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A NUMERICAL INVESTIGATION OF THE EFFECT OF VERTICAL WIND SHEAR ON TROPICAL CYCLONE INTENSIFICATION

M.E. Nicholls and R.A. Pielke
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

1. INTRODUCTION

It is well known that when strong vertical shear exists within a tropical cyclone environment that intensification is strongly inhibited and that the storm may even decay (Gray, 1968; Zehr, 1976; Lunney, 1988). However, it is less certain what magnitude of the vertical wind shear will have a significant impact on the intensification rate. In this paper, numerical simulations of the development of an initial vortex in a non-sheared environment (the control) and a weakly-sheared environment (3 m s^{-1} across the depth of the troposphere), are compared.

2. THE MODEL

The cloud model used in this study is the Colorado State University Regional Atmosphere Modeling System (RAMS; described, for example, in Pielke et al., 1992). The model contains a full set of non-hydrostatic compressible dynamic equations, a thermodynamic equation, and a set of microphysics equations for water- and ice-phase clouds and precipitation. There are parameterizations for longwave and shortwave radiation, surface fluxes and subgrid-scale fluxes. The model has a two-way interactive multiple nested grid capability which makes it possible to resolve cumulus convection in the convectively active region of the tropical cyclone. The nested grids can be moved so that the convection can be kept within the center of the fine grid. Lateral boundaries of the coarse grid incorporate a radiation boundary condition to allow propagation of gravity waves out of the domain. A rigid lid is used for the upper boundary condition and a weak dissipative layer is included at the top of the domain to reduce reflection of upward propagating gravity waves.

3. THE MODEL CONFIGURATION AND INITIALIZATION

Three grids are used with horizontal grid increments of 36 km, 12 km, and 4 km. The number of horizontal grid points for the three grids are 60 for the coarsest grid, 62 for the second grid, and 92 for the third or finest grid. Therefore, the width of the coarse grid is 2124 km, the second grid 732 km, and the fine grid 364 km. There are 27 vertical levels, with a grid increment of 450 m at the surface. The vertical grid increment is gradually stretched to the top of the domain which is at 21 km. The latitude of the center of the model is 20°N. The sea surface temperature is set to 302 K. The model temperature is initialized using an Atlantic hurricane season sounding (Jordan, 1958). The humidity profile is slightly moister than the Jordan (1958) sounding to be more representative of the environment in which hurricanes usually develop. The model is initialized with a deep cyclonic vortex in gradient wind balance. The maximum wind speed is 20 m s^{-1} at a radius of 40 km. For the weak wind shear simulation, a geostrophically balanced horizontally homogeneous westerly wind shear is prescribed, having zero wind speed at the surface, increasing to 3 m s^{-1} at 12 km. The fine grid and second grid move so as to keep the minimum pressure in the center of the domains.

4. RESULTS

Figure 1 shows the minimum surface pressure versus time for the two simulations. For the non-sheared case, the surface pressure decreased most rapidly after t = 20 h. At t = 30 h the minimum pressure is 964 mb, which is 54 mb below the environment. The weakly-sheared case shows a rapid drop in surface pressure in the early stages of the simulation reaching a minimum at t = 11 h. Subsequently the minimum surface pressure increases so that by t = 30 h it is only 10 mb below that of the environment. The early rapid development for the weakly-sheared case was associated with a dynamically induced region of upward motion that developed at low levels on the southeast side of the vortex. This upward motion initiated convection and when this convection rotated cyclonically around the low pressure center an intense cell developed on the north side of the vortex. This is illustrated in Figure 2, which shows a horizontal cross section of the wind vectors and vertical velocity at z = 4.6 km and t = 6 h for the weakly-sheared case. The peak updraft strength is 21 m s^{-1} at this level. The reason for the development of the intense convective cell on the north side of the vortex may have been because the upper level warm core was advected eastward relative

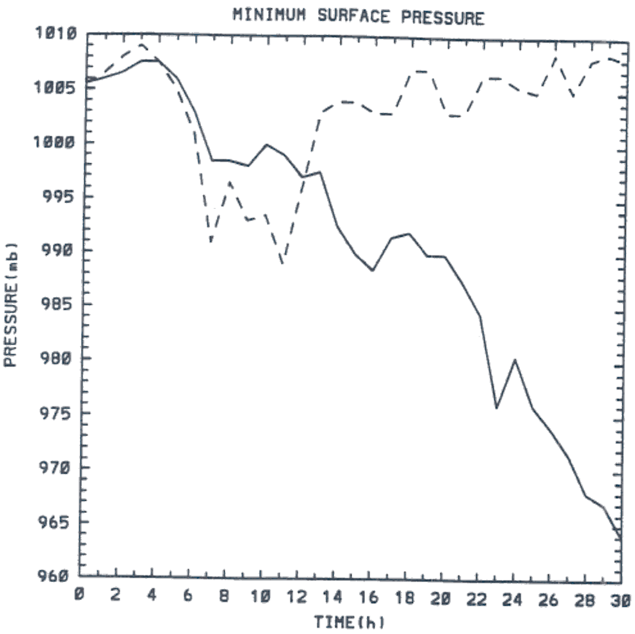

Figure 1: Minimum surface pressure versus time for the non-sheared environment (solid) and the weakly-sheared environment (dash).

