11A.3 TROPICAL CYCLOGENESIS: A MODELING COMPARISON BETWEEN DEVELOPING AND NON-DEVELOPING CLOUD CLUSTERS

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1. INTRODUCTION

Through years of observations and numerical modeling studies dating back to Ooyama's (1969) innovative, yet relatively coarse, axisymmetric tropical cyclone model, several notable theories have emerged in an attempt to describe the formation of tropical cyclones. These include the theory of conditional instability of the second kind (CISK) (Charney and Eliassen 1964), and the more recent and widely accepted wind-induced surface heat exchange (WISHE) (Rotunno and Emanuel 1987). However, as Hendricks et al. (2004) and Reasor et al. (2005) note, there is increasing agreement within the community that tropical cyclone genesis occurs in two stages, as both theories listed above are secondary processes which assume a low-level vortex is already in existence. Although these theories have provided an explanation of the secondary processes of genesis, the primary question of how cumulus convection is able to organize and form a large, low-level vortex still remains without a definitive answer.

In an attempt to answer this question, recent work utilizing higher resolution models (Bister and Emanuel 1997; Ritchie and Holland 1997; Ritchie 2003; Hendricks et al. 2004; Reasor et al. 2005; Tory et al. 2006A; Tory et al. 2006B; Montgomery et al. 2006; Tory et al. 2007) have helped provide insight into how the low-level vortex might form in the initial phases of tropical cyclogenesis. Within these studies, however, competing theories exist in an effort to explain the development of the low-level vortex. As Tory et al. (2006A) explains, vortex enhancement is thought to occur through a combination of stratiform processes, in which a convergent region exists at mid-levels, and convective processes, where low-level convergence and upper-level divergence is dominant.

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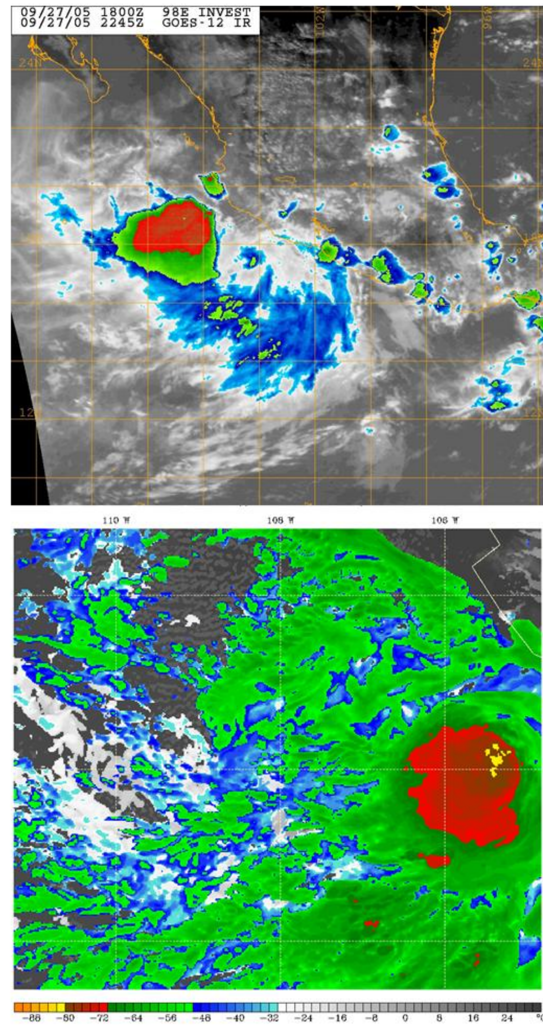

Figure 1: Comparison of cloud top temperatures for Hurricane Otis (2005) derived from GOES infrared satellite at 2245Z September 27 (top) and model simulation at 2300Z September 27 (bottom). Yellow colors denote temperatures less than -80° C and red colors for temperatures less than -70° C.

To illustrate the lack of understanding regarding which processes are dominant during the early stages of genesis, a great deal of uncertainly still remains as to why some cloud clusters develop into tropical cyclones and others, which are embedded within similar environments, do not. As pointed out by Gray (1982), in order to understand the process of tropical cyclogenesis, one must also be able to explain why more often then not, genesis does not occur.

It is therefore believed that gaining a better understanding of the pre-genesis phase could help forecasters identify which clusters will develop. This could translate into a significant increase in lead time for emergency management personnel, especially for storms forming in close proximity to coastal areas.

