9.2 THE RELATIONSHIP BETWEEN VERTICAL SHEAR, STORM MOTION, AND RAINFALL PATTERNS PRODUCED FROM NUMERICAL SIMULATIONS OF TROPICAL CYCLONES

Robert F. Rogers*
NOAA/AOML Hurricane Research Division

1. INTRODUCTION

It is well-known that forecasting the amount and distribution of rainfall that accompanies a tropical cyclone (quantitative precipitation forecasting, or QPF) is one of the most difficult tasks in predicting the impact of a landfalling tropical cyclone. Factors that affect rainfall distributions include the translational speed of the storm, topography and orientation of the coast, and interactions with the environmental wind and thermodynamic fields. These effects can combine to produce vastly different rainfall distributions for different storms, even for the same storm at different periods in its lifetime. The work presented here focuses on one factor, the vertical shear of the environmental wind, and investigates its role in governing tropical cyclone rainfall distributions.

2. METHODOLOGY

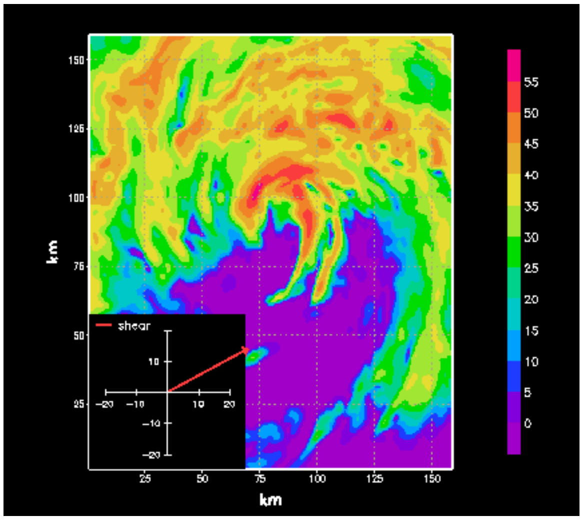
To address the issues described above, high-resolution numerical simulations of various tropical cyclones have been conducted during the past few years to produce a dataset encompassing a variety of tropical cyclone strengths, motions, and rainfall distributions, as well as a variety of environmental shear profiles. The numerical model used is the Penn State/NCAR mesoscale model MM5, a well-documented mesoscale model that has been used in a variety of environments and applications, including tropical cyclone cases (e.g., Liu et al. 1997, Braun 2002, Rogers et al. 2002). Three storms have been simulated here with a reasonable amount of success: Hurricanes Bonnie and Georges from 1998 and Hurricane Floyd from 1999. Simulation lengths range from 5 days for Hurricane Bonnie to 7 days for Hurricane Floyd. A movable-mesh technique has been developed for MM5 that enables a high-resolution domain to follow the storm for considerable periods of time, providing the ability to resolve changes in the inner core over time periods that allow for potentially significant changes in the environment of the storm. The highest-resolution domain for the simulations is 1.67 km for Hurricanes Bonnie and Floyd and 5 km for Hurricane Georges.

The three storms simulated encountered significantly different environments. Hurricane Bonnie encountered strong northwesterly and westerly across-track shear for much of its lifetime (not shown), though the shear weakened and became along-track as the storm approached the North Carolina coast. Hurricane Floyd encountered very weak shear (not shown) and became quite intense, approaching Category 5 strength before being affected by a mid-latitude trough and turning to the north just before hitting Florida and bringing copious amounts of rain to North Carolina. Hurricane Georges was embedded in westerly shear as it was in a region of deep low-level easterlies as it tracked through the eastern and northern Caribbean (not shown), only to change to northerly and northeasterly shear as the low-level flow became southerly. The impact of these changing environmental flow fields on the rainfall fields produced by the storms is the subject of the next section.

