7B.2

MODELING THE EFFECT OF VERTICAL WIND SHEAR ON TROPICAL CYCLONE SIZE AND STRUCTURE

Diana R. Stovern* and Elizabeth A. Ritchie
University of Arizona, Tucson, Arizona

1. Introduction

An ongoing problem in tropical cyclone research is forecasting storm size and structure upon making landfall. Knowing both the size structure of a hurricane upon reaching the coast can help to determine when evacuation orders need to be issued and the magnitude of hazards associated with these powerful and devastating storms. The main hazards associated with hurricanes include; wind damage, freshwater flooding, storm surge, and tornadoes (Anthes, 1982). We can improve our basic knowledge of landfall-impact forecasts by better understanding the mechanisms that effect hurricane structure. The primary mechanisms impacting size and structure are most likely imbalances within the tropical cyclone core and environmental forcing factors. Environmental forcing factors include the mean winds, the large-scale potential vorticity field, cloud properties, oceanic interactions, and vertical wind shear. In this study, we focus on vertical wind shear since the effects that it poses on hurricanes is very well-documented, yet not fully understood.

2. Vertical Wind Shear

Environmental vertical wind shear applied to a developing tropical cyclone has significant implications on size and structure of the storm by changing the symmetry, rainfall distribution, and storm track (Frank and Ritchie 2001). The most common definition of vertical wind shear is a change in magnitude and direction of the upper level winds from the lower level winds. The effect of vertical wind shear on tropical cyclone intensity has been studied since the early 20th century (DeMaria 1995). However, the physical mechanisms associated with the effects of shear on structure and size are generally more vague and unsettled within the research community. It is generally cited that large values of vertical wind shear have a negative impact on the development and intensification of tropical cyclones (Riehl and Shafer 1944, Ramage 1959, Gray 1968, Peng 1999, Frank and Ritchie 2001).

Gray (1968) hypothesized that vertical wind shear “ventilates” the inner part of the storm; the upper level flow advects heat and moisture away from the center of the storm and in turn inhibits storm development. DeMaria (1995) offered the explanation that vertical shear acts to tilt the potential vorticity anomaly in the center of the hurricane which allows for midlevel warming to reduce convective activity. In a study by Frank and Ritchie (2001), it was hypothesized that weakening of a hurricane is induced by asymmetries in the eyewall region caused by vertical wind shear. High values of potential vorticity and equivalent potential temperature are mixed outward rather than into the eye. This allows the shear to ventilate the eye resulting in a loss of the warm core at upper levels, causing the central pressure to rise and the storm to weaken.

DeMaria (1995) posed an important point that although the ventilation process may adversely affect the formation of a tropical cyclone from a low-level disturbance, the

---

* *Corresponding author address:* Diana R. Stovern, Univ. of Arizona, Dept. of Atmospheric Sciences, 1118 E. 4th St., P.O. Box 210081, Tucson, AZ 85721-0081.
Email: dstovern@atmo.arizona.edu

upper-level warm anomaly maximized at the tropopause within the tropical cyclone core acts to stabilize the atmosphere. A process that removes heat from the upper-levels of the tropical cyclone might lead to destabilization, favoring intensification. An alternative hypothesis relating to this concept is that moderate amounts of vertical wind shear within a tropical cyclone may act as a destabilizing mechanism, ventilating the upper warm-core, but not destroying it by transporting too much heat and moisture away from the center. In this respect, the asymmetries associated with the developing cyclone alter the size and structure in a positive way to progress intensification. We test this hypothesis by modeling how a tropical depression vortex changes upon being placed in different shear environments.

3. Methodology

The model used for this study was the Weather Research and Forecast model (WRF-ARW) developed through the National Climate and Research Center (NCAR). The model was set up with 3 domains of 27-, 9-, and 3-km horizontal resolution to adequately resolve different details of the storm including processes involving convection. The inner-most nest was storm following so that detailed structure changes could be adequately observed throughout 120 hours of runtime. Forty-two sigma levels were used with idealized initial conditions within a hypothetical “water world” in order to avoid land-influenced changes within the circulation. Within these domains it was possible to observe how vertical wind shear influenced storm symmetry and intensity from looking at the maximum winds in the inner core and central pressure, and size by looking at the radius of the outermost closed isobar or 34, 50, and 63-knot winds (NHC).

Model schemes used include the rrtm/Dudhia long-wave and short wave radiation scheme along with Kain-Fritsch cumulus physics. The planetary boundary layer physics are supplied by the Mellor-Yamada-Janjic (Eta) TKE scheme with the microphysics being from the WSM 6-class graupel scheme. The shear values imposed are within the range of 5 to 15 m/s in increments of 2.5 m/s. The shear in this case is the difference in magnitude between the 850 hPa and 200 hPa winds. Northerly shear was initialized in the model to allow for the maximum wind velocities to be at the 200 hPa level. A regular tanh profile was used with maximum shear in the center of the profile. Using this method allowed for flexibility in changing the depth and the level at which the maximum shear occurs.

