A comparison of large-scale influences on tropical cyclogenesis in the Eastern Pacific

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ABSTRACT

In a given hurricane season, several tropical disturbances propagate across environments favorable for development; however, only a few disturbances actually strengthen into tropical cyclones. The lack of a consolidated theory on tropical cyclogenesis makes it difficult for forecasters to predict a storm's development. Previous studies have approached this problem by comparing large-scale influences on storms that developed into tropical cyclones and on those that did not. This study used a similar approach to characterize the environmental influences on cyclogenesis in the 2005 Eastern Pacific Hurricane season. Data for each storm were taken from the NCEP/NCAR Final Analysis model and analyzed over a 48-hour period during the development stage. The non-developing storms were selected based on certain atmospheric parameters to resemble the developing storms prior to cyclogenesis. Composites and spatial averaging were used to compare 12 developing storms and 11 non-developing storms during this season. The results showed that the environments of the developing storms had large regions of increased moisture above the boundary layer and greater temperatures in the upper troposphere. Regions of increased potential vorticity penetrated deeper into the troposphere for the developing storms. Lastly, the storms that developed were in environments with relatively strong wind shear to the south of the vortex. The results suggest that the moisture, temperature, and wind shear fields preceded development, while the vorticity fields were more of an indicator of development. Identifying these large-scale characteristics as possible determining influences can lead to a better understanding of tropical cyclogenesis.

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1. INTRODUCTION

The formation of tropical cyclones has always been an intriguing topic in the atmospheric sciences. Numerous studies have sought to determine what causes these potentially devastating storms to develop. The process of tropical cyclogenesis requires certain thermodynamic conditions and atmospheric flow patterns. Identified by Gray (1979), these include a warm oceanic layer of sufficient depth, convergence of surface winds, conditional instability, and above-normal mid-tropospheric moisture. Even though further studies provided more descriptive conditions, a complete understanding of tropical cyclogenesis has still not been attained. Today's meteorologists have significant difficulty in forecasting which tropical disturbances will later develop into tropical cyclones. This uncertainty in prediction reflects the fact that there is no consolidated theory on hurricane formation (Ritchie and Holland 1997). More extensive research is needed to further our understanding of tropical cyclogenesis.

Despite the absence of a formal theory, observational studies have shown that large-scale dynamical circulations have an enormous influence on tropical cyclogenesis. Briegal and Frank (1997) studied the environmental wind fields of several tropical cyclones in the western North Pacific. They found that in a majority of the cases, an upper-level trough and lower-level flow surges were present near the circulation. It is hypothesized that these flow surges and upper-level troughs combine to force the low-level convergence, deep uplifting, and upper-level divergence that is necessary for tropical cyclogenesis. These results were consistent with previous studies on influential dynamical circulations (Sadler 1976, 1978, McBride and Keenan 1982).

With this general description of necessary environmental dynamics comes a great diversity in the actual origins and mechanisms of tropical cyclogenesis. Several studies have identified large-scale atmospheric patterns that were influential in development, with each pattern dominant in different regions of the world. Molinari et al. (2000) performed a case study in the Eastern Pacific and found that pre-existing waves from Africa and monsoonal wind surges were key components in cyclogenesis. Bracken and Bosart (2000) studied environmental wind flows in the North Atlantic and identified two upper-tropospheric flow patterns that were consistent with storm development. These studies do not suggest that a large-scale pattern is unique to any certain region, but that certain conditions are a more effective mechanism for cyclogenesis in its proper basin. The diversity of these results raises an important question: if the identified large-scale influences may exist anywhere at anytime, what causes one to induce cyclogenesis for some storm systems but not others? What are the features seen in all of the previous cases that are most important in characterizing cyclogenesis?

McBride and Zehr (1981) sought to answer these questions by comparing non-developing convective systems and developing convective systems. Many other studies solely identified the conditions that are present during tropical cyclogenesis; however, these features can exist without development ever occurring. Using a comparison approach in their observational analysis, McBride and Zehr identified distinguishing features that characterized only developing convective systems. These include the presence of a warmer atmosphere over a larger horizontal scale, particularly at the mid-tropospheric level. The developing system also had large areas of high values of low-level vorticity. Finally, there was no vertical wind shear near the storm center.

The objective of this study is to extend the work done by McBride and Zehr in an effort to confirm their results and also to identify additional distinguishable features. McBride and Zehr used composites of rawinsonde data from the standard observational networks. This study will use the NCEP/NCAR Final Analysis model data. The analysis data will give additional insight to atmospheric features of each storm because it is a synthesis of several data observations. Rather than the vast Western Pacific and Atlantic Ocean basins, this study focuses on the Eastern Pacific. In terms of genesis events per unit area and per unit time, the Eastern Pacific Ocean is the most active tropical cyclone formation region on earth (Molinari et al. 2000). The smaller formation area also means that data composites will be more representative of individual events, especially since storm tracks have little variation between storms. Instead of focusing on just the genesis time, this study will examine atmospheric features over a longer period including the genesis time. Examining the evolution of atmospheric conditions throughout cyclogenesis can reveal important features that distinguish these events from non-developing systems and characterize the development process. By reinforcing the importance of the characterizing atmospheric conditions or discovering new features, this study will add to the understanding of tropical cyclogenesis and subsequently improve forecasts and warnings.

2. BACKGROUND

The following sections give a description of key concepts needed to understand the scope and methodology of this study.

2.a Tropical cyclogenesis

Simpson et al. (1997) proposed that tropical cyclogenesis incorporates three distinct stages. The first stage is the establishment of the necessary thermodynamic and dynamic conditions. As mentioned earlier, the necessary thermodynamic conditions include a warm ocean layer, conditional instability, and above-normal mid-level moisture. The dynamic conditions that must be met include above-normal low-level vorticity and weak vertical wind shear. Gray (1975) hypothesized that tropical cyclogenesis occurs when these dynamic variables are met in a thermodynamically favorable environment that is adequately far from the equator. It is important to note that these conditions are necessary for tropical cyclogenesis, but they may not be sufficient.

The second and third stages of tropical cyclogenesis involve the formation and amplification of a mesoscale convective vortex (MCV). An MCV forms within a mesoscale convective system (MCS) of a pre-existing tropical disturbance. Such tropical disturbances typically contain several MCSs. This large cloud cluster is a well-known precursor to tropical cyclogenesis (Simpson et al. 1997). After the MCV is formed, it enters the third stage, amplification. This stage is marked by a deepening low pressure center and increasing convection. According to one theory on Eastern Pacific cyclogenesis, this occurs when a mid-level vortex within the storm descends to the lower levels (Bister and Emmanuel 1997). High relative humidity in and above the boundary layer hinders evaporative cooling, and therefore hinders downdrafts from the storm. The expulsion of air from the storm now occurs in the upper troposphere. This allows the MCV to become capable of rapid self-intensification as long as environmental conditions are still favorable (Briegel and Frank 1997). At this stage, tropical cyclogenesis is completed once the storm develops a rotation center at the surface.

