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QUANTIFYING THE ROLE OF TROPOSPHERIC RELATIVE HUMIDITY ON THE DEVELOPMENT OF TROPICAL CYCLONES

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1. INTRODUCTION

Several studies have hypothesized the critical nature moisture plays during the development of tropical cyclones (TCs) (e.g. Bister and Emmanuel, 1997; Nolan, 2007; Ortt and Chen, 2011). Nevertheless, the sensitivities of a developing TC to the tropospheric humidity have not been quantified in detail before.

In this study, we use two different approaches to address this issue. First, an idealized two-dimensional axisymmetric model is used to study the dynamic and thermodynamic processes of relative humidity (RH) in a relatively simplified framework. Efficiencies and energy budgets are calculated to address the following objectives:

a) to understand different spin-up timescales in the model simulations

b) to investigate how the dry air frustrates the conversion of available potential energy to kinetic energy.

Second, model output from three-dimensional, full physical model forecasts of three Atlantic TCs are used to compare with the idealized model results.

2. TC DEVELOPMENT IN IDEALIZED ENVIRONMENTAL CONDITIONS

2.1 Numerical model

The Axisymmetric Simplified Pseudoadiabatic Entropy Conserving Hurricane model (ASPECH), developed by Tang (2010), is being used with a 2-km radial resolution and a 0.3-km vertical resolution. The model has a domain of 1000 km in radius and 24 km in height. Additional in-depth information about ASPECH's prognostic variables, microphysics and other relevant calculations can be found in the model's documentation (Tang 2010).

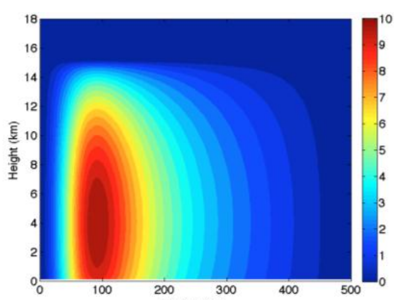

Figure 1. Cross-section showing the tangential wind speed (ms^{-1}) for the initial vortex that was used in the axisymmetric simulations.

2.2 Simulations

Every simulation starts with a mid-level vortex located at 4-km height and 100-km radius, with a maximum tangential wind speed of 10 m s-1 (Fig. 1). The model is initialized with a characteristic sounding with 75% RH at the surface. There is neither background wind nor environmental wind shear in the soundings. The distinguishing thermodynamic factor between experiments is the RH above the PBL, which ranges from 0% to 100% in 20% RH increments to fully sample the range of sensitivities.

2.3 Results

Simulations from the ASPECH model show that those cases with higher tropospheric moisture went through genesis and development faster than the systems with drier environments (Fig. 2). This sensitivity to the initial tropospheric RH, even for the moist cases, is a sign that this quantity plays an important role in the development of TCs.

In order to have a robust definition for genesis, we use the integrated kinetic energy (IKE) as a reference. The IKE is determined by summing the kinetic energy over a domain from 0 to 60 km in radius, and from 0 to 2 km in height. Genesis time is then defined as that time when the IKE first tripled the initial IKE. This designation is more physically relevant because it isolates the time when a surface circulation has formed (Nolan 2007) and has much less inherent uncertainty compared to using some threshold wind speed or pressure.

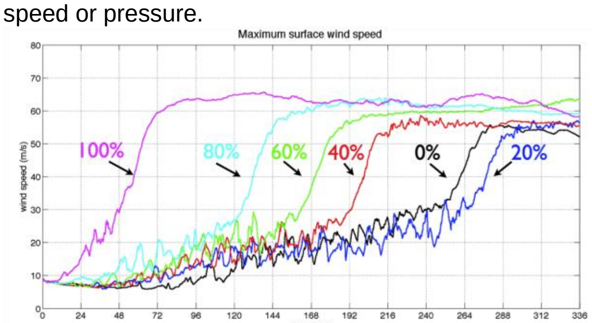

Figure 2. The maximum surface wind speed as a function of time for a set of two-dimensional, idealized tropical cyclone simulations. The numbers indicate the initial tropospheric relative humidity for each case.

Three cases are then selected for detailed study: the two extremes (0 and 100%), and a case with RH similar to that observed in the tropical Atlantic Ocean (60%) (Ortt and Chen 2011). For the 0% case, it takes 122.1 hrs for the IKE to triple, whereas for the 60% and 100% cases take 81.3 and 25.7 hrs, respectively. Fig. 3

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shows that during the 12-hr period when genesis occurs, deep convection extends to mid and upper levels in all cases. In the 0% case moisture is being concentrated only in the PBL and in the clouds that have extended up to 10 km height. The 60% storm shows a somewhat similar structure in terms of moisture, but the convection extends to higher altitudes (Fig. 3). The region of the innermost 50-km radius is dry aloft with increasing moisture in the lower levels. The 100% simulation underwent genesis so early in the 12-hr period that it looks like a strong tropical storm already. Even though this case was completely saturated at the beginning, mass continuity required the downward motion of air from the strong convection. The other 2 cases, on the other hand, required sufficient moistening of the troposphere and reaching nearly saturation in the innermost 50- to 100-km radial region as key conditions for genesis.