4. Results

4.1 Central Pressure

The model produced 3-hourly output for a period of five days (120 hours). A time series of the lowest central pressure indicates how long it took for the storm to undergo rapid development into a tropical cyclone (Fig. 1).

None of the simulations ever showed signs of reaching a steady state or decay. The 5 m/s shear case underwent rapid deepening within the first 24 hours reaching a quasi steady-state around t = 60 hours; however slight intensification occurred during the last 12 hours where the storm reached a minimum central pressure of 941 hPa. Increasing the amount of wind shear delayed rapid intensification by 48 hours for the 7.5, 10, and 12.5 m/s cases and allowed the storm to obtain much deeper central pressures by t = 120 hours of 921, 903, and 899 hPa, respectively. Intensification was delayed the longest for the 15 m/s shear case allowing the central pressure to only to reach minimum value of 964 hPa. It can be concluded with a fair amount of certainty that a shear threshold of 15 m/s imposed on the environment is too large to favor intensification. Optimal values seem to be around the 10 and 12.5 m/s range for producing the most intense tropical cyclone from a tropical depression.

4.2 Eyewall Development

Radar images every 6 hours from 120 hours of model output are used for observing how the size and structure of the tropical depression changed during intensification. The results in Fig. 2 show the approximate time that the eyewall started to form for shear cases 5 – 15 m/s. Increasing the initial amount of vertical wind shear in the environment prolonged eyewall development. For the 5 m/s shear case, the storm started eyewall development at t = 30 hours. By increasing the shear to 7.5 m/s, the time for the same point of development did not occur until t = 42 hours. Increasing the shear further to 10 m/s extended development to t = 60 hours, 12.5 m/s developed at t = 72 hours, and 15 m/s shear developed at t = 96 hours. What is perhaps more notable is the size of the storm and rainfall distribution upon reaching that point.

As the initial amount of shear increased, the number of spiral rainbands and radial distribution increased. Also apparent are the asymmetries that developed from increasing the shear. In most hurricanes, the distribution of rainfall about the center is not fully symmetric; the heaviest rain usually occurs around the right semicircle, facing in the direction of the storm's motion (Anthes 1982). Not only is this statement consistent with what is observed in this figure, but the wave number one asymmetries as described in Frank and Ritchie's 2001 study of numerically simulated hurricanes are apparent as well.

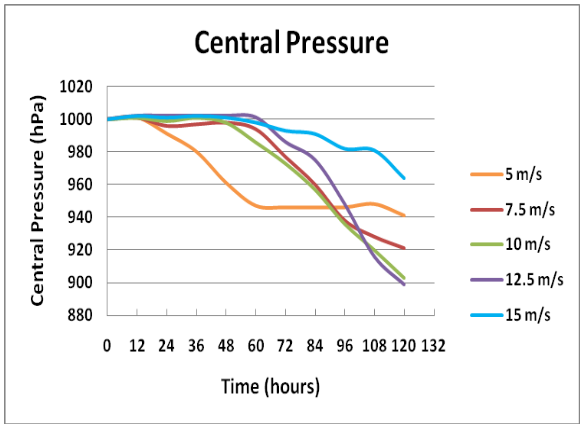

Fig. 1. Minimum central sea level pressure every 12 hours for shear values between 5 and 15 m/s.

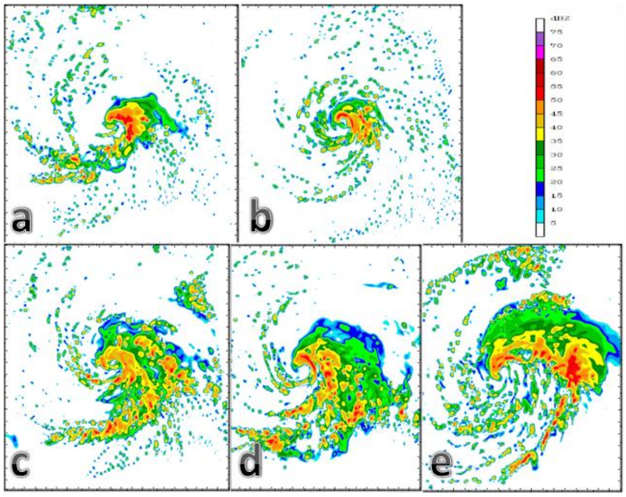

Fig. 2. Radar images showing the approximate time of eyewall formation. (a) 5 m/s shear, t = 30 hrs (b) 7.5 m/s shear, t = 42 hrs (c) 10 m/s, t = 60 hrs (d) 12.5 m/s, t = 72 hrs (e) 15 m/s, t = 96 hrs.