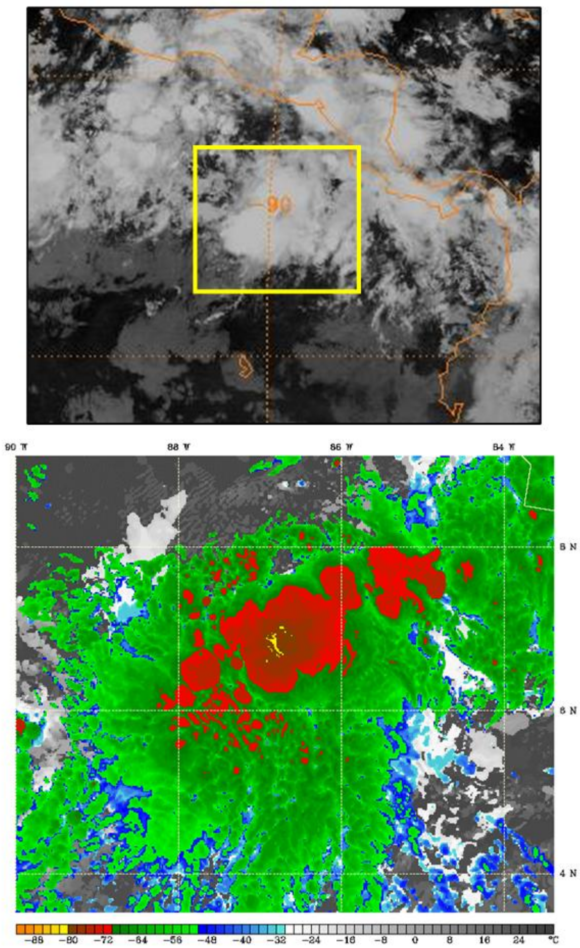

Figure 2: Infrared satellite image of the non-developing cloud cluster chosen for this modeling study at 0545Z on July 20, 2006 (top) and diagnosed cloud top temperatures from a numerical simulation of the same cluster at 0700Z. Yellow colors denote temperatures less than -80° C and red colors for temperatures less than -70° C.

In this paper an ongoing study is described in which tropical cloud clusters of both developing and non-developing systems are analyzed using a numerical model. The model is used as a tool to investigate in detail the microphysical evolution of pre-genesis cloud clusters as they develop into tropical cyclones with hopes that differences between developing and non-developing cloud clusters in the microphysical structure and convective elements will be identified.

The remainder of this paper is divided as follows: part two describes the model setup, briefly outlining the parameters used in the simulations, and discusses how the model simulations compare with observations. Part three discusses the results and part four concludes.

2. METHOD

2.1 Model description

Two numerical simulations were conducted using the Weather Research and Forecasting (WRF-ARW) model version 2.2.1 developed by the National Center for Atmospheric Research's (NCAR) Mesoscale and Microscale Meteorology Division. Each simulation consisted of three nested domains with resolutions of 15-, 5-, and 1.67 km with 33 vertical model levels. The finest resolution grid (1.67 km grid spacing) for the Otis run consisted of 700 x 604 grid points, whereas the high resolution grid for the cluster simulation consisted of 439 x 373 grid points

Microphysical processes were represented by the WRF Single-Moment 6-class (WSM6) scheme which allows for snow, ice, and graupel effects. The Kain-Fritcsh cumulus parameterization scheme was implemented for the coarsest (15 km grid spacing) domain, but convection was explicitly represented (no cumulus scheme) for the two nested domains. Boundary layer processes were parameterized using the Yonsei University (YSU) planetary boundary layer scheme. Each simulation was conducted using 6-hourly National Center for Environmental Prediction (NCEP) Final Analysis (FNL) data.

The Hurricane Otis (2005) model run extended from 00Z September 27th to 12Z October 1st, and the non-developing cloud cluster simulation covered a time period from 00Z July 18th to 00Z July 21st, 2006. Model run times were selected as to allow for adequate model "spin-up" time (~12 hours) before the cloud clusters were deemed to be at their critical stage of development in an effort to help reduce a-physical model adjustments characteristic of a "cold start".

A time was selected for each case in which the spatial structure and magnitude of cloud top temperatures diagnosed from the simulations appeared similar to one another. Vertical cross sections of dynamical and microphysical characteristics were then compared analyzed.

2.2 Comparison between model simulations and observations

The large-scale spatial structure of convection in the simulation resembles observations fairly closely indicating the simulations may provide valuable insights into the microphysical processes of developing and non-developing cloud clusters.