Hövmoller diagrams of time and radius are analyzed using the pseudoadiabatic entropy (sp) at the lowest model level (z = 0.15 km). This quantity is conserved in this model in the absence of sources or sinks at the boundaries, thus indicating that a reduction of sp must be caused by drier and colder air found at midlevels being transported into the PBL by downward motion. The results (Fig. 4) show strong downdrafts in the innermost 100 km region before and after genesis. When downdraft activity is reduced in the TC inner core region, the storms start a rapid intensification (RI) process and eventually become very strong cyclones. This is consistent with the fluctuations in the maximum surface wind speed (Fig. 2), which shows that RI occurred after the surface maximum wind speed exceeded 30 ms^{-1}. These timescales indicate that even though downdraft activity did not affect the genesis time directly, it did affect the time it took for the storm to intensify and reach hurricane strength (maximum surface wind speed > 33 ms^{-1}).

3. ENERGETICS OF THE IDEALIZED SIMULATIONS

3.1 Efficiencies and energy budgets

One of the quantities being used to diagnose the effects of different initial free troposphere RH is the precipitation efficiency (ε_p). For purposes of this study, ε_p is defined as the ratio of precipitation over condensation, and is calculated from the ASPECH model using the following equation:

$$\varepsilon_p = \frac{\int \rho_d v_t q_l r dr}{\iint \rho_d C r dr dz} \qquad (1)$$

where ρ_d is the density of dry air, v_t is the terminal velocity, q_l is the liquid water mixing ratio, C is the condensation rate and r and z are radius and height coordinates, respectively. The calculation is done by integrating the terms of (1) at the surface and at the

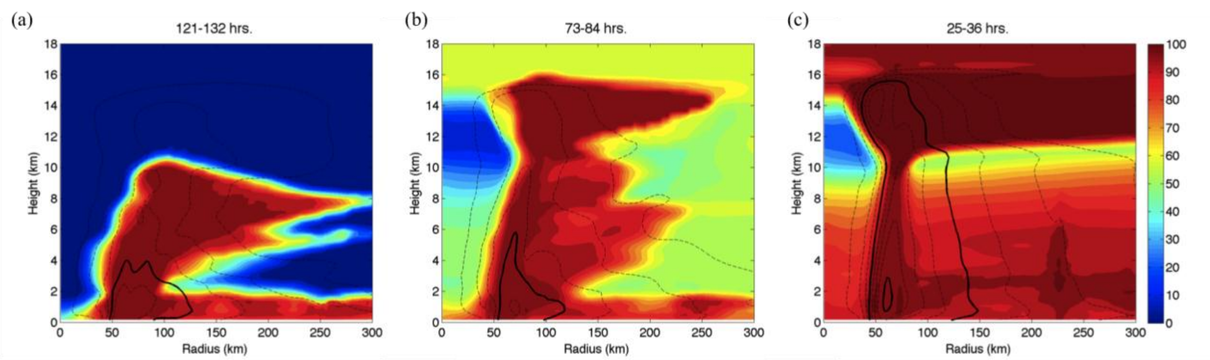

Figure 3. These cross-sections show the RH (color shading) and tangential wind speed (contours plotted every 2.5 m s^{-1}) for the cases with 0% (a), 60% (b) and 100% (c) RH. Both quantities were averaged for the 12-hr period when genesis occurs.

