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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.

T. J. Dunkerton et al.

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The authors thank the reviewer for general and specific suggestions which led to an improved manuscript in revision. We took to heart his overarching desire that the idea of Kelvin cat's eye be articulated clearly, not 'hidden under a bushel.' Although the cat's eye construction with surrounding undulation is quite general – essentially the asymptotic representation of the nonlinear displacement field for a wave's critical layer in shear flow – when applied to Rossby waves it exposes some fundamental issues on the nature of potential vorticity, PV inversion, long-range interaction and the co-existence of waves and turbulence... issues addressed elegantly by the reviewer's writings over the years.[1] Decades of hurricane research have been unable to pry open the secrets of tropical cyclogenesis in tropical waves owing, in part, to a failure to appreciate the Kelvin cat's eye as an organizing entity for PV dynamics and moist thermodynamics. In our revision we have added ’Kelvin cat’s eye’ in places where appropriate, (i) to make the technical distinction with respect to the broader ’critical layer’ and (ii) to highlight its ’wireframe’ streamline pattern as an organizing entity that takes precedence (logically and chronologically) over the redistribution and amplification of PV anomalies within. Further details of the technical distinction were stated clearly in the Interactive Comment, for anyone needing to be reminded of them. It is best that we employ both terms in the paper because both convey useful concepts: e.g., a set of predetermined streamlines that ’do the advecting’ at higher order (cat’s eye), a finite-amplitude wave at its critical latitude where mean flow and wave phase speeds are equal (critical layer). As a practical matter, our definition of ’quasi-closed’ gyre (owing to wave transience and horizontal divergence) is sufficiently imprecise as to obscure the technical distinction. But our diagrams of Okubo-Weiss parameter clearly convey the contrasting properties of cat’s eye center and adjacent separatrix, as does the schematic of Figure 1. So the distinction between the center of the cat’s eye and adjacent regions of the critical layer is important, even in observations. The reviewer’s bigger concern is that we obscure the proper ordering of events in the critical layer: viz., that the Kelvin cat’s eye takes precedence over the evolving distribution of vorticity within. This fact needs to blaze in full glory.

In their text, Samelson and Wiggins highlight the importance of kinematics in the ideal Rossby wave critical layer:

’The stream function in and around the critical layer has a form similar to that of the recirculation cell and surrounding shear flow in the kinematic model (1.1) of the meandering jet, with separatrices connecting hyperbolic points and dividing the domain into an interior recirculation regime and two external zonal flow regimes. Remarkably, the separation of scales between the stream function and the vorticity near the critical layer means that, to first order in the expansion parameter, the stream function is dominated by the larger-scale shear flow and is not affected by the redistribution of vorticity within the critical-layer region. This provides an explicit example of a dynamical model in which the potential vorticity field is advected kinematically, that is, it is advected by a velocity field with a known structure that is itself independent of the resulting potential vorticity advection.'[2]

The last sentence describes the lowest order solution; when higher orders are considered, an effect on the external wave field is seen, along with a slowly decaying oscillation between under-reflection and over-reflection, culminating in perfect reflection (Killworth and McIntyre, 1985). We cannot improve upon the words of Samelson and Wiggins regarding the 'remarkable' quality of the solution resulting from the asymptotic matching, or separation of spatial scales, between inner and outer solutions. In the context of TC genesis in a tropical wave critical layer, that the initial evolution towards a tropical depression is controlled by a larger, and perhaps largely unseen, influence of PV organization by the wave and its critical layer, not by convectively amplified PV anomalies within, is a notion that may seem foreign, if not heretical, to the TC community. But it is fundamentally important, and easily demonstrated numerically.[3]

Samelson and Wiggins go on to note what happens when the basic solution is perturbed by an additional wave, and the chaotic stirring that results, one of several applications of critical-layer concepts to mixing in geophysical fluids. Their comments reinforce that for the most part, the academic community's interest in mixing has been far greater than in 'anti-mixing' of the sort contemplated in our paper. We are interested in the tropical wave critical layer inter alia for its shape-preserving qualities that encourage cyclonic vortex aggregation at meso-beta;, i.e., the coalescence of like-signed (cyclonic) anomalies resulting from vortex-tube stretching at meso-gamma; and radial expulsion of oppositely-signed (anticyclonic) anomalies. Admittedly these qualities demand a revision of the classic dry Rossby wave critical layer inside the cat's eye, which can be regarded as shape-preserving only at its center. Away from center there's the ever-tightening spiral of 'spaghetti on a fork' tending towards mutual annihilation when small-scale mixing is present. These radically different qualities are noted in our Figure 1, and illustrated in observations of the Okubo-Weiss parameter in Figures 12 & 22.