Ideally, a comparison between cloud clusters with similar environmental conditions (SSTs, solar forcing, large-scale circulation patterns, etc.) would be preferred, but the time of season for each disturbance and the background environmental conditions present at the time (see section 3.1) varied to a large degree. However, even though differences existed between the two cases, there were notable similarities (both disturbances originating from easterly waves and possessing similar cloud top temperature patterns), and therefore the Hurricane Otis and the non-developing cloud cluster were selected as preliminary cases for this ongoing study.

Convection represented by the model simulations and diagnosed by the cloud top temperature field (Fig. 1 and Fig. 2) appears to be fairly representative of the structure and intensity observed in IR observations. Although an exact match between the simulation and observations of the timing and location of convective "hot spots" is not observed in either model simulation, the large scale spatiotemporal patterns of convection are preserved. Thus the simulations are believed to provide valuable insights into the microphysical processes of developing and non-developing cloud clusters.

2.2.1 Hurricane Otis

Hurricane Otis (2005) is thought to have originated from an easterly wave and was first classified as a tropical depression at 00Z on the 28th of September off the coast of Manzanillo, Mexico (Beven 2006). As the storm strengthened, its track changed from southwestward to northwestward and it reached its peak intensity of 46 m/s on October 1st south of Baja California, Mexico.

At later times, the Otis simulation tracks the storm too far to the west and over-intensifies it by about 6 mb by the model run end time (12Z on October 1st), which is close in time to when the real storm's peak intensity (970 mb) was recorded. As time progresses towards the end of the model simulation, the spatial structure of the simulated cloud top temperatures tends to match IR observations even more closely than at earlier times (not shown).

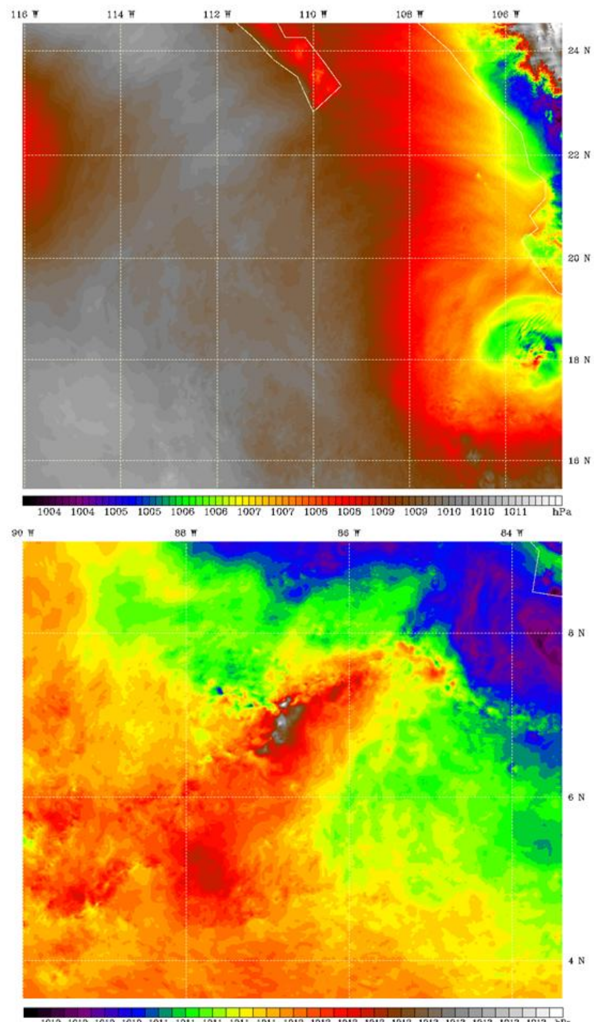

Figure 3: Sea-level pressures at analysis times for the Otis simulation (top) and for the non-developing cluster simulation (bottom) (note that scales for each graphic are different).

2.2.2 Non-developing cloud cluster

Similar to Hurricane Otis, the non-developing cloud cluster also appears to have formed as a result of an easterly wave (see Fig. 4) and could be identified as an area of periodic deep convection that formed off the west coast of Central America and propagated toward to the west before dissipating.

