CORRESPONDENCE

Comments on "Symmetric and Asymmetric Structures of Hurricane Boundary Layer in Coupled Atmosphere–Wave–Ocean Models and Observations"

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(Manuscript received 8 July 2013, in final form 1 December 2013)

1. Introduction

In a recent paper, Lee and Chen (2012, hereafter LC12) presented numerical simulations of symmetric and asymmetric hurricane boundary layer structures in a fully coupled atmosphere–wave–ocean model and used these simulations to compare aspects of the boundary layer structure against an analysis of observations. One of their main conclusions was that "the azimuthally averaged inflow layer tends to misrepresent the overall inflow structure in tropical cyclones, especially the asymmetric structure" (p. 3593). Another main conclusion was that the complicated asymmetric three-dimensional boundary layer structures (attributed by them to be) due in part to the air–sea and wind–wave coupling "make it difficult to parameterize the atmosphere–wave–ocean coupling effects without a fully coupled model" (p. 3593). After careful examination of their study, we have a number of questions regarding their methodology, their interpretations (including their interpretations of previous literature), and their conclusions. Specifically, we inquire about aspects of the methodology for defining the dynamical boundary layer depth, the selection of the boundary layer scheme, and we question the conclusions inferred. In addition to the foregoing concerns, inaccuracies in their literature review are noted and inconsistencies between their conclusions and reported results are identified.

For many decades, physical processes across the air–sea interface and within the atmospheric boundary layer have been known to be essential for the development and maintenance of a tropical cyclone (Ooyama 1969; Emanuel 1986, 1995; Smith et al. 2009; Smith and Montgomery 2010; Bryan and Rotunno 2009; Bryan 2012). However, the boundary layer is the least-observed part of a storm—in particular, its turbulence structure. With the advent of the global positioning system (GPS) dropsonde (Hock and Franklin 1999), the mean boundary layer structure has been progressively studied. Previous studies have concentrated mostly on determining the boundary layer structure in an individual storm (e.g., Kepert 2006a,b; Montgomery et al. 2006; Bell and Montgomery 2008; Barnes 2008; Zhang et al. 2009; Zhang 2010) with the hope that these findings generalize to other storms. Recently, Zhang et al. (2011, hereafter Z11) conducted a composite analysis of the axisymmetric boundary layer structure based on hundreds of GPS

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DOI: 10.1175/JAS-D-13-0207.1

dropsondes from 13 Atlantic hurricanes. They found that there is a clear separation between the boundary layer depths defined kinematically/dynamically and thermodynamically. The kinematic boundary layer depth (i.e., the depth of relatively strong inflow possessing greater than 10% of the peak mean inflow velocity) is much higher than the thermodynamic height (i.e., the mixed-layer depth for virtual potential temperature). They found also that the observed inflow-layer depth, as well as the depth of relatively strong inflow, tends to decrease with decreasing radius toward the center. These results support strongly those found in the earlier studies of specific storms.

The study by LC12 presents an analysis of the asymmetric structure of the atmospheric boundary layer in a strong hurricane vortex. Based on comparisons between simulated and observed vertical profiles of kinematic and thermodynamic parameters, primarily from data collected in Hurricane Frances (2004), they suggested that the atmosphere–ocean coupling reduces the mixed-layer depth in the rear-right quadrant because of storm-induced ocean cooling and that the wind–wave coupling enhances boundary layer inflow beyond the radius of maximum wind speed. They reported also a significant front-to-back asymmetry in the depth of the inflow layer in their numerical simulations. LC12 emphasized the complicated nature of the three-dimensional boundary layer structure in their simulations. However, they offered no discussion or reasoning why such asymmetric structures would be important for hurricane intensification or mature intensity. We communicate our questions here.

As stated above, our study of LC12 has raised what we believe are substantive questions about their analysis method and scientific interpretation that diminish the reliability of some of their conclusions. Inaccuracies in their literature review are noted also.

2. Scientific concerns with LC12's methodology

Our first major scientific concern with LC12 is their definition of the hurricane boundary layer. They wrote "… to distinguish the inflow layer from that of the mixed layer, here we refer to it as dynamic HBL (DHBL)" (p. 3577). Thus, they equated the depth of the dynamical hurricane boundary layer (DHBL) with the height of zero inflow.[1] LC12 wrote also that "The boundary inflow is a result of gradient wind imbalance due to the surface friction (Smith 1968), and the top of the inflow layer is defined as where the inflow vanishes (e.g., Smith et al. 2009; Zhang et al. 2011)" (p. 3577). They cited Smith et al. (2009) and Z11 as if these two studies advocated such a definition for the boundary layer. In fact, Smith et al. (2009) defined the boundary layer depth as the depth of the "the shallow layer of *strong* inflow near the sea surface that is typically 500 m to 1 km deep and arises *largely* because of the frictional disruption of gradient wind balance near the surface" (footnote on p. 1322). This definition does not include the weak midlevel inflow. This depth was easy to distinguish in their numerical experiments. In the same spirit, Z11 defined the boundary layer height as the height at which the inflow falls to 10% of the peak inflow (see their Fig. 5). The inappropriate choice of the inflow layer depth, including the convectively driven deep tropospheric inflow by LC12, seems to be one of the reasons for their misinterpretation of results reported by Z11 and would explain why the DHBL depth shown in their Fig. 17 is as high as 10 km.