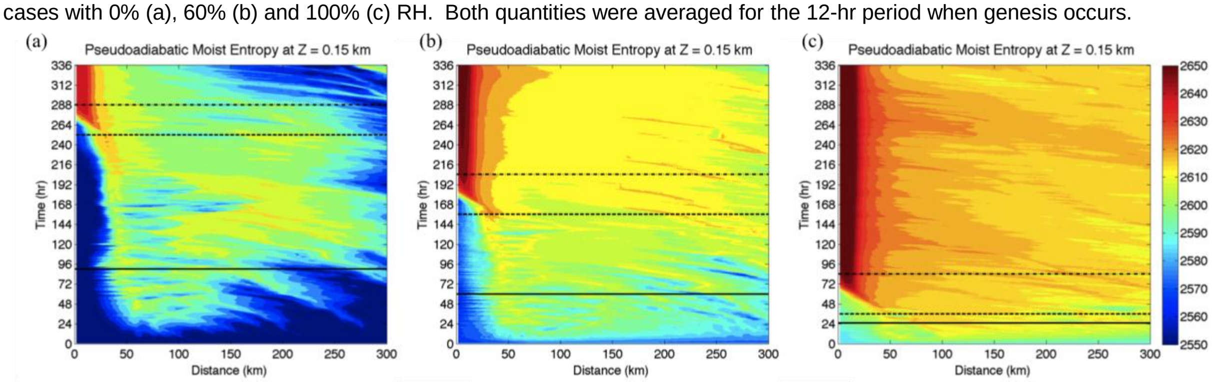

Figure 4. Hovmöller diagrams of the pseudoadiabatic moist entropy (in J kg^{-1} K^{-1}) at the lowest model level for the cases of 0% (a), 60% (b) and 100% (c). From bottom to top, the first line represents the time at which genesis occurs, second line marks the beginning of RI period, and the third line shows the time when the storm reach quasi-steady state.

innermost 200-km radius. The integration in the denominator also includes a height from the surface up to 18 km. This domain is chosen to cover the inner core of the storms by measuring the precipitation at the surface and the condensation throughout the entire troposphere.

Another efficiency being calculated is the conversion of available potential energy (APE), which is "the difference between the total potential energy and the minimum total potential energy which could result from any adiabatic redistribution of mass (Lorenz 1954)," to kinetic energy (KE). According to Pauluis (2007), there are different sources and sinks of APE in the moist atmosphere. Fig. 5 shows the different sources and sinks of APE in the ASPECH model. The radiation term can serve as both a source and sink of APE, but for the present calculation, its contribution is considered to be

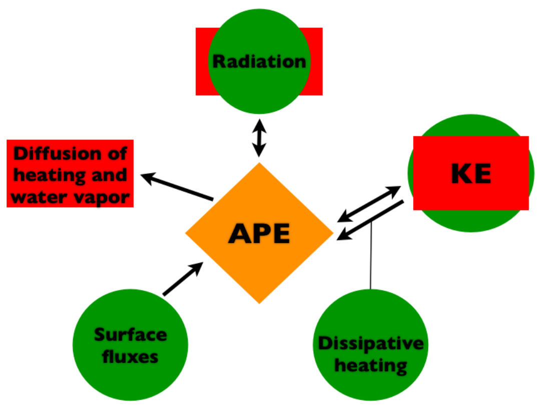

Figure 5. Sources and sinks of APE in the ASPECH model, following Pauluis (2007). Red boxes represent the sinks, while green circles show the sources.

negligible. Likewise, even though the kinetic energy (KE) could be both source and sink, in this case it is considered to be mainly a sink. The efficiency of conversion of APE to KE is thus defined as follows:

$$\varepsilon_{APEtoKE} = \frac{-\iint \left(\frac{dp}{dt}\right) r dr dz}{\int (T_s - T_o) F_{sp} r dr + \iint \left(\frac{T - T_o}{T}\right) D r dr dz} \quad (2)$$

where p is pressure, F_{sp} represents surface fluxes, D is the dissipative heating, and T, T_s, and T_o are the parcel's temperature, surface temperature, and outflow temperature, respectively. Equation (2) uses the same volume domain as in (1) to account for the processes in the TC inner core. The denominator of (2) only includes some of the contributions to the generation of APE represented by the sum of the surface fluxes and dissipative heating (see Fig. 5).

3.2 Results

The ε_p increases with time, albeit more slowly the drier the initial condition (Fig. 6), which reflects a gradual moistening of the troposphere and increasing net latent heating. This inhibits the downdraft activity, which can be seen in the increased ε_p at the same time that downdraft activity is lowered (compare Figs. 4 & 6).

At the end of the simulations all of the storms are very efficient in the sense that ε_p has reached an approximate value of 0.8. This indicates that, even though moisture was not available in all the cases during the first stages of the simulations, in the end all of them had a saturated troposphere.

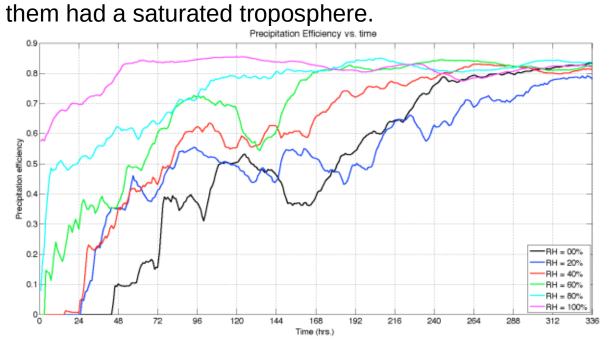

Figure 6. Precipitation efficiency as a function of time for all idealized simulations. Each value was calculated taking a 12-hr running mean of the efficiency.