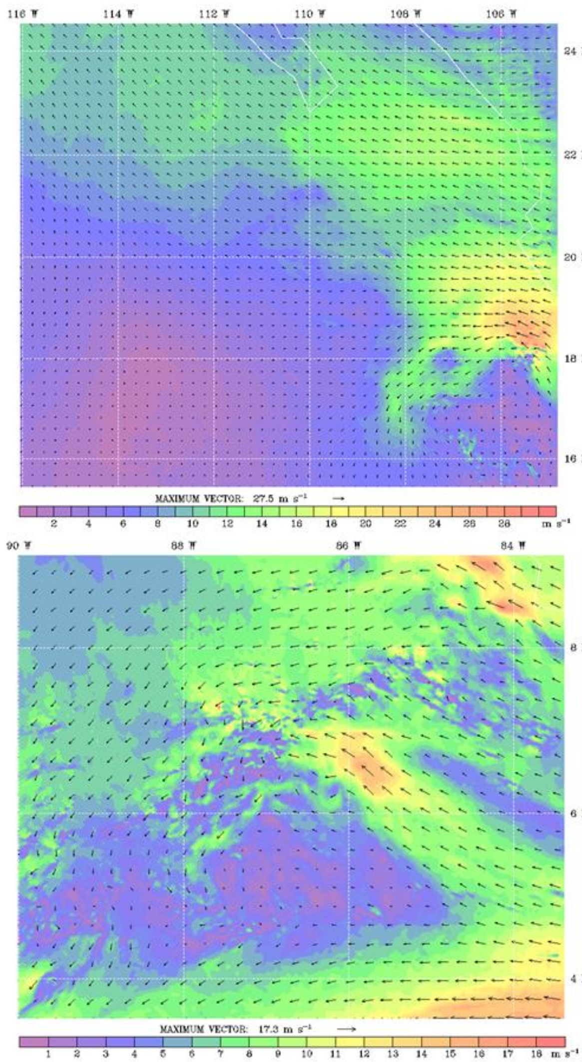

Figure 4: 700 mb wind speeds (shaded with vectors) for the Hurricane Otis simulation (top) and the non-developing cluster simulation (bottom).

Although a similar comparison of cloud top temperatures between the non-developing cluster simulation and satellite IR observations for the same time period (Fig. 2) is not possible, it can be seen that the time evolution of convection for the simulated cluster closely resembles IR observations in which areas of deep convection tend to follow the westward propagation of an easterly wave. The presence of an easterly wave is confirmed in analyzing the time-elapsed 700 mb (see Fig. 4 for analysis at 0700Z) and 500 mb (not shown) wind and geopotential field of the simulation. By the end of the model run (00Z July 21), the area of convection associated with the cloud cluster closely resembles IR satellite observations as it has moved to the west, diminished greatly in intensity, and lacks any discernable organization.

3. RESULTS

3.1 Background environment

Although some conditions of the background environment were similar between the two simulations, such as low values of vertical wind shear (not shown), many differences did exist. At the analysis time, sea surface temperatures (SSTs) analyzed for the Otis simulation (not shown) were on average 2° C warmer near the pre-storm cluster (30° C) than the SSTs that were present during the non-developing cluster simulation (28° C). This is a result of Otis being located near the warm waters off the west coast of Mexico, whereas the non-developing cluster was far removed from similar influences.

Otis also formed in an area of relatively low sea-level pressure (Fig. 3), which most likely aided in its development. The non-developing cluster, on the other hand, formed in a region of much higher sea-level pressure (Fig. 3). As is seen by the 700 mb wind analysis (Fig. 4), both clusters originated from easterly waves, but their magnitudes varied significantly. Wind speeds near the trough of the open wave at 700 mb ranged from nearly 30 m/s for the Otis simulation to 19 m/s for the non-developing cluster. It is believed that the presence of low sea-level pressure as well as being embedding within a vigorous easterly wave aided in Otis' development.

The amount of moisture present at upper-levels (not shown) appears to be very similar for the Otis and non-developing simulations, but as the comparison of 850 mb equivalent potential temperature (θ_e) (Fig. 5) shows, it differs greatly at low-levels. At 850 mb, the pre-Otis cluster is surrounded by a region of high θ_e air which extends radially outwards from the disturbance by more than 100 km in all directions. Areas of low θ_e close to the convective core (shaded green) correspond to regions where precipitative downdrafts have transported low θ_e air down near the surface.