2.b NCEP/NCAR Final Analysis

This study uses data from the NCEP/NCAR Final Analysis to examine the influences on tropical cyclogenesis. The NCEP/NCAR reanalysis is a global model of the atmosphere that assimilates observational data from various sources into a single estimate of the state of the atmosphere. The sources of input data include marine and land surface stations, upper-air balloons, and aircraft measurements. The final analysis is an additional synthesis of the reanalysis with improved data assimilation techniques. The model outputs 6-hourly atmospheric parameters onto gridded domains at 26 pressure levels up to 10 mb. The grid spacing is 90 km in both the meridional and zonal directions.

2.c Potential vorticity

Potential vorticity, or PV, is a fundamental quantity in meteorology that measures the rotational character of the air motion. It is given by the following equation:

$$P = \alpha(2\Omega + \nabla \times \mathbf{u}) \cdot \nabla \theta$$

where α is the specific volume, Ω is the angular velocity of the earth's rotation, **u** is the velocity vector, and θ is the potential temperature. PV differs from absolute vorticity in that it accounts for the effects of friction and diabatic heating. Absolute vorticity, which is defined as $\eta = 2\Omega + \nabla \times \mathbf{u}$, is the sum of the relative vorticity (which is only a vertical component with respect to the earth) and the vorticity of the earth. When the thermodynamic properties of the air are taken into consideration, PV becomes a more conserved property with respect to the atmosphere. Ertel's theorem states that PV is constant for each air particle when in the absence of friction or heat sources (Hoskins et al. 1985). By using this theorem, PV is usually the better quantity for analyzing the air's rotational character during convective processes. Defined by Hoskins et al., PV is given in Potential Vorticity Units (PVU), where 1 PVU = $1.0 \times 10^{-6}\, m^2 \cdot K / kg \cdot s$.

Potential vorticity is an important quantity in this research because it serves as a signature for organized convection, particularly in the tropics. McBride and Zehr noted that both developing and non-developing storms have a signature for low-level vorticity, which is possibly due to the presence of a mid-level vortex and mid-level warm core in the storm. An initial analysis of tropical convection showed that at 950 mb, a system can be identified by its PV signature. This low-level PV is used for this study in the selection of non-developing storms and the tracking of all storm systems.

3. DATA AND METHODOLOGY

3.a Data set

The current study focused on the 2005 Eastern Pacific hurricane season. This year was chosen because the NCEP/NCAR Final Analysis data were readily available from July 1st through September 30th. During these three months, numerous tropical waves traveled across the Eastern Pacific Ocean. Twelve of these disturbances reached tropical depression status and later became named storms. The centers of circulation for every storm were obtained from the National Hurricane Center (NHC) best track data. From the remaining tropical disturbances, several were chosen for study as non-developing storms based on criteria described in section 3.c. Infra-red satellite images, which were used in the selection process, were taken from the GOES-10 satellite.

3.b Storm genesis and track extrapolation

The genesis point and genesis time of each developing storm are defined as the location and time where each storm reached tropical depression status. These were determined by the first

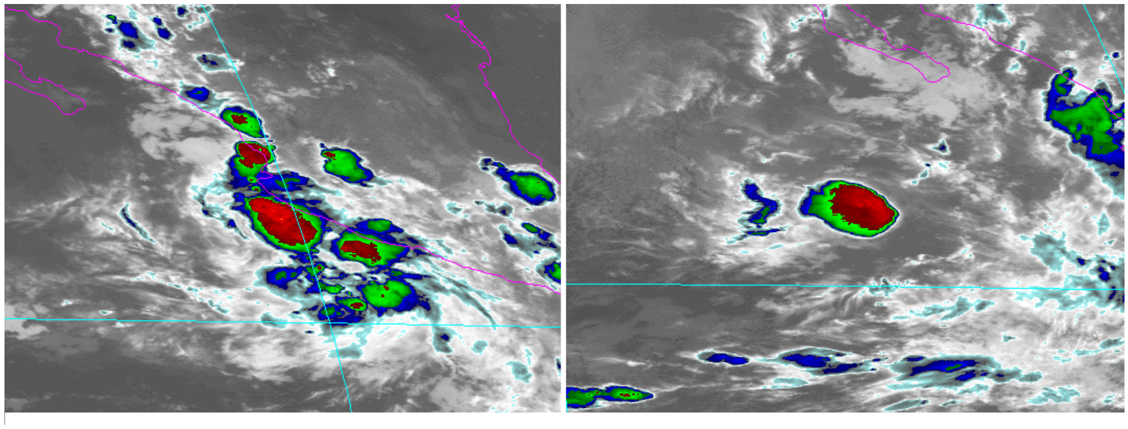

Figure 1. Satellite images of a developing storm at hour 36 (left) and a non-developing storm at hour 24 (right).

Tropical Cyclone Formation Alert issued by the NHC. Advisories of each storm were issued every 6 hours thereafter, giving the position and strength of the storm. In order to examine cyclogenesis, the tracks of the developing convective system were estimated prior to the genesis time. The positions of each storm were taken throughout its first 48 hours as a tropical cyclone and averaged to determine the best linear storm track and average speed. Based on this linear track and average speed, initial estimations of the storm's positions were taken for the 48 hours prior to genesis at 6 hour intervals. The final estimations of the storm's positions were based on PV values at the 950 mb level. The grid point that was chosen as the storm's position met two criteria. First, this point lied within a 5x5 grid box centered on the storm's initial position estimation. Second, this point had the highest averaged PV within this domain, where the average was taken over an area of 129,600 km^2. The 48-hour time frame for study began 48 hours prior to genesis, which was named hour 0. The genesis time became hour 48 for the developing cases.

3.c Non-developing storm selection and tracking

In order to select the non-developing storms used for this study, tropical disturbances throughout the basin needed to meet certain criteria. The storm first had an averaged PV value of at least 0.15 PVU at the 950 mb level consistently for a 48 hour period, where the average was taken over an area of 129,600 km^2 (5x5 grid). Based on an initial investigation of the developing storms, this value and this pressure level were chosen so that the non-developing storms had similar values of PV as the developing storms. This PV value represents an anomaly with respect to the surrounding environment as the background environment generally has a 950 mb PV of zero. Second, the storm had one local maximum of average 950 mb PV within the same domain area. Third, this PV local maximum showed signs of westward propagation over this

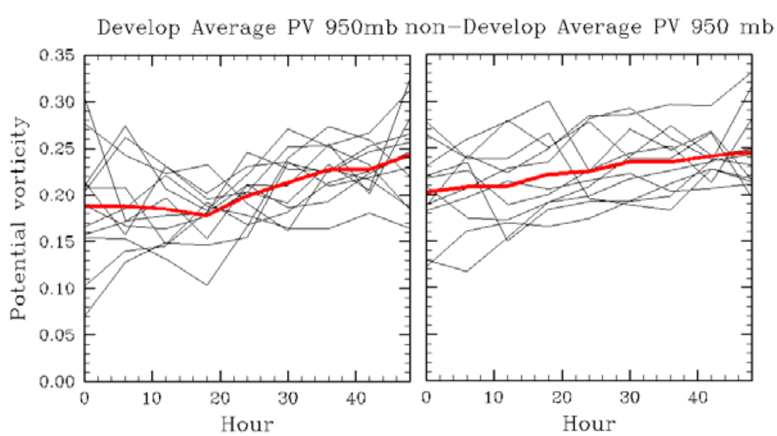

Figure 2. Potential vorticity (in PVU) averaged over 5x5 grid domain for developing and non-developing storms. Individual storms are in black, and average storm is in red.