4.3 Radar at 120 hours

By t = 120 hours, each simulation had distinguishable features as a result of increasing the initial amount of environmental wind shear (Fig. 3). For instance, the 5 m/s shear case was the most axisymmetric of each of the five cases, with the least amount of outer rainbands and smallest in total rainfall distribution. In addition, it had the largest inner core implying that the moisture convergence into the center was much stronger. As the initial amount of shear increased to 7.5 m/s, the radius of rainfall intensity in the inner core decreased and the number of outer spiral rainbands increased. Each case became even more asymmetrical with increasing shear, developing a smaller inner core and a larger region of outer rainbands.

For each case, the thickest swath of precipitation biased toward the right side of the storm and became even larger as the shear increased. The eye itself also decreased in radius, and became less elliptical with increasing shear. The eye failed to organize itself by 120 hours in the 15 m/s case. It is clear from these results that 15 m/s of environmental shear inhibits development in the tropical depression. The hypothesis, as stated in section 2, that moderate amounts of shear may favor intensification is supported by these results. Furthermore, these simulations indicate that optimal values for development range between 10 and 12.5 m/s for the largest, most intense tropical cyclone.

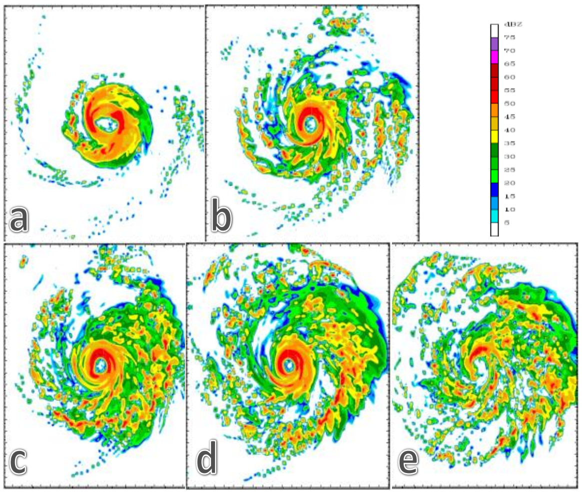

Fig. 3. Radar images of domain 3 showing storm development at t = 120 hours, (a)-(d) are simulations with environmental shear values 5, 7.5, 10, 12.5, and 15 m/s, respectively.

4.4 Radius of 34-kt winds

Changes in size may be correlated with changes in tropical cyclone intensity (Kimball and Mulekar, 2004). Hurricane intensity is generally measured in terms of the radius of 34, 50, and 63 knot winds. In these simulations, identifying the radius of the 34 knot maximum winds at 120 hours is a good indicator of how the initial environmental wind shear imposed on the environment affected the size of the tropical cyclone including intensity (Fig. 4). The 850 hPa level is observed since it is the bottom-most level least likely to be affected by friction. With very little shear to overcome in the 5 m/s case, the storm developed a smaller, more axisymmetric region of winds exceeding 34 knots. Increasing the shear to 7.5 m/s only slightly increased the radius of 34-kt winds, yet caused the shape to become more elliptical and oriented from the NNW to SSE. The size of the ellipse containing the maximum winds increased with increasing shear for cases 10-15 m/s. However, the 15 m/s case at 120 hours is far less organized with a smaller region of winds exceeding 60-kts. The 15 m/s case may have developed the largest radius of 34-kt winds by t = 120 hours, but it is least intense. Therefore, positive correlations between size and intensity for this study only apply to simulations less than 15 m/s.

5. Conclusion

Previous studies modeling the effects of vertical wind shear on tropical cyclone structure conclude the shear results in asymmetries within the vortex, inhibiting intensification (DeMaria 1995, Bender 1996, Frank and Ritchie 2001). The results from this research correlate well with the theory that shear causes asymmetries in the vortex, but environmental shear less than 15 m/s imposed on a tropical depression does not necessarily inhibit development.

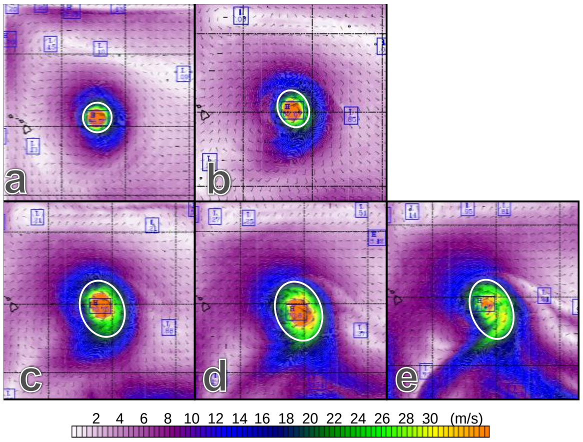

Fig. 4. 850 hPa winds (shaded in m/s). Outlined in white is the radius of 34-kt (17 m/s) winds. (a)-(e) represents shear values 5, 7.5 10, 12.5 and 15 m/s, respectively.