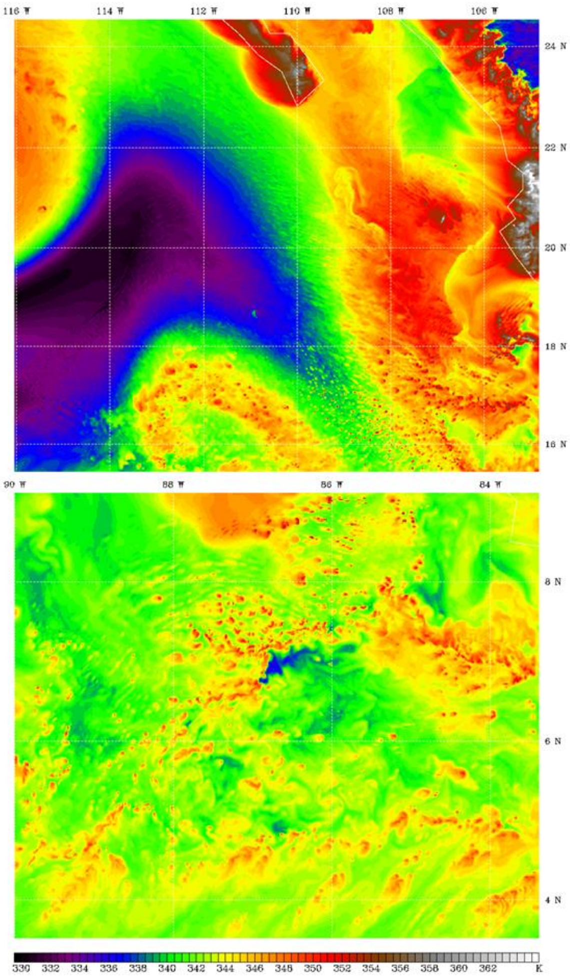

Figure 5: 850 mb equivalent potential temperature (θ_e) for the Hurricane Otis simulation (top) and non-developing cluster simulation (bottom).

A pool of low θ_e air near the center of convection is also is evident in Fig. 5 for the non-developing cluster simulation, but the non-developing cluster does not possess the surrounding "buffer" of high θ_e air that is present in the Otis simulation. It is speculated that due to the relatively high values of θ_e surrounding the pre-Otis cluster, the boundary layer θ_e is able to quickly recover from the vertical transport of low θ_e air down near the surface, minimizing the effects that downdraft-induced low θ_e air might have on convection.

The differences in background environmental conditions are therefore considered important in this comparison. It is thought that the cluster in the Otis simulation was in a better position to strengthen due to its background environment (high values of θ_e at low levels coupled with relatively low sea-level pressure and warm SSTs) which was conducive to sustaining convection.

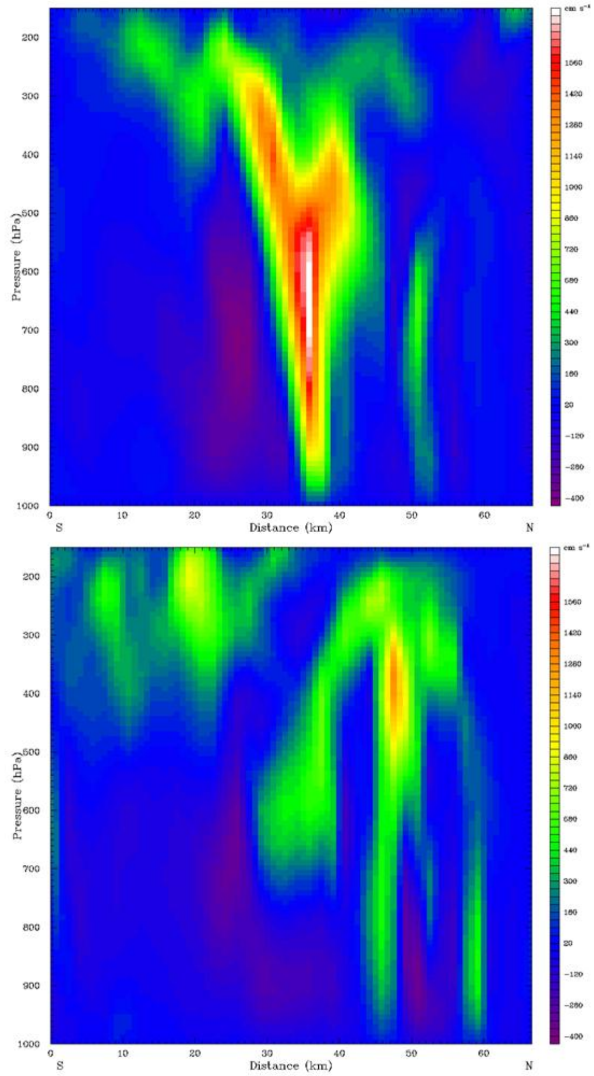

Figure 6: Vertical velocities. Maximum updraft and downdraft velocities are 18 m/s and 4 m/s respectively for the Otis simulation (top) and 13 m/s and 4 m/s respectively for the non-developing simulation (bottom).

