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Interactive Comment

Interactive comment on "Tropical cyclogenesis in a tropical wave critical layer: easterly waves" *by* T. J. Dunkerton et al.

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In fluid dynamics 'Lagrangian' commonly refers to particles or parcels: their (i) displacement, (ii) rate of change of displacement (equal to the local fluid velocity) and (iii) local rate of change of fluid properties or material. Materially conserved quantities, such as adiabatic invariants, experience zero rate of change following the particle or parcel, unless nonconservative sources and sinks of the quantity are present. In elementary textbooks, students usually encounter the material derivative first, in the primitive equations, followed by its expansion into advective Eulerian form.

Since the late 1970s, and more recently, the term 'Lagrangian' has gained two additional meanings: (i) the notion of a Lagrangian mean flow, and various measures of wave activity, developed in the Generalized Lagrangian Mean field theory[1], and (ii) the notion of Lagrangian boundary, a general kind of coherent structure in physical

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space created by an ensemble of particles or parcels passing through or around it[2]. Central to both concepts is the expectation that Eulerian data can be used to evaluate (exactly or approximately) these Lagrangian entities, in some cases without performing trajectory calculations at all. The linear displacement field is the best-known example, evaluated as minus the ratio of velocity and intrinsic phase speed.

In their text, Samelson and Wiggins elucidate the distinction between Eulerian and Lagrangian viewpoints as made in our paper:

'In the ocean, a variety of measurement techniques have revealed the presence of numerous localized, coherent structures at many different scales: major currents like the Gulf Stream, which may extend for thousands of kilometers; mesoscale phenomena including rings, eddies, filaments, and jets, with scales up to hundreds of kilometers; and smaller features such as submesoscale coherent vortices, which may be no more than ten kilometers in width. The atmosphere offers many similar examples, including the polar vortex, which circles the globe between the poles and mid-latitudes, and exerts an important and incompletely understood influence on the distribution of ozone in the stratosphere. In many of these flows, the transport and exchange of fluid, and of properties and materials carried by the fluid, between persistent, organized structures or regimes in the flow is of central scientific and practical importance. The term Lagrangian transport refers in this text specifically to this advective exchange of fluid parcels between different flow regimes, that is, fluid transport and exchange that is measured with respect to coherent structures in the flow field itself. It is distinguished from traditional Eulerian measures of transport, in which fluxes are computed with respect to a fixed external coordinate system.'[3]

To be precise, this text assumes (i) a Lagrangian framework for identification of coherent structures embedded in a fluid, and (ii) a Lagrangian measure of advective transport between different flow regimes. Here we interpret 'regime' in a spatial sense, to denote transport between adjacent flow structures that exist simultaneously. But as the detail of their book reveals, in a later chapter, it is the slight departure from perfect steadiness in the Lagrangian framework that enables such transport, which is effectively irreversible owing to its chaotic nature.

Our paper is concerned mainly with the first of these Lagrangian concepts: viz., the identification of coherent structures embedded in the flow, e.g., the parent wave's critical layer and proto-vortex within. We reserve for future research the details of irreversible transport and TC intensification within the critical layer, emphasizing (as in Samelson and Wiggins) the need for measurements with respect to the coherent structures involved in this multi-scale, multi-stage process.

In agreement with the reviewer's comment, it is important to note that we advocate a wave-centric viewpoint for estimation of Lagrangian boundaries in the context of easterly waves and tropical cyclogenesis, prior to and immediately after genesis. This is in subtle contrast to a storm-centric view in which focuses directly on vorticity, as one would naturally do once the storm itself becomes dominant. The critical latitude and critical layer are uniquely important places in the flow where particles or parcels tend to remain in the same phase of the wave. Viewing the velocity disturbance in this region – in a frame of reference moving with the wave – is equivalent to viewing Lagrangian motions; disturbance and particles/parcels move together. More precisely, disturbance and Lagrangian boundaries move together, while particles and parcels (re)circulate around or within the Lagrangian boundary. Adiabatic invariants likewise (re)circulate, apart from sources and sinks. In the days prior to and immediately after genesis, we contend that the production and advection of vorticity within the recirculating Kelvin cat's eye depends not so much on its own evolution, as on the kinematic flow structure created by the parent wave. Elsewhere in this quartet of responses we elaborate on this theme (response to Interactive Comment 4).

Most of our 'Lagrangian' usage is deemed acceptable, but in one or two instances it is preferable to clarify that 'wave-centric' is meant.

1) It is shown that in order to visualize optimally the associated Lagrangian motions,

one should view the flow streamlines, or stream function, in a frame of reference translating horizontally with the phase propagation of the parent wave.

2) ...available observations on the synoptic scale need to be analyzed in a manner that is consistent with the Lagrangian nature of tropical cyclogenesis.

3) In order to fully appreciate the transport of PV and moist entropy by the flow, their interaction with one another, the impacts of deep convective transport and protection of the proto-vortex from hostile influences requires, among other things, an understanding of material surfaces or 'Lagrangian boundaries' in the horizontal plane.

4) For tropical cyclogenesis it is necessary to understand the morphology of Lagrangian transport, and it is desirable to know whether, and how, suitable information for this purpose can be obtained from an intelligent manipulation of Eulerian data.

5) Central to our presentation of the marsupial paradigm is a rudimentary understanding of the Lagrangian flow and its dynamical and thermodynamical properties in the neighborhood of the developing storm.

6) The Lagrangian mean flow is asymptotically discontinuous on the edges of the critical layer and its horizontal profile consists of three components...

7) ...the Lagrangian mean flow in the critical layer is zero in a frame of reference moving with the critical layer itself: i.e., at the phase speed of the wave.

8) Here we take the Lagrangian mean to be a spatial average in the direction of the Eulerian mean flow...

