4D.8

SENSITIVITY OF TROPICAL CYCLONE SPIN-UP TIME AND CONVECTION TO THE INITIAL ENTROPY DEFICIT

Joshua Alland* and Brian Tang
University at Albany, State University of New York, Albany, New York

1. INTRODUCTION

Previous studies have demonstrated the importance of environmental moisture on tropical cyclogenesis (e.g., Bister and Emanuel 1997; Nolan 2007). Moisture to near saturation promotes deep convection (Dunkerton et al. 2009) and the spin-up of the low-level circulation (Raymond et al. 2007).

The spin-up timescale of a tropical cyclone (TC) is sensitive to the initial nondimensional moist entropy deficit (χ), a measure of the dryness of the free troposphere,

$$\chi = \frac{s^{*}-s}{s^{*}_{SST}-s_b} \tag{1}$$

where $s^{*}, s, s^{*}_{SST},$ and s_b are the moist entropy, saturation moist entropy, saturation moist entropy at the sea surface, and moist entropy of the boundary layer. The numerator is the moist entropy deficit, Δs, above the boundary layer, and the denominator is a measure of the air-sea disequilibrium. A larger entropy deficit decreases the characteristic mass flux through convective downdrafts (Emanuel 1995) and turbulent entrainment of dry air at the top of the boundary layer (Thayer-Calder and Randall 2015).

Emanuel (1989) related the characteristic mass flux to an axisymmetric spin-up timescale (τ), which is directly proportional to the vertical depth scale (H) multiplied by the characteristic tropospheric density (ρ_o) and inversely related to the characteristic mass flux at the top of the boundary layer (M):

$$\tau = \frac{H\rho_o}{M} \tag{2}$$

This study uses an idealized modeling framework to alter the initial moist entropy deficit above the boundary layer in idealized TCs. The goal is to determine the role of environmental moisture on the characteristic mass flux and spin-up timescale. An analysis of convective motions within the simulated TCs will isolate the physical processes responsible for the decreased characteristic mass flux and increased spin-up timescale in a drier initial environment.

2. MODELING FRAMEWORK

The Axisymmetric Simplified Pseudoadiabatic Entropy Conserving Hurricane (ASPECH) model (Tang and Emanuel 2012) is utilized in this study. This modeling framework conserves entropy in the absence of sources and sinks, allowing for a precise accounting of the entropy evolution. This benefit will be important for the isentropic and trajectory analyses presented below. Eleven experiments were conducted, each with a different initial moist entropy deficit between the boundary layer and free troposphere. Each experiment had twenty ensemble members with random initial moisture perturbations to account for the stochastic nature of the spin-up process. All experiments had the same initial temperature, sea surface temperature, and initial vortex with no environmental vertical wind shear.

This study analyzes four representative experiments with initial moist entropy deficits of 0, 20, 50, and 100 J kg^{-1} K^{-1} (Fig. 1).

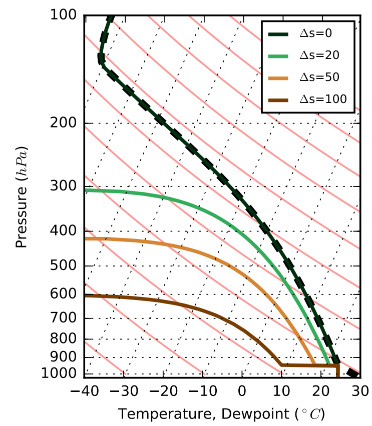

Figure 1: Initial skew T-log p soundings for each experimental set. Temperature is given by the dashed black line. Dewpoint is given in the colored lines.

These four experiments represent the evolution of convective processes from a saturated to a very dry initial environment within the modeling framework.

The spin-up time is defined as when the kinetic energy of the initial low-level vortex doubles. The ensemble mean spin-up times are given in Table 1.

Δs=0	Δs=20	Δs=50	Δs=100
53	104.3	133.2	156.6

Table 1: Ensemble mean spin-up times (in hours) for each initial moist entropy deficit (J kg^{-1} K^{-1}).

Clearly, the spin-up time increases as the initial moist entropy deficit increases. This increase in spin-up time is hypothesized to be from a decrease in the characteristic mass flux due to dry air intrusion at mid-levels, low-levels, or at both mid- and low-levels. An analysis of the vertical mass flux is presented in the next

* *Corresponding author address:* Joshua Alland, University at Albany, State University of New York, 1400 Washington Avenue, DAES 325, Albany, NY 12222; email: jalland@albany.edu.

section. Note that subsequent plots have been time-averaged 24 hours before each ensemble's spin-up time to analyze the differences in convective processes between experiments during this time period.

3. VERITCAL MASS FLUX

The strength of convective upward and downward motions is presented in contoured frequency by altitude diagrams (CFADs) of the vertical mass flux (Fig. 2).