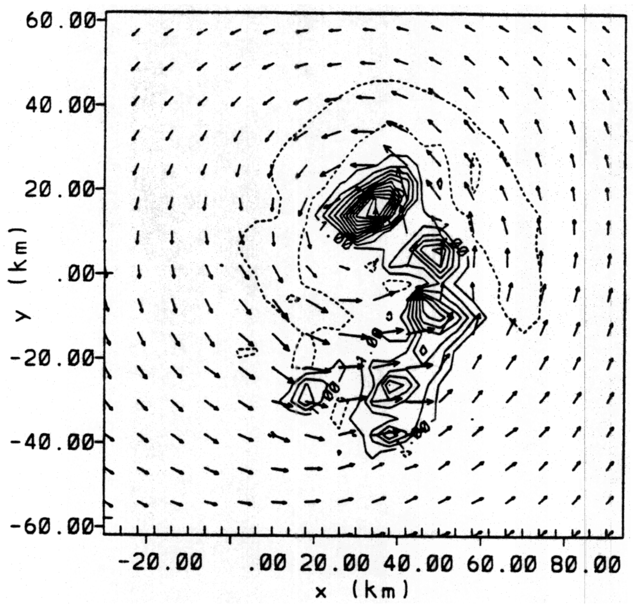

Figure 2: Horizontal cross-section of the wind vectors (maximum wind speed is 36 m s^{-1}) and vertical velocity (contour interval is 2 m s^{-1}; solid is upward motion and dash is downward motion), at z = 4.6 km and t = 6 h.

to the low-level air so that there was a large amount of convective available potential energy for the developing convection at this location. Coincident with the rapid development of convection the radius of maximum wind contracted and by t = 11 h was only 6 km. This is in contrast to the non-sheared case which had a more circularly symmetric region of convection and a more gradually decreasing radius of maximum winds.

Figure 3 shows the total hydrometeor mass in the fine grid domain versus time for the two simulations. Even though the weakly-sheared case did not intensify to

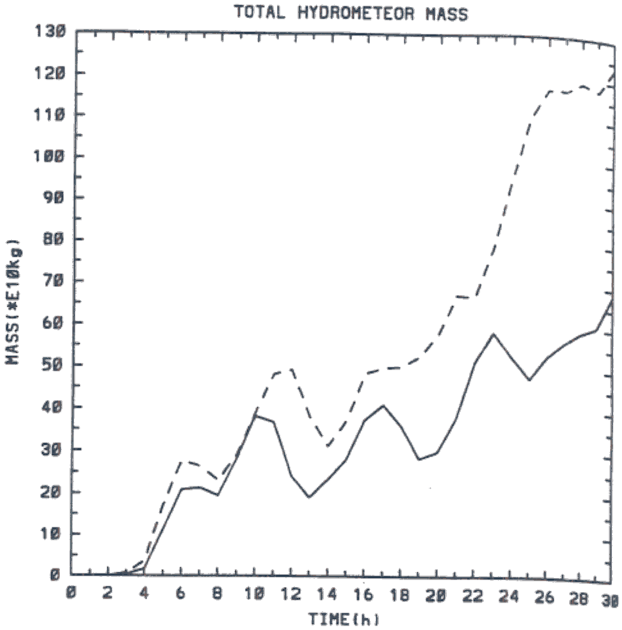

Figure 3: Total hydrometeor mass versus time for the non-sheared environment (solid) and the weakly-sheared environment (dash).

hurricane strength the total hydrometeor mass was more than for the non-sheared case. Pulsations in the hydrometeor mass are evident, particularly for the non-sheared case. The reason why there is more convection for the weakly-sheared case requires further analysis, but may be because the vortex advects eastward with the steering flow and convection can feed on air which is less modified by convective downdrafts than it is for the non-sheared case. Another interesting aspect of the weakly-sheared case is that there is a significantly larger cross-isobars component of the flow at low levels than for the non-sheared case. Again, this may be due to the eastward advection of the warm core aloft and the corresponding movement of the surface pressure minimum. Since the surface pressure minimum is constantly influencing new air the low-level flow may be less close to gradient wind balance than for the non-sheared case.