same 48 hour period. Fourth, this storm had significant convection over or near the PV maximum for at least 12 hours. The 48-hour time frame of study was chosen so that Hour 24 was the time at which the convective cloud cover reached cloud-top temperatures less than -59°C with a diameter of 130 km. Figure 1 shows satellite images of an example developing and non-developing storm. These specifications were chosen so that the non-developing storm best matched the developing storm's extent and timing of convection eruption as seen in the example images. Last, this storm could not be one of the 12 named tropical storms.

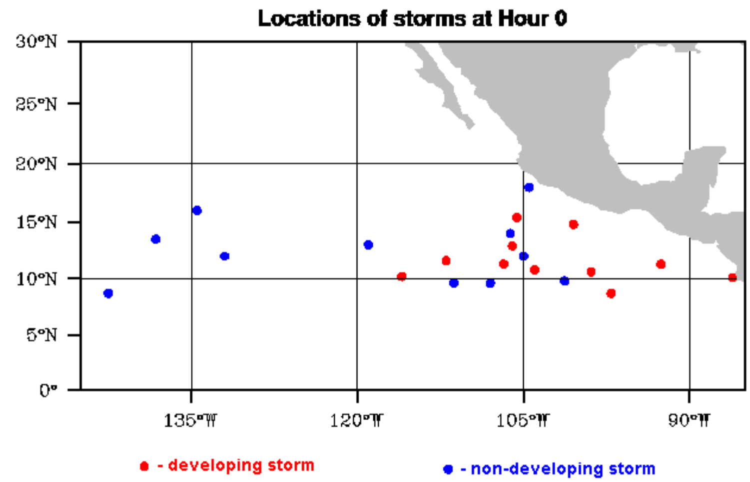

Figure 3. Locations of developing and non-developing storms at hour 0.

There were 11 storms during the 2005 Eastern Pacific hurricane season that matched the above criteria. Just as in the developing storms, their positions and tracks were determined by a maximum in the averaged 950 mb PV at 6 hour intervals over the 48-hour time frame. Figure 2 is a plot of the average 950 mb PV over time for the developing and non-developing storms. Over the selected 48 hour period, both storms increase similarly in PV value. In fact, there is no time when the difference between the two was statistically significant (See Appendix). This shows that the chosen storms were similar enough so that a comparison study could yield useful information. Figure 3 shows the locations of the developing and non-developing storms at hour 0.

3.d Compositing and averaging domains

Three domain types were often used in the analyses. All domains were defined and centered on the locations of each storm (developing and non-developing) throughout the 48-hour time frame. The first data domain spanned 1,800 km in the meridional and zonal directions with data on a 21x21 grid. This domain was used for compositing multiple storms in order to illustrate the spatial patterns of atmospheric parameters. The second data domain spanned 900 km in the meridional and zonal directions with data on an 11x11 grid. The third data domain spanned 360 km in the meridional and zonal directions with data on a 5x5 grid. Data in these last 2 domains were averaged to give single values that were representative of the atmospheric conditions over the general area of each storm.

3.e Data comparison and analysis

The following atmospheric parameters were examined in this analysis: temperature, wind speed and direction, geopotential height, potential vorticity, divergence, wind shear, specific humidity, and relative humidity. The parameters were examined at multiple pressure levels, from the surface to the 100 mb level. Data averages and composites were compared between developing and non-developing storms to determine similarities and differences in atmospheric conditions. The statistical significance of the comparisons was determined based on the standard t-distribution (See Appendix).

4. RESULTS AND DISCUSSION

4.a Thermodynamic variables: Moisture

The amount of moisture in the atmosphere is an important factor in determining the probability of tropical cyclogenesis. As with all convective storm systems, the condensation of water vapor gives the storm the necessary energy so that it may continue to thrive. For this reason, all storm systems will tend to have a moister environment than their surroundings. But is there a critical amount or distribution of moisture that may cause or influence convective storms to undergo cyclogenesis? To investigate this question, the integrated precipitable water (IPW) of the atmosphere was first examined in the environments of developing and non-developing storms. The IPW measures the amount of water that would be condensed from water vapor in a given column of air. It is given by the equation,

$$I = \frac{1}{\rho_w g}\int^{n} q\,dp \ ,$$

where I is the IPW, ρ_w is the density of water, g is Earth's gravitational acceleration, q is specific humidity, and dp is the increment of atmospheric pressure at the nth pressure level. IPW is used instead of specific or relative humidity at particular levels because it is a vertically integrated quantity and is therefore less susceptible to random analysis errors in moisture. High values imply deep columns of moist air. This moist air would primarily be above the boundary layer since the water vapor content of this layer in the tropics is relatively homogenous.

Figure 4 presents the IPW of the composite developing storm and the composite non-developing storm at hours 0, 24, and 48. Throughout the evolution of the developing storm, it was encompassed by an extensive area of

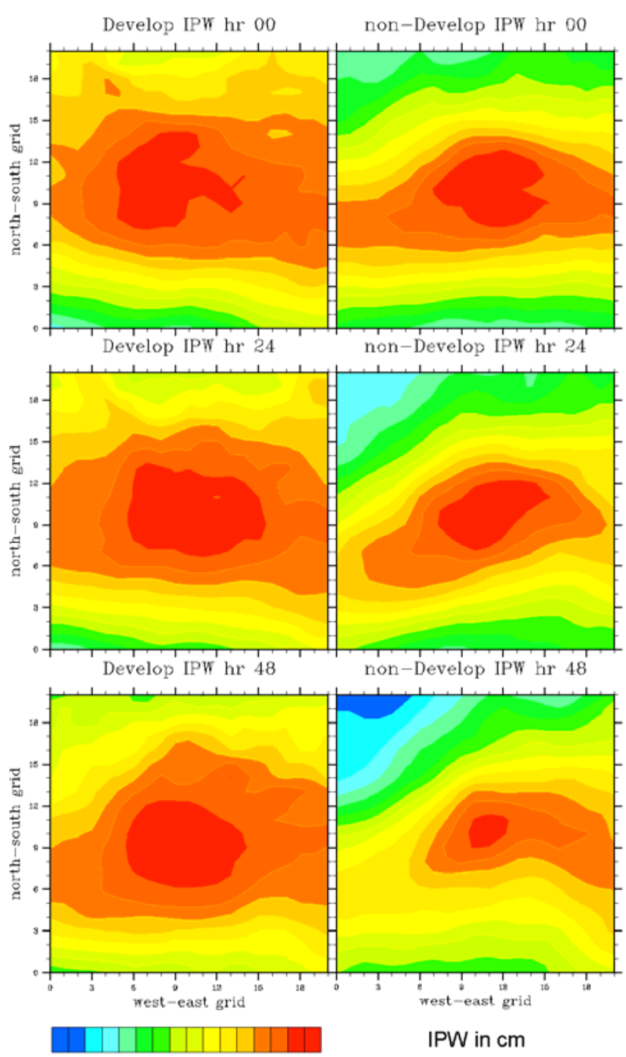

Figure 4. IPW (in cm) for composite developing and non-developing storms at hours 0, 24, and 48.

