

## **An Investigation of Tropical Cyclogenesis from African Easterly Waves**

### **Introduction:**

Tropical cyclogenesis (TCG) is one of the least understood processes in tropical meteorology today. The formation of tropical depressions (TDs), which under the right conditions, grow into tropical storms (TSs), has a plethora of interacting processes. These phenomena and processes range from easterly waves to mesoscale convective systems as well as cloud microphysics, aerosol and radiative processes. Moreover, NOAA/National Hurricane Center has started 5-day forecasts of tropical cyclones (TCs) since 2003, which would require the prediction of TCG far upstream, i.e, off the shore of West Africa. However, our ability to understand and predict TCG is limited due partly to the lack of high-resolution observations at the birthplace and partly to the deficiencies in current TC models. One of the major problems is that little evidence of mesoscale cyclonic rotation can be detected at the surface prior to genesis, yielding the inability to predict and probe where or when a tropical disturbance may grow into a TS.

### **Background:**

Previous studies have referred to TCG as a two-step problem: a) the preconditioning of the synoptic and meso- $\alpha$  environment and b) the construction and organization of a TC-scale vortex at the meso- $\beta$  scale<sup>1</sup>. The first step involves the general characteristics of the synoptic-scale environment being favorable, such as little vertical wind shear, warm sea surface temperatures (SSTs), sufficient column moisture content and the preexistence of a low-level cyclonic disturbance. Accompanying these criteria are the different synoptic-scale phenomena including Intertropical Convergence Zone (ITCZ) breakdowns<sup>2</sup> in the East Pacific and African easterly waves (AEW) in the Atlantic basin<sup>8</sup>. Further advancing the idea of an 'ideal' synoptic environment is the theory of the marsupial pouch<sup>3,7</sup>. This theory revolves around the idea that the pre-depression perturbation is protected dynamically from adverse conditions such as dry air or large vertical wind shears. The idea of the marsupial pouch has been investigated intensively for disturbances found in AEWs.

While there has been general agreement on the first step of TCG, dissenting opinions emerge for the formation of the meso- $\beta$ -scale vortex. The bottom-up and top-down hypotheses have been proposed as two of the possible processes leading to TCG<sup>1,13-18</sup>. Extensive research has been conducted on both theories, spanning numerous papers as seen just from the snapshot of references. In the top-down frame of mind, the low-level cyclonic circulation is an extension of a pre-existing midlevel cyclonic vortex, which may be reconstituted downward to create the surface circulation. Also within the top-down realm is the merging of two mid-level vortices within a region of already large-scale low-level cyclonic circulation and development of the meso- $\beta$  vortex. This merging then leads to an intensification of the low-level circulation. Contrasting this view is the bottom-up hypothesis. This theory uses the notion of pre-existing low-level cyclonic vorticity that is typically weak in the initial stages of development. The circulation is then spun up via deep convection, leading to the generation of the meso- $\beta$  cyclonic vortex. The bottom-up theory has been recently augmented by the concept of vortical hot towers (VHTs)<sup>1,2,17</sup>. These VHTs are small regions of intense cyclonic vorticity, which in the presence of large-scale cyclonic rotation, can act as 'building blocks' for TCG via low-level convergence and diabatic processes.

The above hypotheses have been debated for many years, but most research on TCG has agreed on one major problem: the lack of observational data at the birth place<sup>2,6,7</sup>. The regions in

which TCs form are considered data sparse regions where in situ observations are for the most part nonexistent. Furthermore, there has been a lack of field campaigns that focus on TCG, with greater focus on mature and land-falling systems. Since the launching of meteorological satellites in the 1970s, great improvements have been made in observing TCs from birth to death. Various instruments on board these satellites have given forecasters the ‘story’ of a TC using various wavelengths of radiation. The rule of thumb has been to use satellite imagery and derived products to predict the path and intensification of TCs in conjunction with numerical weather prediction models. The use of satellites and weather models has led to greater forecasting lead-times and thus improved preparation for disaster mitigation. Unfortunately, the use of satellites has been overlooked until recently with respect to TCG. Past forecasters would use satellites to assess where a *mature* TC might make landfall and its intensification using the Dvorak technique. With the increase in horizontal resolution of satellite-based instruments coupled with numerous satellite-derived products, the investigation of TCG via satellites has been on the rise in the past decade. Satellite imagery is valuable in tracking convection associated with easterly waves propagating across Africa. By tracking this convection, one can determine many important factors that could lead to TCG once the wave moves off the coast. Some of the common traits that are looked at are: the strength, depth and origin of the convection; how moist the atmospheric column is; and last but not least, if there is any preexisting low-level rotation. Furthermore, once the disturbance moves off the western shore of Africa, satellite data can be used to observe the distribution of SSTs across the ocean where the tropical disturbances are traveling over. SSTs of at least 26.5 degrees Celsius are needed for the creation and sustainment of a TC. It is evident from just the simple examples above that satellite data can play an intricate role in investigating TCG.