9) As a region of re-circulating quasi-horizontal flow, the Kelvin cat's eye is bounded by closed material contours – a Lagrangian concept that provides a more general definition of the TC 'pouch' in cases where a critical layer is not well defined or consists of a solitary shed vortex...

10) But actual flow fields are transient and contain mesoscale finestructure, making the

Lagrangian kinematics rather messy.

11) Regarding separatrix angle, a pronounced dearth of angles occurs near -90 degrees (due south)– a key observation for identifying the Lagrangian flow around the proto-storm and the air mass from which environmental properties have been entrained.

12) ...the Lagrangian mean flow in the critical layer is zero in a frame of reference moving at the phase speed of the wave...

13) Such features correspond to regions of closed Lagrangian circulation which, on the southern side of the AEJ axis, have cyclonic vorticity and abundant moisture.

14) Meteorological charts displaying Earth-relative streamlines are a standard tool in the forecasting industry, but generally provide a misleading picture of actual flow kinematics, or Lagrangian displacement of air, in propagating tropical waves.

15) ...it is likely that the Lagrangian shear seen by the developing vortex is small as well.

16) The need to translate the coordinate system zonally for an optimum view of Lagrangian flow kinematics has been stressed throughout the paper.

17) The definition of Lagrangian boundary in steady flow can be made precise by locating the separatrix nearest the gyre center and equating the gyre boundary with the value of stream function intersecting that point.

18) We have produced and advocated in this paper a Lagrangian or wave-centric view for the study of tropical cyclogenesis and have chosen the simplest of all scenarios to present the fundamental concepts of genesis in a tropical wave critical layer.

19) By examining streamlines in the co-moving frame a wave-centric picture of the flow is obtained in which trajectories and streamlines are nearly equivalent over a time span of a few days.

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20) This device enables us to identify approximate Lagrangian boundaries in the flow without actually performing trajectory calculations.

21) To confirm inferences from streamlines in the co-moving frame we calculated back-trajectories from within the closed gyre (Section 4a).

22) It preserves the vortex because the Lagrangian boundaries formed by the wave at its critical layer remain in the same phase of the wave.

23) With a Lagrangian framework for flow kinematics (relevant to the forward cascade) and a cloud-system resolving model (needed for the inverse cascade) a direct assault on mesoscale processes leading to tropical cyclogenesis at meso-beta; is now feasible.

24) ...the total flow (except for its high-frequency component) defines critical layers, stream function or streamlines, Lagrangian boundaries, and so forth.

25) The subjective nature of the operational procedure will become evident in one of the cases highlighted below (Chris 2000) wherein a depression-strength closed gyre in the co-moving frame ˜30 h prior to 'genesis' in the Eulerian frame.

26) This flow configuration is the point-vortex analogue of the discontinuous Lagrangian mean flow associated with a steady wave critical layer described in Section 2a.

27) In our case, the proper choice of gauge – a function that converts the stream function into something appropriate for visualizing the Lagrangian flow – is not obvious from a Helmholtz decomposition of the Eulerian flow in a resting frame.

28) In a nonlinear critical layer the Lagrangian mean zonal flow is asymptotically discontinuous at the edge of the cat's eyes...

29) Whether or not entrainment of pre-existing moisture is significant, the Lagrangian boundaries of the developing gyre serve to protect this region from lateral intrusions of dry air.

(reference titles)

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30) An exact theory of nonlinear waves on a Lagrangian mean flow.

31) Detection of Lagrangian coherent structures in 3D turbulence.

32) Lagrangian coherent structures and mixing in two-dimensional turbulence.

33) Lagrangian data assimilation for point-vortex systems.

(endnotes)

34) The elusive but sometimes exposed ’low cloud swirls’ and other stratiform cloud or water vapor anomalies represent Lagrangian entities to the extent that they are passively advected by the flow.

35) ...animation of the accumulated horizontal displacement of cloud or water vapor anomalies (away from their sources and sinks: viz., deep convection and other regions of moist ascent) effectively provides a Lagrangian view.

36) ...it is unnecessary for such images (as from QuikSCAT or ASCAT) to display a closed circulation in order for a closed circulation to exist in a Lagrangian sense...

37) By viewing the sequence of frames, the viewer obtains a sense of Lagrangian horizontal motions weighted by the vertical profile of moisture, together with the impacts of convective moistening and horizontal entrainment.

38) Extraction of quantitative Lagrangian information from sequential imagery is far from trivial, but a worthwhile goal.

39) When it comes to closed circulations in propagating waves, the difference between Eulerian and Lagrangian flow is critically important, as will become clear in this paper.

40) In latitudinal shear, the cat’s eye of the critical layer is uniquely where a wave-centric view is Lagrangian, in the sense described in our response to Interactive Comment 2. In the marsupial paradigm, a storm-centric view is approximately equivalent to a wave-centric view, for as long as proto-storm and parent wave move together.

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41) Such criteria, in any case, must be invariant under a Galilean transformation, that is, Lagrangian properties of the flow.

42) ...these challenges (and others not mentioned) make the identification of Lagrangian boundaries more difficult in such cases.

43) Our point is that, in some cases, even the best-track estimate is late, relative to the analyzed Lagrangian criteria.

44) A more general construction of Lagrangian boundaries from an Eulerian diagnostic is possible in 2D and 3D flows...

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

[2] Haller, G. and G. Yuan: Lagrangian coherent structures and mixing in two-dimensional turbulence. Physica D, 147, 352-370, 2000.

[3] R.M. Samelson and S. Wiggins, Lagrangian Transport in Geophysical Jets and Waves, Interdisciplinary Applied Mathematics, Vol. 31, Springer, 147 pp., 2006.

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