Z11 were fully aware of the potential limitations of using the inflow-layer depth as the top of the hurricane boundary layer and wrote an entire paragraph articulating the issues involved. On p. 2531–2532, they wrote:

> Notwithstanding the variability of different boundary layer height scales, it is thought that the inflow layer depth represents the top of the hurricane boundary layer better than does the thermodynamic boundary layer depth. Direct flux measurements in the outer-core regions of hurricanes suggest the turbulent flux transport mainly occurs in the inflow layer (Zhang et al. 2009). The budgets and discussion presented by Kepert and Wang (2001) and Kepert (2010a) support the statement that the momentum flux occurs mainly in the inflow layer. In his numerical simulations, Kepert (2010a) also showed that the momentum flux is a significant part of the dynamics of the layer of outflow immediately above the inflow and suggested that it is therefore appropriate to include at least part of this layer in the boundary layer.

LC12 challenged Z11's results (see their last sentence on p. 3589) without comment on the foregoing caveats.

A second major scientific concern that we have with LC12's study is a fundamental flaw in their methodology of comparing the model asymmetric structure with the observed composite symmetric structure from many storms in Z11. We would argue that this comparison is logically ill founded. For a single-valued function of azimuth θ, the azimuthal structure is a periodic function of θ at a given radius r and height z. The axisymmetric structure is represented by azimuthally averaging the field. By definition, at any point in time, the azimuthal-mean structure is mathematically orthogonal to the asymmetric structure. For this reason, Z11 never suggested (either explicitly or implicitly) that their azimuthal-mean structure would represent the asymmetric structure.

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[1] Note that the definition in the reply (Lee and Chen 2014) as the contour of $-2\,\mathrm{m\,s^{-1}}$ is different from that in the original paper.

3. Concerns with LC12's interpretations of results relating to past literature

Besides their misinterpretation of the methodology of defining the kinematic/dynamic boundary layer depth used by Z11 and Smith et al. (2009), LC12 questioned several times the representativeness of Z11's results. For instance, they stated that "Many [storms] have a much deeper inflow layer in parts of the hurricanes than the composite in Z11, which raises a question of whether the composite inflow can represent the true structure in hurricanes" (p. 3577). They go on to say that "Unlike the azimuthally averaged fields shown in Zhang et al. (2011), the low-level outflow layer above DHBL [dynamic hurricane boundary layer; our insertion] exists only in the front-left quadrant (Kepert 2006a)" (p. 3578). They stated also that "These features are different from the mean inflow layer described in Zhang et al. (2011), but they are consistent with that in Hurricane Georges (1998) shown in Kepert (2006a)" (p. 3586). Furthermore, they stated that "It also causes concern regarding the representativeness of the azimuthally averaged HBL properties as shown in Zhang et al. (2011), which mask some dominate [*sic*] features in the inflow depth and asymmetry" (p. 3593). These misinterpretations have the potential to confuse readers.

Figure 16 of LC12 shows that the mixed-layer depth decreases with decreasing radius in all four quadrants. Moreover, the mixed-layer depth is within the inflow layer in all four quadrants. These findings are entirely consistent with the main conclusions of Z11 and the conceptual model proposed by Z11 (see their Fig. 12 on p. 2532). Thus, the conclusion made by LC12 in terms of the behavior of the mixed-layer depth as compared to Z11 is not supported by their own results. Furthermore, their Fig. 16 shows that the simulated strong inflow layer is generally well below 1–2 km for all four quadrants relative to the storm motion, again supporting the conceptual model of Z11. Note that Zhang et al. (2013) conducted analyses of the asymmetric boundary layer structure relative to the environmental shear, supporting also Z11's conceptual model for boundary layer height variations, even considering variations in azimuth.