Of particular concern is that only fewer than 10% of AEWs could spawn named TSs, while the others remain non-developing disturbances throughout their lifetime. Furthermore, most TCG events from AEWs take place over a narrow equatorial trough region off the west coast of Africa near the Cape Verde Islands<sup>12,19</sup>. Although there have been more studies of TCG from AEWs than that from other regions in literature, our understanding of the pertinent processes still remains speculative due to the lack of observations from central Africa to the central Atlantic. Further compounding the issue is the lack of high-resolution numerical simulations in the region. Most of the previous observational studies have focused on large-scale aspects of TCG from AEWs. Currently, an emerging view that the development of an AEW into a TS may contain a wide range of scale interactions has sparked a shift in the studies of TCG in the north Atlantic basin toward multi-scale investigations.

Recently, field campaigns have taken place to further utilize satellite data and numerical weather forecasts in conjunction with other observational data sets to better understand TCG. The NASA-funded Genesis and Rapid Intensification Processes (GRIP) experiment<sup>9</sup>, the NSF-funded Pre-Depression Investigation of Cloud-systems in the Tropics (PREDICT) project<sup>10</sup>, and the NOAA-funded Intensity Forecasting Experiment 2010<sup>4</sup> (IFEX10) are three recent major field campaigns that have employed aircraft, satellite, in situ and model data to better understand the formation of TCs in the Atlantic basin. The observational data sets put together by these three projects are by far the most robust in understanding TCG. Each project made use of aircraft that had dropsondes for atmospheric soundings along with on-board instruments to better understand the dynamical and thermodynamical processes taking place during genesis. The observational data from these campaigns combined with numerical simulations will lead to a better understanding of the mechanisms surrounding TCG.

**Objectives:**

In this project, I propose to study the predictability and the multi-scale interactive processes leading to TCG from AEWs using the Weather Research and Forecast (WRF) model with the finest grid size of 1km. This will be achieved by taking advantage of the GRIP, IFEX10 and PREDICT observations for better defining large-scale flows, AEWs and the Saharan Air Layer (SAL) structures upstream in the model initial conditions, and downstream over the eastern and central Atlantic ocean for diagnostic analyses and model verifications. In this study, I wish to test the fundamental hypotheses that (a) AEWs provide the necessary quasi-balanced forcing (i.e., vertical motion and vorticity) for the development of deep convection and rotation via stretching, as indicated by the success of global models in predicting TCG over the Atlantic basin; (b) TCG occurs through a bottom-up process, upscale growth through vortex mergers and the axis-symmetric conglomeration of cyclonic vorticity associated with VHTs and other convectively generated vortices; and (c) TCG from AEWs tends to be suppressed by the presence of strong vertical shear and the SAL. After reaching this threshold, TCs will intensify as moving downstream where SSTs increase westward. In order to validate the above hypotheses, the following objectives will have to be achieved:

- 1) Obtain a reasonable nested-grid, cloud resolving simulation of one TCG (i.e., developing) case originating from an AEW over west Africa and occurring during the GRIP, PREDICT and IFEX10 experiments. The simulation will be conducted using the Weather Research and Forecasting (WRF) model at the finest grid of 1km, with model initial conditions (ICs) occurring at the pre-depression stage;*
- 2) Assuming the reasonable simulations can be attained, diagnoses will be performed to determine what favorable and unfavorable environmental conditions are present during formation and what role(s) the SAL plays in TCG;*
- 3) Examine the predictability of the case using ensemble numerical forecasts with different members via the use of perturbed initial conditions and different physical parameterizations;*
- 4) Explore the multi-scale interactions involved in the TCG, with emphasis on the organization of deep convection with TDs. Further emphasis will be put on the roles of deep convection on larger-scale flows in spinning up or dissipating the cyclonic vorticity during TCG.*

**Methodology:**

Objective 1(O1) requires a selection of an appropriate TCG case that may be traced back to a distinct tropical disturbance in a co-moving<sup>1</sup> framework, rather than from a locally developed MCS. I believe that the required realistic case simulation in O1 can be achieved, based on many previous TS modeling studies, provided that the larger-scale flows can be well defined in the model initial conditions. The use of observational data from the aforementioned field campaigns will aid in the selection of a worthy case study. The ‘successful’ simulation in O1 can also be validated via data and findings from the three field campaigns mentioned earlier. Depending on the amount of observational data present, O1 has the potential to serve as an excellent opportunity to connect numerical weather prediction with the recent field campaigns.

Assuming a reasonable simulation can be obtained, I will document as part of objective 2(O2) the three-dimensional larger-scale flow patterns, the trigger of TCG, the likely impact of the SAL, the distribution of deep convection, and the convectively generated vortices and VHTs at the pre-TD stage. Furthermore, I will document the subsequent evolution of the aforementioned, along with the large and mesoscale interactive processes taking place during TCG.