Idealized simulations with environmental shear initialized in the environment were run using WRF-ARW to study the effects of environmental wind shear on a developing vortex. In each simulation, the vortex started out as a tropical depression for the purposes of observing how moderate amounts of shear affect size and structure during intensification. Although each simulation was able to achieve tropical cyclone strength, the size and structure developed quite differently for each case.

Six-hour time steps of radar images created from 120 hours of output not only aided in showing changes in size and structure, but also were useful for observing the time of initial eyewall development. As expected, larger amounts of shear delayed development of the eyewall. It is possible that delayed eyewall development occurred as a result of having to overcome the larger amount of shear imposed.

Each individual case also exhibited large differences in structure and rainfall distribution. Smaller amounts of shear lead to a relatively axisymmetric tropical cyclone with a much larger inner core. Even though the size of the inner-core decreased with increasing shear, the outer rainband structure became more complex. More asymmetries also developed with the strongest convection occurring in the northeast quadrant of the storm. Furthermore, the inner-core of the 15 m/s case was much less organized than each of the cases with lesser shear. The eyewall never completely formed a symmetric region of precipitation, indicating that that this was a much weaker storm.

A time series of central pressure indicated that larger amounts of shear delay tropical cyclone development. Each case was still undergoing intensification by t = 120 hours, but the storm that was by far the weakest was in the 15 m/s case. Perhaps counter-intuitively, the most intense tropical cyclones with the deepest central pressures occurred from initial shear environments of 10 – 12.5 m/s.

The National Hurricane Center incorporates six tropical cyclone size parameters in their operational forecasting procedures. These include: the radius of the eye; radius of maximum winds; mean radius of the outer-most closed isobar; and mean radius of the 34, 50, and 63-kt winds. For the purposes of this study, it was most useful to identify the region 34-kt winds at the 850 hPa level. The 5 m/s shear case developed a fairly small, symmetric area of maximum winds exceeding 34 knots. As the amount of initial wind shear increased the radius of winds exceeding 34 knots increased. The largest storm in terms of the radius of maximum winds was the 15 m/s shear case. However, the magnitude of the winds within this radius was comparatively weaker. This shows not only that 15 m/s of shear is too much to favor development, but that size is not necessarily correlated with intensity.

The most concrete fact we can take away from this study is that an initial environmental shear value of 15 m/s is too large to favor development from a tropical depression into a tropical cyclone. It seems that optimal environmental shear values favoring intensification from a tropical depression into a tropical cyclone are in the range of 10 to 12.5 m/s. These cases created the most intense storms in terms of maximum central pressure and radius of maximum winds.

6. Future Work

Currently, there is no direct correlation between vertical wind shear and tropical cyclone intensification. Calculating the vertical shear throughout different stages of intensification may be useful in explaining why these particular shear thresholds of 10 – 12.5 m/s are ideal for the most intense tropical cyclone. It may also be useful to use the model output to graph precipitation rates and vertical velocities through time to have a more complete idea of how the structure is changing. In addition, the results from the central pressure time series indicated that each storm was still intensifying by t = 120 hours. Running the model out longer may be useful in finding a correlation between environmental wind shear and time of decay.

Acknowledgements. This work has benefited from help from Mr. S. Felker. Funding for this research has been provided by the National Science Foundation. The WRF model was provided by NCAR.

7. References

Anthes, R. A., *1982: Tropical Cyclones: Their Evolution, Structure and Effects. Meteor. Monogr*., No. 41, Amer. Meteor. Soc., 208 pp.

DeMaria, M., 1996: The effect of vertical wind shear on tropical cyclone intensity change. *J. Atmos. Sci*., **53**, 2076-2087.

Frank, W. M. and E. A. Ritchie, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev*., **129**, 2249 -2269.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669-700.

Kimball, S. K. and M. S. Mulekar, 2004: A 15-year climatology of North Atlantic tropical cyclones. Part I: Size Parameters. *J. Climate*, **17**, 3555-3757

Peng, M. S., B.- F. Jeng, and R. T. Williams, 1999: A numerical study on tropical cyclone intensification. Part 1: Beta effet and mean flow effect. *J. Atmos. Sci.*, **56**, 1404-1423.

Riehl, H., ad R. J. Shafer, 1944: The recurvature of tropical storms. *J. Meteor.*, **1**, 42-54.

Ramage, C. S., 1959: Hurricane Development. *J. Meteor*., **16**, 227-237.