3.2 Microphysical structure comparison

3.2.1 Vertical velocity

Immediately evident from comparing vertical cross sections of vertical velocity for the two simulations (Fig. 6) is that the non-developing cluster's updrafts are relatively weak and have been replaced by downdrafts near the surface. This suggests its convective life-cycle is in the decaying stages even though extremely cold cloud top temperatures are still present (Fig. 2). Vertical velocities for the Otis simulation, on the other hand, are stronger (nearing 18 m/s compared with 13 m/s in the non-developing case) and extend from the surface to upper levels. Downdrafts are present in the Otis simulation but are not vertically co-located with the updrafts as in the non-developing simulation.

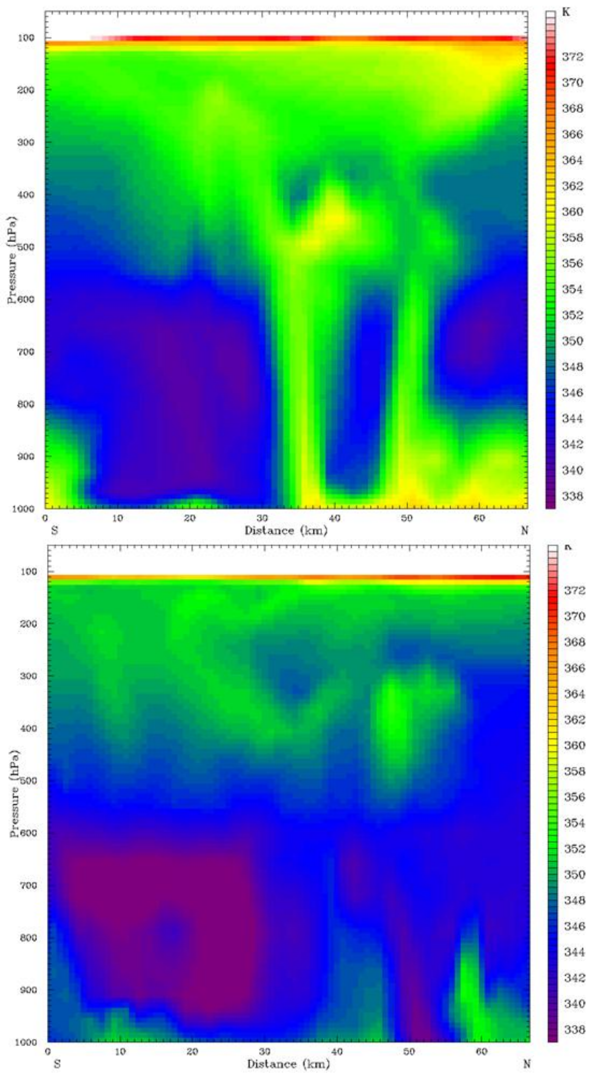

Figure 7: Equivalent potential temperature (θ_e) for the Hurricane Otis simulation (top) and the non-developing cloud cluster simulation (bottom).

3.2.2 Moisture

Values of equivalent potential temperature in and surrounding the convective core at both low and mid-levels are far higher for the Otis simulation than for the cluster simulation (Fig. 7), evidencing that the Otis mid and low-level environment was far more conducive to initiating and sustaining convection. Higher levels of moisture were also shown to exist in the area surrounding the pre-Otis cluster near 850 mb (Fig. 5). In addition to the abundant low-level moisture, the presence of moisture at mid-levels, evident in the convective core (Fig. 7) and 500 mb θ_e analysis (not shown), likely aided in Otis' development by reducing the entrainment of low θ_e air into the storm's vertical circulation and thus increasing the efficiency at which heat is transported vertically.

Vertical cross sections of convective available potential energy (CAPE) (not shown) also confirm that differences in the background moisture and temperature fields existed between the two simulations. Close to 2500 J/kg of CAPE was present in the Otis simulation, whereas only 1500 J/kg is calculated for the non-developing case. An area with high values of CAPE is located to the north of the strongest updrafts for both simulations.

3.2.3 Divergence

Comparing vertical cross sections of divergence (Fig. 8) from the two simulations helps to illustrate the difference in organization between the disturbances. For the non-developing cluster, divergence generally dominates aloft and regions of convergence exist near the surface, but both appear in a relatively disorganized manner. For the Otis simulation, on the other hand, large values of convergence exist near the surface and strong divergence is present at upper-levels, both of which are highly concentrated near the center of convection. Perhaps noteworthy is that the broad region of convergence that is often observed extending from the surface to near 400 mb in mature tropical cyclones is not evident at this analysis time.