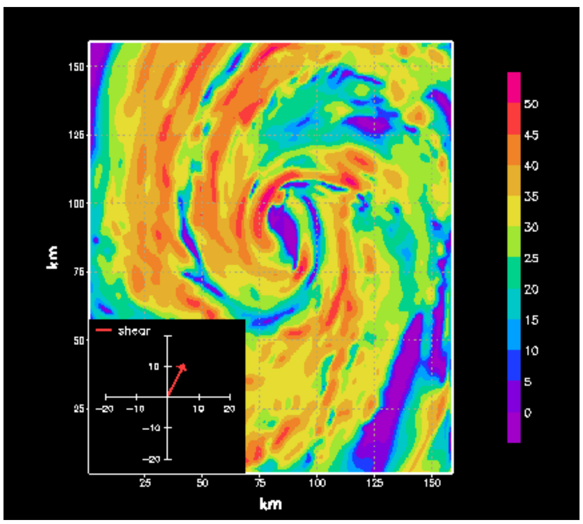
3. RESULTS

Figure 1 shows model-derived reflectivity at 650 hPa for the simulation of Bonnie at two different times – when the shear is strong and across-track and weaker and along-track. From this figure it is clear that the azimuthal distribution of convection in the core follows the conceptual model developed from observational and theoretical studies over the past several years: convection in the core tends to become concentrated on the left side of the storm, when looking downshear. This is especially evident when the shear is strong (> 20 m s^{-1}; Fig. 1a). As the shear weakens to about 10 m s^{-1} (Fig. 1b) the convection becomes more symmetrically distributed around the storm. A plot of the 12-hr total rainfall produced by the storm along with 12-hr averaged shear and storm heading vectors (Fig. 2) shows considerably different rainfall patterns. When the

* *Corresponding author address:* Robert Rogers, NOAA/AOML Hurricane Research Division, 4301 Rickenbacker Causeway, Miami, FL 33149, e-mail: Robert.Rogers@noaa.gov



(a)

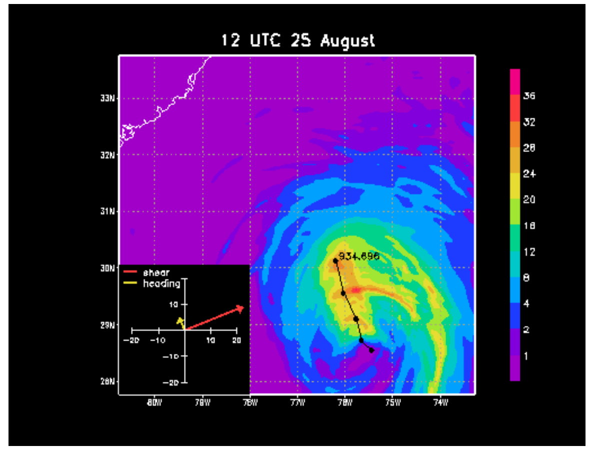


(b)

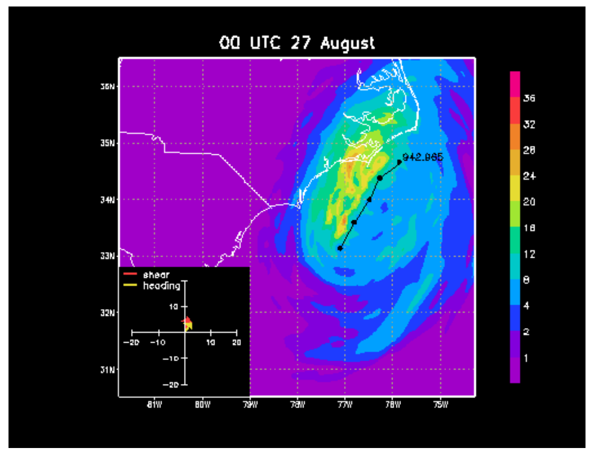
Figure 1. Plot of model-derived reflectivity at 650 hPa for Hurricane Bonnie at (a) 06 UTC 25 and (b) 18 UTC 26 August 1998. Box in lower-left corner denotes the shear of the 900-400 hPa environmental wind (m s^{-1}) valid at same time.

shear is strong and across-track the rainfall pattern is relatively symmetric across the track of the storm, with peak values coinciding with the areas traversed by the center of the storm and smaller rainfall amounts at locations displaced from the storm track. When the shear is weaker and along-track in the direction of storm motion the rainfall is maximized on the left side of the track.

Similar analyses were performed for the simulation of Hurricane Floyd. Figure 3 shows the reflectivity when Floyd is encountering weak



(a)



(b)

Figure 2. Plot of 12-hr accumulated rainfall for Hurricane Bonnie ending at (a) 12 UTC 25 and (b) 00 UTC 27 August 1998. Box in lower left corner shows 12-hr averaged 900-400 hPa shear of the environmental wind (red arrow; m s^{-1}) and 12-hr averaged storm heading (yellow arrow; m s^{-1}). Black line shows track of storm over previous 12-hr time period; number shows minimum sea-level pressure at time indicated.

shear (<5 m s^{-1}). The convection is symmetrically distributed around the core. Figure 4 shows rainfall, shear, and storm motion fields at two times, when the shear is about 7 m s^{-1} and has a component both along the storm motion vector (Fig. 4a) and when the shear is very weak (Fig. 4b). At both times the rainfall pattern shows a double-maximum pattern across the track of the storm, with a minimum value corresponding to the path traversed by the center of the storm and maximum values located at distances from the storm track corresponding to the radius of the maximum convection within the core.

