Atmos. Chem. Phys. Discuss., 8, S10564–S10568, 2009
www.atmos-chem-phys-discuss.net/8/S10564/2009/

Atmospheric Chemistry and Physics Discussions

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

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Received and published: 21 January 2009

The paper was shortened by eliminating Sections 4.3 and 4.4; the results of Table 2 are summarized in a paragraph at the end of Section 4.3 (formerly 4.5). For reader's benefit a Glossary was added, and all footnotes converted to endnotes. Section 3 was moved to Appendix A, three of the highlighted cases were moved to Appendix B, and paragraphs from the Conclusion describing topological aspects of the marsupial paradigm were moved to Appendix C. These changes shortened the main text by about 35%, without sacrificing content.

In oral presentations of the highlighted cases we select DEBBY and FABIO as exemplary of hydrodynamically stable and marginally unstable pathways, respectively. These two cases afford a minimal foundation for discussion. Nevertheless there is added value in showing CHRIS, BERYL and SHANSHAN in order to illustrate how the marsupial paradigm applies in other regions and flow configurations, and to strengthen the overall argument. CHRIS illustrates early detection of a tropical depression in the co-moving frame; BERYL extends the marsupial concept to the Gulf of Mexico and illustrates gyre formation resulting from an easterly wave incident on a pre-existing frontal zone; SHANSHAN further extends the concept to the central Pacific and illustrates an evolving vertical phase tilt, resulting in alignment at genesis time.

Concerning the two specific points in the interactive comment, it is true that ocean surface currents are generally much slower than atmospheric surface wind speeds. Therefore as the reviewer correctly infers, surface fluxes are defined with respect to Earth, not the co-moving frame of the parent wave. When a quasi-closed gyre or 'pouch' translates horizontally with respect to the nearly stationary surface – the ultimate source of moisture, moist static energy and moist entropy – its ability to tap this source requires moisture fluxes via boundary layer eddies and deeper penetrative convection. Over the ocean, these small-scale vertical transports may be assumed to be embedded in, and steered by, the atmospheric motion (e.g., as observed in cold-air outbreaks and their associated cloud streets) but the lower boundary condition is tied to the nearly stationary surface.

These considerations introduce another dimension to the complicated problem of tropical cyclogenesis. Three possible outcomes may be imagined, and each of them are interesting: (i) the tropical boundary layer is uniformly moist, such that the hybrid diabatic Rossby wave/vortex varies due solely to its internal dynamics and effects on the boundary layer; (ii) the pouch translates into a region of warmer underlying SST, bringing it into disequilibrium with the surface in such a way as to lead to explosive growth if the pouch is already close to saturation[1] ; (iii) the pouch translates horizontally into a region of cooler SST (e.g., a previous storm's wake) making development less likely.

Note that although the marsupial paradigm does not require that the pouch be moist initially, part or most of it usually is: (i) development often occurs along a moisture gradient, as discussed in connection with BERYL and FABIO, and (ii) approaching genesis

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time, the nearby environment is anomalously moist in most cases (Figures 16-17). The detailed evolution of moisture within the pouch varies from case to case, as might be expected from Figure 1. If the environment is moist to the south, moist air is entrained northward by cyclonic roll-up in the eastern half of the gyre, but as time progresses, this moisture reaches the western (forward) side, and additional moistening may have occurred as a result of deep convection within the pouch. In such cases a moisture 'front' develops at the forward edge of the pouch. In a recent study we found Hovmöllers of total precipitable water to provide a useful alternative measure of zonal phase speed[2].

Note also that we generally refer to the gyre as 'quasi-closed' owing to unsteady and/or divergent flow in the co-moving frame (H2).

Regarding the relation of 'moist columns' to the surface fluxes, a Lagrangian viewpoint is preferred over the traditional Eulerian view of wind-induced surface heat exchange (WISHE). In the traditional view, a feedback is postulated between an anomalous evaporative flux, due to anomalous wind, and its almost immediate impact on the overlying column. In the future, we anticipate that WISHE will be generalized to account for Lagrangian transport of moisture in the boundary layer and free troposphere above. This generalization will bring the concept into better agreement observations of the tropical circulation and convection[3]. The point of discussing moisture transport within the pouch will be to identify where the input of latent energy to the system is eventually realized in deep moist convection. This location seldom coincides with the anomalous evaporation, in the context of TC genesis, or in other tropical flows. We regard the Eulerian representation of WISHE as defective, along with theories that depend on this representation.

Our emphasis on kinematics is appropriate for an introductory paper that represents a paradigm shift for tropical cyclogenesis in which kinematics plays a fundamental role. Flow kinematics is an area where oceanographers have made significant strides, for the greater good of GFD. In their text, Samelson and Wiggins exemplify a study of Gulf Stream meanders by Bower:

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'This model was purely kinematic: based on general aspects of the observational record, a representative form of the stream function was proposed, and the corresponding trajectories analyzed, without any specific dynamical reasoning or restriction. This approach places the focus squarely on the relation between velocity field and fluid trajectory, and provides an important example of the manner in which this relation can become the natural subject of study. The model stream function described a jet of uniform width deformed by a sinusoidal meander that propagated steadily downstream. In a reference frame moving with the meander, the corresponding fluid motion was steady and consisted of three regimes: a central jet, exterior retrograde motion, and intermediate closed circulations above meander troughs and below crests.'[4]

Here the reader will detect several similarities with the atmospheric problem at hand. That Lagrangian kinematics can become a 'natural subject of study' in its own right emphasizes the inherent value of kinematics. When coupled to the existence of adiabatic invariants that constrain the motion via a balanced invertibility relationship, kinematics becomes inextricably linked with dynamics. Thanks to the layer-wise conservation properties of potential vorticity 'substance' and its associated impermeability theorem[5], this linkage remains intact even when strongly turbulent processes punctuate the quasi-horizontal flow (e.g., deep moist convection).

For additional discussion regarding the dynamics of the critical layer, refer to our response to the Interactive Comment by Michael McIntyre.

[1] K.A. Emanuel, personal communication, 2008.

[2] Z. Wang, M.T. Montgomery and T.J. Dunkerton, A dynamically based method for forecasting tropical cyclogenesis location in the Atlantic sector using global model products, Geophys. Res. Lett, to appear, 2008.

[3] A.H. Sobel, S.E. Yuter, C.S. Bretherton, and G.N. Kiladis: Large-scale meteorology and deep convection during TRMM KWAJEX. Mon. Wea. Rev., 132, 422–444, 2004.

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

[5] 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.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 11149, 2008.

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