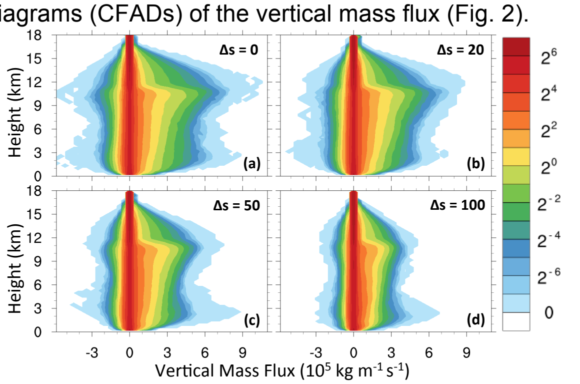

Figure 2: Ensemble-mean CFADs (%) of vertical mass flux within the inner-300 km for an initial moist entropy deficit of (a) 0 J kg^{-1} K^{-1}, (b) 20 J kg^{-1} K^{-1}, (c) 50 J kg^{-1} K^{-1}, and (d) 100 J kg^{-1} K^{-1}.

The logarithmic contour scale captures the tails of the distributions. Weaker upward motions are more frequent for drier simulations. Additionally, weaker downward motions are slightly more frequent for drier simulations, although this difference is not as large. These differences result in a weaker characteristic mass flux for drier simulations, which increases the theoretical spin-up timescale. The physical processes behind the decrease in the characteristic mass flux is presented in the next section through isentropic and trajectory analyses.

4. ISENTROPIC AND TRAJECTORY ANALYSES

Previous studies examined convective motions in an isentropic framework by mapping physical space into a moist entropy-height coordinate system (Pauluis et al. 2013; Mrowiec et al. 2015). This framework separates upward, high entropy streams from downward, low entropy streams, allowing one to characterize the properties of these two streams separately.

Fig. 3 shows the vertical mass flux and isentropic streamfunction in the moist entropy framework. Two circulations exist and are most distinguishable in the drier simulations. One circulation is present within the lowest 3 km and represents shallow convection at the outer radii of the domain. Parcels rising in this circulation have decreasing moist entropy due to turbulent mixing with the surrounding environment. The other circulation is the troposphere-deep secondary circulation. Parcels in this circulation begin with a moist entropy between 2600 and 2650 J kg^{-1} K^{-1} at low-levels and ascend to the top of the troposphere. Interestingly, the moist entropy in this upward stream is relatively constant for all experiments.

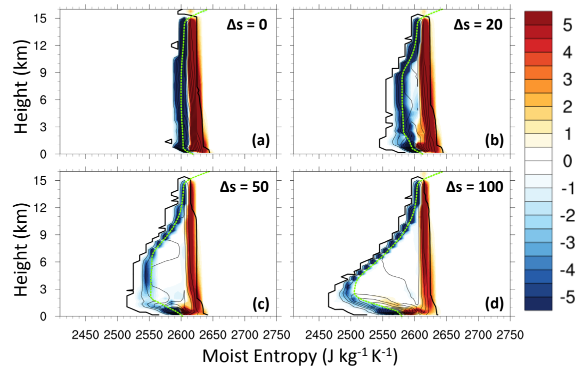

Figure 3: Isentropic vertical mass flux (shaded every 10^{-4} kg s^{-1}) and streamfunction (contoured every 2×10^{-4} J s^{-1} K^{-1}) for an initial moist entropy deficit of (a) 0 J kg^{-1} K^{-1}, (b) 20 J kg^{-1} K^{-1}, (c) 50 J kg^{-1} K^{-1}, and (d) 100 J kg^{-1} K^{-1}.

Turbulent entrainment of dry air at the top of the boundary layer does not play a major role in decreasing the moist entropy and the characteristic mass flux in the drier simulations. Instead of mid-level dry air entrainment, low-level dry air entrainment into the inflow layer could decrease the characteristic mass flux of rising parcels.

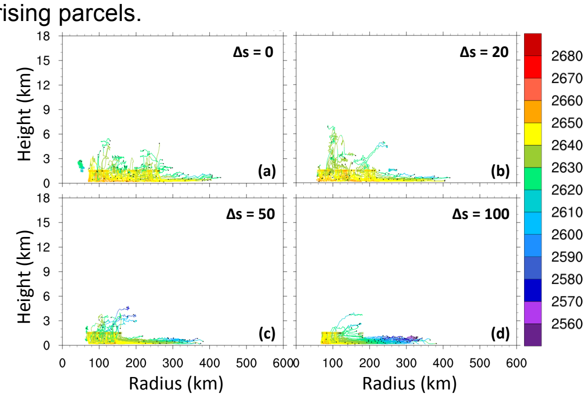

Figure 4: Backward trajectories of parcels from representative ensemble runs originating in convective updrafts at the top of the boundary layer for an initial moist entropy deficit of (a) 0 J kg^{-1} K^{-1}, (b) 20 J kg^{-1} K^{-1}, (c) 50 J kg^{-1} K^{-1}, and (d) 100 J kg^{-1} K^{-1}. The colors represent the moist entropy (J kg^{-1} K^{-1}) of the parcels.