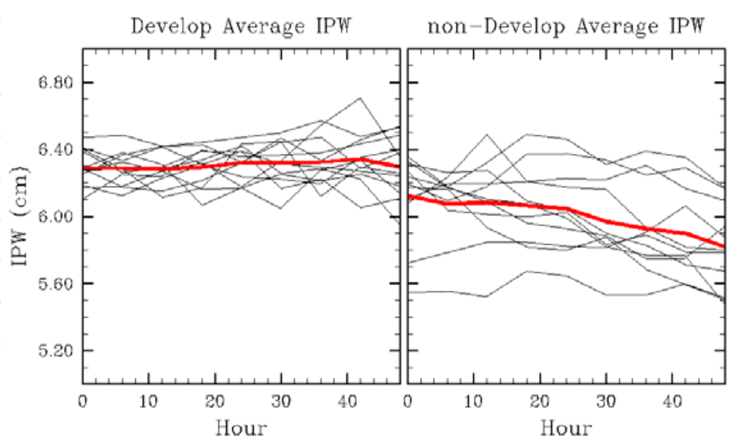

Figure 5. IPW (in cm) averaged over 11x11 grid domain for developing and non-developing storms.

moist air that became even moister as time progressed. At hour 48, this moist air reached IPW values greater than 6.6 cm at the location of the storm. In the evolution of the non-developing storm, the IPW reached similar values, but the area over which the moister air covered was smaller than in the developing storm case. Instead of expanding with time, the coverage of moister air shrunk. The water vapor near the storm seemed to be influenced by the storm's presence and development; however, the composites suggest that the water vapor far from the storm was a pre-existing feature of the environment. The differently behaving moisture fields can be more clearly seen by taking an areal average of the IPW. Figure 5 presents the averaged IPW within the 11x11 grid domain. The graphs show the IPW values for the individual storms (black lines) and the average storm (red line) over the 48 hour period. The developing storms had an average IPW value of about 6.3 cm that was consistent over time and had little variance among the individual cases. On the other hand, the non-developing cases began with a smaller IPW value that decreased over time and was more variant among the individual storms. The difference between the two storm types was statistically significant throughout the time period, reaching a difference of 0.48 cm by hour 48.

Since the large swath of moist air remained extensive over the time period in the developing cases, it is safe to assume that this was a pre-existing environmental feature that was not a byproduct of the developing storm. This large abundance of moisture may be an influential or necessary factor in tropical cyclogenesis as this feature was not present in most of the non-developing cases. With this large source of water vapor, a tropical disturbance would successfully generate the energy to strengthen. Furthermore, a tropical disturbance that is immediately surrounded by a drier environment would reach its limit of energy production and would not be able to further develop.

An analysis of the vertical distribution of moisture revealed that the composite storms differed most in the 400-600 mb level range. These differences were statistically significant from hours 12-48, where the developing storm reached a relative humidity that was 10% greater than the non-developing storm. A temporal analysis of the 500 mb relative humidity revealed consistent moisture amounts in the developing cases, which suggests a pre-existing abundance of moisture at this level that was not seen in the non-developing cases. These findings support the cyclogenesis theory presented by Bister and Emmanuel (1997). When a storm is developing, it must overcome the hindering effects of downdrafts which are driven by the evaporation of the falling precipitation. As the troposphere becomes more saturated, particularly in the middle levels as seen in the results, evaporative cooling decreases and downdrafts no longer cause anti-cyclonic circulation at the surface. This allows for a consistent rising motion as the air is expelled from the storm in the upper-levels rather than at the surface. Since the tropical boundary layer remains mostly moist and uniform, the excess moisture at higher levels could have been the determining factor that gave a tropical disturbance enough energy to undergo cyclogenesis.

4.b Thermodynamic variables: Temperature

Air temperature is another thermodynamic variable that plays a role in the development of convective storm systems. Cloud clusters form due to the rising of air that is warmer than its immediate environment. Previous studies have shown that this conditional instability must be present through a deep atmospheric layer in order for a system to develop into a tropical cyclone (Gray 1975). The constraints of this study required that the chosen non-developing storms must also show signs of deep conditional instability by having a minimum cloud height and cloud coverage area. Temperature profiles and fields were compared in the evolutions of the

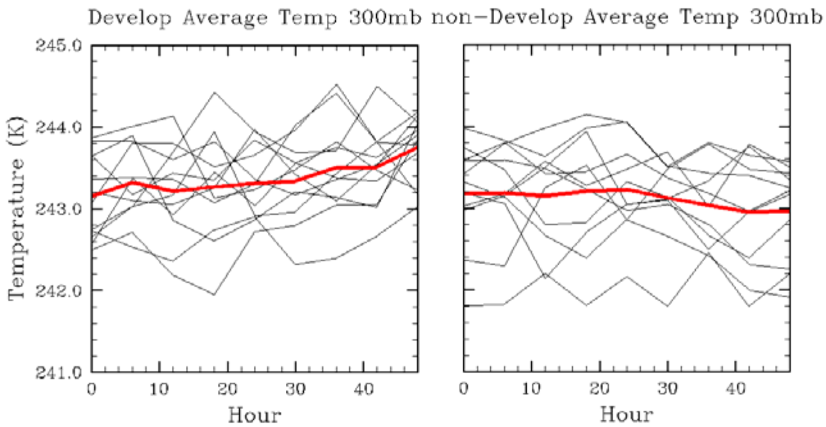

Figure 6. Temperature (in K) at 300 mb averaged over 11x11 grid domain for developing and non-developing storms.