Figure 4 shows the tangential wind speed at t = 30 h. The non-sheared case has a maximum wind speed of 56 m s^{-1} at a radius of 18 km. The weakly-

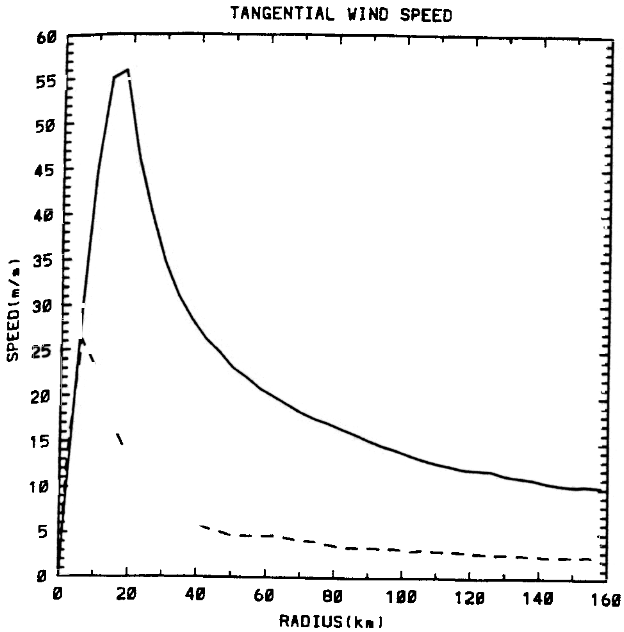

Figure 4: Tangential wind speed versus radius from the minimum surface pressure, for the non-sheared environment (solid) and the weakly-sheared environment (dash), at $t = 30$ h.

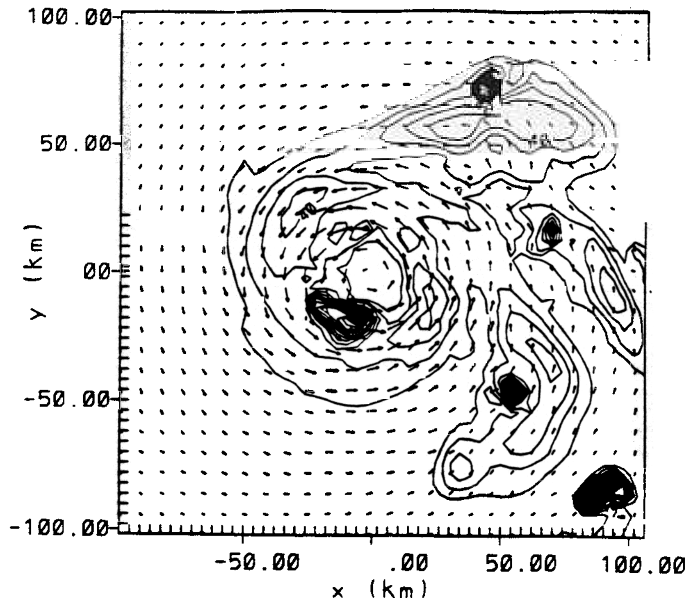

Figure 5: Horizontal cross-section of the wind vectors (maximum wind speed is 50 m s^{-1}) and ice mixing ratio (contour interval is 1 g kg^{-1}), at $z = 6$ km and $t = 30$ h.

sheared case has much weaker winds with a maximum of 26 m s^{-1} occurring at a smaller radius of 6 km. Figure 5 shows wind vectors and ice mixing ratio (pristine ice, aggregates and graupel) at $t = 30$ h and $z = 6$ km for the non-sheared case. An eye is evident and a strong cyclonic circulation. The weakly-sheared case was much less organized with only a barely discernible cyclonic circulation at this level and it did not form an eye (not shown).

5. CONCLUSIONS

There are major differences between the non-sheared and weakly-sheared simulations. The weakly-sheared case failed to intensify, whereas the non-sheared case produced a strong hurricane by $t = 30$ h. Nevertheless, the total hydrometeor mass was larger for the weakly-sheared case than for the non-sheared case. The initial condition, consisting of a vertically oriented vortex in a sheared environment is idealized and so some caution should be exercised when interpreting these results. Further experiments are planned with the tropical cyclone being allowed to develop in a non-sheared environment for 12 h, after which the wind shear will be gradually increased for a 12 h period. This should be a more realistic model of a developing tropical cyclone moving into a sheared environment.

6. ACKNOWLEDGMENTS

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