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Cumulative latent heat release is important, as the reviewer infers, and is built into each of our three hypothesis, implicitly or explicitly. (re: H1) Vortex-tube stretching and subsequent aggregation/segregation lead to an intense concentration of cyclonic, not anticyclonic, vorticity because cyclonic relative vorticity was present initially, favoring cyclonic rollup of the entire mass, segregation of anticyclonic anomalies to the exterior of the proto-vortex, and convective triggering that accompanies the cyclonic vortical finestructure. (re: H2) The vertical profile of latent heat release depends critically on moisture entrainment and/or convective moistening within the pouch, and protection from dry air without. (re: H3) Cumulative heating helps to maintain the parent wave, and its critical layer, creating a positive feedback for hybrid wave/vortex development.

We cannot avoid the notion of 'cyclonic rollup' in this discussion, for theoretical and observational reasons. The theoretical reasons were reiterated above, and reinforced below; for observational evidence the reader is advised to view the morphed animations of total precipitable water (TPW) cited in endnote 1. The classic 'Cape Verde wave' rolling off of Africa is a wonder to behold in TPW! These rolling motions are of course cyclonic. In Appendix C we speculate on a possible role for the forward enstrophy cascade in creating vortical finestructure at the mesoscale which may play a role subsequently in deep convective triggering. We view tropical cyclogenesis as resulting from a collision (in spectral space) of forward enstrophy and inverse energy cascades; the details of this process will be revealed in future studies, as observations and models are applied more effectively to the problem than done so far.

We are tempted to expand on the reviewer's comment that 'Contrary to what's suggested by 'cyclonic rollup...', what rolls up within each cat's eye is not pure-cyclonic PV at first.' Taken at face value, this statement is incorrect; the PV in the southern critical layer is purely cyclonic. But we give the reviewer the benefit of the doubt here: the point he is making is that cyclonic rollup by itself does not favor the creation or emergence of a predominantly cyclonic anomaly within the Kelvin cat's eye. Here, we take 'anomaly' to be defined with respect to the value of vorticity at the original critical latitude, running

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from west to east precisely along the centerline of the cat's eye. There is no cyclone-anticyclone asymmetry contemplated in the ideal dry Rossby-wave critical layer. Fair enough.

To this comment we append some basic comments. (i) Cyclonic rollup is observed in the cat's eye equatorward of the easterly jet axis because the relative vorticity is cyclonic there. The rollup is viewed in a rotating planetary frame, and relative vorticity is defined with respect to this frame. If one were to instead view the rollup in a frame 'relative to the stars' the cyclonic motion would appear about twice as fast (equatorward of the easterly jet axis) according to the magnitude of absolute vorticity, while anticyclonic motions (poleward of the axis) would appear much slower, or absent altogether, if absolute vorticity were nearly zero here, as suggested by Figure 2. (ii) The fact that PV anomalies as defined above are symmetrically distributed about the mean value, in the dry critical layer, does not alter that the total (relative or absolute) vorticity is cyclonic in the cat's eye. A distinction must be made between the existence of the yin-yang pattern, and the direction of rollup experienced by this pattern. Its existence is embodied in the symmetric distribution about the cyclonic mean. Its direction of rollup is dictated by the cyclonic mean itself. (iii) Regardless of the sign of the PV anomaly, vortex-tube stretching tends to amplify the total relative and absolute vorticities in a cyclonic sense, since both are cyclonic everywhere in the cat's eye. (Cyclone relative vorticity is not necessary to the argument.) Vortex-tube stretching acts on absolute vorticity, in such a way to enhance or diminish it, but never to change its sign. (iv) The sign of absolute vorticity can be reversed by extreme tilting (imagine a pancake vortex turned upside-down, reversing the vector). If adiabatic, this reversal is accompanied by overturning of isentropic surfaces, resulting in static instability if the stratification is initially stable. (v) Convective adjustment to a stable final configuration requires subgrid-scale turbulent heat fluxes that may be imagined to leave the tilted vorticity in place (by acting systematically on thermodynamic fields only) resulting in an irreversible local creation or destruction of potential vorticity. (vi) In principle, anomalous values of PV can be created; not by stretching alone, but by tilting, or stretching in tandem with tilting. Such