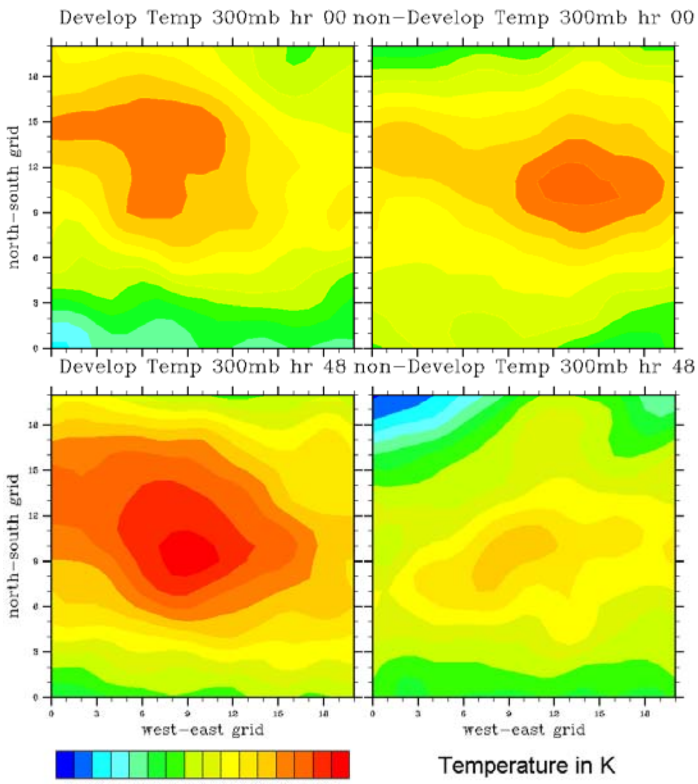

Figure 7. Temperature (in K) at 300 mb for composite developing and non-developing storms at hours 0 and 48.

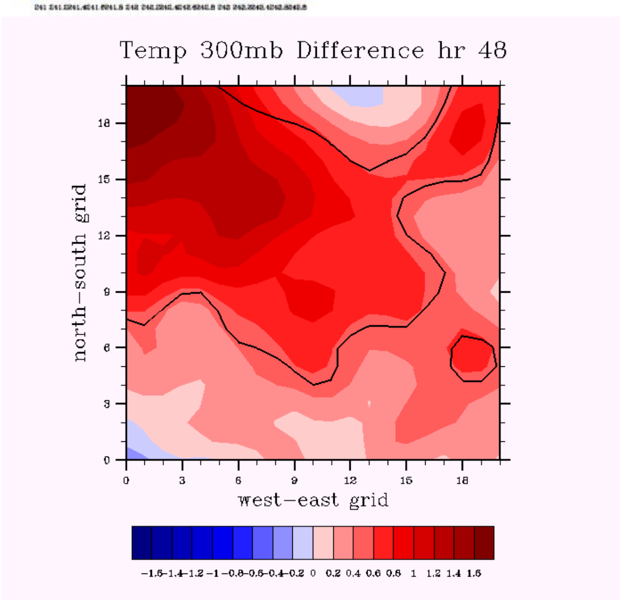

Figure 8. Temperature difference at 300 mb between composite developing and non-developing storms and its statistical significance (black contour line) at hour 48. Values are developing storm minus non-developing storm.

developing and non-developing storms in order to determine if there was a difference that characterized the environments of both types of storms.

An initial comparison of temperature profiles revealed that the largest statistically significant difference occurred at the 300 mb level from hours 36-48. Figure 6 presents the average values over time for the individual storms and the composite storm. These temperature values were averaged over the 5x5 grid domain (all subsequent graphs of this kind will use the same averaging domain). Both storms began with the same average temperature, but towards the end, the developing storm became about 0.8° warmer than the non-developing storm. The significance of the 300 mb temperature is consistent with McBride and Zehr, who found that at this level, the warm core is more pronounced in developing storms. The warmer core at this level is due to increased latent heat of condensing water vapor. This is accompanied by a cyclonic vortex that becomes more intense and deeper in the middle and lower troposphere.

Further analyses were performed on the environmental field. Figure 7 shows the 300 mb temperature of the composite storms at hours 0 and 48. It can be seen that both storms began with an area of warm air, but over time, the developing storm became warmer while the non-developing storm became cooler. The difference and statistical significance at hour 48 is illustrated in Figure 8. The positive values indicate that the composite developing storm had higher values. Those areas where the differences in values are statistically significant (based on the distribution of data) are outlined in black. The developing case had a significantly higher temperature over much of the storm's environment. This large area of warmer air is also consistent with McBride and Zehr as they concluded that the developing storm has a warmer atmosphere over a large horizontal scale. The extent of this warm air mass may be related to the results of the moisture field examined earlier. The higher temperatures over a larger area in the mid-troposphere may allow for rising motion to be dominant over this larger area as long as evaporatively driven downdrafts are hindered by high relative humidity. The abundance of warmer, moister air would then benefit the development of storms.

4.c Dynamic variables: Potential vorticity

The airflow dynamics of an environment have an enormous influence on tropical cyclogenesis occurrences. The necessary conditions, which occur over short time scales, include high low-level vorticity, high upper-level divergence, and low vertical wind shear at the storm's center. Higher low-level vorticity increases the rising motion of air, while higher upper-level divergence allows for this same air to flow out of the storm in the upper troposphere. In order for this airflow to increase and deepen in the atmosphere, there must be low vertical wind shear so that the flow cycle is not disrupted. While previous studies have shown that these are characteristics of developing storms, it should be expected that these parameters in non-developing storms will be present to a lesser degree assuming that they are determining factors for cyclogenesis.

Figure 9 is a vertical cross section of the composite developing and non-developing storms along the center latitude line. This plot presents the storms' potential vorticity (PV) as a function of longitude and pressure for hours 0, 24, and 48. Both storms were seen to have strong vorticity signals from the surface extending into the upper troposphere. Also in both storms, the vorticity signal strengthened over time and developed its maximum value (~1.0 PVU) at the 900 mb level. Similar PV values at this level were expected since this was the criteria for selecting the non-developing storm cases. Based on these plots, the key difference between the developing and non-developing storms was the extension of the strong vorticity signals. The developing

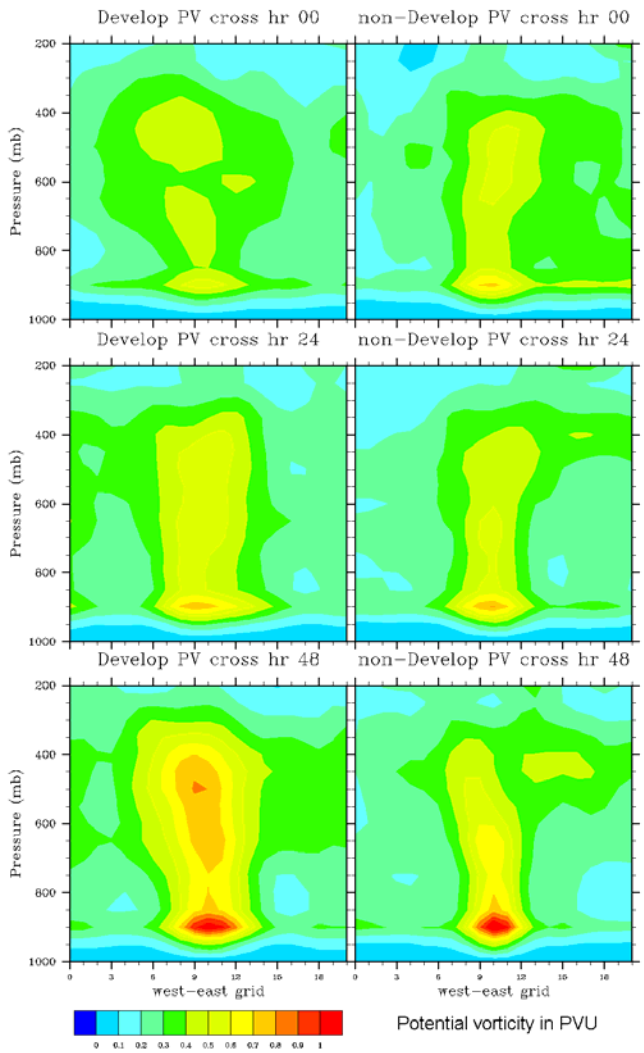

Figure 9. Vertical cross section of potential vorticity (in PVU) for composite developing and non-developing storms at hours 0, 24, and 48.