3.2.4 Potential vorticity

The potential vorticity (PV) field for the non-developing cluster reveals positive PV existed at mid-levels, but that small or negative PV dominated the near surface environment (Fig. 9). The negative PV anomaly evident at mid-levels in the bottom of Fig. 9 (just to the north of the vertical cross section's center) is collocated with an updraft maximum shown in the bottom of Fig. 6. This suggests that PV values near the updraft were largely negative without considering the positive stretching effect that the updraft might have on PV in that region.

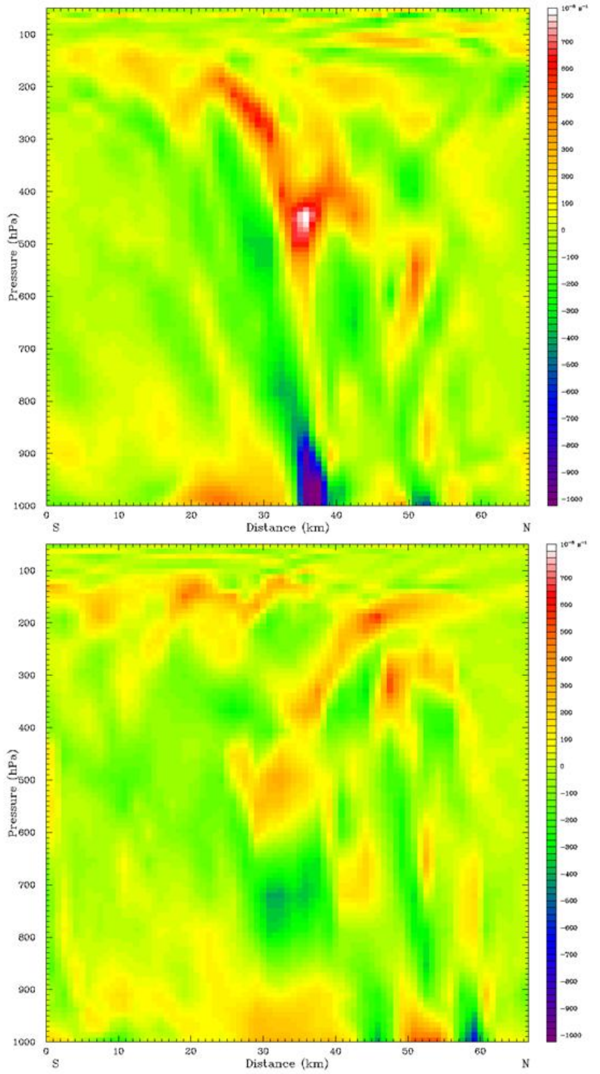

Figure 8: Divergence from the Hurricane Otis simulation (top) and non-developing cluster simulation (bottom).

Perhaps indicative of a stratiform precipitation region is the concentration of PV at mid-levels in the non-developing cluster simulation. Comparing with vertical velocities (bottom of Fig. 6) near the same area reveals that the mid-level PV anomaly is co-located with a broad region of ascent that overlies a large area of descent. This vertical profile of vertical velocities is considered characteristic of a stratiform precipitation region as the precipitative effects help concentrate PV at mid-levels.