4. Concerns with LC12's conclusions

Finally, we question the conclusion drawn by LC12 in terms of the fully coupled model in the last sentence of the abstract (and echoed in their conclusions) that "the complex, three-dimensional asymmetric structure in both thermodynamic and dynamic properties of the HBL indicates that it would be difficult to parameterize the effects of air–sea coupling without a fully coupled model" (p. 3576). Previous studies have shown very encouraging comparisons between model and observed boundary layer mean and turbulent structure without using a fully coupled model (e.g., Nolan et al. 2009a,b; Gopalakrishnan et al. 2013). Also, in an idealized study examining both a stationary and a moving vortex, Thomsen et al. (2014) showed that tropical cyclone intensification and mature intensity are not sensitive to stochastic variations in the drag coefficient whose variations lie within a reasonably wide envelope. Finally, in a recent study, Cione et al. (2013) found evidence to suggest that processes in the atmospheric boundary layer are more responsible for intensity change than the ocean response based on an analysis of a large number of buoy observations. Together, the foregoing results suggest that wind–wave coupling may not be necessary for simulating hurricane intensity.

5. Discussion and recommendations regarding LC12

It should be noted that most of LC12's conclusions were drawn using one planetary boundary layer (PBL) scheme (the Blackadar scheme) in a comparison of three deterministic calculations with distinct model configurations of Hurricane Frances (2004). These configurations included an atmospheric model only, an atmosphere and ocean model, and an atmosphere–wave–ocean model. As pointed out by Braun and Tao (2000) and more extensively in a recent study by Smith and Thomsen (2010), detailed aspects of the simulated hurricane boundary layer structure are generally sensitive to the selection of PBL scheme. We note also that the Blackadar scheme used a constant vertical mixing length, which is not realistic according to direct flux measurements in the hurricane boundary layer by Zhang and Drennan (2012).

We have an additional concern with LC12's methodology of using a single deterministic calculation for each model configuration in light of the variability associated with the stochastic nature of deep convection. For example, it has been shown in a recent paper by Thomsen et al. (2013, manuscript submitted to *Mon. Wea. Rev.*) that this variability may lead to substantial fluctuations in the asymmetric inflow structure on time scales as short as 15 min. Thus, without suitable time averaging of the model or observational data, it is unclear whether the findings of LC12 regarding the asymmetries are robust.

Given all of the issues discussed here, further analysis and scientific interpretation of existing numerical hurricane simulations following the same methodology for defining the boundary layer height scales as used in the recently published boundary layer studies cited above is strongly encouraged.

Acknowledgments. The NOAA Hurricane Forecast Improvement Project (HFIP) supported this work. We thank Robert Rogers for helpful comments to improve the paper. We are grateful also to Eric Uhlhorn and Sundararaman G. Gopalakrishnan for providing an internal review of the manuscript.

REFERENCES

Barnes, G. M., 2008: Atypical thermodynamic profiles in hurricanes. *Mon. Wea. Rev.,* **136,** 631–643, doi:10.1175/2007MWR2033.1.

Bell, M. M., and M. T. Montgomery, 2008: Observed structure, evolution, and intensity of category 5 Hurricane Isabel (2003) from 12 to 14 September. *Mon. Wea. Rev.,* **136,** 2023–2036, doi:10.1175/2007MWR1858.1.

Braun, S. A., and W.-K. Tao, 2000: Sensitivity of high-resolution simulations of Hurricane Bob (1991) to planetary boundary layer parameterizations. *Mon. Wea. Rev.,* **128,** 3941–3961, doi:10.1175/1520-0493(2000)129<3941:SOHRSO>2.0.CO;2.

Bryan, G. H., 2012: Effects of surface exchange coefficients and turbulence length scales on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev.,* **140,** 1125–1143, doi:10.1175/MWR-D-11-00231.1.

——, and R. Rotunno, 2009: The maximum intensity of tropical cyclones in axisymmetry numerical model simulations. *Mon. Wea. Rev.,* **137,** 1770–1789, doi:10.1175/2008MWR2709.1.

Cione, J. J., E. A. Kalina, J. A. Zhang, and E. W. Uhlhorn, 2013: Observations of air–sea interaction and intensity change in hurricanes. *Mon. Wea. Rev.,* **141,** 2368–2382, doi:10.1175/MWR-D-12-00070.1.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.,* **43,** 585–605, doi:10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2.

——, 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.,* **52,** 3969–3976, doi:10.1175/1520-0469(1995)052<3969:SOTCTS>2.0.CO;2.

Gopalakrishnan, S. G., F. Marks, J. A. Zhang, X. Zhang, J.-W. Bao, and V. Tallapragada, 2013: A study of the impacts of vertical diffusion on the structure and intensity of the tropical cyclones using the high-resolution HWRF system. *J. Atmos. Sci.,* **70,** 524–541, doi:10.1175/JAS-D-11-0340.1.

Hock, T. F., and J. L. Franklin, 1999: The NCAR GPS dropwindsonde. *Bull. Amer. Meteor. Soc.,* **80,** 407–420, doi:10.1175/1520-0477(1999)080<0407:TNGD>2.0.CO;2.