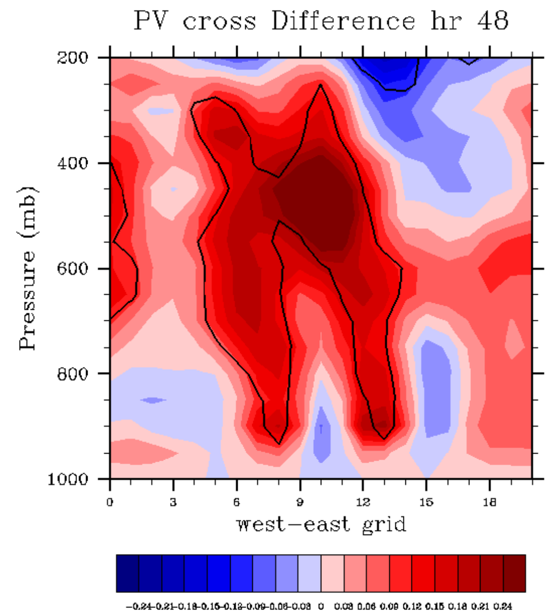

Figure 10. Vertical cross section of PV difference between composite developing and non-developing storms and its statistical significance (black contour line) at hour 48. Values are developing storm minus non-developing storm.

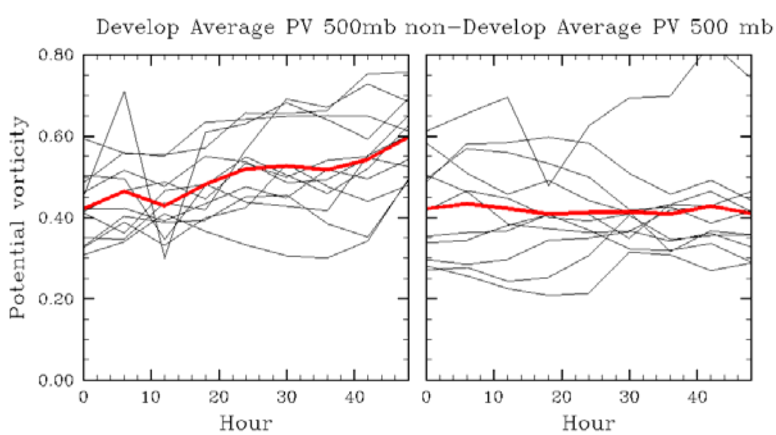

Figure 11. Potential vorticity (in PVU) at 500 mb averaged over 5x5 grid domain for developing and non-developing storms.

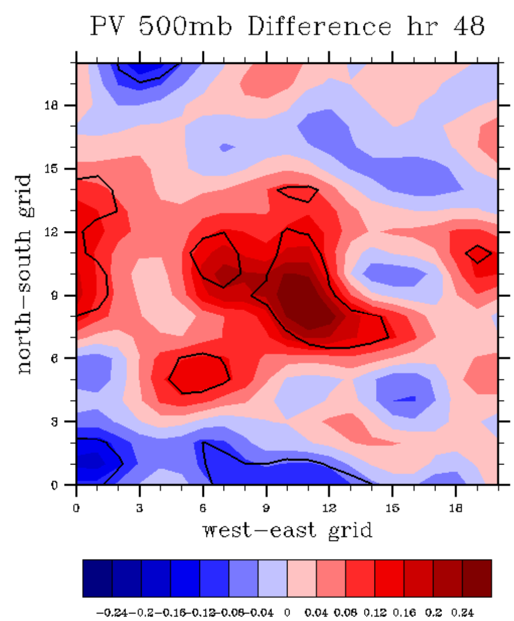

Figure 12. Potential vorticity difference at 500 mb between composite developing and non-developing storms and its statistical significance (black contour line) at hour 48. Values are developing storm minus non-developing storm.

storm had a longer zonal extension than the non-developing storm at every pressure height and at every time. The differences between the storms can be better seen in Figure 10, which is a difference and significance plot of the PV cross section at hour 48. At every hour, the developing storm had substantial statistically significant areas of larger PV values around the vertically structured storm. This is particularly true at hour 48 as the greater extension of the developing storm's vorticity signal is illustrated by the areas of positive difference values. The findings from this cross section can most likely be translated to the other dimensions of the storm, which would suggest that the developing storm has a larger areal coverage of stronger vorticity signals in all directions at all pressure levels. Another difference between the increased PV cross-sections is that the non-developing composite had a PV tower that tilts slightly while the developing PV tower was upright. The non-developing PV tower was more prone to tilting because of its thinner structure. The developing PV tower was less prone to tilting because of its more stable aspect ratio and the increased wind circulation about the storm.

Since the 500 mb pressure level had the largest difference in PV values, this level was chosen for further examination. Figure 11 is a plot of the average 500 mb PV for all storms over time. At hour 24, the greater PV values seen in the developing storm became statistically significant, and reached a difference of +0.187 PVU. The developing storm strengthened in its average 500 mb PV while the non-developing storm remained steady. Although there was some variance between the storms, this behavioral trend suggests that the 500 mb pressure is a key level that distinguishes the two types of storms. Figure 12 is a difference and significance plot of the 500 mb PV at hour 48. This plot illustrates the larger coverage area of stronger vorticity signals in the developing storm. The statistical significance of these areas suggests that a tropical disturbance is more likely to develop if it has a sufficiently large area of increased PV at the 500 mb pressure level. However, it is still unclear from the results as to whether the increased PV signal is a predictor of development or an indicator of development.

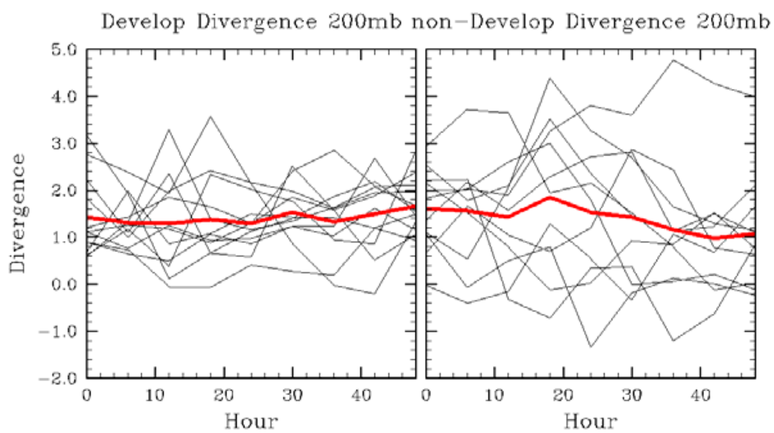

Figure 13. Divergence (in 10^{-5} s^{-1}) at 200 mb averaged over 5x5 grid domain for developing and non-developing storms.

