IDEALIZED TROPICAL CYCLOGENESIS EXPERIMENTS IN A CLOUD RESOLVING MODEL IN RADIATIVE-CONVECTIVE EQUILIBRIUM

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1. Introduction

Our understanding of the dynamics of tropical cyclones (TCs), the large (L $\sim$ 10-1000 km) rapidly rotating weather systems found seasonally over the warm waters of the tropical North Atlantic, Pacific, and Indian Oceans, has improved considerably over the past three decades. The fundamental air-sea interaction instability that underlies their existence has been identified and a general theory of tropical cyclones as a highly efficient Carnot heat engine is now widely accepted (*Emanuel*, 1986). Furthermore, both theory and relatively simple dynamical models (*Emanuel*, 1995) can reproduce the characteristic features of mature tropical cyclones, including maximum wind speed, central sea level pressure, and thermodynamic structure.

However, one variable that has attracted minimal serious theoretical or modeling effort is storm size, often taken as the radius of tropical storm force winds (17.49 ms^{-1}; denoted r_{17}) or the radius of vanishing winds (denoted r_0). Despite wide recognition of the sensitivity of both storm surge (*Irish et al.*, 2008) and wind damage (*Iman et al.*, 2005) to storm size, size remains largely unpredictable.

In the absence of land interaction, size is observed in nature to vary only marginally during the lifetime of a given tropical cyclone prior to recurvature into the extra-tropics (*Merrill*, 1984; *Frank*, 1977; *Chavas and Emanuel*, 2010; *Lee et al.*, 2010), but significant variation exists from storm to storm, regardless of basin, location, and time of year. size is found to only weakly correlate with latitude as well as intensity (*Merrill*, 1984; *Weatherford and Gray*, 1988; *Chavas and Emanuel*, 2010), as the outer and inner core regions appear to evolve almost independently. *Chavas and Emanuel* (2010) found that the global distribution of r_0 is approximately log-normal, though distinct median sizes exist within each ocean basin, suggesting that the size of a given TC is not merely a random variable but instead is likely modulated either by the structure of the initial disturbance, the environment in which it is embedded, or both.

Minimal work has been done examining the sensitivity of storm size to ambient thermodynamic variables. Idealized modeling studies in *Hill and Lackmann* (2009) and *Xu and Wang* (2010) found that TCs tend to be larger when embedded in moister mid-tropospheric environments due to the increase in spiral band activity and subsequent generation of diabatic potential vorticity which acts to expand the wind field laterally. *Rotunno and Emanuel*

(1987) demonstrated in an idealized axisymmetric framework a strong relationship between the scales of the initial and mature vortex, but it remains unclear whether this is a direct or indirect scaling, i.e. whether the mature surface vortex develops directly from the mid-level vortex or whether it develops within a local thermodynamic environment conducive for surface vortex formation whose scale is modulated by that of the initial vortex (e.g. *Raymond and Carrillo* (2010); *Bui et al.* (2009)).

2. Tropical cyclones in radiative-convective equilibrium

The tropical atmosphere tends towards a state of radiative-convective equilibrium (RCE). *Nolan et al.* (2007) employed the Weather Research and Forecasting (WRF) model in RCE to explore the sensitivity of tropical cyclogenesis to environmental parameters. By running the model in an RCE state, the parameter space of the equilibrium environmental sounding was reduced to only three parameters: sea-surface temperature, the Coriolis parameter, and the imposed background surface wind speed; zero mean wind shear was assumed. Importantly, though, *Bretherton et al.* (2005) demonstrated using the System for Atmospheric Modeling (SAM) that a tropical cyclone can form spontaneously in RCE from random convection in the absence of an initial vorticity perturbation.

3. Methodology

To expand on the above idealized modeling work, version 15 of the Bryan Cloud Model (CM1; original version described in *Bryan and Fritsch* (2002)), a three-dimensional non-hydrostatic cloud resolving model (CRM), is employed to explore tropical cyclogenesis in the simplest of idealized environments: pure radiative-convective equilibrium on an f-plane with zero initial background vertical wind shear and doubly-periodic boundary conditions. The RCE profile is determined by running the model in a 192x192 km^2 domain, small enough to inhibit convective organization, for 100 days and taking the mean environmental profile over the final 30 days when it has reached a statistical equilibrium.

