3) The discussion about the role of the Lee air mass in the genesis of Nate relies on the description of manifolds on isobar p=700hPa. However, Figs. 4, 5, 10 show that interpretations are highly sensitive to different parameters (altitude, divergence of the flow, SST...). Moreover, vertical motions are not included in the computation of the manifolds. It would be important to include these motions to see how the manifolds are dependent on this parameter as well. From what I see from the different figures, it is not clear to me that the positions in space of the manifolds are well defined. The very filamentary lobes may only exist because of advection by very small scales or errors in the velocity field. Manifold analysis is a powerful tool when the large-scale *velocity fields is responsible of chaotic advection. Here, a lot of inertio-gravity waves seem to be emitted during convection and I wonder if they are quite energetic in terms of horizontal flow. If it is the case, that challenges a lot the interpretations of the paper.*

We agree that the manifold filaments are sensitive to integration time, vertical level, divergence, SSTs, moist processes, or inertio-gravity waves. The contents of these filaments may also be quickly diffused, particularly when entrained into the core. While we show these filaments, the discussion in this paper is concentrated on the entrainment of the lobes from the dry air region which is not sensitive, as it appears in both ECMWF and WRF, with constant and varying SSTs, and aligns very closely with isolines of O_3. Thus, the key structures that we highlight are driven primarily by the large-scale velocity field, and only the filamentary regions, which have very little circulation, are strongly influenced by the small scales. A comparison of Figure 4 and 6 shows very similar manifolds even under separate model simulations. We have further explored the role of vertical motions by computing the manifolds in isentropic coordinates, and the same conclusions hold, even though the filamentary details are again different. The comparison of the non-divergent flow in Figure 5 to Figures 4 and 6 should not be seen as a sensitivity analysis but rather the demonstration of a dynamic process, since the non-divergent manifolds were created using only the non-divergent part of the velocity field, and not by turning off divergence in the WRF model. To clarify this issue, the new manuscript includes further discussion on the verification of robustness of large-scale Lagrangian structures. Specifically, we have added a paragraph of text when introducing O_3 and also in the Conclusions.

4) Page 9, second paragraph. What is the true definition of air coming from Lee? PV>some constant value ? air coming from latitude > 30 ? relative humidity < 50% ?

The air coming from Lee is that coming from above the attracting LCS within the pouch that is shown in the new Figure 2 (a) in the region labeled R_1.

5) Panels in Figure 3 are unreadable. The color scale for PV does not highlight low and *high values; also it is not possible to discriminate positive and negative values in OW criterion.*

We have changed the text color where needed to make the figures more readable, and have changed the color scale on the PV and OW plots to highlight low and high values.

6) How are precisely defined R_1 and R_2? This is important to follow the interpretation.

R_1 and R_2 are precisely defined by closed Lagrangian loops comprised of specific manifold segments terminating at specific endpoints and the regions are separated by an attracting boundary between them shown as a yellow curve in the new Figure 2 (a). The circulation values of these regions are precise because of the exact locations of the Lagrangian curves bounding them.

7) The authors give average values of relative vorticity. However there are two subtleties. First, there is some uncertainty in the exact area of the lobes. This should be quantified. Second, there are a lot of gravity waves and I guess there are local spots with high values of vorticity. This can strongly affect the average value, so that the average would be meaningless.

While there may be uncertainty in the manifold locations due to the spatio-temporal resolution of velocities, there is almost no uncertainty in the area of lobes or of the circulation since both the area and circulation are computed by a contour integral along the manifold using Green's Theorem and Stokes' Theorem, respectively. Mean vorticity is then computed as the ratio of circulation and area. Of course, the vorticity distribution is not constant, but the mean vorticity or circulation is a common and meaningful diagnostic of tropical cyclone strength.

8) Page 13. you should compare manifolds computed from trajectories along eta=0.6 and along p=600hPa surfaces to assess uncertainties in the position of the manifolds in the WRF simulation.