4.d Dynamic variables: Divergence

Figure 13 is a plot of the average 200 mb divergence over time. In both storm types, there did not appear to be a trend in the divergence. There were small differences in values throughout the time period, but due to the sizeable variances, none of the differences were statistically significant. Analyses of the horizontal and vertical distributions also did not show any distinguishable temporal or spatial patterns of divergence. Since divergence is often a difficult quantity to analyze correctly, satellite-based derivations of divergence were examined to assess the accuracy of the NCEP/NCAR analysis. This brief examination showed noticeable differences in the two divergence fields for multiple events. The two analyses agreed on the relative regions of very high divergence, but their values always differed by as much as 10×10^{-5} s^{-1}.

4.e Dynamic variables: Wind shear

The vertical wind shear is a measure of the change in wind speed and direction with altitude. The wind shear vector is the difference between two velocity vectors at certain altitudes. Since tropical disturbances typically extend deep into the troposphere, the wind shear over the entire storm is important in assessing the dynamic conditions of the environment. The wind shear in this study was calculated by subtracting the 900 mb wind field from the 200 mb wind field.

Figure 14 is a plot of the wind shear vectors averaged over all storms and all times. In both the developing and non-developing cases, the wind shear varied very little over time, which allowed for the time average to be an adequate analysis of the wind shear field. In both storm types, there was a clear rotational pattern of the wind shear that is illustrative of the storms' outflow from the center. Also in both cases, the wind shear at the storm's center was near zero. Although McBride and Zehr concluded that cyclogenesis must have near-zero wind shear at the storm's center, Figure 14 suggests that this condition is not unique to just developing storms. The apparent differences in the wind shear fields were the shear values north and south of the storm center. The westerly/southwesterly shear in the north was stronger for the non-developing cases, while the northeasterly shear in the south was stronger for the developing cases. These value

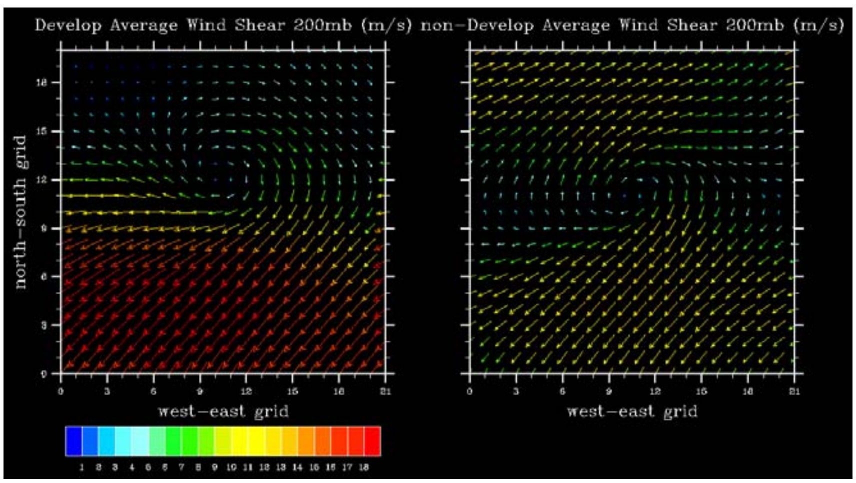

Figure 14. Wind shear between 900 mb and 200 mb levels (in m/s) for composite developing and non-developing storms. Vectors are averaged over all times and all storms.

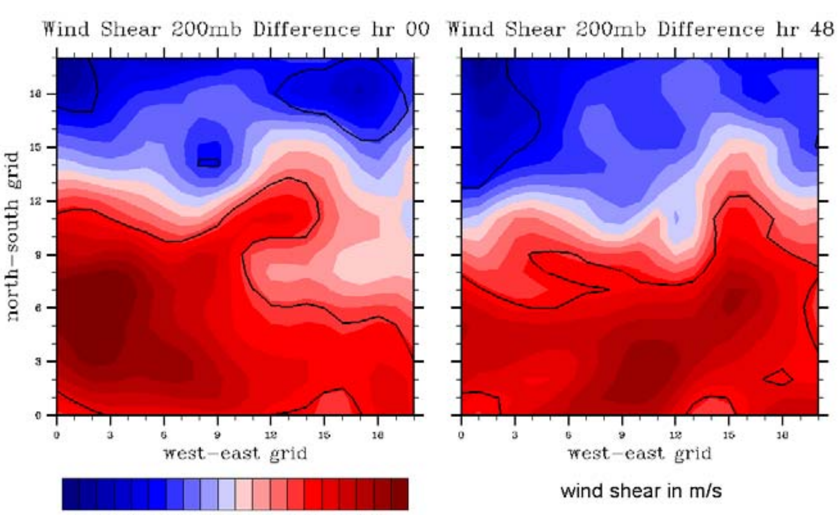

Figure 15. Wind shear difference between composite developing and non-developing storms and its statistical significance (black contour line) at hours 0 and 48. Values are developing storm minus non-developing storm.

differences and their statistical significance are better illustrated in Figure 15, which captures the differences at hours 0 and 48. As it was seen throughout the time period, the beginning and the end both had significantly larger shear just north and south of the storm. However, the statistical analysis showed that the shear to the south was the more significant environmental shear. This finding is partially consistent with McBride and Zehr as they suggested an equal importance of northern and southern shear in tropical cyclogenesis.

A closer analysis of the wind field at multiple levels showed that this northeasterly wind shear was due to stronger easterly winds in the upper troposphere than at the surface. This means that cases of tropical cyclogenesis had significantly stronger higher-level easterlies south of the storm than in the non-developing cases. The consistency of this distinct wind pattern over time demonstrates that this environmental feature was established prior to the storm's development or non-development. Changes in the storm did not have an influence on the larger-scale environment. Also, the reoccurrence of stronger shear to the south in the developing cases and the absence of this stronger shear in the non-developing cases suggest that this feature is an influential factor on tropical cyclogenesis in this region. One plausible explanation would be that the stronger easterlies aloft enhance the outflow that is necessary for a strengthening storm. This stronger wind shear does not hinder the development of the storm because it is sufficiently far from the storm's center, where the wind shear is near zero.

Figure 16 is a difference and significance cross-section of the meridional wind component (V-wind) at hour 48. The developing storm had significantly larger winds on both sides of its center in the lower levels. This is due to its broader surface circulation and is reflective of the broader vorticity fields at these levels. Strong wind shear was also to the east of the center. In the upper levels, the developing storm had significantly smaller meridional winds. This means that its values were larger negative numbers, so the winds were actually stronger. The developing storm's larger surface circulation and stronger wind shear away from the center are both consistent with previous results and the theorized movement of air within a strengthening storm.