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values are inertially unstable and will experience rapid inertial adjustment, analogous to the convective adjustment of statically unstable flow. Anticyclonic anomalies in a predominantly cyclonic environment are also likely to segregate to the outer edge of the proto-vortex, to the extent they can survive at all (as might conceivably occur in shallow-water models designed expressly to prohibit inertial instability). (vii) Production of weakly anomalous or nearly zero PV in the upper troposphere in proximity to mesoscale convective systems, mesoscale convective vortices, hurricanes, and so on, is a plausible outcome of this process. A consensus on this point seems to exist in the literature, although its ramifications have not been fully explored. (viii) All nonconservative effects, such as moist diabatic heating and turbulent mixing, may be written as a nonadvective flux of potential vorticity when the PV conservation law is written in flux form.[4] Moist convection leads to an intense concentration of cyclonic PV substance in the proto-vortex at the expense of PV substance outside its periphery (but within the cat's eye). PV substance is neither created nor destroyed by diabatic heating. Convection does not alter the pouch-integrated PV substance unless PV is borrowed from the exterior flow, either by transient entrainment or horizontal convergence.

These basic comments may be distilled to pair of statements relevant to the problem at hand. (i) For practical purposes, tropical depression formation in the marsupial paradigm is cyclonic and can occur only in a cyclonic cat's eye, not an anticyclonic one. We took this statement for granted when choosing the southern, not northern, critical layer as the focus of interest. (ii) TD formation requires convective heating to achieve the desired levels of cyclonic PV and concentration of cyclonic PV substance. We took this statement for granted in the expression of H1, deferring elaboration of it to the Conclusion. Insofar as the reviewer believes that we have engendered confusion or made unwarranted assumptions about the reader's level of understanding, these points are now made explicitly, but briefly, in proximity to H1.

Regarding the term 'gauge' (or 'gauge function' as defined in the Glossary) we employ the classic meaning of a scalar harmonic function. In deference to the reviewer

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we replaced most instances of 'gauge' and 'translating frame' with the standard term 'co-moving frame'. Strictly speaking we avoided 'gauge transformation' in the original version. From the mathematics of gauge theory we are implicitly permitted to use 'gauge' to describe a particular function or operator that renders stream function and trajectories locally equivalent. Perhaps this usage is novel, if applied to classical fluid mechanics, but we see nothing wrong with it. The appropriate 'gauge transformation' between the Earth-relative and co-moving frames is a Galilean transformation at the Earth-relative phase speed of the parent wave. In his objection to this semantic the reviewer is narrow-minded, evidently swayed by an observation that, to date, the physics of gauge theory and gauge transformations has been predominantly associated with classical and quantum electrodynamics; e.g.,

'It is now understood that the spin liquid (defined as having an odd number of electron spins on each lattice unit cell) is a new state of matter with properties we have never encountered before. For example, the excited states may be spinons – charge-neutral objects that possess magnetic properties. Depending on the type of spin liquid, the spinon may obey Fermi or Bose statistics and there may or may not be an energy gap. Furthermore, these spinons cannot live by themselves but are generally accompanied by gauge fields, just as electrons are always accompanied by electromagnetic gauge fields (5). This is a dramatic example of emergent phenomena, where new particles and fields emerge at low-energy scales but are totally absent in the Hamiltonian that describes the initial system.'[5]

But there is no need to restrict the mathematical theory to this realm, nor to demand a particular meaning: the Coulomb gauge (scalar harmonic function) is one meaning, the Lorenz gauge is another, and so on. Unless one believes that 'Coulomb gauge' is an anachronism, its mathematical definition as a scalar harmonic function motivates at once its application to Galilean transformations. We then use the metaphor in reverse, noting that the Coulomb gauge is misleading, or at best difficult, when applied to the full set of Maxwell's equations and electromagnetic wave propagation. The analogies

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drawn by us to Maxwell's equations and their subsequent heritage in the Special Theory of Relativity should be regarded as analogies only, illustrating that a proper fixing of gauge is not only necessary (as when adding homogeneous solutions to the inhomogeneous solution of a partial differential equation in order to satisfy boundary conditions) but intensely helpful for interpretation (to avoid all sorts of misleading inferences).