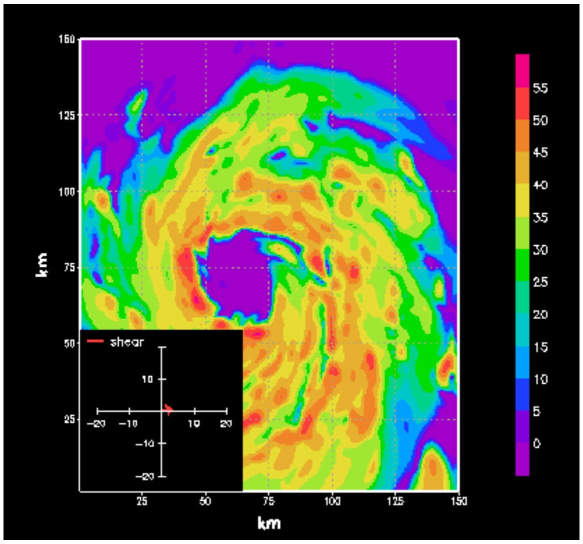
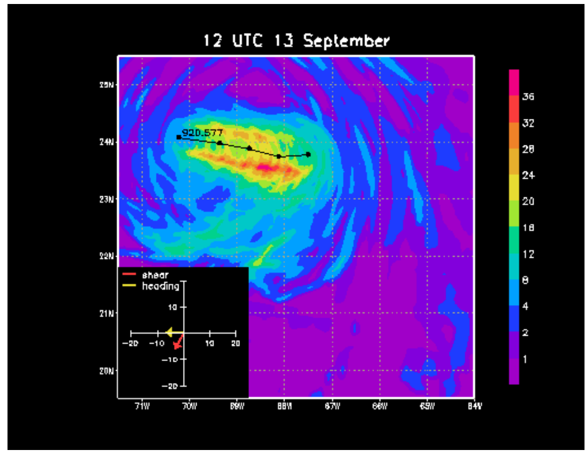


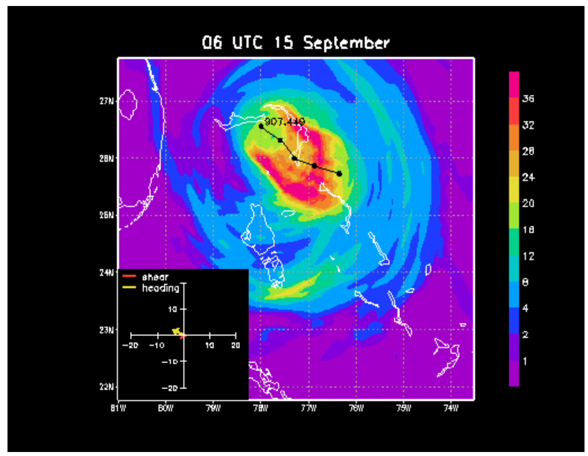
Figure 3. Same as Figure 1, but for Hurricane Floyd at 00 UTC 13 September 1999.

The simulation of Hurricane Georges encounters shear (≈5-10 m s^{-1}) that changes from mostly across-track but with a component of the shear vector antiparallel to the motion of the storm (Fig. 5a) to shear that is still largely across-track but that changes by 180 degrees to have a component parallel to the motion of the storm (Fig. 5b). When the shear vector has a component antiparallel to the storm motion the rainfall field is maximized on the right side of the storm track, but when the shear vector has a component parallel to the storm track the rainfall maximum switches to the left side of the storm track.

These results for different storms in different environments suggest that a fairly robust relationship exists between environmental shear, storm motion, and total rainfall (Fig. 6); namely, when the shear is weak, the rainfall tends to show a double peak whose minimum is centered on the track of the storm. When the shear is strong, then for across-track shear the maximum rainfall is centered along the track of the storm and decreases with increasing distance from the track. For along-track shear parallel to the direction of motion of the storm, the rainfall is maximized on the left side of the storm track, while for along-track shear antiparallel to the direction of motion of the storm the rainfall is maximized on the right side of the storm track.



(a)

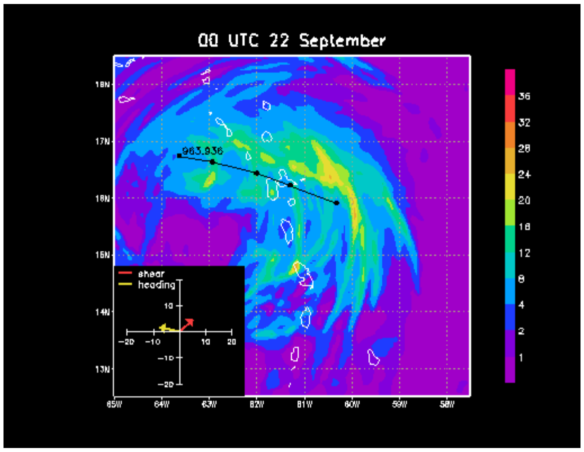


(b)