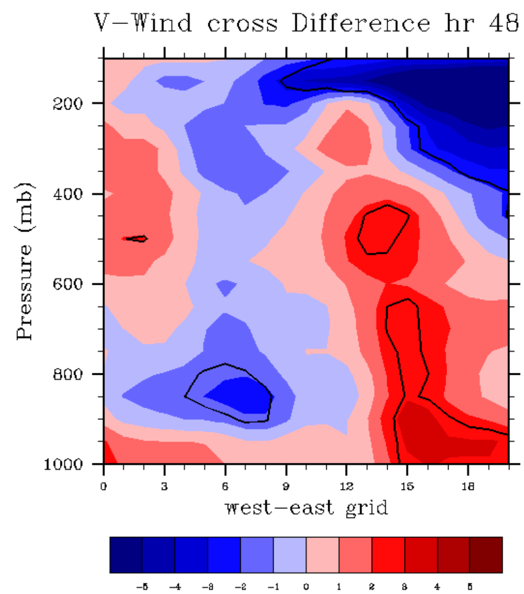

Figure 16. V-wind speed difference between composite developing and non-developing storms and its statistical significance (black contour line) at hours 0 and 48. Values are developing storm minus non-developing storm.

5. CONCLUSIONS

This research compared large-scale environmental features of two types of tropical disturbances: those that developed into tropical cyclones and those that did not. Since several tropical disturbances occur in a given hurricane season, the comparison began by first defining the characteristics of the non-developing storm. After meeting several criteria, 11 non-developing storms were selected to compare with the 12 storms that developed into tropical cyclones during the 2005 Eastern Pacific hurricane season. The major conclusions from the study are the following:

- Cloud clusters are more likely to undergo tropical cyclogenesis in large regions of increased moisture above the boundary layer and greater temperatures in the upper troposphere.
- A storm is more likely to develop large areas of increased PV that penetrate deep into the troposphere.
- Environments with significant northeasterly wind shear to the south of the vortex are more favorable for the storm to undergo tropical cyclogenesis.

The thermodynamic variables, moisture content and air temperature, were analyzed for the two storm types. Although McBride and Zehr concluded that the moisture anomaly with the surrounding environment was similar for both the developing and non-developing storms, the results showed that the difference in moisture content was significant across the larger environment. All of the developing storms were engulfed in large areas of air with increased moisture content, while such large moisture swaths were not present for most of the non-developing storms. The developing storms also only occurred in large swaths of increased temperatures, which allowed for greater moisture content of the air. In particular, the mid-troposphere, (300-500 mb), had significantly larger values and a larger swath area in the developing storm composite. When a disturbance is present in extensive horizontal and vertical distributions of increased moisture and temperatures, it can generate more rising air motion and enhance the middle and lower level cyclonic vortices within the storm. In turn, this disturbance is more likely to undergo cyclogenesis than other storms that are not present in such a thermodynamically favorable environment.

Potential vorticity, divergence, and vertical wind shear were the dynamic variables analyzed in this study. Although the importance of upper-level divergence in cyclogenesis is established and well-documented, the results found that there was no significant difference in the environmental divergence for developing and non-developing storms. On the other hand, the PV fields were significantly different in both the horizontal and vertical directions. The developing storm began at hour 0 with larger horizontal regions of increased PV particularly at the 500 mb level. Over the course of the studied time frame, both storms increased in maximum PV values, but the developing storm continued to have larger swaths of increased PV. During this development stage, larger regions of increased PV near the surface are a signal that evaporatively driven downdrafts are less occurrent. This enhances the ascent of moist air, generating more energy for the storm. The increased PV values are also consistent with the 300 mb warming when considering thermal wind balance. As suggested by Schubert and Hack (1982), the better organized PV may be evidence of the storms' enhanced efficiency due to increased inertial stability within the vortex. A storm is most likely to further develop in this environment, whether the dynamic environment was pre-existing or a result of the storm.

An analysis of the vertical wind shear fields showed that both the developing and non-developing storms had near-zero wind shear at the storm's center. The key difference between the storms was the stronger northeasterly shear to the south in the developing storm. This shear indicated that the upper-level northeasterly winds in the region were stronger in cases of developing storms than in cases of non-developing storms. This suggests that the winds were an established background environmental influence that enhanced the chances for development by aiding the outflow of the storm.

The results from this study identified large-scale features that influenced the development of tropical disturbances into tropical storms. Although the scope of this study was limited to one hurricane season, the distinguished characteristics were significant among the dataset. These characteristic features, which were consistent with the physical processes of cyclone development and sustainment, can be used to assist operational forecasters in predicting the development of certain convective systems in the tropics. This also could contribute to the development of a consolidated theory on tropical cyclogenesis.

6. FUTURE WORK

Several improvements can be made to extend this analysis of tropical cyclogenesis. First, an investigation of more hurricane seasons in several ocean basins can better assess the common environmental influences on tropical cyclogenesis and strengthen the significance of the results. Identifying influential features that are independent of the season or ocean basin can stimulate the development of a general theory. Second, the analysis time frame can be extended beyond 48 hours. By examining environmental influences over longer time scales, relationships between these features and developing or non-developing storms can be better understood. Third, a denser observational network can improve the model's estimations of the state of the atmosphere. More data is needed over the ocean where hurricanes form so that assessments on cyclogenesis can be more accurate. Comparisons with satellite data analyses can determine whether there are important deficiencies in the model analysis data that would provide more about mesoscale structures. These additional features could lead to a better understanding of hurricane formation.

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APPENDIX

Significance testing

The statistical significance of the differences between two datasets is determined by hypothesis testing. Hypothesis tests are used to determine whether or not a dataset is consistent with a hypothesized model. A null hypothesis is a parameter value that describes an established belief about certain data. The null hypothesis used for this test is that the difference between the two datasets is zero ($H_0 = X - Y = 0$). A test statistic T is calculated using the equation:

$$T = \frac{(\overline{X} - \overline{Y}) - H_0}{s\left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{1/2}}$$

where $\overline{X}$ and $\overline{Y}$ are the average of the datasets X and Y, n_1 and n_2 are the number of values in the X and Y datasets, and H_0 is the null hypothesis. The variable s is the pooled estimator of the common variance of X and Y, calculated by

$$s^2 = \frac{\sum(X_i - \overline{X})^2 + \sum(Y_i - \overline{Y})^2}{n_1 + n_2 - 2}.$$

Under the null hypothesis, H_0, T is distributed as the t-distribution with n_1+n_2-2 degrees of freedom. The null hypothesis is rejected at the α significance level if T is greater than or equal to the t-score, $t(1- \alpha/2)$. In the two-sided hypothesis tests in this study, the significance level is 90% ($\alpha = 10$). When the null hypothesis is rejected, the difference between the two datasets is statistically significant (Green and Margerison 1978).