To determine if low-level dry air entrainment decreases the characteristic mass flux, a backward trajectory analysis was carried out on parcels originating in convective updrafts. Trajectories were initialized 24 hours prior to the spin-up time at the top of the boundary layer. These trajectories were re-initialized every hour and were integrated backward using a fourth order Runge-Kutta scheme. Fig. 4 shows a substantial decrease in moist entropy of the parcels in drier simulations as they move backward. Surface fluxes attempt to recover the moist entropy of these parcels, but the moist entropy does not recover before reaching the convective updrafts.

Fig. 5a displays probability density functions (PDFs) of the trajectories' moist entropy values once reaching the convective updrafts. There is a statistically significant shift in the means of the PDFs from higher moist entropy values in the moister experiments to lower moist entropy values in the drier experiments. This shift is even greater if the time averaging is extended to the full spin-up period (Fig. 5b). Thus, dry air entrainment into the inflow layer from Ekman suction reduces the moist entropy of parcels in the inflow layer. These moist entropy values do not fully recover, which results in a lower characteristic vertical mass flux and an increased spin-up timescale.

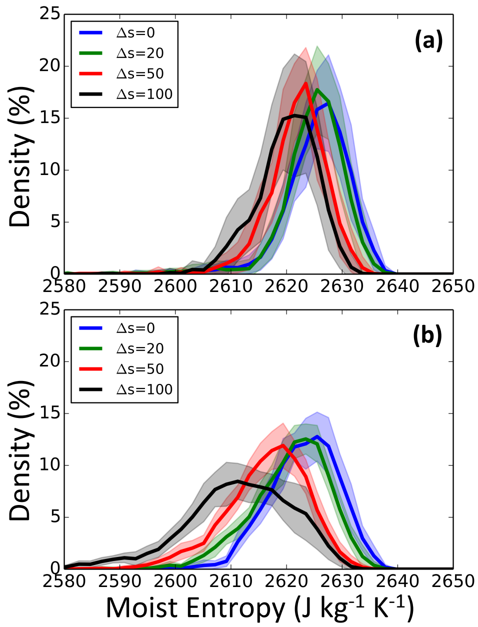

Figure 5: Ensemble mean PDFs (solid lines) for the moist entropy of parcels entering convective updrafts averaged (a) 24 hours before spin-up and (b) over the entire spin-up period. Lighter shading represents percentages within one standard deviation of the ensemble mean.

As a caveat, this study is highly idealized and cannot represent asymmetric processes. Future work plans to investigate the impact of dry air in a 3D model with vertical wind shear to understand the role of asymmetries on the convective evolution of simulated TCs.

Acknowledgements

Thank you to Drs. Brian Tang and Kristen Corbosiero for their guidance and support with this work. This research is funded by the NSF Graduate Research Fellowship NSF-DGE-1060277.

References

Bister, M., and K. A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analyses and a modeling study. *Mon. Wea. Rev.*, **125**, 2662–2682.

Dunkerton, T. J., M. T. Montgomery, and Z. Wang, 2009: Tropical cyclogenesis in a tropical wave critical layer: easterly waves. *Atmos. Chem. Phys.*, **9**, 5587–5646.

Emanuel, K. A., 1989: The finite-amplitude nature of tropical cyclogenesis. *J. Atmos. Sci.*, **46**, 3431–3456.

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.

Mrowiec, A.A., O.M. Pauluis, and F. Zhang, 2016: Isentropic analysis of a simulated hurricane. *J. Atmos. Sci.*, in press.

Nolan, D. S., 2007: What is the trigger for tropical cyclogenesis? *Australian Meteorological Magazine*, **56**, 241–266.

Pauluis, O. M., and A. A. Mrowiec, 2013: Isentropic analysis of convective motions. *J. Atmos. Sci.*, **70**, 3673–3688.

Raymond, D. J., S. L. Sessions, and Z. Fuchs, 2007: A theory for the spin-up of tropical depressions. *Q.J.R. Meteorol. Soc.*, **133**, 1743–1754.

Tang, B., and K. Emanuel, 2012: Sensitivity of tropical cyclone intensity to ventilation in an axisymmetric model. *J. Atmos. Sci.*, **69**, 2394–2413.

Thayer-Calder, K., and D. Randall, 2015: A numerical investigation of boundary layer quasi-equilibrium. *Geophys. Res. Lett.*, **42**, 550–556.