Balanced and unbalanced aspects of tropical cyclone intensification

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Abstract: We investigate the extent to which the azimuthally-averaged fields from a three-dimensional, nonhydrostatic, tropical cyclone model can be captured by axisymmetric balance theory. The secondary (overturning) circulation and balanced tendency for the primary circulation are obtained by solving a general form of the Sawyer-Eliassen equation with the diabatic heating, eddy heat fluxes and tangential momentum sources (eddy momentum fluxes, boundary-layer friction and subgrid-scale diffusion) diagnosed from the model. The occurrence of regions of weak symmetric instability at low levels and in the upper-tropospheric outflow layer requires a regularization procedure so that the Sawyer-Eliassen equation remains elliptic. The balanced calculations presented capture a major fraction of the azimuthally-averaged secondary circulation of the three-dimensional simulation except in the boundary layer, where the balanced assumption breaks down and where there is an inward agradient force. In particular, the balance theory is shown to significantly underestimate the low-level radial inflow and therefore the maximum azimuthal-mean tangential wind tendency. In the balance theory, the diabatic forcing associated with the eyewall convection accounts for a large fraction of the secondary circulation. The findings herein underscore both the utility of axisymmetric balance theory and also its limitations in describing the axisymmetric intensification physics of a tropical cyclone vortex.
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References:
- Bell, M.M., Montgomery, M.T., Observed structure, evolution, and potential intensity of category 5 hurricane Isabel (2003) from 12 to 14 September (2008) Mon. Weather Rev., 65, pp. 2025-2046
- Challa, M., Pfeffer, R.L., Effects of eddy fluxes of angular momentum on model hurricane development (1980) J. Atmos. Sci., 37, pp. 1603-1618
- Emanuel, K.A., An air-sea interaction theory for tropical cyclones. Part I: Steady state maintenance (1986) J. Atmos. Sci., 43, pp. 585-604
- Emanuel, K.A., The finite amplitude nature of tropical cyclogenesis (1989) J. Atmos. Sci., 46, pp. 3431-3456
- Emanuel, K.A., Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics (1995) J. Atmos. Sci., 52, pp. 3969-3976
- Emanuel, K.A., The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium (1995) J. Atmos. Sci., 52, pp. 3960-3968
- Emanuel, K.A., Some aspects of hurricane inner-core dynamics and energetics (1997) J. Atmos. Sci., 54, pp. 1014-1026
- Emanuel, K.A., Tropical cyclones (2003) Annu. Rev. Earth Planet. Sci., 31, pp. 75-104
- Hendricks, E.A., Montgomery, M.T., Davis, C.A., On the role of 'vortical' hot towers in formation of tropical cyclone Diana (1984) (2004) J. Atmos. Sci., 61, pp. 1209-1232
- Möller, J.D., Shapiro, L., Balanced contributions to the intensification of hurricane Opal as diagnosed from a GFDL model forecast (2002) Mon. Weather Rev., 130, pp. 1866-1881
- Möller, J.D., Smith, R.K., Thedevelopmentofpotentialvorticityin a hurricane-like vortex (1994) Q. J. R. Meteorol. Soc., 120, pp. 1255-1265
- Montgomery, M.T., Kallenbach, R., A theory for vortex-Rossby waves and its application to spiral bands and intensity changes in hurricanes (1997) Q. J. R. Meteorol. Soc., 123, pp. 435-465
- Montgomery, M.T., Nguyen, S.V., Smith, R.K., Do tropical cyclones intensify by WISHE? (2009) Q. J. R. Meteorol. Soc., , in press
- Montgomery, M.T., Nicholls, M.E., Cram, T.A., Saunders, A.B., A vortical hot tower route to tropical cyclogenesis (2006) J. Atmos. Sci., 63, pp. 355-386
- Nguyen, S.V., Smith, R.K., Montgomery, M.T., Tropical cyclone intensification and predictability in three dimensions (2008) Q. J. R. Meteorol. Soc., 134, pp. 563-582
- Ogura, Y., Phillips, N.A., Scale analysis of deep and shallow convection in the atmosphere (1962) J. Atmos. Sci., 19, pp. 173-

- Ooyama, K.V., Numerical simulation of the life cycle of tropical cyclones (1969) J. Atmos. Sci., 26, pp. 3-40
- Persing, J., Montgomery, M.T., Hurricane superintensity (2003) J. Atmos. Sci., 60, pp. 2349-2371
- Persing, J., Montgomery, M.T., Tuleya, R.E., Environmental interactions in the GFDL hurricane model for hurricane Opal (2002) Mon. Weather Rev., 130, pp. 298-317
- Pfeffer, R.L., Challa, M., A numerical study of the role of eddy fluxes of momentum in the development of Atlantic hurricanes (1981) J. Atmos. Sci., 38, pp. 2393-2398
- Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., (1992) Numerical Recipes in C: The art of scientific computing, , Cambridge University Press: Cambridge, UK
- Schubert, W.H., Alworth, B.T., Evolution of potential vorticity in tropical cyclones (1987) Q. J. R. Meteorol. Soc., 113, pp. 147-162
- Schubert, W.H., Hack, J.J., Transformed Eliassen balanced vortex model (1983) J. Atmos. Sci., 40, pp. 1571-1583
- Schubert, W.H., Rozoff, C.M., Vigh, J.L., McNoldy, B.D., Kossin, J.P., On the distribution of subsidence in the hurricane eye (2007) Q. J. R. Meteorol. Soc., 133, pp. 1-20
- Shapiro, L.J., Montgomery, M.T., A three-dimensional balance theory for rapidly rotating vortices (1993) J. Atmos. Sci., 50, pp. 3322-3335
- Shapiro, L.J., Willoughby, H., The response of balanced hurricanes to local sources of heat and momentum (1982) J. Atmos. Sci., 39, pp. 378-394
- Shin, S., Smith, R.K., Tropical cyclone intensification and predictability in a minimal three-dimensional model (2008) Q. J. R. Meteorol. Soc., 134, pp. 1661-1671
- Smith, R.K., Tropical cyclone eye dynamics (1980) J. Atmos. Sci., 37, pp. 1227-1232
- Smith, R.K., The role of cumulus convection in hurricanes and its representation in hurricane models (2000) Rev. Geophys., 38, pp. 465-489
- Smith, R.K., Accurate determination of a balanced axisymmetric vortex (2006) Tellus, 58 A, pp. 98-103
- Smith, R.K., Montgomery, M.T., Balanced boundary layers in hurricane models (2008) Q. J. R. Meteorol. Soc., 134, pp. 1385-1395
- Smith, R.K., Montgomery, M.T., Nguyen, S.V., Tropical cyclone spinup revisited (2009) Q. J. R. Meteorol. Soc., 135, pp. 1321-1335
- Smith, R.K., Montgomery, M.T., Zhu, H., Buoyancy in tropical cyclones and other rapidly rotating vortices (2005) Dyn. Atmos. Oceans., 40, pp. 189-208
- Sundqvist, H., Numerical simulation of the development of tropical cyclones with a ten-level model. Part I (1970) Tellus, 22, pp. 359-389
- Willoughby, H.E., Forced secondary circulations in hurricanes (1979) J. Geophys. Res., 84, pp. 3173-3183
- Willoughby, H.E., Gradient balance in tropical cyclones (1990) J. Atmos. Sci., 47, pp. 465-489
- Zhang, D.-L., Liu, Y., Yau, M.K., A multi-scale numerical study of hurricane Andrew (1992). Part IV: Unbalanced flows (2001) Mon. Weather Rev., 129, pp. 92-107