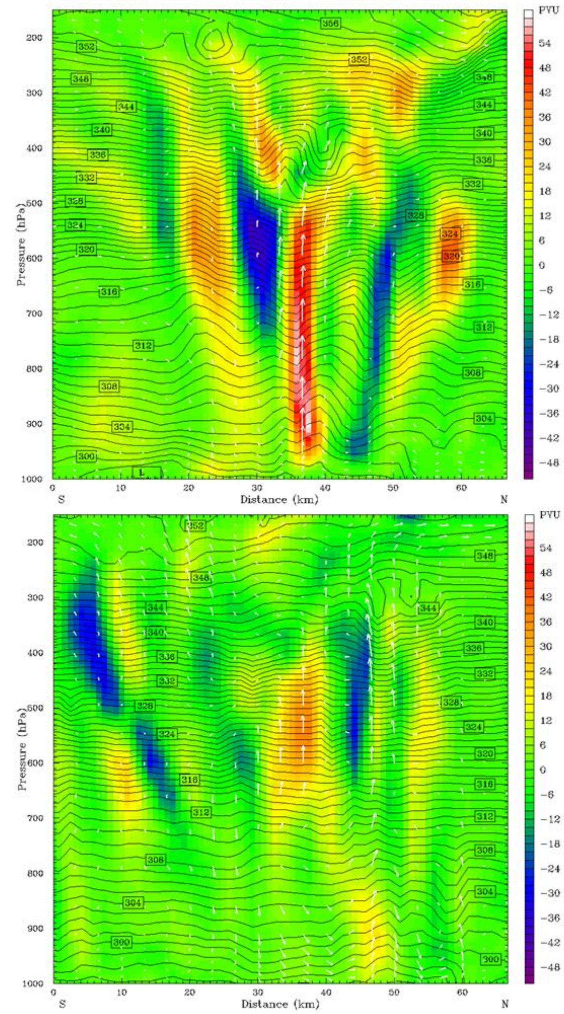

Figure 9: Vertical cross section of potential vorticity (shaded) with potential temperature (black contours) and vertical velocity (white vectors). Maximum and minimum PV values are >50 PVU and -30 PVU respectively for the Otis simulation (top) and 35 PVU and -35 PVU respectively for the non-developing simulation (bottom).

The vertical structure of PV for the Otis simulation is much different from the non-developing cluster simulation. Relatively large values of PV extend from mid-levels down near the surface suggesting that the strong low-level convergence (Fig. 8) and large vertical velocities (Fig. 6) have acted to concentrate and stretch the PV in the vertical direction. An interesting feature evident in the Otis simulation PV field, of which at present lacks an explanation, are the alternating areas of negative and positive PV that lie to the north and south of the highly concentrated positive PV column.

Interestingly, areas of low potential temperature ("domed" isentropes near the surface) exist under regions of positive vertical velocity in both simulations (Fig. 9). This suggests that the low-level cold pools, which are generated by evaporative downdrafts, may play an important role in acting as a focus for sustained convection. Converging low-level air is forced to ascend over the relatively cool and dry air near the surface, creating a preferential location for convection to continue to occur.

4. SUMMARY AND CONCLUSIONS

A brief description and preliminary results of a modeling study comparing developing and non-developing cloud clusters was presented. Hurricane Otis (2005) and a non-developing cloud cluster from July 2006 were simulated using the WRF-ARW numerical model.

Background environmental conditions for each simulation were compared and it is believed that these factors (SSTs, moisture, sea-level pressure) played an important role in determining the evolution of each disturbance. It was shown that the environment for the pre-Otis cluster was more favorable in all regards for the continued strengthening of the disturbance.

A microphysical analysis of the two cloud clusters was also conducted. It was shown that the pre-Otis cluster possessed a much stronger updraft core (Fig. 6) and greater organization (Fig. 8 and Fig. 9). Although cloud top temperatures appear fairly similar in intensity and spatial coverage (Fig. 1 and Fig. 2), the non-developing cluster was considered to be in the decaying stages while the pre-Otis cluster was continuing to strengthen.

An analysis of the vertical velocity and PV fields suggest that a mesoscale vortex was present at mid-levels in the non-developing simulation. Areas of ascent overlying an area of descent, considered characteristic of a stratiform precipitation region, can be identified in the bottom of Fig. 6 and corresponds to a region of positive PV in the bottom of Fig. 9. This supports the theory that mesoscale vortices form in stratiform precipitation regions.

It is also suggested from the analysis of potential temperature and PV (Fig. 9) that precipitative downdrafts may play an important role in acting as a focus mechanism for continued convection. Bulging isentropes near the surface exist underneath the most convectively active regions and appear to initiate the forced ascent of converging low-level air.

Even thought the environmental conditions varied between the preliminary case studies selected, important insights were gained through the comparison. Similar vorticity enhancement processes to those described in the literature appear to be evident in these preliminary simulations, but additional case studies are needed before conclusions can be made about what role and importance these processes may have in cyclogenesis. Future work will include an analysis of the time evolution of the microphysical structure during the pre-genesis phase.

It is hoped that additional comparisons between developing and non-developing disturbances with similar environmental conditions will provide useful clues that will help determine why some cloud clusters develop into tropical cyclones while others do not.

Acknowledgments

This project was made possible in part by a Science Foundation of Arizona graduate research fellowship. We thank the National Center for Environmental Prediction (NCEP) for providing the meteorological data and the National Center for Atmospheric Research (NCAR) for developing and providing support for the Weather Research and Forecasting (WRF) model. We also thank the High Performance Computing (HPC) center at of the University of Arizona for providing the computing resources necessary for this study.

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