1. INTRODUCTION

Dry air and vertical wind shear (VWS) can work together to affect tropical cyclone (TC) development via ventilation. Ventilation occurs when TC structural changes, due to VWS, act to flux low-moist static energy (MSE) air from the environment into the high-MSE reservoir of the inner core (Simpson and Riehl 1958; Cram et al. 2007; Marin et al. 2009; Riemer et al. 2010; Tang and Emanuel 2012a,b; Munsell et al. 2013), frustrating the TC heat engine.

Previous studies have documented different ventilation pathways and their effects on mature TCs. Dry air can ventilate midlevels (mid-level pathway) and reduce the MSE of rising parcels in the eyewall. Dry air can also ventilate the subcloud layer (low-level pathway), via either convective downdrafts (Riemer et al. 2010) or subsidence associated with the downward branch of the TC secondary circulation (Alland et al. 2017).

The relative importance of the mid- and low-level ventilation pathways, and the situations in which these pathways operate, remain unclear (Riemer and Laliberté 2015). Previous literature has studied ventilation pathways in mature TCs from an axisymmetric perspective (Tang and Emanuel 2012a), but the structure of these ventilation pathways during early development in a 3D model is unexplored. Previous literature has also relied on case studies (Cram et al. 2007) or modeling studies with differing magnitudes of VWS (Riemer et al. 2010; Riemer and Montgomery 2011), but the structure of these ventilation pathways may depend on the magnitude of the VWS and the thermodynamic environment, such as the mid-level moisture content.

This study will investigate the structure of ventilation pathways in a moisture–VWS bivariate parameter space to gain a better understanding of these structures during early development, which is vital to improving forecasts of TC intensity change.

2. MODELING FRAMEWORK

This study employs a set of 3D idealized simulations using Cloud Model 1 (CM1) (Bryan and Fritsch 2002). Each simulation has a constant initial relative humidity (RH) above the subcloud layer, ranging from 20 to 80%, and a specified westerly VWS magnitude, ranging from 0 to 12.5 m s\(^{-1}\), as shown in Fig. 1.

Figure 1: The RH–VWS bivariate parameter space. Each grid box represents one simulation. Only the simulations highlighted in yellow are analyzed below.

Figure 2 shows the evolution of the maximum, azimuthally-averaged 10-m wind for the simulations highlighted in yellow in Fig. 1. When no VWS exists (solid lines), intensification occurs sooner for a moister initial environment, in agreement with Tang et al. (2016). For a VWS of 5 m s\(^{-1}\) (thin, dashed lines), intensification starts earlier than when no VWS exists, especially for moister simulations, but the intensification rate is not as large thereafter. For a VWS of 10 m s\(^{-1}\) (bold, dashed lines), intensification occurs more slowly. In fact, the simulation with an initial RH of 40% does not reach 20 m s\(^{-1}\).

3. MID-LEVEL VENTILATION

Mid-level ventilation is given by \(\lambda u's'\), where \(u\) is the storm-relative radial velocity, \(s\) is the MSE, and primes...
denote perturbations from the azimuthal mean. This term represents the lateral transport of MSE by eddies (Tang and Emanuel 2010), and will be compared across the bivariate parameter space to determine the structure of mid-level ventilation.

Figure 3 shows spatial distribution of (a) $u'$, (b) $s'$, and (c) $\rho u's'$ at 700 hPa, averaged over the early development period, for an initial RH of 40% and VWS magnitude of 5 m s$^{-1}$. Only values where $u'<0$ are plotted. The center of the plot represents the center of the TC at 850 hPa.

Figure 4 shows $\rho u's'$ for a subset of simulations in the bivariate parameter space with initial RH values of 60 and 80%, and VWSs of 0, 5, and 10 m s$^{-1}$. For no VWS, $\rho u's'$ has no clear pattern. As the VWS increases, a more coherent pattern emerges with positive values in the upshear semicircle. This pattern encompasses a larger area as the VWS magnitude increases, and moves into the upshear-right quadrant as the initial RH decreases. Other vertical levels above 700 hPa show a similar pattern.

### 4. LOW-LEVEL VENTILATION

Low-level ventilation is given by $\rho w's'$, where $w$ is the vertical velocity. This term represents the vertical transport of MSE by shear-induced downdrafts (Riemer et al. 2010), and is compared across the bivariate parameter space to determine the structure of low-level ventilation (Fig. 5). Note that we only concentrate on areas where $w'<0$ to isolate the downward flux of low-MSE at 850 hPa. For no VWS, generally positive values of $\rho w's'$ exist and are distributed symmetrically about the center. With the addition of VWS, positive values of $\rho w's'$ tend to the right of the VWS vector inside a radius of 50 km and to the left of the shear vector outside a radius of 50 km. The positive values represent the flux of low-MSE air into the subcloud layer.
This study explored how the spatial structure of mid-
and low-level ventilation varies as a function of both RH 
and VWS during early development. These ventilation 
pathways can decrease the strength of convection and 
inhibit TC development, so understanding the structure 
of ventilation provides new insight into their effects on 
the structure of convection and controls on TC intensity, 
which is the subject of complementary and future work.

References

Alland, J. J., B. H. Tang, and K. L. Corbosiero, 2017: 
effects of midlev dry air on development of the 
axisymmetric tropical cyclone secondary circulation. J. 
Atmos. Sci., 74, 1455–1470.

simulation for moist nonhydrostatic numerical models. 

Cram, T. A., M. T. Montgomery, and S. A. Braun, 2007: 
A Lagrangian trajectory view on transport and mixing 
processes between the eye, eyewall, and environment 
using a high-resolution simulation of Hurricane Bonnie 

Marin, J. C., D. J. Raymond, and G. B. Raga, 2009: 
Intensification of tropical cyclones in the GFS model. 

Munsell, E. B., F. Zhang, and D. P. Stem, 2013: Predictability and dynamics of a nonintensifying tropical 

Riemer, M., and F. Laliberté, 2015: Secondary 
circulation of tropical cyclones in vertical wind shear: 
Lagrangian diagnostic and pathways of environmental 

Riemer, M., and M. T. Montgomery, 2011: Simple 
kinematic models for the environmental interaction of 
tropical cyclones in vertical wind shear. Atmos. Chem. 
Phys., 11, 9395–9414.

Riemer, M., and M. T. Montgomery, and M. E. Nicholls, 
2010: A new paradigm for intensity modification of 
tropical cyclones: Thermodynamic impact of vertical 
wind shear on the inflow layer. Atmos. Chem. Phys., 10, 
3163–3188.

Simpson, R., and R. Riehl, 1958: Mid-tropospheric 
ventilation as a constraint on hurricane development 
and maintenance. Tech. Conf. on Hurricanes, Amer. 

Tang, B., and K. Emanuel, 2010: Midlevel ventilation’s 
constraint on tropical cyclone intensity. J. Atmos. Sci., 
67, 1817–1830.

Tang, B., and K. Emanuel, 2012a: Sensitivity of tropical 
cyclone intensity to ventilation in an axisymmetric 