JOBNAME: MWR 00#00 2020 PAGE: 1 SESS: 8 OUTPUT: Tue Nov 3 10:14:45 2020 Total No. of Pages: 1
/ams/mwr/0/mwrD200300

CORRESPONDENCE

Reply to ''Comments on 'On the Structure and Formation of UTLS PV Dipole/Jetlets in Tropical Cyclones by Convective Momentum Surges'''

MATTHEW H. HITCHMAN[a] AND SHELLIE M. ROWE[a]

[a] *Department of Atmospheric and Oceanic Sciences, University of Wisconsin–Madison, Madison, Wisconsin*

KEYWORDS: Convective storms/systems; Hurricanes; Potential vorticity

We would like to thank Dr. Ong for his thoughtful comment (Ong 2020) on our manuscript Hitchman and Rowe (2019, hereafter HR19). We are glad that he finds merit in our convective momentum hypothesis regarding the production of potential vorticity (PV) dipoles and their associated jetlets in the upper troposphere–lower stratosphere (UTLS). In his comment, he provides a careful description of terms in the conservation equation for Ertel's potential vorticity, emphasizing the salient role of diabatic tilting in producing PV dipoles in potential temperature coordinates. We agree with his interpretation, except for mischaracterizing our canoe paddle analogy as a ''flaw.'' This was intended as a conceptual, intuitive aid to understanding how a PV dipole/jetlet forms in the UTLS. We also would like to point out the different challenges involved in interpreting PV dipole formation in altitude coordinates versus theta coordinates.

HR19 were clear in stating that the ''canoe paddle stroke'' idea is an analogy, and that consideration of it as a ''tangential forcing term'' is by analogy, and that all of the flow features discussed in that paper were, in actuality, resolved, advective flows in the model. From p. 4118 of HR19: ''The transition from troposphere to stratosphere is similar to that between water and air for a canoe paddle, such that a momentum pulse impinging on the interface will yield a local jetlet, hence a vorticity dipole. This point of view is closely related to human experience.'' In addition, from p. 4119: ''Numerical gridpoint models can provide momentum flux estimates but do not distinguish between updraft and ambient air. To ask the question of how deep convection influences its environment, one must impose a conceptual distinction.'' On p. 4120: ''the UWNMS does not distinguish between the updraft and ambient air, so the appropriate interpretation is that the acceleration is due to vertical advection.'' We feel that the analogy between a canoe paddle stroke and the tangential forcing term in the PV equation is insightful and helpful, but strictly as an analogy. In fact, numerical noise and the parameterized effects of subgrid-scale transport constitute the effective viscous force in Eulerian gridpoint models [term 3 on the right-hand side of Eq. (1a) in Ong (2020)]. This term should give only weak and vague patterns, which are unlikely be related to the formation of UTLS PV dipole/jetlets. Instead, the PV anomalies that are advected upward are likely to be formed by the diabatic tilting term, in agreement with Ong's (2020) interpretation.

Our intention in HR19 was not to carry out detailed calculations of terms in a PV conservation equation in the University of Wisconsin Nonhydrostatic Modeling System (UWNMS), but rather to provide a simpler, more intuitive understanding of PV dipole formation, which occurs by resolved upward advection of momentum in this 3D gridpoint model. Geometrical altitude is the vertical coordinate of the UWNMS, which monotonically increases upward. In this framework, it is natural to calculate the vertical component of PV based on relative vorticity at constant height. Upward advection of a momentum anomaly into the UTLS can lead to a PV dipole, calculated with horizontal winds on constant height surfaces, which is the convective momentum transport hypothesis. Both HR19 and Ong (2020) emphasize the intimate relationship between the effects of local convective momentum transport and the concept of vortex tilting. In considering his Fig. 1b, adiabatic tilting could create a PV dipole on a constant altitude surface. This would imply that warping of theta surfaces relative to altitude surfaces can explain the existence of a PV dipole on an altitude surface. His diabatic tilting term depicted in Fig. 1c would create a PV dipole in both potential temperature and altitude coordinates. We look forward to reading future papers on detailed calculations of the PV budget in theta coordinates, but have a concern that it might be hard to diagnose convection in theta coordinates, since one theta value can correspond to an array of values in altitude.

Acknowledgments. We would like to acknowledge support from NSF Grants AGS-1555851 and AGS-1947658 during the process of writing HR19 and this reply.

REFERENCES

Hitchman, M. H., and S. M. Rowe, 2019: On the structure and formation of UTLS PV dipole/jetlets in tropical cyclones by convective momentum surges. *Mon. Wea. Rev.*, 147, 4107–4125, https://doi.org/10.1175/MWR-D-18-0232.1.

Ong, H., 2020: Comments on '''On the structure and formation of UTLS PV dipole/jetlets in tropical cyclones by convective momentum surges.''' *Mon. Wea. Rev.*, https://doi.org/10.1175/MWR-D-20-0156.1, in press.

Corresponding author: Shellie M. Rowe, rowe1@wisc.edu

DOI: 10.1175/MWR-D-20-0300.1