We now show the ECMWF at 700 hPa and WRF simulation at $\eta = .7$ for our primary analysis so that a more meaningful comparison between the ECMWF and WRF data can be made.

9) Figure 3 and 4 do not correspond to the same domain and the longitude axis is labelled differently. Please modify accordingly.

We have modified the figures so that the WRF and ECMWF plots show the same domain.

10) Page 13, line 18. "the flow on isobaric surfaces". I thought that it was on eta=0.6???

We have changed the text to indicate that the flow is on the eta=.7 level, where the new analysis is performed to make the WRF and ECMWF analysis more consistent.

11) I don't see the point to the paragraph about SST sensitivity. It does not seem to me that this paragraph is important for the discussion.

The forecast discussions for Nate indicate that actual intensity was lower than forecast intensity. Environmental interaction and lower SSTs from upwelling were given as possible causes for the lower intensity, and the paragraph about SST sensitivity shows the impact of lower SSTs in the WRF model. We demonstrate that the SST difference has little impact on the manifold configurations and only a modest impact on the strength of the vortex. The SST sensitivity paragraph has been revised to make the importance of this simulation more apparent.

12) I do not agree with the discussion on the the vortex radial structure. First, how do you define an "average" radial profile? The vortex is not axisymetric at all. How is defined its center? From Figure 3, OW and PV are quite noisy due to convection, so radial average may be meaningless. I thus do not understand what is plotted in Fig.8. Second, your definition of u and v is awkward. From the definition of T, we have $T(u,v) = (u,v)$ with $T = (u,n)/|u|$ Then $T(u,v) = (uu, -vvv, uv + uv)$ Hence $u = |u|$ and $v = 0$ So I don't see why the use of u would be interesting.

While the vortex is not axisymmetric, the flow near center is nearly circular so that radial

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profiles for small radii are meaningful. The center location is unambiguous as there is almost no difference between the locations from the best-track data set and the MRG pouch products, which were computed independently. The transformation matrix T orients the velocity field to give the tangent and normal components, thus $\tilde{u} = |\mathbf{u}|$ and $\tilde{v} = 0$. However, T is used to project derivatives of the velocities onto the tangent and normal directions, providing a 'natural coordinate' definition of normal strain and shear strain. We have made this more clear in the revised manuscript.

13) What are the uncertainties on the curves in Fig 7.

The curves in Figure 7 show the circulation interior to the manifolds, and the circulation is taken as a line integral along the curve, which has point spacing <=.01 degrees. There is no visible variation in the curves using a larger point tolerance. Any uncertainty in the circulation would be based on the location of the manifolds, and this sensitivity is discussed further in the conclusions, as indicated by our response to a previous concern.

14) Page 14,Line 21, the phrasing "vorticity moves inward" is misleading as it is not a 2D nondivergent transport. Also, it seems that the pouch boundary is defined through the OW criterion, which is quite different from the invariant manifold. Please clarify.

The flow near the center is not 2D non-divergent transport as upward mass flux causes convergence toward center, and we have changed the wording of this statement to indicate that vorticity increases toward the center due to convergence. The pouch boundary is defined through the invariant manifold locations, and not by the OW criterion, and the wording has been changed to make this point more clear. High OW is a characteristic of the core, and negative OW is characteristic of the shear sheath, not of the pouch boundary.

15) Panels of Fig. 10 should be at the same times as the Fig.2 Also, red/magenta colors are reversed with Fig.2

We have changed the colors on Figures 1 and 10 and times on Figure 10 to match those in Figure 2 so that the manifold colors are the same on all figures.

16) Conclusions. The fact that air cannot penetrate the vortex core while it can enter the pouch was discussed by Lapeyre Chaos 2002 and Babiano et al. Physics of Fluids 1994.

We have added a discussion including the results of these studies and references at the point in the paper where the vortex core is first defined in Section 2.

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