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THE COMPOSITED TROPICAL CYCLONE OUTFLOW LAYER & THE BALANCED VORTEX RESPONSE

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1. INTRODUCTION

Early research efforts to determine the structure of the tropical cyclone outflow layer relied on spatially and temporally sparse data sources such as balloon soundings, rawinsondes, and dropsondes (Hughes 1952; Jordan 1952; Miller 1958; Izawa 1964). In an attempt to increase data coverage, later research combined large numbers of rawinsonde and aircraft data (e.g., Black and Anthes 1971; Frank 1977; Holland and Merrill 1984; Molinari and Vollaro 1989). This increased data coverage allowed for research on the role of eddy momentum fluxes on the secondary circulation tropical cyclones (Challa and Pfeffer 1980; Pfeffer and Challa 1981; Holland and Merrill 1984). Molinari and Vollaro (1990) extended these analyses to include all eddy forcing terms in both the momentum and thermodynamic equations. But, they examined only a single case study.

This study focuses on a broad range of tropical cyclones of all intensities in order to examine the structure of the outflow layer and the impact of azimuthal eddies. We use the spatially and temporally complete ECMWF ERA-Interim Reanalysis to generate azimuthally averaged composites of a subset of tropical cyclones over a 36 year period (1979-2014) in the Atlantic basin. ERA-Interim provides data which covers every storm, at every time, at every gridpoint horizontally and vertically. Composites were stratified by intensity and created for a number of meteorological variables. We then implement the Eliassen (1952) balanced vortex equations on the composite fields to illuminate the response of the secondary circulation to eddy momentum and eddy heat sources.

2. DATA

2.1 *Tropical Cyclone Data*

Four times daily Atlantic basin tropical cyclone location and intensity over a 36 year period (1979-2014) were obtained from the Hurricane Database (HURDAT2, Landsea and Franklin 2013). We focus on the outflow layer of tropical disturbances of at least tropical depression strength by applying three filters to tropical cyclone center times which removed times after: 1) the storm center passed 40 N, 2) a storm was classified as extra-tropical, or 3) a storm made landfall for greater than 6 h.

2.2 *Meteorological Data*

Data from the six-hourly ECMWF ERA-Interim Reanalysis (Dee et al. 2011) were retrieved for the 36 year period 1979-2014. The ERA-Interim dataset is available on 37 pressure levels with a horizontal resolution of 0.7 x 0.7 degrees.

3. COMPOSITES

3.1 *Methodology*

The ERA-Interim data were bilinearly interpolated to cylindrical grids centered on each individual tropical cyclone center radially every 100 km (from 100 km to 2000 km outside the storm core) and vertically every 25 hPa (from 1000 hPa to 50 hPa).

Structurally, tropical cyclones of each intensity from tropical depression through major hurricane were similar. Maxima and minima varied in magnitude but not location. Thus, this work focuses on the major hurricane grouping of tropical cyclones.

3.2 *Results*

The outflow layer exists between 100-300 hPa, with a radial outflow maximum at 600 km and 175 hPa and an anticyclonic flow minimum at 1200 km and 150 hPa. At outer radii, radial outflow narrows to the 100-200 hPa layer and extends to beyond 2000 km (Fig. 1). Maxima in divergence and anticyclonic vorticity are present at 175 hPa at inner radii (Fig. 2). Additionally, the outflow layer is associated with inward fluxes of mean and eddy momentum at outer radii (Fig. 3). There, the eddy momentum flux maximum is two times as large as the maximum mean momentum flux which indicates that the outflow layer readily interacts with its environment. As expected, a warm potential temperature anomaly (Fig. 4) is present from 150-900 hPa at middle radii with a maximum warm core located in the upper troposphere at 250 hPa at inner radii. Negative values present directly above the warm core indicate an elevated tropopause relative to the Dunion (2011) moist tropical sounding.

4. THE BALANCED VORTEX RESPONSE

4.1 *Methodology*

Eddy momentum and heat effects are incorporated in the results discussed above. The Eliassen (1952) balanced vortex equations are:

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$$\boldsymbol{A}\psi_{pp} + 2\boldsymbol{B}\psi_{rp} + \boldsymbol{C}\psi_{rr} - \frac{4B}{r}\psi_p - \left[\frac{1-\kappa}{p}B + \frac{C}{r}\right]\psi_r = r\frac{\partial}{\partial p}\left[\left(\frac{2\overline{v_\lambda}}{r} + f\right)\left(\frac{\partial \overline{v_\lambda}}{\partial t}\right)_{eddy}\right] + \frac{r\pi R}{p}\frac{\partial}{\partial r}\left(\frac{\partial \bar{\theta}}{\partial t}\right)_{eddy} \tag{1}$$

$$\boldsymbol{A} = \left(f + \frac{2\overline{v_\lambda}}{r}\right)\left(f + \frac{\partial \overline{v_\lambda}}{\partial r} + \frac{\overline{v_\lambda}}{r}\right) \tag{2}$$

$$\boldsymbol{B} = -\left(f + \frac{2\overline{v_\lambda}}{r}\right)\left(\frac{\partial \overline{v_\lambda}}{\partial p}\right) \tag{3}$$

$$\boldsymbol{C} = -\frac{R\pi}{p}\frac{\partial \bar{\theta}}{\partial p} \tag{4}$$

$$\left(\frac{\partial \overline{v_\lambda}}{\partial t}\right)_{eddy} = -\frac{1}{r^2}\frac{\partial}{\partial r}r^2\overline{v'_r v'_\lambda} - \frac{\partial}{\partial p}\overline{\omega' v'_\lambda} - \overline{f' v'_r} \tag{5}$$

$$\left(\frac{\partial \bar{\theta}}{\partial t}\right)_{eddy} = -\frac{1}{r}\frac{\partial}{\partial r}\overline{\theta' v'_r} - \frac{\partial}{\partial p}\overline{\theta' \omega'} \tag{6}$$

where π is non-dimensional pressure, and red terms in Eq. (1) are defined in Eq. (2) through Eq. (6) as the inertial stability, the baroclinicity, the static stability, the eddy momentum source, and the eddy heat source, respectively.

4.2 *Results*

Solutions to the balanced vortex are shown in Fig. 5. The full vortex response (Fig. 5c) to the eddy momentum and heat sources is an increased in-up-out circulation. Outflow aloft is concentrated within the 175-225 hPa layer while inflow extends over a deeper region. Since the equations are linear, the response to just the momentum forcing (Fig. 5a) and just the heat forcing (Fig. 5b) can be visualized. Overall, the eddy momentum source induces a larger response by the vortex than the eddy heat source.

Composites of each of the red terms in Eq. (1) above will be shown and discussed in the presentation.

5. CONCLUSION

Prior composites of the general structure of tropical cyclones were plagued by data density issues. This left many unanswered questions about the outflow layer such as where is the typical tropical cyclone outflow layer located, how fast is air streaming out of the tropical cyclone core, and how is the tropical cyclone circulation impacted by momentum and heat fluxes. The research presented here addresses these and other fundamental questions regarding the outflow structure and its properties.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Black, P. G., and R. A. Anthes, 1971: On the asymmetric structure of the tropical cyclone outflow layer. J. Atmos. Sci., 28, 1348–1366.

Challa, M., and R. L. Pfeffer, 1980: Effects of eddy fluxes of angular momentum on model hurricane development. J. Atmos. Sci., 37, 1603–1618.

Dee, D. P., and Coauthors, 2011: The ERA-interim reanalysis: Configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc., 137, 553–597.

Dunion, J. P., 2011: Rewriting the climatology of the tropical north Atlantic and Caribbean Sea atmosphere. Journal of Climate, 24, 893– 908.

Eliassen, A., 1952: Slow thermally or frictionally controlled meridional circulation in a circular vortex. Astrophisica Nor., 5, 19–60.

Frank, W. M., 1977: The structure and energetics of the tropical cyclone storm structure. Mon. Wea. Rev., 105, 1119–1135.

Holland, G. J., and R. T. Merrill, 1984: On the dynamics of tropical cyclone structural changes. Q. J. R. Meteorol. Soc., 110, 723–745.

Hughes, L. A., 1952: On the low-level wind structure of tropical storms. J. Meteorol., 9, 422–428.

Izawa, T., 1964: On the mean wind structure of typhoon. Japan Meteorol. Agency.

Jordan, E. S., 1952: An observational study of the upper wind-circulation around tropical storms. J. Meteorol., 9, 340–346.

Landsea, C. W., and J. L. Franklin, 2013: Atlantic hurricane database uncertainty and presentation of a new database format. Mon. Wea. Rev., 141, 3576–3592.

Miller, B. I., 1958: The three-dimensional wind structure around a tropical cyclone. Weather Bur. Office, Miami, Florida.

Molinari, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy angular momentum fluxes. J. Atmos. Sci., 46, 1093–1105.