Kepert, J. D., 2006a: Observed boundary layer wind structure and balance in the hurricane core. Part I: Hurricane Georges. *J. Atmos. Sci.,* **63,** 2169–2193, doi:10.1175/JAS3745.1.

——, 2006b: Observed boundary layer wind structure and balance in the hurricane core. Part II: Hurricane Mitch. *J. Atmos. Sci.,* **63,** 2194–2211, doi:10.1175/JAS3746.1.

——, and Y. Wang, 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part II: Nonlinear enhancement. *J. Atmos. Sci.,* **58,** 2485–2501, doi:10.1175/1520-0469(2001)058<2485:TDOBLJ>2.0.CO;2.

Lee, C., and S. S. Chen, 2012: Symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere–wave–ocean models and observations. *J. Atmos. Sci.,* **69,** 3576–3594, doi:10.1175/JAS-D-12-046.1.

——, and ——, 2014: Reply to "Comments on 'Symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere–wave–ocean models and observations.'" *J. Atmos. Sci.,* **71,** 2786–2787.

Montgomery, M. T., M. M. Bell, S. D. Aberson, and M. L. Black, 2006: Hurricane Isabel (2003): New insights into the physics of intense storms. Part I: Mean vortex structure and maximum intensity estimates. *Bull. Amer. Meteor. Soc.,* **87,** 1335–1347, doi:10.1175/BAMS-87-10-1335.

Nolan, D. S., J. A. Zhang, and D. P. Stern, 2009a: Evaluation of planetary boundary layer parameterizations in tropical cyclones by comparison of in situ data and high-resolution simulations of Hurricane Isabel (2003). Part I: Initialization, maximum winds, and outer-core boundary layer structure. *Mon. Wea. Rev.,* **137,** 3651–3674, doi:10.1175/2009MWR2785.1.

——, D. P. Stern, and J. A. Zhang, 2009b: Evaluation of planetary boundary layer parameterizations in tropical cyclones by comparison of in situ data and high-resolution simulations of Hurricane Isabel (2003). Part II: Inner-core boundary layer and eyewall structure. *Mon. Wea. Rev.,* **137,** 3675–3698, doi:10.1175/2009MWR2786.1.

Ooyama, K. V., 1969: Numerical simulation of the life cycle of tropical cyclones. *J. Atmos. Sci.,* **26,** 3–40, doi:10.1175/1520-0469(1969)026<0003:NSOTLC>2.0.CO;2.

Smith, R. K., and M. T. Montgomery, 2010: Hurricane boundary-layer theory. *Quart. J. Roy. Meteor. Soc.,* **136,** 1665–1670, doi:10.1002/qj.679.

——, and G. L. Thomsen, 2010: Dependence of tropical-cyclone intensification on the boundary layer representation in a numerical model. *Quart. J. Roy. Meteor. Soc.,* **136,** 1671–1685, doi:10.1002/qj.687.

——, M. T. Montgomery, and S. V. Nguyen, 2009: Tropical cyclone spin-up revisited. *Quart. J. Roy. Meteor. Soc.,* **135,** 1321–1335, doi:10.1002/qj.428.

Thomsen, G. L., M. T. Montgomery, and R. K. Smith, 2014: Sensitivity of tropical-cyclone intensification to perturbations in the surface drag coefficient. *Quart. J. Roy. Meteor. Soc.,* doi:10.1002/qj.2048, in press.

Zhang, J. A., 2010: Estimation of dissipative heating using low-level in situ aircraft observations in the hurricane boundary layer. *J. Atmos. Sci.,* **67,** 1853–1862, doi:10.1175/2010JAS3397.1.

——, and W. M. Drennan, 2012: An observational study of vertical eddy diffusivity in the hurricane boundary layer. *J. Atmos. Sci.,* **69,** 3223–3226, doi:10.1175/JAS-D-11-0348.1.

——, ——, P. G. Black, and J. R. French, 2009: Turbulence structure of the hurricane boundary layer between the outer rainbands. *J. Atmos. Sci.,* **66,** 2455–2467, doi:10.1175/2009JAS2954.1.

——, R. F. Rogers, D. S. Nolan, and F. D. Marks, 2011: On the characteristic height scales of the hurricane boundary layer. *Mon. Wea. Rev.,* **139,** 2523–2535, doi:10.1175/MWR-D-10-05017.1.

——, ——, P. D. Reasor, E. W. Uhlhorn, and F. D. Marks, 2013: Asymmetric hurricane boundary layer structure from dropsonde composites in relation to the environmental vertical wind shear. *Mon. Wea. Rev.,* **141,** 3968–3984, doi:10.1175/MWR-D-12-00335.1.