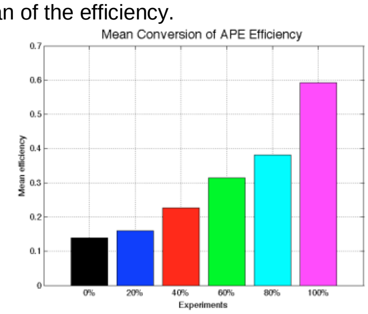

Figure 7. Mean conversion of APE efficiency for the different idealized simulations.

The $\varepsilon_{APEtoKE}$ shows more variability than the ε_p, hence an average of $\varepsilon_{APEtoKE}$ for the 14-day output is calculated. In this case we see how the mean $\varepsilon_{APEtoKE}$ growths with increasing initial RH. The residual of this efficiency, that is 1-$\varepsilon_{APEtoKE}$, gives an approximation for the average amount of APE being used to moisten the troposphere through diffusion of heat and water vapor. The residual is larger for drier cases, thus confirming that APE being generated by surface fluxes and dissipative heating cannot be converted into kinetic energy to spin up the cyclones until enough heat and water vapor is essentially being diffused to carry moisture aloft.

4. TC DEVELOPMENT IN A THREE-DIMENSIONAL MODEL

4.1 Numerical model

The three-dimensional model forecasts are produced using the Advanced Research Weather Research and Forecasting (ARW) model. The ARW is configured with triple-nested grids that consist of a 12-km resolution outer domain and two inner moving nests with 4-km and 1.33-km resolutions, respectively. Additional information regarding the ARW model can be found in the model documentation (Skamarock et al., 2008).

4.2 Three TCs

Three storms are studied using ARW forecasts: Rita (2005), Earl (2010) and Igor (2010). These particular cases were chosen based on the location of genesis and also based in the fact that all went through the RI process that was observed in the idealized simulations.

4.3 Model forecasts of RH field

For these cases, the pattern is different: the drier the environmental midlevels in the initialization, the shorter time it takes for TC development and intensification in the ARW forecasts. The difference in time that it takes for a surface circulation to be established can be related to the fact that in the idealized simulations the inner-core troposphere needs to become moistened over a large region up to the upper levels. Moistening of such a larger area takes longer to occur in the ASPECH model than in the ARW simulation because the high levels of humidity in the 3D fields are concentrated on a smaller area. As a consequence, the TC inner-core, which extends outward from the center of circulation and covers the eyewall, has a smaller radius in the 3D fields. Nevertheless, there are moist areas between the TC-inner core and the environment in the ARW forecasts (see for example Rita, Fig. 8). This intermediate region, referred now as the TC outer rainband region,

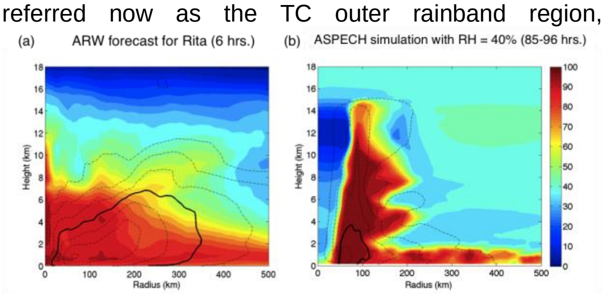

Figure 8. RH (colored shading) and tangential wind speed (contours, as in Fig. 3) for a 3D model forecast for Rita (a) and its comparable idealized simulation. The comparison is made for an approximate time when both had a surface circulation.

contains convective features that are not simulated in the 2D axisymmetric model. This possibly indicates that rainbands and other elements of the TC outer region may act as protectors of the TC inner-core region. It is then hypothesized that the outer region provides moisture that protects the inner-core from being affected by entrainment of dry air from the TC environment. The relatively moist inner-core region in a 3D model, therefore, can spin-up an eyewall much faster than in a 2D model with a similar environment RH values. Nevertheless, a further study is required to confirm what had being inferred in this part of the project.

5. SUMMARY AND CONCLUDING REMARKS

The effects of tropospheric RH were studied using two different approaches. The first one consisted of a set of axisymmetric, idealized simulations with different moisture environments, whereas the second one used a three-dimensional full-physics model to study the TC development on a 3D environment.

It can be concluded with the present results that moisture in the TC inner-core region plays an important role during the early stages of TC development. Interests in better understanding those stages should take into consideration the tropospheric RH when monitoring the evolution of TC disturbances. This suggests that assimilation of RH observations in the inner core, when available, should be implemented in numerical models to better simulate the genesis and intensification of TCs.

ACKNOWLEDGEMENTS

This research work was performed under the auspices of the SOARS program. The author would like to thank Dr. Brian Tang and Dr. Shuyi S. Chen for their guidance on this project. Also thanks to Dr. Chen's research group for their help in the acquisition and analysis of the ARW model data.

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