Molinari, J., and D. Vollaro, 1990: External influences on hurricane intensity. Part II: Vertical structure and response of the hurricane vortex. J. Atmos. Sci., 47, 1902–1918.

Pfeffer, R. L., and M. Challa, 1981: A numerical study of the role of eddy fluxes of momentum in the development of Atlantic hurricanes. J. Atmos. Sci., 38, 2393–2398.

8. FIGURES

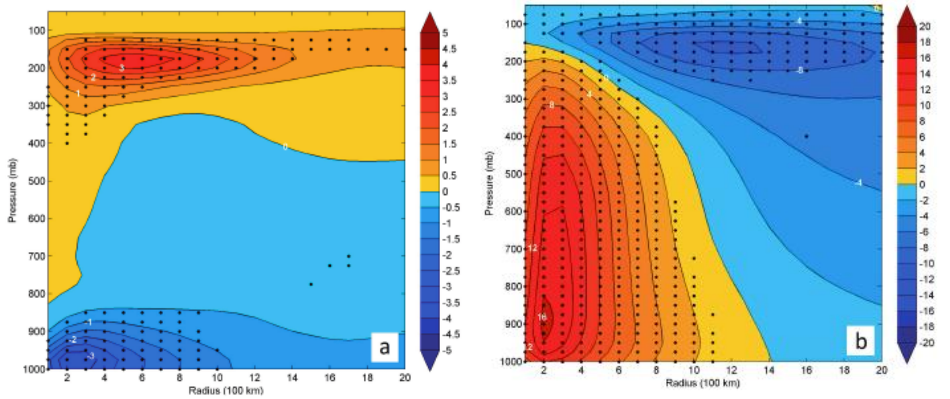

Fig. 1. Composites of radial (a) and tangential (b) wind for major hurricanes. The radial wind composites' contour interval is 0.5 ms^{-1} with contour labels every 1 ms^{-1}. The tangential wind composites' contour interval is 2 ms^{-1} with contour labels every 4 ms^{-1}. The sample size used to generate the composites is 740. Stippling (dots) indicate locations significance at the 99% confidence level between tropical depressions and major hurricanes of the same variable as calculated by a bootstrap test.

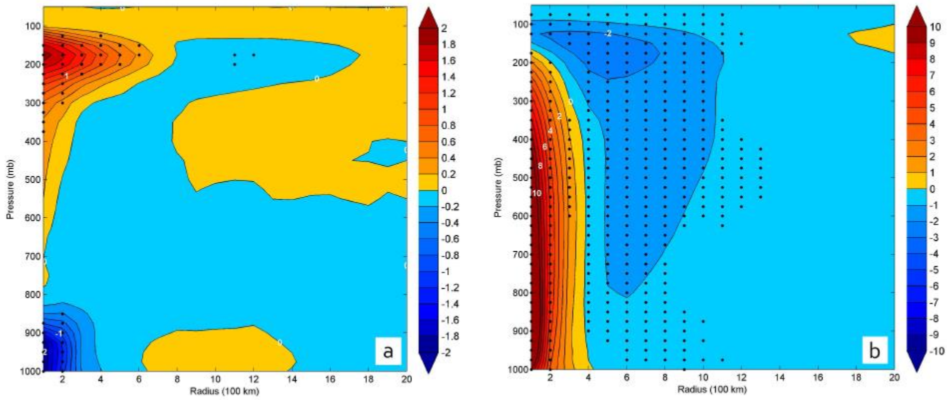

Fig. 2. Composites of divergence (a) and relative vorticity (b) for major hurricanes. The divergence composites' contour interval is 0.2 $10^{-5}s^{-1}$ with contour labels every 1 $10^{-5}s^{-1}$. The relative vorticity composites' contour interval is 1 $10^{-5}s^{-1}$ with contour labels every 2 $10^{-5}s^{-1}$. The sample size used to generate the composites is 740. Stippling (dots) indicate locations significance at the 99% confidence level between tropical depressions and major hurricanes of the same variable as calculated by a bootstrap test.