The model is then run at 4km horizontal resolution over a 2000x2000 km^2 and is initialized with a circularly-symmetric localized moisture perturbation above the boundary layer and a collocated mid-level vorticity anomaly in thermal wind balance, which in combination represent the precursor disturbance. Importantly, thermal wind balance imposes two constraints (wind, virtual temperature) on the three variables of interest (wind, temperature, and moisture) thereby leaving one degree of freedom over which initial perturbations with a range of different vorticity and water vapor structures (amplitude, horizontal scale) can be tested in order to explore the roles of the initial vortex and mid-level moisture perturbation independently in setting storm size. For all experiments, SST is prescribed to $T_s = 26.13\ C$; Coriolis parameter $f = 5 * 10^{-5}\ s^{-1}$; wind speed at the lowest model level $u_s = 5\ ms^{-1}$; and zero vertical wind shear. Results are then compared with output from the CM1 model run using identical parameters but in axisymmetric configuration.

References

Bretherton, C. S., P. N. Blossey, and M. Khairoutdinov, 2005: An energy-balance analysis of deep convective self-aggregation above uniform SST. *J. Atmos. Sci.*, 62, 4273-4292.

Bryan, G. H., and J. M. Fritsch, 2002: A benchmark simulation for moist nonhydrostatic numerical models. *Mon. Wea. Rev.*, 130, 29172928, doi:10.1175/1520-0493.

Bui, H. H., Smith, R. K., Montgomery, M. T. and Peng, J. (2009), Balanced and unbalanced aspects of tropical cyclone intensification. *QJRMS*, 135: 17151731. doi: 10.1002/qj.502.

Chavas, D. R., and K. A. Emanuel, 2010: A QuikSCAT climatology of tropical cyclone size. *Geophys. Res. Lett.*, 37, L18816, doi:10.1029/2010GL044558.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: steady-state maintenance. *J. Atmos. Sci.*, 43, 585-605.

Emanuel, K.A., 1995: The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium. *J. Atmos. Sci.*, 52, 3960-3968.

Frank, W. M., 1977: Structure and energetics of the tropical cyclone, Part I: Storm structure. *Mon. Wea. Rev.*, 105, 1119-1135.

Hill, K., G. M. Lackmann, 2009: Influence of environmental humidity on tropical cyclone size. *Mon. Wea. Rev.*, 137, 3294-3315.

Iman, R. L., Johnson, M. E., and C. C. Watson Jr., 2005: Sensitivity analysis for computer model projections of hurricane losses. *Risk Analysis*, 25(5), 12771297.

Irish, J. L., D. T. Resio, and J. J. Ratcliff, 2008: The Influence of Storm Size on Hurricane Surge. *J. Phys. Oceanogr.*, 38, 20032013. doi: 10.1175/2008JPO3727.1

Lee, C.-S., K. K. W., Cheung, W.-T. Fang, and R. L. Elsberry, 2010: Initial Maintenance of Tropical Cyclone Size in the Western North Pacific. *Mon. Wea. Rev.*, 138, 32073223. doi: 10.1175/2010MWR3023.1

Merrill, R. T., 1984: A comparison of large and small tropical cyclones. *Mon. Wea. Rev.*, 112, 1408-1418.

Nolan, D. S., E. D. Rappin, and K. A. Emanuel, 2007: Tropical cyclogenesis sensitivity to environmental parameters in radiativeconvective equilibrium. *Quart. J. Roy. Meteor. Soc.*, 133, 2085-2107.

Raymond, D. J. and Lpez Carrillo, C.: The vorticity budget of developing typhoon Nuri (2008), *Atmos. Chem. Phys.*, 11, 147-163, doi:10.5194/acp-11-147-2011, 2011.

Rotunno, R. and K. A. Emanuel, 1987: An air-sea interaction theory for tropical cyclones, Part II: evolutionary study using axisymmetric nonhydrostatic numerical model. *J. Atmos. Sci.*, 44, 542-561.

Weatherford, C. L., and W. M. Gray, 1988: Typhoon structure as revealed by aircraft Reconnaissance. Part I: Data analysis and climatology. *Mon. Wea. Rev.*, 116, 1032-1043.

Xu, J., and Y. Wang, 2010: Sensitivity of the simulated tropical cyclone inner-core size to the initial vortex size. *Mon. Wea. Rev.*, In Press.