Objective 3(O3) can be accomplished by performing the ensemble Kalman simulations with the initial perturbations generated through the WRF 3DVAR system<sup>5</sup>. The use of breeding vectors<sup>11</sup> will also aid in describing the predictability of and the dominant instabilities associated with TCG. The knowledge of the various instabilities will yield a better understanding on how to better predict the TCG and related mechanisms. The results obtained from Kalman and breeding simulations will also help reveal whether or not the TCG case is deterministic or stochastic. Furthermore, the results will yield qualitative and quantitative evidence for the predictability of TCG, which holds valuable information into increasing forecasting skill and lead-times. The sensitivity of the WRF simulation to uncertainties in the air-sea interaction and boundary layer processes can be investigated by changing various parameters in the physics schemes employed. Understanding the predictability of TCG due to uncertainties in both the initial conditions and the selected physics schemes is both of significant scientific interest and of great practical importance to the protection of life and property in the U.S coastal regions.

Objective 4(O4) will be achieved by calculating various budgets, e.g, relative vorticity or potential vorticity, as well as heat and kinetic energy. Calculating covariances of various meteorological parameters will also aid in quantifying the transfer of potential to kinetic energy and the transfer of energy across various disturbance scales<sup>12</sup>. Fourier analysis may also be performed to reveal the contribution of different scale processes to the TCG.

If sufficient computational resources exist, an investigation of a non-developing case is also desired. This case would be valuable in comparing and contrasting the dominant mechanisms associated with the suppression of TCG and development as described by the TCG case. A non-developing case, rather than a weak tropical disturbance, would be selected to examine clearly what some of the processes suppressing TCG are. In particular, it would be important to find a non-developing case with the larger-scale flows being as analogous as possible to those in the TCG case. By taking this approach, a comparison of the two cases will help reveal positive and negative factors for TCG. The non-developing case would follow the same objectives and methodologies as above, but with the goal to isolate the dominant processes that *suppress* TCG. Using a TCG case in conjunction with a non-developing case can lead to a better understanding of the predictability of TCG.

#### **Anticipated Results:**

Successful completion of this project will provide a new understanding of the predictability of and the multi-scale processes leading to TCG from AEWs. The results will also help confirm the current TCG theories, while also demonstrating that other mechanisms might be involved in the genesis of tropical disturbances. Furthermore, this study will give insight on the state of numerical weather prediction with respect to TCs. Sensitivity experiments within this study will aid in demonstrating how well the WRF model is representing TCG. A better understanding on the predictability of TCG will also be possible from this study via the use of ensembles and breeding. Additionally, the use of breeding will ‘pull out’ the dominant modes of instabilities within the various processes leading to TCG. This knowledge can give further insight into the predictability and understanding of TCG, possibly yielding an increase in forecasting skill and lead-time.

As mentioned at the end of the methodology, the use of a non-developing case as a comparison to the TCG case has great potential to better our understanding of TCG. The non-developing case has the potential to isolate the dominant mechanisms relating to the suppression of formation, while also providing additional insight into the predictability of TCG. By choosing a case with a similar large-scale flow pattern as the TCG case, the opportunity exists to better

understand small-scale mechanisms and their role in whether a particular disturbance becomes a TC or does not. Furthermore, the information retrieved from the non-developing case would give more insight the SAL has in the suppression of TCG. Numerous finding have been made about how the SAL interacts with mature storms, but little work has been conducted to see how the SAL plays a role in TCG.

#### **PI Qualifications:**

PI has taken all necessary graduate-level courses with straight “A”s, including data assimilation, and has passed the Department’s Ph.D. Qualifying Exams. Based on previous research, PI has reasonable experience running the WRF model that will be an intricate part of this investigation. The PI is currently running WRF simulations on tropical disturbances, and is using methods that will be employed in this study. The PI is competent in his understanding of mesoscale and synoptic processes through past studies and educational background. He has been adequately prepared via class work while also demonstrating his understanding of various scale processes in previous research. The PI has worked on collaborative projects that have entailed detailed knowledge of mesoscale and synoptic-scale dynamics.

#### **Broader Impacts:**

The work related to this investigation will help determine the state of numerical weather prediction models and their representation of TSs. The knowledge revealed about certain parameterization schemes can be applied to other mesoscale investigations, as well as tropical predictions. In particular, the results obtained may directly benefit the operational 5-day prediction of Atlantic hurricanes using the WRF model. The broad impact of this research will help improve evacuation planning and disaster reduction and facilitate the protection of life and property in the coastal regions. Valuable insight can also be gained by creating a link between the numerical simulations in this study with past field campaigns and satellite data. The comparison and validation of model data with robust data sets as found in GRIP, IFEX10 and PREDICT will create a bridge that forecasters can use to create a more accurate forecast with a better lead-time. In addition, this project will generate both peer-reviewed journal publications and conference presentations.

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