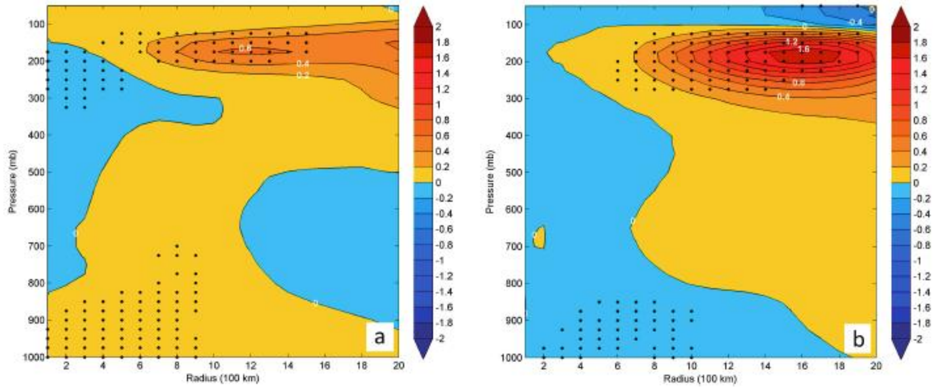

Fig. 3. Composites of mean momentum flux (a) and eddy momentum flux (b) for major hurricanes. Both composites' contour interval are 0.2 10^{16} kg m^2 s^{-2} with contour labels every 0.2 10^{16} kg m^2 s^{-2} for the mean momentum flux and every 0.4 10^{16} kg m^2 s^{-2} for the eddy momentum flux. The sample size used to generate the composites is 740. Stippling (dots) indicate locations significance at the 99% confidence level between tropical depressions and major hurricanes of the same variable as calculated by a bootstrap test.

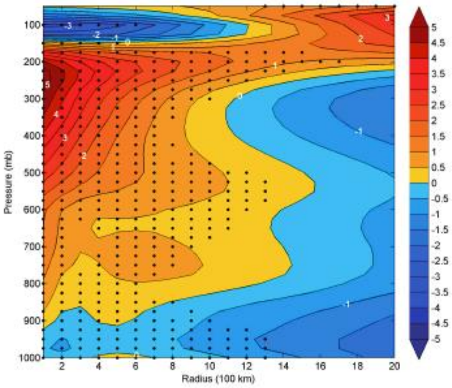

Fig. 4. Composite of potential temperature anomaly for major hurricanes. The anomaly was calculated as $\bar{\theta} - \theta_{MT}$ where θ_{MT} is the moist tropical sounding from Dunion (2011), interpolated to 25 hPa to match the vertical resolution of the data. Smoothing was performed for aesthetic purposes. The potential temperature composite's contour interval is 0.5 K with contour labels every 1 K. The sample size used to generate the composites is 740. Stippling (dots) indicate locations significance at the 99% confidence level between tropical depressions and major hurricanes of the same variable as calculated by a bootstrap test.

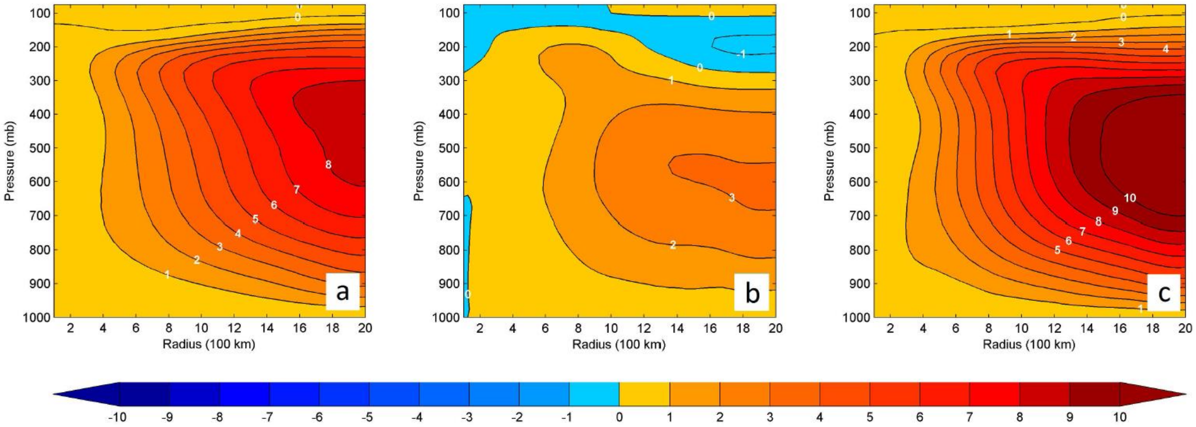

Fig. 5. Balanced vortex streamfunction composites of the momentum only response (a), the heat only response (b), and the total response (c) for major hurricanes. The contour interval and labels are 1 Pa $m^2 s^{-1}$. The sample size used to generate the composites is 740. No stippling (dots) are shown since the input to the balanced vortex equations were composited azimuthally averaged fields. Statistical significance cannot be calculated between the tropical depression composite and major hurricane composite as the sample size of each field needs to be greater than one to determine variance.