For a tropical forecaster working the graveyard shift, trying the visualize the sequence of events leading to the formation of a tropical depression, misleading inferences are liable to occur, not because of imagery (which never lies) but on account of Earth-relative meteorological streamlines (which do). The classic 'inverted-V' pattern in low cloud or moisture, associated with an easterly wave just poleward of the ITCZ, is a good example. The imagery in this case seems to agree with Earth-relative streamlines, as if to vindicate the latter. But such is not the case; the resemblance is an unfortunate coincidence. Actually, the two are not coincident! The Earth-relative streamlines bend poleward over the trough, while poleward displacement of air is to the east, behind the trough. Another misleading example is a wave that appears open in the Earth-relative frame but is accompanied by closed loops of low stratocumulus. In weather briefings the summer before last we witnessed a renowned expert on western Pacific TCs misled by such contradictory evidence. When a passively advected cloud pattern is closed, the flow is obviously closed, as revealed in the co-moving frame, not the Earth-relative one.

Regarding over-reflection in wave instability, this concept has proven useful in the majority of instances to which it has been applied, despite its obviously linear formulation and inapplicability to certain situations, and we see little point in rekindling an old trans-Atlantic feud. Suffice it to say that exceptions exist, some of which are noted in the revised endnote.

On writing style: the heart of linguistic interpretation is disambiguation, which is normally resolved by additional words. Proliferation of words, however, runs an increased risk of falsehood, wordiness, imprecision, over-precision, or simply, precision to a de-

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gree that makes a sentence unreadable. It is better to be concise and a little ambiguous, provided that the ambiguity is resolved in context, or elsewhere. Writers normally commit all of these errors to varying degrees, their style being determined by the distribution of error types. We find instances of all in the Discussion Paper, particularly an excess of precision, where a little ambiguity might be preferred. The revision improves readability in hundreds of places. Whatever ambiguities that have been introduced thereby can be resolved (if not in context) by consulting the Discussion Paper. We suppose this to be a legitimate, if unexpected, role for the ACPD archive! Is there such a thing as a needless word? We think seldom, unless exactly redundant. Take 'ambient environment'. Here, 'ambient' specifies the local environment, not 'environment' anywhere on the planet, or in our galactic group. Nevertheless there is something to be said for omitting 'ambient' insofar as the reader is more likely to think 'local environment' by default.

Regarding 'material' and 'Lagrangian' we provide some historical background in our response to Interactive Comment 2. Our usage is not unconventional, provided that the concepts of 'Lagrangian mean' and 'Lagrangian boundary' are admitted into the record. These modern terms convey the distinct ideas of (i) field theory, and (ii) coherent structure, respectively, neither of which refer to the motion of a single particle or parcel. Rather, they are defined with respect to a subset of all particles/parcels, viz., those that participate in the 'mean' or 'boundary'. Moreover, the subset may be 'open' in the sense that a distinct particle/parcel participate only once, and subsequent particles/parcels come along to maintain the Lagrangian boundary. In general it's moot whether the other side of the boundary is 'closed' – but for our purpose this property is important, insofar as recirculation of moist columns is essential to tropical cyclogenesis.

[1] A reference to Killworth and McIntyre (1985) was included in an earlier draft of our paper, but inadvertently deleted somewhere along the way. It has been reinstated with citation.

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

[3] M.T. Montgomery, Z. Wang and T.J. Dunkerton: Intermediate and high-resolution simulations of the transition of a tropical wave critical layer to a tropical depression. Atmos. Chem. & Physics, in preparation, 2008

[4] P.H. Haynes and M.E. McIntyre, On the evolution of vorticity and potential vorticity in the presence of diabatic heating and frictional or other forces, J. Atmos. Sci., 44, 828–841, 1987.

[5] P.A. Lee, An end to the drought of quantum spin liquids. Science, 321 (5894), 1306-1307, 2008.

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