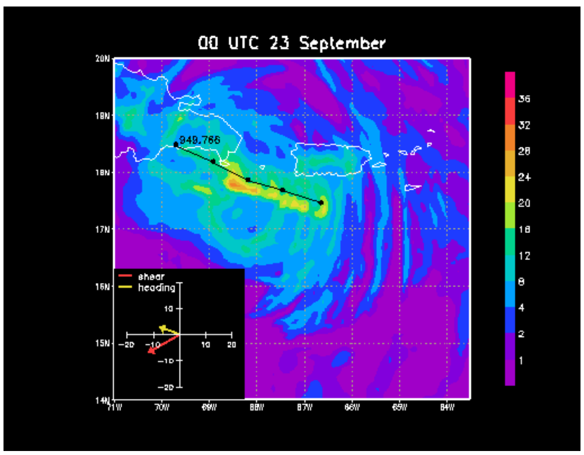
Figure 4. Same as Figure 2, but for Hurricane Floyd at (a) 12 UTC 13 and (b) 06 UTC 15 September 1999.

4. FUTURE WORK

Future work will involve testing these ideas with simulations of additional storms to provide a more statistically robust dataset with which to refine these concepts. Also, observed rainfall fields from the NASA TRMM satellite can be combined with global-model analyses of environmental shear to produce a plethora of observations against which these ideas can be tested and quantified. The relationships obtained from this work can potentially add skill to the rainfall CLIPER that has recently been developed.



(a)



(b)

Figure 5. Same as Figure 2, but for Hurricane Georges at (a) 00 UTC 22 and (b) 00 UTC 23 September 1998.

REFERENCES

Braun, S.A., 2002: A cloud-resolving simulation of Hurricane Bob (1991): Storm structure and eyewall buoyancy. *Mon. Wea. Rev.*, **130**, 1573-1592.

Liu, Y., D.-L. Zhang, and M.K. Yau, 1997: A multiscale numerical study of Hurricane Andrew (1992). Part I: Explicit simulation and verification. *Mon. Wea. Rev.*, **125**, 3073-3093.

Rogers, R.F., S.S. Chen, J.E. Tenerelli, and H.E. Willoughby, 2002: A numerical study of the impact of vertical shear on the distribution of rainfall in Hurricane Bonnie (1998). *Mon. Wea. Rev.*, in press.

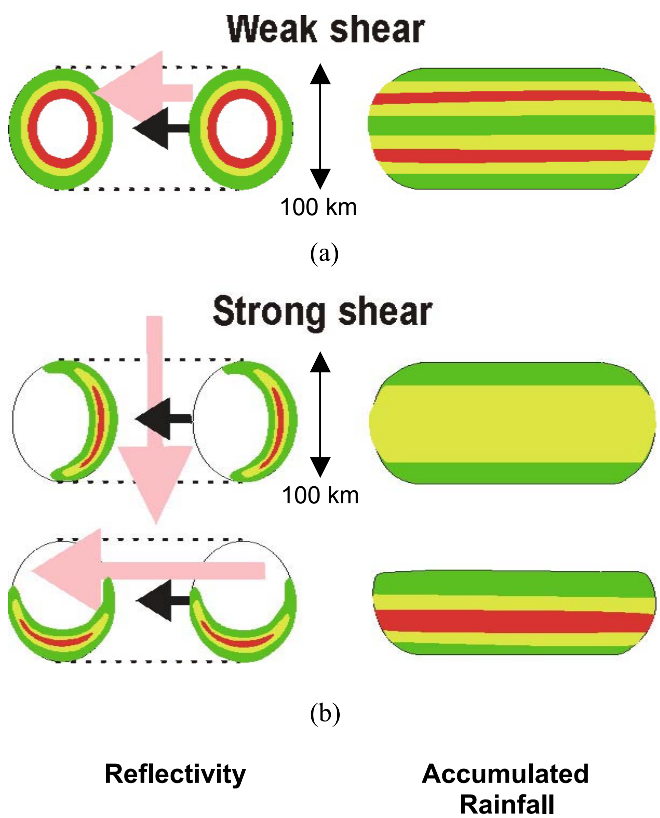


Figure 6. Idealized schematic showing relationship between environmental shear, storm motion, and total rainfall for a case with (a) weak shear and (b) strong shear. In both (a) and (b), the left column shows the environmental shear vector (large pink arrow) and storm heading (black arrow), and a representation of radar reflectivity within the core. In the right column is a representation of the total accumulated rainfall pattern produced by the storm traveling over the distance indicated at the left. Green values are relatively low values of rainfall, increasing to a maximum depicted by the red. For the strong shear example, the case where there is across-track shear is shown in the first example, while along-track shear is shown in the second example.